Climate Policy

ISSN: 1469-3062 (Print) 1752-7457 (Online) Journal homepage: www.tandfonline.com/journals/tcpo20

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CLIMATE POLICY
https://doi.org/10.1080/14693062.2024.2443464

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ABSTRACT

Addressing the increasingly urgent climate crisis requires a profound transformation of traditional high-emission technologies. Emissions trading systems (ETSs), as a typical market-based environmental policy instrument, are intended to incentivise technological innovation for climate change mitigation (TICCM). However, reviews of the evidence for this relationship are often methodologically unsystematic, analytically limited and vary in conclusions. In response, we establish a rigorous and transparent procedure to systematically review and synthesise evidence from 78 selected papers published between 2001 and 2023 on the impact of ETSs on TICCM. Our findings indicate that the European Union ETS (EU ETS) and China ETS (CN ETS) pilots exert positive and statistically significant impacts by incentivising technological investment, patenting, and the adoption of new technologies, despite some limited evidence of null or negative impacts. The heterogeneity of incentive impact in different industries and regions is the primary cause of divergent conclusions in the literature. Variations in the study periods and the subjects investigated account for part of the observed discrepancies. Although the incentive effect is significant, its extent is moderate and potentially weaker for long-term and radical TICCM impacts. The incentive effect is largely limited by insufficient stringency and high uncertainty of the ETSs. Coordinated efforts to address these limitations are crucial for bolstering the innovation incentives from the ETSs. Lastly, evidence of the impact of ETSs on TICCM remains incomplete. The limited focus on heterogeneity across industries, regions, and technologies, along with the lack of evaluation of recent incentive effectiveness, restricts a comprehensive understanding of ETS incentive effectiveness.

Key policy insights

- The European Union ETS (EU ETS) and China ETS (CN ETS) pilots have generally provided positive and statistically significant incentives for multiple stages of technological innovation for climate change mitigation (TICCM).
- The incentives from the EU ETS and CN ETS pilots for TICCM remain moderate. Achieving climate goals will require enhancing the effectiveness of ETS-driven innovation incentives.
- The effectiveness of ETS incentives varies across regions and sectors. Sector- or region-specific adjustments are necessary to broaden the impact of these incentives.
- Collaboratively enhancing the stringency and reducing the uncertainty of the ETSs is a critical avenue for boosting incentives for TICCM.

ARTICLE HISTORY
Received 13 June 2024
Accepted 10 December 2024

KEYWORDS
ETS; climate policy; technological innovation for climate change mitigation; induced innovation; stringency; uncertainty

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/14693062.2024.2443464.

1. Introduction

Technological innovation for climate change mitigation (TICCM) has advanced substantially in recent years (Blanco et al., 2022). However, it needs to further accelerate to help address the climate crisis (Dhakal et al., 2022). Innovation and environmental economists have argued that due to the double externalities of knowledge spillovers and the environment, fostering adequate incentives for such technological innovation is unlikely in a free market setting (Jaffe et al., 2005; Popp et al., 2010; Rennings, 2000). Additional interventions are thus required to incentivise TICCM (Borghesi et al., 2015a; Rennings, 2000).

Environmental regulation is critical for incentivising environmentally beneficial innovation (Jaffe et al., 2002; Jaffe et al., 2005; Rennings, 2000; Rennings & Rexhäuser, 2011). While standard economic reasoning posits that environmental regulation can hinder innovation by increasing production costs and thus crowding out resources from innovation (Chen et al., 2021; Ren et al., 2022), the Induced Innovation Hypothesis and the Weak Porter Hypothesis argue otherwise. The former suggests that regulation can implicitly or explicitly raise the costs of environmental factor inputs, thereby incentivising innovation aimed at reducing their use (Hicks, 1963; Jaffe et al., 2002). The latter suggests that well-designed environmental regulation can limit profit opportunities for businesses, thereby encouraging innovation to address the constraint (Jaffe & Palmer, 1997; Porter & Linde, 1995).

Emissions trading systems (ETSs) are seen as a key policy tool for incentivising TICCM due to their cost-effectiveness and ability to provide dynamic and sustainable innovation incentives (Jaffe et al., 2002; Liu et al., 2022; Rennings, 2000; Requate, 2005; Rogge et al., 2011a). However, studies assessing the impact of ETSs on TICCM have yielded divergent insights, even reflected in review studies. Several review articles synthesising empirical evidence on the European Union ETS (EU ETS) suggest that it has positively influenced innovation investment, research and development (R&D), and adoption of new technologies (Joltreau & Sommerfeld, 2018; Laing et al., 2014; Teixidó et al., 2019). Conversely, Mandaroux (2023) concluded that the EU ETS has not demonstrated effectiveness in promoting the technological innovation needed to achieve long-term climate targets. Similarly, Lilliestam et al. (2020) reported insufficient support for the argument that the ETS incentivises technological innovation towards net-zero carbon emissions. Such conflicting evidence may hinder research progress and adversely affect policy development and adoption.

There are three further main limitations in the existing reviews. First, most of them focus only on the evidence of the EU ETS ignoring other important ETSs, such as China ETS (CN ETS), Korea ETS and California ETS (Hermwille et al., 2015; Joltreau & Sommerfeld, 2018; Laing et al., 2014; Mandaroux et al., 2023; Teixidó et al., 2019). Second, several studies examine the effects of ETSs on specific aspects of TICCM. For instance, Laing et al. (2014) evaluated only investment in low-carbon technologies, addressing just one facet of TICCM rather than offering a comprehensive view of its broader processes. Third, most existing reviews are not systematic, with some studies lacking transparency in their methods for literature search, screening, and validity assessment. This can introduce bias into their conclusions. Therefore, there is a clear need to improve both study methodology and scope to better clarify the current state of knowledge on the impact of ETSs on TICCM.

We seek to systematically synthesise the existing evidence on the role of ETSs in TICCM. A transparent and rigorous evidence synthesis process was developed based on a novel framework in which a citation-chasing search strategy was used to minimise bias from missing evidence. A total of 78 modelling, qualitative and quantitative studies on various ETSs worldwide published between 2001 and 2023 were selected for the evidence synthesis. Our article synthesises the evidence on the effectiveness of ETSs on TICCM with a focus on the EU ETS and CN ETS pilots. We offer an in-depth exploration of the reasons for earlier divergent conclusions and contribute new insights into the size of the ETS incentive effect. By identifying the main constraints on incentive effectiveness, we also identify potential remedies and offer policy recommendations.

In what follows, Section 2 outlines the key concepts and methodologies. Section 3 synthesises the literature on the impact of ETSs on TICCM and addresses reasons for divergent findings. Section 4 examines the extent and constraints of incentive effects. Section 5 summarises the main findings and suggests directions for future research.

2. Methodology

Systematic review is a method for assessing the current state of knowledge on a specific question by synthesising all evidence satisfying a set of predetermined criteria (Higgins et al., 2023). The approach was chosen for its ability to minimise research bias and ensure credible and accurate results by using a standardised, transparent and repeatable process (Collaboration for Environmental Evidence (CEE), 2022). Based on methodological guidance (CEE, 2022; Higgins et al., 2023), detailed processes of question clarification, search strategy, screening strategy, validity assessment and data extraction were developed as explained below.

2.1. Research question clarification and concept definition

This research seeks to determine the impact of ETSs on TICCM. To delineate the research scope and guide subsequent steps, the question was articulated based on the Population-Intervention-Comparator-Outcome (PICO) framework widely used in synthesising environmental evidence (CEE, 2022). The details of each element are shown in column (1) of Table 1.

There is no agreed upon definition of TICCM, a key concept of our research question. It can be interpreted as a qualification of the direction and scope of wider technological innovation or eco-innovation. In line with the discussion on the above two concepts (Garcia & Calantone, 2002; Grubb et al., 2021; Manual, 2005; Rennings, 2000; Schiederig et al., 2012), we define TICCM as 'an iterative process from the invention, development, piloting and adoption to the diffusion of technologies for controlling, reducing and preventing atmospheric greenhouse gas (GHG) emissions from productive activities'.

2.2. Literature search, screening and validity assessment

The search strategy included both a classic bibliographic search and a novel citation-chasing search, ensuring comprehensive literature capture. Web of Science and Scopus were searched to identify relevant peer-reviewed literature, while ProQuest and Google Scholar were searched for dissertations and grey literature. The search string contained multiple search terms related to the P, I, and O elements, developed iteratively through author suggestions and pilot searches. The scope and search term string applied to the databases are indicated in Table 2. The citation-chasing strategy focused on the references of the benchmark literature (forward citation chasing) and publications citing the benchmark literature (backward citation chasing). The benchmark literature consists of all relevant review articles obtained from the bibliographic search, following the approach of Andor and Fels (2018). Since citation-chasing results vary when using different tools, we tested and compared the performance of the three main tools (Scopus, Web of Science, and Citationchaser (Haddaway et al., 2021)). The Citationchaser, which had the best-combined performance in terms of validity and comprehensiveness, was ultimately chosen to perform the citation-chasing search. There was no restriction on the time of publication in either search strategy, but non-English publications were excluded.

The screening strategy involved setting eligibility criteria: studies that included all key elements of PICO (as detailed in column (2) of Table 1) and focused on the impact of the ETS on TICCM were included. Non-primary

Table 1. PICO elements and eligibility criteria.

Elements	(1) Describe	(2) Eligibility criteria
Population	TICCM	Included studies must focus on one or more stages of technological innovation. These stages include technological invention, development, piloting, adoption, and diffusion. The technological innovation of interest should be relevant to climate change mitigation. This means that qualifiers such as 'low-carbon', 'carbon-reducing', 'zero-carbon' or 'green' should be present.
Intervention	ETS	Included studies should focus on the ETS that constrain GHG emissions. Studies focusing on ETSs that limit non-GHGs such as sulfur dioxide or nitrogen oxides will be excluded.
Comparator	A control with no ETS or a counterfactual scenario	In modelling and qualitative publications, the comparator can be implicit.
Outcome	Changes in TICCM	Included studies have to assess the impact of the ETS on technological innovation, with outcomes being positive, negative, or null.

Table 2. The scope and the search term string.

Database	Scope	Search string
Scopus	TITLE-ABS-KEY	('carbon trading' OR 'emission trading' OR 'carbon market' OR 'cap and trade' OR 'emission trade' OR 'tradable emission' OR 'emission permit' OR 'carbon permit' OR 'tradable permit') AND ('innovation' OR 'innovate' OR 'technology change' OR 'technological change' OR 'technological advance' OR 'technology advance' OR 'technological advancement' OR 'technological revolution' OR 'technology revolution' OR 'technological transition' OR 'technology transition' OR 'technological upgrading' OR 'technology upgrading' OR 'technological progress' OR 'technology progress' OR 'development technology')
Web of Science	TS	
ProQuest	noft	
Google Scholar[a]	-	

[a]To accommodate the 256-character limit in Google Scholar for search strings, we first segmented the original long string into shorter parts. These segments were then reassembled into multiple new search strings, each conforming to the character constraint while collectively covering the entire scope of the original string. Subsequently, we used the 'Publish or Perish' (Harzing, 2007) tool to retrieve the search results for each of these shorter strings. By consolidating all retrieved results, we ultimately achieved an accurate search outcome based on Google Scholar.

research publications, such as reviews and comments, were excluded. The screening process began by merging search results and eliminating duplicates, with priority given to retaining the most recent or peer-reviewed version. All publications were then screened sequentially by title, abstract and full text against the eligibility criteria. Any publications with inconclusive screening results were retained for the next stage. If a publication failed to meet the criteria at any stage of the screening process, it was excluded.

Assessing the validity of publications is a critical step for reducing bias and improving the robustness of results (CEE, 2022; Higgins et al., 2023). The first step in this process is the creation of appraisal tools. We tailored the standard tools from CEE (Konno et al., 2021) to design validity appraisal tools specifically for modelling, qualitative and quantitative studies (each tool is described in detail in Supplementary Material A). These tools can assess external validity in modelling studies, and both internal and external validity in qualitative and quantitative studies. The external validity assessment focused on applicability and transportability, while the internal validity assessment addressed the risk of confounding, post-intervention/exposure selection, detection, outcome reporting and outcome assessment biases. Each screened publication was assessed with the corresponding tool and those deemed to be of low validity were excluded.

Using the above pre-set protocol, literature search, screening and validity assessment were conducted from November 2023 to January 2024 (see Figure 1). A total of 1927 publications were initially identified in the bibliographic search. After de-duplication and screening, 100 publications were retained. The bibliographic search and screening identified eight relevant review articles that were used as benchmark literature for the citation-chasing search. A total of 1174 publications were identified through citation-chasing, of which 484 were forward citations and 690 were backward citations. After de-duplication and screening, nine additional publications were identified. Then, the publications identified by the two search strategies and screening were assessed for validity. Thirty-one publications were deemed to be of low validity and were excluded. In the end, a corpus of 78 publications was retained for data extraction and evidence synthesis (the study design characteristics of our paper and the eight related review articles, the results of the validity assessment and

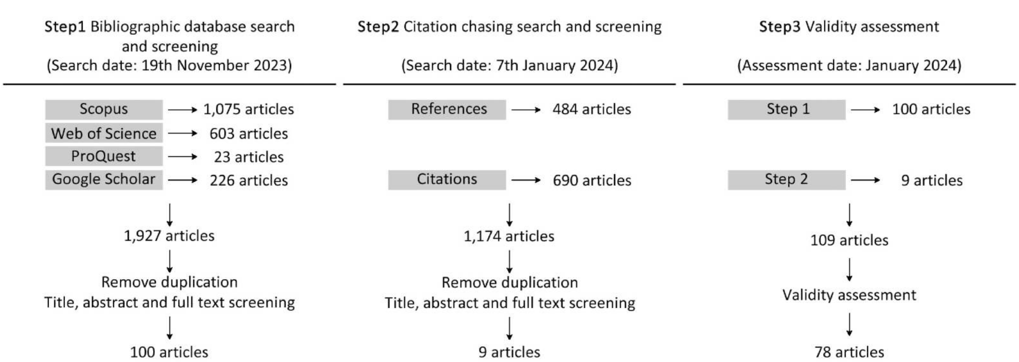

Figure 1. Search, screening and validity assessment process and results.

the list of all retained publications are presented in Table S1, S2 and S3 in Supplementary Material B, respectively).

2.3. Data extraction and evidence synthesis

The data extraction and synthesis methodologies followed standard guidelines while considering the characteristics of the research question. Through iterative testing and optimisation, we developed an evidence database, covering publication-level information, study design and study results. Particular attention was given to the details of the study design, such as subject, region, period, indicators used, and level of data, which provided the basis for exploring the reasons for the divergence of the reported results. Publications containing multiple results, such as those examining the impact of the ETS on multiple TICCM indicators, were treated as distinct studies and information from them was extracted separately.

The narrative synthesis approach and visual descriptive statistical analysis were used to analyse the data and draw conclusions. While quantitative synthesis methods, such as meta-analysis, can effectively use available data, optimise the precision of effect estimates, and quantify conflicts and reasons for divergent results, they are inappropriate for our study because of the significant heterogeneity of the included publications in research design and conclusions, as well as the small sample size, which limited the potential to generate robust and generalisable findings (CEE, 2022; Higgins et al., 2023; Homar & Cvelbar, 2021).

2.4. Methodological limitations

Despite our efforts to ensure the comprehensiveness, objectivity, and validity of the systematic review, certain methodological limitations remain. First, potentially relevant literature may have been missed due to incomplete access to grey literature and the exclusion of non-English publications. While most grey literature might not meet our stringent validity assessment criteria, the exclusion of Chinese-language publications could result in missing studies on the CN ETS, thereby introducing potential bias. Second, the process of identifying reviewed publications may involve some subjectivity, as resource constraints prevented multiple authors from independently conducting the entire screening and validity assessment process. Finally, although we developed a rigorous and detailed validity assessment tool, it does not assess the internal validity of modelling studies, which may affect the reliability of the reviewed studies and the robustness of our overall conclusions.

3. Results

Our methodology identified 78 relevant publications, comprising 88 distinct studies. The subsequent analysis first examines the characteristics of the reviewed publications, providing an overview of the research in the field (Section 3.1). We then employ vote-counting to describe and preliminarily interpret the impact of ETSs on TICCM (Section 3.2). The findings are presented by the type of research method employed in the reviewed publications because different methodologies can yield varying results, complicating the synthesis of evidence across all approaches (Peñasco et al., 2021). Reasons for divergent conclusions in the reviewed studies are explored at the end of the results (Section 3.3).

3.1. Overall characteristics of the literature

Figure 2 portrays the 78 publications in the corpus by the publication year, research methodology employed, and population studied. The reviewed publications have been published since 2001. Until 2020, their cumulative number remained relatively low, with no more than five publications appearing per year. However, the number of publications increased significantly from 2020 to 2023 due to the influx of quantitative analyses of the CN ETS. Modelling studies (N = 7) formed the smallest methodological group and were also the first to appear. Qualitative studies (N = 11) were mostly published between 2007 and 2015, with an exclusive focus on the EU ETS. Quantitative studies (N = 60) were the largest group, and have mainly been published since 2018. Whilst over 30 ETSs are currently in use globally, the reviewed publications focus on either the

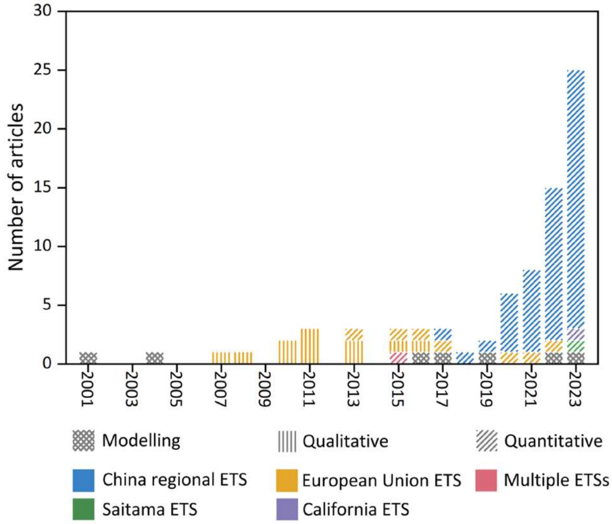

Figure 2. Publication year, methodology and population of the 78 publications reviewed.

EU ETS or the CN ETS, with only one study each on the Saitama ETS, California ETS, or multiple ETSs. This implies the importance of EU ETS and CN ETS and the shortage of evidence for other ETSs in the research field.

Figure 3 illustrates the types of reviewed publications and the journal affiliation. Journal articles account for 90% (N = 70) of the corpus. They were published in 45 different journals, most of them in the field of economics or environmental sciences. Two of the journals, *Environment Science and Pollution Research* and *Energy Policy* contained at least five relevant articles, while 33 journals contained only one.

3.2. Impact of ETSs on TICCM

3.2.1. Findings from modelling studies

Analysis of the seven articles based on modelling or simulations suggests a mixed impact of ETSs on TICCM (see Figure 4 (a)). Two articles found that ETS incentivised investment and deployment of climate change mitigation technology. Specifically, Ju and Fujikawa (2019) provided the insight that the ETS incentivises technological progress by raising factor input costs of producers, which resonates with the Induced Innovation Hypothesis.

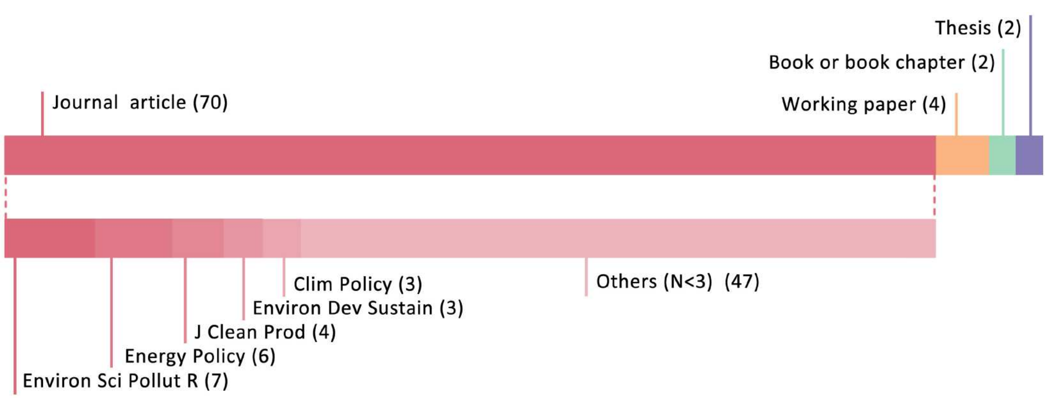

Figure 3. Types of publications reviewed and the journal affiliation.

Note: N < 3 means that the journal contains less than three relevant articles.

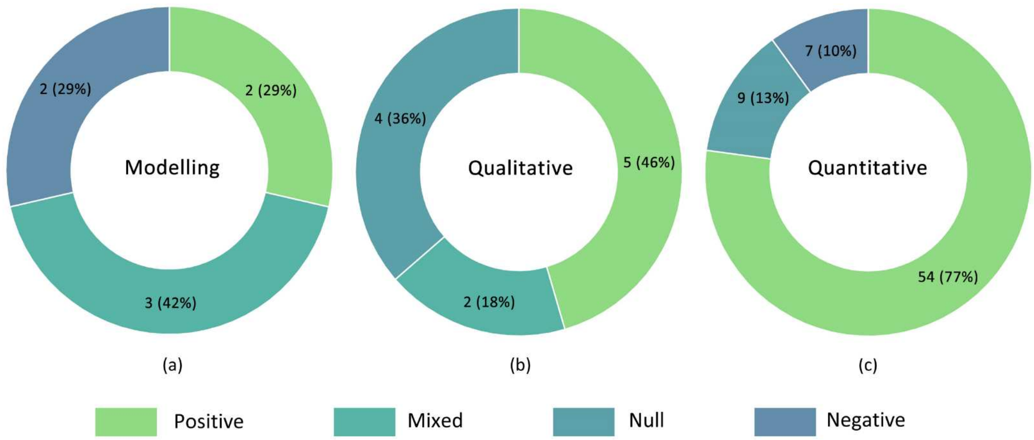

Figure 4. Impact of ETSs for TICCM: modelling, qualitative and quantitative research.
Note: Mixed results refer to a study that reports both positive and null or negative impact.

Two studies argued that compliance with environmental policy by allowance trading would be an alternative to pursuing technological innovation, suggesting that the ETS could discourage technological innovation (Barreto & Kypreos, 2004; Buonanno et al., 2001). This underscores the importance of allowance price, as a lower price makes trading allowances a more attractive strategy. Some modelling studies have also highlighted the role of allowance price in incentivising innovation (Lyu et al., 2023; Yang et al., 2016). Wei et al. (2022) found a threshold effect, that the CN ETS with a stable price of 30–40 CNY/ton fails to motivate technological innovation in the electricity sector, whereas marked incentives emerge once the price rises to 50–60 CNY/ton. External factors, such as patent time limits, market power, and the interplay of firm R&D decisions, may also lead to inadequate and distorted R&D incentives from the ETS (Lechthaler-Felber & Krysiak, 2017).

Modelling articles can only provide ex-ante predictive evidence of the impact of ETS on technological innovation and their external validity is limited due to the numerical simulation conclusions being highly sensitive to the model assumptions and parameter settings. Moreover, the complexity of simulating technological innovation processes constrains the analysis of the relationship between ETSs and technological innovation (Grubb et al., 2021). This limitation is manifested in the reliance of the modelling literature solely on R&D investment or technology implementation as proxies for technological innovation.

3.2.2. Findings from qualitative studies

Most qualitative studies have found a positive (46%) or null (36%) impact of the ETS on TICCM (see Figure 4 (b)), but two studies reported mixed results with limited negative evidence.

Qualitative evidence of positive impacts originates from diverse countries and sectors. The electricity sector, the largest contributor to global GHG emissions (IEA, 2023), experienced the most substantial incentive effects (Rogge et al., 2011a; Skjærseth & Eikeland, 2016). An influential article by Rogge et al. (2011a) stands out with its multi-case analysis of the German electricity sector. This study, which draws on 61 interviews with power producers, technology suppliers, and project developers, found that the EU ETS has significantly expedited the research, development and demonstration of low-carbon coal power generation technologies and carbon capture technologies, in addition to accelerating the shift toward renewable energy generation technologies. Other industries, such as ceramics, cement, coke, and oil refining, have also experienced positive impacts of the ETS on technological investments, R&D activities, as well as demonstration and adoption of new technologies (Anderson et al., 2010; Skjærseth & Eikeland, 2016).

Qualitative evidence of null effects is only reported for the pulp and paper industry. Research on Germany, Italy, and the Nordic countries found a negligible EU ETS impact on technological investment, R&D, and technology adoption in the sector (Gasbarro et al., 2013; Gulbrandsen & Stenqvist, 2013; Pontoglio, 2008; Rogge et al., 2011b). The reasons for the null effect evidence clustering in a single industry have not been thoroughly explored. One plausible explanation is that concerns about competitiveness and uncertainty of the ETS prompted pulp and paper companies to adopt passive strategies toward the policy, thereby constraining the incentive effects (Borghesi et al., 2015b; Pontoglio, 2008; Rogge et al., 2011b; Skjærseth & Eikeland, 2016). The negative effect was found in Hoffmann's (2007) investigation of the German power sector and in the comprehensive analysis by Borghesi et al. (2015a) of several sectors in eight EU ETS participating countries. Both studies highlighted the detrimental effect of regulatory uncertainty on technological investments.

An obvious common feature and limitation of qualitative studies is their exclusive focus on EU ETS Phases I (2005-2007) and II (2008-2012), with no assessment of the more recent performance of the EU ETS or the effectiveness of other ETSs, limiting the generalisability of their findings. Their small sample sizes also contribute to this limitation, further challenging the applicability of their results. Finally, some qualitative research employs ambiguous terminology such as 'innovation activity' or 'innovation decision-making processes' when referring to technological innovation (Borghesi et al., 2015b; Pontoglio, 2008), complicating the assessment of the ETS impact on different innovation phases. So, although qualitative research has found that the EU ETS has incentivised technological innovation in some industries and regions, the finding lacks generalisability, particularly for areas outside the scope of the EU ETS and for more recent periods.

3.2.3. Findings from quantitative studies

Quantitative publications (N = 60) have mostly found that ETSs stimulate TICCM: 54 out of 70 reviewed studies (77%) report positive effects, while only 9 and 7 studies reported a null or adverse effect (see Figure 4 (c)). Quantitative studies have examined a wide range of ETS from the CN ETS pilots to the California ETS and Japan's regional ETS, but most focus on the CN ETS pilots (56 studies, 80%) and the EU ETS (9 studies, 13%) (see Figure 5). For this reason, our subsequent analysis concentrates on these two ETSs.

Many studies (N = 44) have corroborated the positive effect of the CN ETS pilots on TICCM with diverse indicators. Studies reporting positive effects mainly employed patent-related indicators of TICCM, particularly the number of patents (30 studies). An article by Zhu et al. (2019) stands out for using comprehensive firm-level data to identify the causal effect of the CN ETS pilots on TICCM, finding a 10.1% surge in low-carbon patents in regulated firms. Other studies have demonstrated that the CN ETS pilots positively influence both the proportion of patents for climate change mitigation technologies (CCMT) among total patents (Shao et al., 2023; Yang et al., 2023) and their citation frequency (Qin & Xie, 2023). Positive impacts have also been reported in studies on R&D investment (6 studies) and by using a composite index (4 studies). Few studies found null or adverse effects, but the innovation indicators they used are also broad and focused on patents (9 out of 12 studies). R&D investment, carbon intensity, and composite index were each used in one study. A notable limitation of the studies with null or adverse effect findings is the construction of control and treatment groups from an industry or regional perspective. This approach invariably leads to treatment groups including entities not constrained by the ETS, thereby undermining the validity of the conclusions. Nevertheless, two prominent studies on the number and share of patents for CCMT provide compelling evidence of the significant negative impact of the CN ETS pilots (Chen et al., 2021; Zhang et al., 2022).

The findings of the quantitative studies on the EU ETS are generally more positive than those from the qualitative studies, with positive results increasing from 46% to 78%. Quantitative evidence of the EU ETS's positive impact is documented in studies focusing on patents (2 studies), R&D investment (4 studies), and technology adoption (1 study). Calel and Dechezleprêtre (2016) generated comprehensive evidence at the patent level. By integrating patent data with company information to create a unique dataset encompassing about 80% of EU ETS facilities and emissions, they found a 9.1% increase in patents for CCMT among regulated firms. Calel (2020) and Goerger (2021) reported comparable findings, indicating a 32% and 28% increase in investment in CCMT due to the EU ETS. The latter further highlighted the increasing impact of the ETS across phases – from negligible in Phase I to significant in Phases II (24.7%) and III (38.4%[1]). Only two studies found a null effect, assessing the impact of the EU ETS on Swedish R&D investment (Löfgren et al., 2014) and Norwegian patent applications (Lunde, 2022).

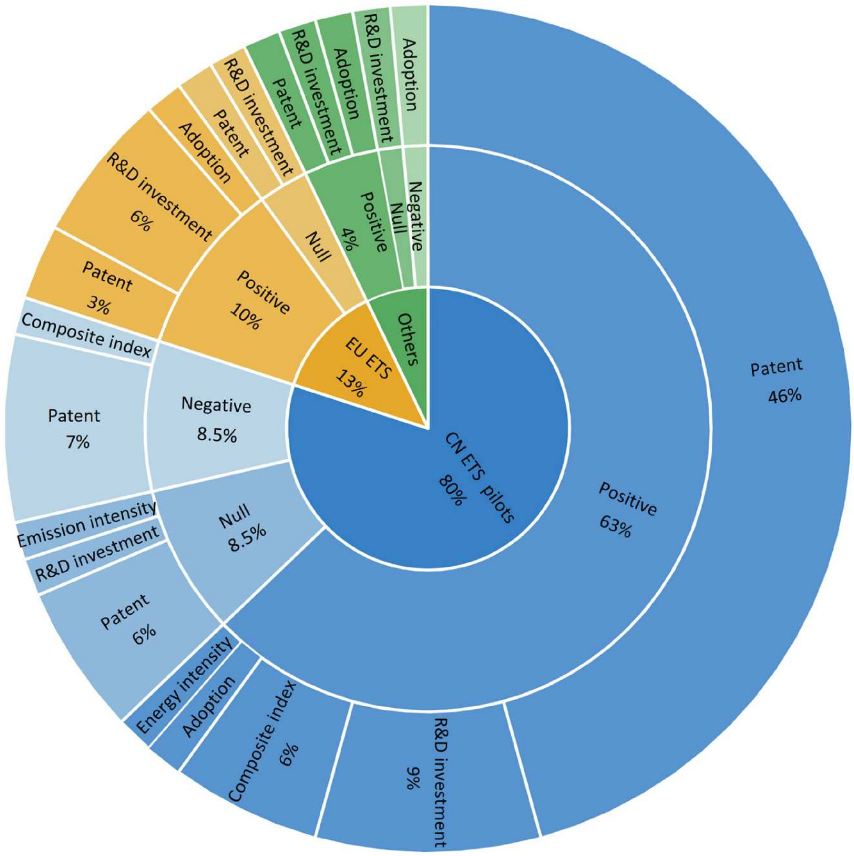

Figure 5. Quantitative results based on research object classification.

Note: The innermost layer reflects the weighting of the different research subjects. The middle layer reacts to the study results. The outermost layer responds to the TICCM indicator used for studies.

3.3. Analysis of the causes for divergent findings

The divergence in findings from the modelling, qualitative and quantitative studies highlights the complexity of the impact of ETSs on TICCM. Understanding the reasons for this divergence is crucial for synthesising evidence and making judgements about the relationship. By comparing the research designs of the divergent studies, we suggest that, although some of the divergence is difficult to explain, the variation in industry, region, subject and time period contributed to it, whereas the selection of technological innovation indicator is not the cause.

The majority of the divergence can be attributed to differences in studied industries or regions. The industry heterogeneity of the results is most evident in that the EU ETS incentive effect is absent in the pulp and paper industry, whereas it is pronounced in other sectors, particularly in the electricity sector. The research on the CN ETS pilots also suggests significant incentives in energy- and resource-intensive industries but not in manufacturing (Zhao et al., 2022). This heterogeneity likely arises from variations in sectoral characteristics and ETS design across sectors, such as emissions intensity and abatement potential and quota allocation rules (Skjærseth & Eikeland, 2016). The regional heterogeneity of incentive effects is observed in the regional CN ETS pilots.[2] For example, the Chongqing pilot fails to generate incentives for TICCM (Wang et al., 2020; Wang et al., 2022; Yao et al., 2021; Zhao et al., 2023), while the opposite holds true for the Hubei pilot (Fu et al., 2022; Liu & Sun, 2021; Ren & Liu, 2023; Wang et al., 2020; Wang et al., 2022; Yao et al., 2021). The divergence is attributed to the design differences in quota caps, quota allocation rules, inclusion thresholds, and penalty severity across the regional CN ETS pilots (Wang et al., 2022; Yao et al., 2021).

Differences in the study periods explain only a small part of the divergence. The incentive effects of ETSs likely vary between early and later phases of implementation due to the lagged response of technology innovation indicators to environmental policies (Teixidó et al., 2019). For example, the early results of the effectiveness of incentivising technological investment in Phase I of the EU ETS (Gasbarro et al., 2013; Gulbrandsen & Stenqvist, 2013; Löfgren et al., 2014) align with that from the later research, but contrast with the overall assessment from Phase I to III (Goerger, 2021). However, similar evidence is limited, and although there is a vague tendency for the overall findings to be more positive, no clear relationship exists between the findings and the study time frames or publication dates (see Figure 6).

Variations in the study population also explain only a small part of the divergence of results. This is particularly evident in the higher amount of negative evidence against CN ETS than against EU ETS. Nonetheless, both CN ETS and EU ETS have generated positive incentives for TICCM, as reflected in a relatively high proportion of

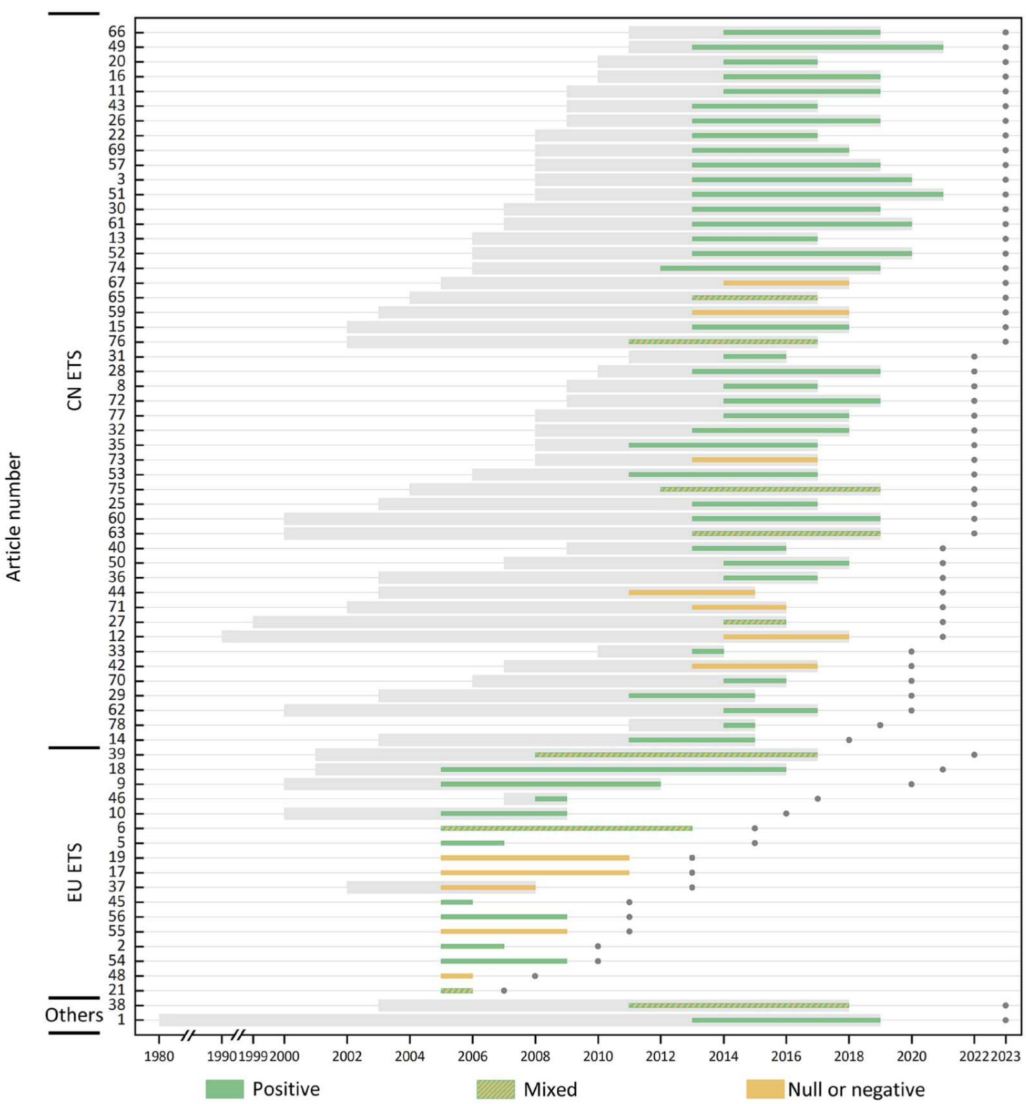

Figure 6. Relationship between study period and year of publication and conclusion.

Note: Grey bars indicate the time period of the sample studied. Green, yellow, and mixed-colour bars indicate the time period of the ETS effect assessed. Grey dots represent the publication date of the paper. Publications with unknown or difficult-to-determine study or sample periods were excluded.

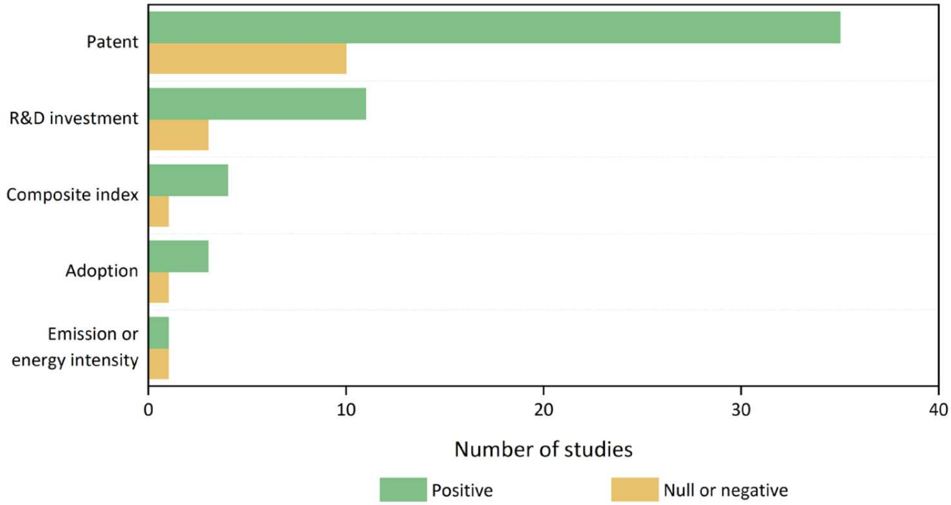

Figure 7. Quantitative studies indicators and conclusions.

positive studies (around 79% and 65%, respectively), despite differences in policy design and context. This underscores the capacity of market-based environmental policy to stimulate technological innovation.

Finally, the choice of innovation indicators does not appear to correlate with the findings on the effectiveness of ETS incentives. Across all indicators, the results consistently show a predominantly positive impact, with only a few null or negative outcomes (see Figure 7). In other words, the incentive effect of ETSs is not confined to any specific stage of innovation but spans the entire process.

4. Discussion

While the ETSs have not generated transformative impacts on innovation in specific industries or regions, they have had a statistically significant positive impact on technological innovation overall. However, this conclusion, derived from a simple vote-counting synthesis, does not elucidate the extent of the impact. To better understand the limited incentives in specific industries and regions, it is also crucial to explore underlying factors contributing to these outcomes. Identifying these aspects could guide potential improvements to the ETS design. In the following sections, we focus on (1) the extent of the incentive effect of ETSs and (2) the constraints limiting their effectiveness.

4.1. Analysis of the extent of the incentive effect

Determining the extent of the incentive effect helps clarify the relationship between the ETSs and TICCM. This topic has already attracted attention and generated debate. Most reviews of the EU ETS agree that while it has had a positive impact, it has been limited or moderate (Joltreau & Sommerfeld, 2018; Laing et al., 2014; Van Den Bergh & Ivan, 2021). Reviews also frequently conclude that the current ETS has failed to incentivise radical and long-term technological innovation to achieve long-term climate change goals (Hermwille et al., 2015; Lilliestam et al., 2020; Mandaroux et al., 2023). Conversely, Teixidó et al. (2019) argue that the impact of the EU ETS on innovation has been positive and substantial, particularly in patent applications. Furthermore, Joltreau and Sommerfeld (2018) and Van Den Bergh and Ivan (2021) suggest that while the incentive effect is weak in absolute terms, it is significant in relative terms.

Our study provides novel insights into the size of the incentive effects of the EU ETS and CN ETS. First, about half of the qualitative studies and one key quantitative study suggest that the incentive effect of the EU ETS is limited or moderate. Three studies conducted in Germany indicate that even in the electricity sector, where the

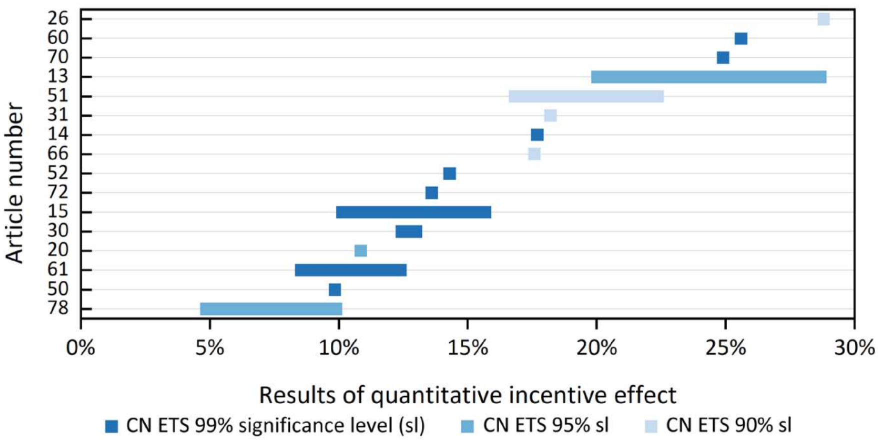

Figure 8. Percentage increase in patents for CCMT attributed to the CN ETS pilots.

Note: The line segments represent multiple numerical results from one study, with the start and end of the line representing the maximum and minimum impact. The results are presented in ascending order based on their mean values, ranging from lowest to highest.

ETS incentive effect is the strongest, its impact on renewable energy and demand-side energy efficiency is still limited (Rogge et al., 2011a) and that the existing incentive has failed to motivate transformative changes in innovation (Hoffmann, 2007; Rogge et al., 2011a; Rogge & Hoffmann, 2010). The cross-country case study by Skjærseth and Eikeland (2016) similarly suggests that the impact of the ETS on radical and long-term technological innovation is limited to drawing increased attention. Another detailed quantitative study shows that in the early years of the EU ETS (2005–2009), its incentive for constrained firms added 183 additional low-carbon patents, explaining only 0.83% of the increase in the total number of such patents filed at the European Patent Office (Calel & Dechezleprêtre, 2016). Second, a synthesis of quantitative studies examining the CN ETS pilots suggests that its incentive for TICCM is limited and has failed to significantly drive low-carbon transformation in technological innovation. 16 reviewed quantitative studies on the impact of the ETS on patents provide an opportunity to quantitatively assess the extent of the incentive effect. A ranking of their findings suggests that the CN ETS pilots account for about 10%–25% of the growth in patents for CCMT (see Figure 8). Even under the exaggerated assumption that the CN ETS pilots have had impacts in all eight pilot regions since the policy launched in 2011, based on the quantitative evidence above, they explain only 4.27%–10.66% and 0.8%–2.00% of the number of patents applications for CCMT and all types of technologies during 2011–2023 respectively.[3]

Our analysis suggests that the incentive effect of the ETSs on technological innovation is limited or moderate, but it does not imply that they have failed to promote technological innovation. Undoubtedly, motivating the innovations to achieve long-term climate change goals requires a multi-policy or policy-mix strategy (Rennings, 2000; Rogge & Reichardt, 2016; Van Den Bergh & Ivan, 2021). Thus, it is unreasonable to expect that an ETS alone could achieve the desired goal. Also, the reviewed studies focus on the first two phases of the EU ETS and the pilot phase of the CN ETS. As ETSs continue to evolve and improve, their incentive effect on TICCM is likely to strengthen (Teixidó et al., 2019). Therefore, although ETSs have not yet achieved the expected effect in fostering TICCM, the limited but positive and significant impact from the early phase of their implementation should not be ignored.

4.2. Analysis of constraints on the incentive effect

The analysis above suggests that while the ETSs have stimulated TICCM, the effect is neighter large nor uniform across sectors and regions, highlighting the need and potential for further improvement. We seek to identify the primary constraints on the ETS-driven technological innovation incentives to uncover promising avenues for improvement.

Of 29 publications discussing constraints on the incentive effect, insufficient stringency (mentioned in 20 publications) and high uncertainty (in 16 publications) are identified as the primary constraints, as both are noted by more than half of the studies. Insufficient stringency refers to the lack of regulatory constraints on firms imposed by the ETS. It is mainly manifested in low allowance prices, limited enterprise inclusion, and weak penalties. With insufficient stringency, enterprises encounter low compliance costs, and the financial gains from selling surplus allowances are limited. The weak cost-push and revenue incentives constrain motivation for innovation (Chen et al., 2021; Hoffmann, 2007; Skjærseth & Eikeland, 2016).

High uncertainty in ETSs usually refers to the high unpredictability of compliance costs and emission reduction benefits, as manifested in the volatility of allowance prices and regulatory uncertainty. As the TICCM is often complex and large in scale (Grubb et al., 2021), resulting in a substantial time lag between investments in technological innovation and generating effects (Joltreau & Sommerfeld, 2018; Van Den Bergh & Ivan, 2021), evaluating future benefits is crucial for innovation decisions. Under high uncertainty, volatile allowance prices and the mismatch between short-term regulatory flux and the long amortisation periods for investment in technologies complicate the assessment of expected returns. It leads enterprises to employ cautious or wait-and-see strategies, such as postponing R&D investments or abandoning innovation, thereby weakening the incentives created by the ETS for TICCM (Borghesi et al., 2015b; Gasbarro et al., 2013; Gulbrandsen & Stenqvist, 2013; Pontoglio, 2008).

Our study identified two key challenges faced by the ETSs in incentivising technological innovation, but this finding may not apply to the latest developments as both the stringency and uncertainty of the ETSs have improved over time. In Phase III of the EU ETS, the quota-setting authority was centralised, and the market stability reserve (MSR) was established to adjust the supply of allowances, preventing excessively low allowance prices. Similarly, the CN ETS Beijing pilot lowered the inclusion threshold from 10,000 to 5,000 tons of carbon dioxide emissions annually in 2015. Both EU ETS and CN ETS pilots exhibit a general upward trend in quota prices over time (see Figure S1 in Supplementary Material B), reflecting improvements in stringency. Uncertainty in the EU ETS was also mitigated by extending implementation periods from 3 and 5 years in Phases I and II to 8 and 10 years in Phases III and IV. These changes suggest that policymakers have begun addressing the ETS shortcomings, yet raise questions about whether insufficient stringency and high uncertainty remain constraints on the effectiveness of incentives going forward. Furthermore, increasing stringency or reducing uncertainty alone may not yield desired improvements as they are interdependent. For example, addressing the oversupply of allowances to enhance stringency requires policy interventions, which may increase policy uncertainty (Sato et al., 2022). This indicates that enhancing the incentive effect of the ETSs on innovation in practice may be complex and challenging, necessitating further in-depth research and exploration in this field.

5. Conclusions

It is crucial to assess the ability of the ETSs to stimulate TICCM. However, the evidence on the impact of ETSs has remained inconclusive, partly due to methodological limitations. To address this gap, we conducted a systematic and rigorous review of the literature and narratively synthesised modelling, qualitative and quantitative studies that examined the impact of ETSs on TICCM. The review additionally offers novel evidence and insights into the reasons for the divergence of findings in the earlier literature, as well as the controversy over the extent of the incentive effect. The review also explores the key factors that constrain the effectiveness of the ETSs in incentivising TICCM and identifies potential avenues to address these constraints.

Our synthesis of evidence suggests that ETSs have a positive and statistically significant effect on TICCM. The incentive effect exists for several innovation indicators, such as patent-related outputs, investment, and technology adoption for both the EU ETS and the CN ETS pilots. However, the incentive effect is absent from specific sectors and regions. Sector and regional heterogeneity are the major reasons for divergent findings in the earlier literature. Divergence also partly arises from differences in the study periods and study subjects. While the findings on the positive incentive effect are encouraging, the incentive effect is moderate or limited and weaker for long-term and radical technology innovation. There is scope for enhancing the incentive effect of the ETS. The main factors limiting the incentive effect are insufficient stringency and high uncertainty of the ETSs. Effective utilisation of flexible policy tools, such as the MSR, which can synergistically address both limitations, represents a valuable improvement strategy.

The impact of ETSs on TICCM is complex, and the evidence in this field remains incomplete. The scope of research is significantly constrained by the limited focus on heterogeneity. The lack of in-depth discussion on industry and regional heterogeneity restricts the exploration of key relationships, such as the effectiveness of ETSs and factors like industrial cost pass-through capacity, carbon leakage risk, and regional ETS design. Insufficient attention to technological innovation heterogeneity further limits the granularity and robustness of conclusions. In particular, the lack of focus on radical versus incremental technological innovation makes our conclusions about the extent of the incentive effect remain less robust than those about its existence. Moreover, the scarcity of studies on the recent ETS incentive effects, as well as non-EU and non-CN ETS becomes more evident as ETSs continue to evolve and extend. This leaves several questions inadequately addressed, such as whether the incentive effects have strengthened with the improvements in ETSs and whether insufficient stringency and high uncertainty still persist and undermine incentive effects. Addressing these gaps in future research would be beneficial for improving the design and effectiveness of ETSs.

Notes

1. This estimate applied only to the part of Phase III of the EU ETS (2013–2016) and not to the entire period (2013–2020).
2. China launched ETS pilots in seven provinces or cities (Beijing, Shanghai, Tianjin, Hubei, Guangdong, Chongqing and Shenzhen) in 2011, with trading starting gradually from 2013. The Fujian ETS pilot was launched and began trading in 2016.
3. Patent data from the incoPat database. Identification of patents for climate change mitigation is based on the Y02 label from the Cooperative Patent Classification (CPC). The data retrieval date is September 2024, and only patents with the status of valid and filed by Chinese were considered.

Acknowledgements

The authors are grateful to Dr. Zexiang Wang from Sun Yat-sen University for his insightful comments on early drafts and to Niklas Döbbeling-Hildebrandt from the University of Leeds for his valuable support in addressing the reviewers' feedback. We also extend our sincere thanks to the anonymous reviewers and the editor for their constructive suggestions, which have greatly contributed to the improvement of this article. The authors alone are responsible for any remaining errors or omissions.

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Zihong Chen: Conceptualisation, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualisation. **Paul E. Brockway:** Conceptualisation, Validation, Writing – review & editing, Supervision. **Sheridan Few:** Conceptualisation, Validation, Writing – review & editing, Supervision. **Jouni Paavola:** Conceptualisation, Validation, Writing – review & editing, Supervision.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Zihong Chen acknowledges the support of the China Scholarship Council-University of Leeds Scholarship, award number: 202306040026. Paul Brockway's contribution was partially funded by the UK Research Council under EPSRC Fellowship, award EP/R024254/1. Jouni Paavola acknowledges the support of the UK Economic and Social Research Council (ESRC), grant/award number: ES/K006576/1 to the Centre for Climate Change Economics and Policy (CCCEP).

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