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ADVANCED REVIEW

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The effect of carbon pricing on technological change for full energy decarbonization: A review of empirical ex-post evidence

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Abstract

In order to achieve the temperature goals of the Paris Agreement, the world must reach net-zero carbon emissions around mid-century, which calls for an entirely new energy system. Carbon pricing, in the shape of taxes or emissions trading schemes, is often seen as the main, or only, necessary climate policy instrument, based on theoretical expectations that this would promote innovation and diffusion of the new technologies necessary for full decarbonization. Here, we review the empirical knowledge available in academic ex-post analyses of the effectiveness of existing, comparatively high-price carbon pricing schemes in the European Union, New Zealand, British Columbia, and the Nordic countries. Some articles find short-term operational effects, especially fuel switching in existing assets, but no article finds mentionable effects on technological change. Critically, all articles examining the effects on zero-carbon investment found that existing carbon pricing scheme have had no effect at all. We conclude that the effectiveness of carbon pricing in stimulating innovation and zero-carbon investment remains a theoretical argument. So far, there is no empirical evidence of its effectiveness in promoting the technological change necessary for full decarbonization.

This article is categorized under:
Climate Economics > Economics of Mitigation

KEYWORDS
carbon pricing, climate policy, decarbonization, technological change

1 | INTRODUCTION

Carbon pricing, either in the shape of a cap-and-trade emissions trading system (ETS) or a carbon tax, is widely seen as the main policy instrument needed to solve the climate problem and achieve the goal of the Paris Agreement of keeping the global temperature increase below 2°C (Bureau, Henriet, & Schubert, 2019; Edenhofer, Flachsland, Kalkuhl, Knopf, & Pahle, 2019; Löschel, 2019; Stiglitz et al., 2017). Indeed some scientists suggest that a carbon price is the *only* policy intervention needed for climate protection (Blum et al., 2019), and that further climate or technology policy instruments would reduce the cost-efficiency and/or the effectiveness of climate policy (German council of economic experts, 2019;

Nordhaus, 2013). Many take the increasing number of countries that put a price on carbon as evidence of success (World Bank, 2019), despite first indications that existing systems have not triggered substantial emission reductions (Haites, 2018).

The argument for using carbon pricing as the central mitigation instrument is simple and compelling: with a price on carbon, polluters have an economic incentive to immediately reduce their emissions. The price signal will trigger both development and deployment of lower- or zero-emitting technologies such as renewable energy or insulating buildings. We discuss the underlying theory in detail in Section 2.1.

Another line of argumentation suggests there may be limits to carbon pricing's value. Achieving the objectives of the Paris Agreement requires not just a reduction in emissions of carbon dioxide (CO_2), but rather its complete elimination, by about mid-century, from the energy sector (Hoegh-Guldberg et al., 2018). For this, a complete reconfiguration of the energy system, mobility, and of carbon-emitting industry is necessary. To be most helpful, near-term emissions cuts must align with enhancing society's capacity to quickly replace all sources of fossil carbon emissions with other forms of energy (Patt, van Vliet, Lilliestam, & Pfenninger, 2019).

Complete decarbonization requires development and deployment, up to full market penetration, of zero-carbon technologies and systems. The literature on technological transitions suggests that the factors influencing the direction and pace of technological change go well beyond differences in costs: through their existing systems of infrastructure and institutions, societies can be "locked in" to using high carbon technologies. This lock-in is exacerbated by economic mechanisms such as decreasing costs (learning) and increasing returns (e.g., network effects), which put new technologies at a competitive disadvantage (Unruh, 2000). Spillover effects mean that markets tend to achieve suboptimal levels of innovation, suggesting that state interventions to increase the rate of innovation, including via learning-by-doing, are needed (Arthur, 1989; Bertram et al., 2015; Fremstad, Petach, & Tavani, 2019; Klitkou, Bolwig, Hansen, & Wessberg, 2015; Romer, 1990). Hence, factors other than relative costs play an important role in the initial adoption and later diffusion of zero-carbon technologies. That would imply that even with changes in relative costs due to carbon prices, market behavior could remain constant, simply because other barriers are present. Policies addressing these other factors could play a large role in stimulating a technology transition to an entirely carbon-neutral one (Geels, Sovacool, Schwanen, & Sorrell, 2017; Patt & Lilliestam, 2018; Rosenbloom, Markard, Geels, & Fuenfschilling, 2020).

In short, there are competing theoretical arguments about the effectiveness of carbon pricing for triggering the technological change needed to solve the climate problem: a simple and intuitive argument based on economic incentives and price signals, calling for carbon pricing as the central policy instrument; and a more complicated argument based on the specifics of climate change targets, combined with the mechanisms of technological transitions, suggesting that carbon pricing's value may be limited. Whenever contradictory theoretical insights are present, empirical investigation is critical.

Here, we review the empirical peer-reviewed research on the effects of carbon pricing policies on technological change—innovation and investment toward a completely decarbonized energy system, including transport, consistent with the Paris Agreement. In this, we distinguish between different effects. Carbon prices can trigger short-term effects, originating in operational changes in existing assets, such as a switch within a power plant fleet from coal toward gas power (Vogt-Schilb, Meunier, & Hallegatte, 2018). This would reduce emissions quickly, so that the remaining carbon budget is exhausted slower, but it does not constitute the necessary technological change. Of more relevance for full decarbonization, carbon pricing can have longer-term effects, both by triggering investments in new low- or zero-carbon assets (e.g., more efficient airplanes, or new wind farms) or by inducing innovation in new low- or zero-carbon technologies or practices (e.g., private R&D in enhanced solar energy production). In these, the rate of technological progress, and the change rate of emission reductions, rather than the immediate emission level, is relevant (Patt, 2015; Vogt-Schilb et al., 2018).

We show that the empirical evidence for the effectiveness of carbon pricing for triggering technological change is on the one hand thin, and on the other hand discouraging. As to the former, there are surprisingly few studies that empirically document a link between carbon pricing and technological change. As to the latter, the few studies that have taken place document emission reductions originating in short-term operational shifts, but find only very minor effects, if any effects at all, on low- and zero-carbon investment and innovation. We thus conclude that the empirical evidence, while limited, in fact contradicts claims for the effectiveness of carbon pricing schemes in promoting the technological change necessary for the full decarbonization aim implied by the Paris Agreement.

2 | BACKGROUND

In this section, we briefly describe the theoretical background of how carbon pricing works, why it would be needed, and what effects it is expected to trigger (Section 2.1). Based on this, we discuss how the effects of carbon pricing schemes can be evaluated, including different evaluation perspectives, and the underlying theoretical reasons for our choice of evaluation framework (Section 2.2).

2.1 | Economic theory in support of carbon pricing

In perfect markets, producers and consumers communicate via the price signal, and the market finds an equilibrium that equates producers' marginal cost and consumers' marginal willingness-to-pay for any given good, and which achieves an efficient allocation of resources. There are, however, numerous sources of market failure, leading to sub-optimal outcomes. One of these is an environmental externality: when a traded good causes environmental damage that is not included in the price. An early recognition was that in these cases, putting a price on pollution, such as on carbon emissions, effectively corrects the market failure (Pigou, 1920). The "internalization" of externalities through "Pigouvian taxes" ensure that the cost of damage is factored into the decisions of firms and individuals and that an efficient level of pollution is reached.

Pricing pollution, and carbon in the case of climate change, promotes decarbonization to take place in a cost-effective way, by incentivizing lower-cost abatement options to the point that equalizes marginal abatement costs across the sources and sectors to which the carbon price applies. Carbon pricing does so by creating economic incentives for markets to use all levers available to reduce emissions: the type of activity pursued, the structure and energy intensity of a particular industry or of the economy as a whole, and the fuel chosen (Nordhaus, 1991; Pearce, 1991).

In addition to the cost-minimization rationale, the establishment of a price for pollution—here for carbon—is expected to generate dynamic incentives for the development and diffusion of less emitting technologies (for an overview in the carbon context, see (Verbruggen, Laes, & Woerdman, 2019). In theory, pricing pollution provides incentives for continuous innovation that other policy instruments—in particular technology standards often referred to as "command and control" policies—can fail to provide (Jaffe, Newell, & Stavins, 2002; Popp, Newell, & Jaffe, 2010; Requate, 2005). When firms anticipate a higher price on emissions, they have an incentive to reduce the emissions intensity of their output. The induced innovation hypothesis, dating back to Hicks (1932) and restated in the context of environmental policy by Acemoglu, Aghion, Bursztyn, and Hemous (2012), suggests that part of this new investment will be directed toward developing and commercializing new low- or zero-carbon technologies, in anticipation of higher carbon prices in the future.

Economists practically unanimously agree that some sort of Pigouvian tax is desirable, even as the questions related to the optimal design of the pricing instrument remains debated (Jenkins, 2014; Tang, Wang, & Wei, 2019). Many economists have argued for a direct carbon tax (Hassler, Krusell, & Nycander, 2016; Metcalf & Weisbach, 2009; Weitzman, 1974), also because the carbon tax can be directly controlled whereas a cap-and-trade system yields a fluctuating, and hence uncertain, carbon price that interacts stronger with other climate policies (Goulder & Schein, 2013). Others have advocated cap-and-trade systems, highlighting their better dynamic performance (Keohane, 2009; Krysiak, 2008; Storrøsten, 2014; Weber & Neuhoff, 2010). Some find that the two instruments are functionally equivalent (Aldy, Krupnick, Newell, Parry, & Pizer, 2010), while yet others have proposed and analyzed hybrid approaches (Abrell & Rausch, 2017; Pizer, 2002). Within each of these options, there are numerous different ways to design the pricing scheme, each with its own implications and advantages (Carl & Fedor, 2016). Economists generally prefer and advocate price-induced innovation over innovation induced by other instruments, such as technology subsidies, which are considered not cost-effective (Verbruggen et al., 2019); in specific cases, authors argue for combining carbon pricing with technology R&D to correct innovation market failures (Fischer, Preonas, & Newell, 2017), or if long-term targets require measures that are slow to implement (Vogt-Schilb & Hallegatte, 2014). Nonacademic policy advice tends to open up for broader policy mixes, with more instruments beyond carbon pricing (OECD, 2015; World Bank, 2015).

2.2 | Evaluating carbon prices: A matter of perspective

The evaluation of carbon pricing experiences implies dealing with several conceptual and methodological challenges (Verbruggen et al., 2019). Before performing an evaluation, it is essential to clarify the main alternative assessment approaches related to different objectives, temporal perspectives, and possible side effects of carbon pricing. Figure 1 shows three different approaches used in recent economic analyses. Part of the economic literature has focused on the macroeconomic effects of carbon pricing (Metcalf & Stock, 2020), especially its impacts on economic growth and the

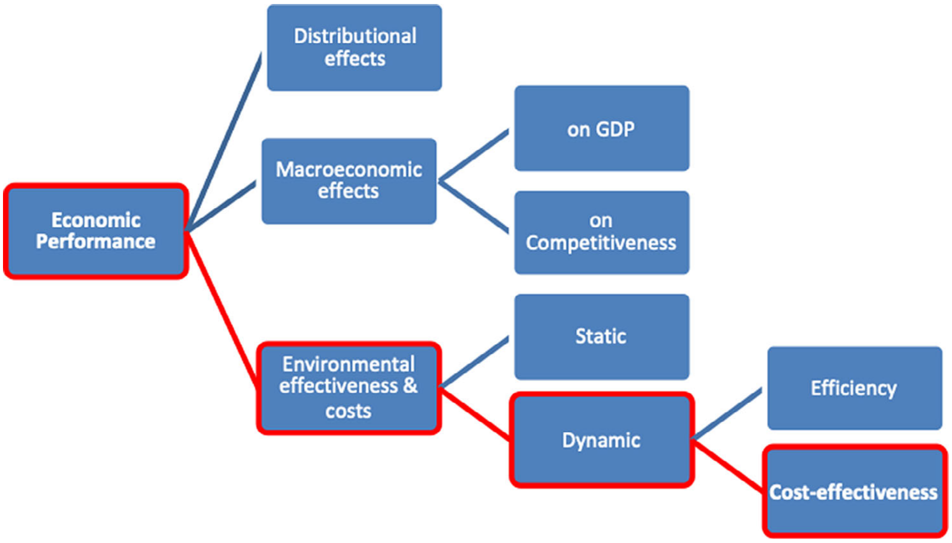

FIGURE 1 Evaluating the economic performance of carbon pricing

competitiveness of regulated industries. For instance, this approach is often used by articles analyzing carbon leakage (Naegele & Zaklan, 2019). A second group of studies has focused on the distributional consequences of carbon pricing (Dorband, Jakob, Kalkuhl, & Steckel, 2019; Wang, Hubacek, Feng, Wei, & Liang, 2016). A third group has studied the environmental performance of carbon pricing and the associated costs.

In this review, we focus on the evaluation of the primary aim of climate policy under the Paris Agreement, namely, to limit greenhouse gas (GHG) emissions to an extent that keeps the temperature rise below 2°C compared to preindustrial times. Unlike the Kyoto Protocol, which had a short-term emission reduction objective, the Paris Agreement sets out a long-term objective that requires not merely the reduction, but the complete elimination of net GHG emissions: as the carbon budget associated with any temperature target is finite, the carbon emissions must eventually reach net-zero. This distinction between emission reduction (Kyoto) and emission elimination (Paris) is relevant for the evaluation of successful instruments (Patt & Lilliestam, 2018). If the objective is to ensure the attainment of short-term emission reductions, a static perspective, considering only the short-term and immediate development of aggregate carbon emissions, suffices. If the objective is to achieve a long-term cap, or a total carbon budget, and the associated decarbonization of regulated sectors by shifting R&D and investment at the lowest cost (i.e., an intertemporal perspective, which considers the entire time horizon), then a dynamic perspective assessing costs and effects over a longer period, is needed. In carbon pricing systems, the dynamic perspective is the most relevant: both carbon taxes and emission trading schemes are typically designed to operate over decades (Fuss et al., 2018).

Figure 1 shows two alternative frameworks that can be used to analyze the intertemporal environmental and economic performance of taxes and cap-and-trade systems. The first is the dynamic efficiency framework, also known as the welfare-maximizing paradigm (Aldy et al., 2010), which uses the social cost of carbon (SCC) as the benchmark for cap-and-trade allowance price or tax levels. The SCC is a measure of the economic harm from the impacts of climate change, generally expressed as the monetary value of the total damages from emitting one ton of carbon dioxide into the atmosphere. This dynamic efficiency framework is rooted in social benefit–cost analysis (e.g., Pachauri et al., 2014). It implies that by maximizing social welfare, dynamically efficient climate policy would implement carbon prices such that the discounted sum of future marginal climate damages is equal to marginal abatement costs at each point in time (Fuss et al., 2018). This means that the optimal SCC defines a price path that depends not only on abatement costs and the interest rate but also on current and future climate change damages—which are highly uncertain by nature and very difficult, if at all possible, to estimate (Pezzey, 2019). This framework is used to assess the SCC, and hence the optimal carbon price, but is not used to assess the effects of actual carbon pricing schemes.

The second is the dynamic cost-effectiveness framework, which identifies the socially cost-optimal allocation of mitigation options over time, given an exogenously defined emissions target or carbon budget (Fuss et al., 2018). In this type of analysis, the primary objective of carbon pricing is neither short-term abatement nor compliance with annual caps, but rather achieving specific long-term emission reduction pathways at minimum societal costs. Short-term abatement targets must be consistent with long-term least-cost pathways but do not represent an objective per se (Vogt-Schilb et al., 2018). The dynamic cost-effectiveness framework concentrates on investment in long-lived emissions-producing capital stocks (e.g., power plants, means of transportation), and research and development efforts. In other terms, it focuses on innovation and diffusion of new technologies and is often used for ex-post analysis of existing carbon pricing schemes.

Here, we review and evaluate the findings of ex-post analyses of carbon pricing experiences along the lines of the dynamic cost-effectiveness framework, focusing specifically on the effectiveness of carbon pricing to induce technological change in the energy sector, including transport. This framework fits the challenge inscribed in the Paris Agreement (2015): a long-term trajectory to a clearly defined target—zero carbon emissions from energy by mid-century, with cumulative emissions staying below the associated carbon budget—for which deep technological change is necessary. In practice, the short- and long-term perspectives are interconnected and we include both in our evaluation. For example, weak dynamic effectiveness today, reflected by poor induced technological change, may negatively affect the static effectiveness of the instrument in the future, because it will relatively increase the abatement costs for the coming decades. When evaluating carbon pricing is thus important to take into account both types of effects.

3 | CASE SELECTION AND EVALUATION FRAMEWORK

An increasing number of countries and regions have introduced carbon pricing. In 2019, there were 57 carbon pricing initiatives implemented or scheduled for implementation. This consists of 28 ETSs in supranational, national, and subnational jurisdictions, and 29 primarily national carbon tax systems. In total, these carbon pricing initiatives cover 11 gigatons of carbon dioxide equivalent ($GtCO_{2eq}$), or about 20% of global GHG emissions (including the new Chinese national ETS). The carbon prices vary substantially, from the less than US$1/$tCO_{2eq}$ carbon taxes in Ukraine, Poland, and Mexico to the US$127/$tCO_{2eq}$ carbon tax on non-European ETS (non-EU ETS) sectors in Sweden; only 10 carbon pricing schemes achieved prices of US$25/$tCO_{2eq}$ or higher in 2019 (World Bank, 2019). In 2018, carbon pricing schemes generated some US$44 billion, almost equally distributed between ETS certificate sales and carbon taxes (World Bank, 2019).

In this article, we review empirical peer-reviewed ex-post analyses of existing carbon pricing schemes. As we describe below, we focus our analysis on the existing carbon pricing schemes that have a more-than-symbolic price, and for which there has been at least one peer-reviewed ex-post analysis, and utilize a well-defined framework in order to aggregate the observed effects. We do not investigate theoretical or ex-ante modeling but only ex-post, peer-reviewed analyses of existing schemes. Hence, our findings only refer to past, observed effects.

3.1 | Case selection: Carbon price schemes and article identification

As we analyze the empirical evidence about the effects of carbon pricing on technological change, we focus our analysis on schemes with nonsymbolic prices. This includes the EU ETS, which is largest ETS in the world and for which several ex-post evaluations are available. It also includes the carbon taxes in Nordic countries, which were implemented some 30 years ago[1] and are among the highest carbon prices in the world. Also New Zealand launched an ETS (NZ ETS) in 2008, following a decade of policy deliberation (Leining, Kerr, & Bruce-Brand, 2020). The NZ ETS is interesting in the sense that it includes all emitting sectors except agriculture; we thus included it, despite its low carbon price (US$17/$tCO_{2eq}$ in 2019). In addition, we analyze the experiences in British Columbia, with has had a carbon tax since 2008, covering about ¾ of all CO_2 emissions. It started at C$10/$tCO_2$ in 2008 and increased to about US$30/$tCO_2$ (C$40/t) by 2019. The carbon tax is designed to be revenue-neutral, meaning that all revenues are to be recycled to households and businesses, largely in the form of tax cuts (Rivers & Schaufele, 2015). Switzerland has had a carbon tax and a national ETS (CH ETS) since 2008. The CH ETS has had very low prices, because of overallocation and strong imports of certificates from the clean development mechanism, and has not triggered any need for emission-reducing activities in the trading sector (EFK, 2017). The carbon tax is a steering tax on fossil fuels, especially heating fuel, and is connected to the verified emissions of the taxed sectors: if they are on track, the tax remains constant, if they are below the indicative trajectory, the tax increases. Since its implementation in 2008, the carbon tax has increased from CHF12/tCO_2 to CHF96/tCO_2 (approximately the same in US$) in 2019 (World Bank, 2019). Finally, the French carbon tax was introduced in 2014 at a modest level (EUR7/tCO_2), applying to energy sectors not covered by the EU ETS, prominently transport and heating fuels. The tax increased according to a predefined schedule, to EUR45/tCO_2 in 2018.

Following social protest by the Yellow Vest movement, the planned doubling of the carbon tax was halted and, at least for the moment, the tax has not further increased (Douenne & Fabre, 2020; Gloriant, 2018).

Only in these relatively ambitious carbon pricing systems can we reasonably expect any effects on technological change to have become apparent, as very low carbon prices should not be expected to have substantial effects. We exclude many interesting schemes, including the Californian and Quebecoise ETS and the various pilot schemes in China, as they have too low prices. Nevertheless, there are some studies evaluating such low-price schemes. For example, the Regional Greenhouse Gas Initiative (in several northeastern U.S. states) has been evaluated by several studies, showing weak or no effects on emission reductions, partially explained by leakage of electricity generation and emissions to other states (Chan & Morrow, 2019; Fell & Maniloff, 2018; Murray & Maniloff, 2015).

For our review, we thus focus only on the ETS in the EU and New Zealand, and the carbon tax systems in British Columbia, France, Switzerland, and four Nordic countries (minus Iceland). Table 1 summarizes the main characteristics of these systems. At the global level, 27% of carbon pricing revenues are used to subsidize "green" spending in renewable energy or energy efficiency, 26% goes toward governments general funds, and 36% are returned to corporate or individual taxpayers to paired tax cuts or direct rebates. There is, however, a significant difference in the use of ETS and tax revenues. Across ETSs, governments have allocated 70% of revenues toward green spending, while in the case of taxes, they allocate 72% of revenues toward refunding private revenues and government's general budgets (Carl & Fedor, 2016).

For our analysis, we exclude all carbon pricing schemes not described in Table 1, on the basis of having a price below US\$25/tCO_{2eq} in 2019. If a carbon pricing scheme exceeded this price level in 2019, we include the entire history of the scheme, also for earlier years with lower carbon prices.

Finally, we searched the standard academic search engines, including ScienceDirect and Google Scholar, to identify the peer-reviewed articles for our analysis. We excluded all theoretical and ex-ante simulation-based articles. For this, we performed both a generic search for analyses of carbon pricing schemes ("carbon pricing," "carbon tax," "emission trading,") and targeted searches for the specific schemes included (e.g., "carbon tax + Sweden," "EU ETS," and so on). This resulted in a high number of articles, which we scanned for contents, finally identifying 19 peer-reviewed articles describing empirical ex-post evaluation of at least one of the selected carbon pricing schemes during any time period between the policy introduction and 2019 (see Table 2). We found no peer-reviewed ex-post analysis for the Swiss and French carbon taxes, although there are several gray literature reports on the systems (e.g., Ott and Weber (2018) (Switzerland) or Gloriant (2018) (France), both showing insignificant effects of the two carbon tax schemes). Hence, we do not include these two systems in our review. One article (Lin & Li, 2011) investigates the Dutch carbon/energy tax alongside with the Nordic carbon taxes.

3.2 | Method for identifying and reporting the effect of carbon pricing

The articles selected for analysis in this review, in Table 2, have in common that they are empirical *ex-post* analysis of at least one of the comparatively high-price carbon pricing schemes that exists today, shown in Table 1. In terms of the methods used or research questions asked, they differ strongly. Some articles deployed qualitative methods based on surveys or questionnaires to understand the response of firms to carbon price signals. Among the quantitative analyses, some are based on firm-level data and others on country-level data and use different definitions and indicators to measure effectiveness (e.g., the carbon intensity, the number of patents or the total CO_2 emission reduction). The heterogeneity in methods and scope of the reviewed papers do not allow us to combine the results quantitatively, for example, through statistical meta-analysis techniques. However, the direction and the intensity of the observed effects are reported. Hence, we base our analysis on the main results of each study about the effectiveness of the carbon pricing scheme(s), as described by the authors of each individual article. When a quantitative result is available, we explicitly report it in our results alongside with a qualitative conclusion. When no numbers are available, we report the main qualitative effect.

For analyzing the effects on technological change, it is not sufficient to investigate the immediate impact of carbon pricing on CO_2 emissions, but we need a decomposition of results to see which type of effects are triggered by the carbon price. In addition to the observed emission reductions, we specifically investigate four different root causes for emission reduction effects (Table 3), of which the latter three constitute "technological change," whereas the first does not.

TABLE 1 Main characteristics of selected carbon pricing schemes

Scheme	Introduced in year	Emissions covered	Sectors	Allocation	Price US $/tCO$_{2eq}$[a]	Revenues million US $ (2018)	Revenues use %[b]
European emission trading system (EU ETS)	2005	45%	industry, electricity, aviation	free and auctioning	32	15,948	Green spending: 80 General funds: 20 Revenue recycling: 0
New Zealand ETS	2008	51%	industry, electricity, waste, transport, forestry	mainly free	16	0.4	Green spending: unknown General funds: unknown Revenue recycling: unknown
Sweden carbon tax	1991	40%	Mainly transport and heat	N/A	121	2,572	Green spending: 0 General funds: 50 Revenue recycling: 50
Denmark carbon tax	1992	40%	Mainly transport and heat	N/A	25	543	Green spending: 8 General funds: 47 Revenue recycling: 45
Finland carbon tax	1990	36%	Industry transport heat	N/A	58–68	1,459	Green spending: 0 General funds: 50 Revenue recycling: 50
Norway carbon tax	1991	62%	All sectors, but with exemptions	N/A	3–57	1,644	Green spending: 30 General funds: 40 Revenue recycling: 30
Switzerland carbon tax	2008	33%	Heat, transport (Industry, electricity)	N/A	96	1,178	Green spending: 33 General funds: 0 Revenue recycling: 67
France carbon tax	2014	35%	Heat, transport	N/A	49	8,968	Green spending: 100 General funds: 0 Revenue recycling: 0
British Columbia carbon tax	2008	70%	All sectors with several exemptions	N/A	30	1,145	Green spending: 0 General funds: 0 Revenue recycling: 102

Note: Green spending is state revenue earmarked for climate protection measures, general funds go to the government budget without earmarking, in revenue recycling income is paid back to consumers and companies through other tax reductions or subsidies.

[a] Nominal prices on November 01, 2019.

[b] Estimation for 2013 (Switzerland, France 2014; Denmark 2010) by Carl and Fedor (2016).

Source: https://carbonpricingdashboard.worldbank.org/ (consulted in March 2020).

We report the observed effects of carbon pricing in CO_2 emission reductions and in each of the four effect categories (when the information is available) of each article in three qualitative degrees:

- *No effect*: The article found that the carbon pricing scheme did not have any effect on general emission reductions or on the respective effect category. We report "no effect" only when the article shows no statistically significant effect or when explicitly concludes that the investigated carbon pricing scheme had no observable effect (for qualitative evaluations).
- *Weak effect*: The effects the authors of each article attribute to the carbon pricing scheme are small, not explaining a large share of observed emission reductions, investments or innovation activities; or they find that the effects of the carbon pricing are smaller than those attributed to other policies.
- *Strong effect*: The effects the authors of each article attribute to the carbon pricing scheme are large, explaining a large share of observed emission reductions, investments or innovation activities; or they find that the effects of the carbon pricing are considerably larger than those attributed to other policies.

Finally, we gather information about the reasons identified in each of the articles as to why the carbon pricing scheme did or did not trigger effects. We report the explanations provided by each article, such as design failures of the specific carbon pricing instrument or the influence of other explanatory variables.

4 | RESULTS OF THE REVIEW

We describe the main findings, including the key explanations for each finding of the 19 investigated articles for carbon pricing schemes in the emission trading schemes of the European Union (EU ETS, Section 4.1) and New Zealand (NZ ETS, Section 4.2), and of the carbon taxes in the Nordic countries (Section 4.3) and British Columbia (Canada; Section 4.4). We synthesize the results in Section 4.5, showing that the investigated articles identify some emission reduction effect through fuel switching (especially in the power sector) and a reduction of gasoline consumption, weak or no effects on low-carbon investment and innovation, and no effects on zero-carbon investment.

4.1 | Effects of the EU ETS

The EU ETS has been the subject of several evaluations, both for single countries and the EU as a whole, analyzed through a variety of methods, time periods, and evaluation criteria. Nine of the 19 articles investigate the EU ETS. These studies allow for two main findings. First, they identify no or weak effects on short-term emission reductions from operational or behavioral shifts. Second, we find no evidence that the EU ETS has triggered substantial innovation and diffusion of new technology, and some evidence that it has not.

Rogge et al. (2011) analyzed the German power sector through interviews carried out in 2008/09 for 19 case studies (power generators, technology providers, and project developers). They found that the initial phases of the ETS had minor effects in firm decision-making but no impact on innovation and deployment of low- or zero-carbon technology. They also found some impacts on the increase of R&D on carbon capture and storage (CCS) and coal technologies, often in cooperation with chemical industry players. They explain the observed underperformance by the scheme's initial lack of stringency and predictability, and the much larger importance of context factors, such as fuel price fluctuations or renewables support. In the observed period, the CO_2 price was too low to trigger new investment, or to make CCS profitable. Furthermore, the free allocation increased the economic attractiveness for new coal power plants and extended operation of existing ones. Finally, Rogge et al. conclude that even with higher prices, the EU ETS on its own will insufficiently incentivize the necessary fundamental changes for meeting the long-term mitigation targets.

Schmidt et al. (2012) studied the effect of ETS on the rate and direction of corporate innovation activities through regression analysis for the electricity sector in seven EU countries. They found no or negative effects on technological change: as fossil fuel power generators reaped windfall profits through the free allocation and were not constrained by the too high cap, they could increase investment in new emitting assets. This led to a positive perception of the EU ETS by many firms, but neither to emission reductions nor to technological change. Schmidt et al. also show that the scheme triggered no zero-carbon investment and no additional R&D activity in Phases 1 and 2. Finally, they show that

TABLE 2 Articles included in the review

Author (year)	Policy	Period	Country	Objective	Method
Rogge, Schneider, and Hoffmann (2011)	European emission trading system (EU ETS)	2005–2008	Germany	Impact on RD&D, new tech adoption, and organizational change	Case studies/ interviews
Schmidt, Schneider, Rogge, Schuetz, and Hoffmann (2012)	EU ETS	2000–2012	7 EU countries	Effect on the rate and direction of innovation	Multivariate linear regression
Löfgren, Wråke, Hagberg, and Roth (2014)	EU ETS	2002–2008	Sweden	Effect on firms' investments in carbon-reducing techs	Difference-in-differences
Borghesi, Crespi, D'Amato, Mazzanti, and Silvestri (2015)	EU ETS	2000–2012	8 EU countries	Effect of ETS and RE policy on innovation	Interviews
Jaraite-Kažukauske and Di Maria (2016)	EU ETS	2003–2010	Lithuania	Impact on CO_2 emissions, intensity, investment behavior and profitability	Differences-in-differences
Calel and Dechezlepretre (2016)	EU ETS	2005–2010	23 EU countries	Effect on low-carbon techs patenting	Difference-in-differences
Bel and Joseph (2018)	EU ETS	2005–2012	EU	Impact on innovation	Count data model
Schaefer (2019)	EU ETS	2005–2015	Germany	Isolate the impact of the EU ETS on CO_2 emission reduction	Linear regression
Klemetsen, Rosendahl, and Jakobsen (2020)	EU ETS	2001–2013	Norway	Impact on total CO_2 emissions and on carbon intensity	Difference in-differences and fixed effects
Richter and Mundaca (2013)	NZ ETS	2008–2012	New Zealand	Ex-post assessment of market behavior	Interview/ document analysis
Bohlin (1998)	Tax	1990–1995	Sweden	Effects on biofuel use and CO_2 emissions	Not specified
Bruvoll and Larsen (2004)	Tax	1990–1999	Norway	Effect on the carbon intensity of GDP	Applied general equilibrium model
Lin and Li (2011)	Tax	1981–2008	Denmark, Norway, Sweden, Finland, the Netherlands	Effect on per capita CO_2 emissions	Difference-in-differences
Shmelev and Speck (2018)	Tax	1961–2012	Sweden	Impact of carbon and energy taxation on CO_2 emissions	Econometrics
Andersson (2019)	Tax	1960–2005	Sweden	Causal effect on CO_2 emissions	Synthetic control method
Rivers and Schaufele (2015)	Tax	2007–2011	British Columbia	Effects on gasoline consumption	Regression analysis
Lawley and Thivierge (2018)	Tax	2001–2012	British Columbia	Effects on gasoline consumption	Regression analysis
Xiang and Lawley (2019)	Tax	1990–2014	British Columbia	Effects on natural gas consumption	Synthetic control
Bernard and Kichian (2019)	Tax	2008–2016	British Columbia	Effects on diesel demand	Times series

TABLE 3 Carbon pricing effects investigated in this review

	Effect category	Description
Short term	Operational shifts	Near-term changes in operation mode among existing assets, leading to immediate emission reductions. Examples include shifts of generation from coal to already existing gas power stations, or driving less by shifting some trips to a bike
Long term: technological change	Low-carbon investments	Investments in technologies or practices that are less carbon intensive than old technologies and practices but still depend on fossil fuels. Examples include the construction of new, more efficient gas- or coal-fired power stations or replacing a gasoline car with a more carbon-efficient diesel car
	Zero-carbon investments	Investments in carbon emission-free technology or practices. Examples include renewable energy or nuclear power, or zero-energy buildings/renovation
	Innovation	Investments in research and development of low- or zero-carbon technologies, generally measured by the number of patents

technology support, both R&D and technology-specific deployment support had significant effects on zero-carbon technological change, compensating for the insufficient impact of the EU ETS.

Löfgren et al. (2014) analyze the impact of the scheme on firms' investment decisions in carbon-reducing technologies, using firm-level data from Sweden in 2000–2008. The difference-in-difference method identifies the isolated effect of a policy through comparison of outcomes before and after a policy change for a group affected by the change (i.e., the firms included in the ETS) to a group not affected by the change (the control group). They show that the introduction of the EU ETS did not have a significant effect on firms' investment or operational decisions in CO_2-reducing measures in Sweden. They note substantial investments in carbon-reducing equipment, especially in bioenergy and district heating systems, but find that these investments would have happened also without the EU ETS, triggered by other policy measures or because they were economically attractive on their own.

Borghesi et al. (2015) interviewed industry representatives in eight EU countries in 2013. Their results show that the EU ETS did not trigger investments, but it did promote fuel switching, mainly from coal to gas power. They also conclude that the EU ETS did trigger some innovation in CCS, but not in the renewable energy segment—there, renewables support and other policies were innovation drivers.

Jaraite-Kažukauske and Di Maria (2016) used a panel data set to analyze the environmental and economic effect on some 5,000 Lithuanian firms for 2003–2010. They show that the EU ETS did not reduce emissions, but it did improve carbon intensity. They also show that the EU ETS did not trigger fuel switching within existing assets, but it likely induced the retirement of old, inefficient assets during the first trading years, and some additional investments into new, more efficient equipment after 2010. The exact nature of this new investment is not specified, but appears to be low-carbon assets. The authors note that the increase in investment after 2009 coincides with a new law mandating that the revenues from allowance sales must be spent on environmental measures.

Employing econometric methods, Calel and Dechezlepretre (2016) investigated the effects of the EU ETS on firm-level low-carbon R&D (patenting activity) in Europe, in 2005–2010. They compare innovation activities in trading sector firms with nontrading firms before and after the introduction of the EU ETS through a matched difference-in-differences method. They show that the EU ETS triggered a 36% increase in low-carbon patenting among the sample of 3,428 EU ETS firms, corresponding to +9% across all of the 5,500 regulated firms. Because the regulated firms account for only a small portion of all low-carbon patents, only 2% of the post-2005 surge in low-carbon patenting can be attributed to the EU ETS. They conclude that "the system so far has had at best a very limited impact on the overall pace and direction of technological change." Instead, they find that the key innovation driver was renewable energy policies, although their method does not allow them to quantify this non-ETS effect.

Bel and Joseph (2018) analyzed the effect on low-carbon patent registration in 2002–2012, at the European level. They applied a similar method as Calel and Dechezleprêtre and confirm their finding, showing that the scheme had little or effect on innovation. They explain this by the too high cap which "cannot be considered conducive to technology change" as it does not create pressure to reduce emissions.

A recent study focused on the effects of the EU ETS on the German electricity sector, Schaefer (2019) by contrasting reality with a counterfactual emissions scenario without the EU ETS, from 2005 to 2015. The method differentiates the impact of EU ETS from the impact of subsidized renewable energy and fuel prices for hard coal and gas. Schaefer finds that carbon pricing had a lower impact on emission reduction in the German electricity sector than assumed: they attribute 1.2–4.6% emission reduction to the EU ETS, and all of it before 2010; Schaefer finds that the EU ETS had no effect on emission reductions in the German power sector in 2010–2015. Instead, the renewables support accounted for at least 50% more emission reductions in 2010, and 460% more in 2015.

Finally, Klemetsen et al. (2020) used firm-level data to evaluate the impacts of the EU ETS on the Norwegian manufacturing plants' environmental and economic performance in 2005–2013. They find weak evidence that the EU ETS triggered some emission reductions in Phase II (2008–2012), but also that it had no effects before and after that. However, the authors note that the results for Phase II holds in some but not all robustness tests. Most importantly, the results show no effects on the emissions intensity of any of the three phases, implying that decreased production could be one cause for the reduced emissions. The authors do not explain which mechanisms may explain the emission reduction in Phase II.

4.2 | Effects of the NZ ETS

The NZ ETS is unique in its design and comprehensive sectoral coverage, including forestry. Also, the system was linked with the global Kyoto emissions allowance market to enhance its efficiency. Richter and Mundaca (2013) performed the, to our knowledge, only ex-post evaluation of market behavior in the NZ ETS in its first phase (2008–2012), based mainly on qualitative information from interviews and questionnaires of key market participants and authorities. Their findings show that the NZ ETS had no impact on investment decisions or on operational shifts. Concerning the reasons for the underperformance, respondents highlighted the low prices of allowances and the more significant influence of other economic factors: “renewable energy projects were profitable in New Zealand without the carbon price.”

4.3 | Effects of the carbon taxes in Nordic countries

Introduced in the early 1990s, the carbon taxes in the Nordic countries (except Iceland) are the oldest and among the highest-priced carbon pricing schemes in the world. However, only few peer-reviewed studies offer ex-post empirical assessments. Of the five peer-reviewed articles we found for our analysis, all show no effects on investments, but some effects on operational shifts; no article investigated the effects of Nordic carbon taxes on innovation. Furthermore, one article finds strong emission reduction effects in the transportation sector.

Bohlin (1998) evaluated the effect of the carbon tax in Sweden in 1990–1995. He found an effect only in the district heating sector, triggered by the co-existence of the carbon tax and investment support policies, where bioenergy (forestry residue) use replaced primarily coal, accompanied by a growth in the industry for densified wood fuels (e.g., wood bricks or pellets), through operational shifts. Bohlin found no effect of the carbon tax in the transport and electricity sectors.

Bruvoll and Larsen (2004) studied the effects of the carbon tax in Norway in the period 1990–1999, using decomposition analysis to find the drivers for observed emission reductions. They showed that the carbon tax had a small effect – 2.3% reduction of CO_2 emissions—caused by a small decrease in the energy intensity (−1.3% of emission reduction) and fuel switching in heating (fossil fuel to electricity, −1%). They explain the underperformance of the tax mainly by the numerous exemptions for fossil fuel-intensive industries.

Lin and Li (2011) used a difference-in-differences framework to estimate the effects of carbon taxation on emissions in Sweden, Denmark, Finland, Norway, and the Netherlands 1981–2008. They found a significant effect for Finland only, where the tax caused a reduction in emission growth by 1.7% compared to a scenario without the tax. They found no effect in Norway, Sweden, Denmark, and the Netherlands, especially as these countries provided tax exemptions for the manufacturing industry and related energy-intensive industries. Lin and Li state that the effects that could be observed, however, small, were connected to the use of the carbon tax revenues and not the steering effect of the carbon price signal.

The econometric model applied by Shmelev and Speck (2018) for the Swedish carbon tax (1961–2012) showed no statistically significant effect on CO_2 emissions. The author highlighted that the CO_2 tax should not be seen in isolation from other, earlier policy measures. Importantly, the introduction of low-carbon technologies, such as nuclear and hydro power, were very important for the Swedish CO_2 emission trajectory, but happened before the carbon tax was introduced.

Finally, Andersson (2019) analyzed the transport sector in 1960–2005, applying an econometric approach called "the synthetic control method" in which the *real Sweden* trajectory is compared with a *synthetic Sweden* constructed from a comparable group of OECD countries without a carbon tax. His results contradict Lin and Li's—and he criticizes their research design—and show that the carbon tax effect reduced transport emissions by 6% compared to what would otherwise have been the case in 1991–2005. He finds that the carbon tax elasticity of demand for gasoline is three times larger than the price elasticity, and remarks that a shift from gasoline to diesel cars happened in the observed time period, but does not explicitly disaggregate and explain the emission reductions mechanisms. Andersson remarks that his is the first study to find a significant causal effect of carbon taxes on emissions.

4.4 | Effects of the carbon tax in British Columbia

A set of recent papers investigate the impact of the British Columbian carbon tax. All find effects on fossil fuel demand and related emission impacts, caused by a higher consumer response to the carbon tax than to other price developments, but do not disaggregate why and where these effects happened.

Utilizing several econometric models, Rivers and Schaufele (2015) evaluated the effects of the tax on gasoline consumption and related CO_2 emissions in 2007–2011. They found that the carbon tax generated a much larger response than is attributable to an equivalent change in the carbon tax-exclusive price. They do not disaggregate the results or mention the causal effect triggering the observed emission reductions. They conclude that the carbon tax has larger effects than other taxes due to the high "salience" of the carbon tax resulting from media coverage and significant public debate, combined with the fact that the tax may reduce free-ridership in emissions mitigation since all households pay for emitting CO_2.

Lawley and Thivierge (2018) performed a regression analysis and arrived at similar findings, showing a 2.9 times higher carbon tax elasticity than price elasticity. They find very substantial effects: a 5 cent/l carbon tax reduced gasoline consumption by on average 8%, without specifying why this effect happened. Moreover, they found that households residing in Vancouver and other cities responded to the carbon tax, whereas households in small towns and rural areas did not. They conclude that the BC carbon tax is an effective means of reducing gasoline consumption in densely populated areas, but not in sparsely populated regions where households lack alternative means of transportation; this suggests that operational shifts (e.g., from car to bus for some trips) is an important reason.

Xiang and Lawley (2019) used panel regression and synthetic control methods for the period 1990–2014 to estimate the effect on residential natural gas consumption. They found that gas consumption declined by an annual average of 35 m^3/capita/year, or 6.9%, in BC relative to a group of synthetic control provinces and states. They do not explain why this happens (e.g., investment in isolation or new heaters, or just heating less). They also conclude that the carbon tax elasticity was seven times market price elasticity, but do not discuss the reasons for this effect.

Bernard and Kichian (2019) investigated the impact on diesel demand in 2008–2016, thereby explicitly complementing the household focus of Xiang and Lawley, also by including sectors for which "leakage" (e.g., fuelling in the near-by US) is harder. In this, they distinguish between short- and long-term effects of the tax. They found that the tax raised the pump price by 5.85 cent/l, which reduce diesel consumption by 1.24 l/month per capita, or 1.3%. They do not explain the causal driver for the demand reduction (e.g., driving less, public transport). They also note that the carbon tax is part of a policy package implemented in 2008, and part of the observed decrease may be attributed to other climate measures. As the other BC studies, the find a higher carbon tax than price elasticity, but also note that the CO_2 reductions are insufficient to meet the long-term climate objectives.

4.5 | Synthesis of the results

The results of our review show that all empirical ex-post studies of the carbon pricing schemes in the EU, New Zealand, British Columbia, and the Nordic countries find no or weak effects of the carbon price on technological change, whereas several articles find substantial effects on short-term carbon emissions (Table 4).

Three of the six studies that explicitly investigate and report on the effect on operational shifts find immediate effects on CO_2 emissions triggered by fuel switches, including through higher utilization of existing gas power stations at the expense of coal power generation. The other three studies conclude that there was no effect. Importantly, a set of articles, including all for British Columbia and one for Sweden, find strong emission reductions in the transport sector,

TABLE 4 Synthesis of results in the analyzed articles and decomposition of observed effects (on operational shifts, low-carbon and zero-carbon investment, and low- and zero-carbon innovation)

Article	Policy	Main finding	Operational shifts	Low-carbon Investment	Zero-carbon Investment	Innovation	Explanation
Rogge et al. (2011)	European emission trading system (EU ETS)	*Weak effect* Almost no impact on technological change *No effect* on investments	N/A	No effect	No effect	Weak	Lack of stringency and predictability of ETS; relatively greater importance of context factors and policies; some impacts on carbon capture and storage R&D
Schmidt et al. (2012)	EU ETS	*No effect* on the adoption of non-emitting technologies or on innovation in phases 1&2	N/A	N/A	No effect	No effect	The flawed ETS design leading to low prices; other policy (renewables support) had strong effect on new tech adoption
Löfgren et al. (2014)	EU ETS	*No effect* on firms' investment and operational decisions	No effect	No effect	No effect	N/A	The investment decisions are determined by other factors like "environmental internal knowledge"
Borghesi et al. (2015)	EU ETS	*Weak effect* on fuel switching and innovation in CCS	Weak	No effect	No effect	Weak	Greater effect on innovation of renewable energy policy and regulation to promote energy efficiency in the residential sector
Jaraite-Kažukauske and Di Maria (2016)	EU ETS	*No effect* on emission reduction *Weak effect* on carbon intensity	No effect	Weak	N/A	N/A	Overallocation and stronger influence of other factors, like gas prices
Calel and Dechezlepretre (2016)	EU ETS	*Weak effect* On low-carbon patenting (~2% increase)	N/A	N/A	N/A	Weak	The EU-ETS concerns a relatively small number of firms, so the aggregate effect is not strong; other factors have played a stronger role in innovation
Bel and Joseph (2018)	EU ETS	*Weak effect* Very weak or no effect in new patents	N/A	N/A	N/A	Weak	The allowances oversupply, reducing the price and the incentive to innovate in climate protection
Schaefer (2019)	EU ETS	*Weak effect* On emission reduction (1.2–4.6%) before 2010; No effect on emission reductions post-2010	N/A	N/A	N/A	N/A	Renewable power support led to at least 50% more to emission reduction in the German electricity sector in 2010 and at least 460% more in 2015 than the EU-ETS. Study did not disaggregate where, why effects happened.
Klemetsen et al. (2020)	EU ETS	*No effect* on carbon intensity in Phases I–III;	N/A	N/A	N/A	N/A	The allowances oversupply and low prices

(Continues)

TABLE 4 (Continued)

Article	Policy	Main finding	Operational shifts	Low-carbon Investment	Zero-carbon Investment	Innovation	Explanation
		no effect on emission reduction in phases I and III *Weak effect* on emission reduction in phase II					
Richter and Mundaca (2013)	ETS—New Zealand	*No effect* On firms' behavior or on investment decisions	No effect	No effect	No effect	N/A	Too low carbon price and greater importance of other economic factors
Bohlin (1998)	Tax—Sweden	*Strong effect* Use of biofuel in district heating doubled in 5 years; effect in policy mix with subsidies. *No effect* On investments or operational shifts in other sectors.	Strong	No effect	No effect	N/A	Undifferentiated co-effect of carbon tax and direct investment support: other policies (subsidizing the conversion of CHP stations) reduced the fixed cost and supported the district heating fuel switch
Bruvoll and Larsen (2004)	Tax—Norway	*Weak effect* On fuel switching and energy efficiency, leading to −2.3% CO_2 emissions *No effect* on investments	Weak	No effect	No effect	N/A	The exemption for a broad range of fossil fuel-intensive industries motivated by concern about competitiveness diminished the effects; relatively inelastic demand; direct regulations have proven far more successful
Lin and Li (2011)	Tax—Norway, Sweden, Denmark, Finland	*No effect* on emission reductions in Norway, Sweden, and Denmark *Weak effect* on emission reductions in Finland (~1.6% of the observed per capita emission reduction)	N/A	N/A	N/A	N/A	Substantial tax exemptions for manufacturing industry and related energy intensive industries removed pressure for action of firms. Observable effects related to revenue use Study did not disaggregate where, why effects happened
Shmelev and Speck (2018)	Tax—Sweden	*No effect* The carbon tax taken in isolation had no effect on CO_2 emissions	N/A	N/A	N/A	N/A	The introduction of low carbon technologies has played a significant role in CO_2 emission reduction, as did the higher oil prices Study did not disaggregate where, why effects happened

TABLE 4 (Continued)

Article	Policy	Main finding	Operational shifts	Low-carbon Investment	Zero-carbon Investment	Innovation	Explanation
Andersson (2019)	Tax—Sweden	*Strong effect* A reduction of 6.3% of CO_2 emissions in the transport sector between 1990 and 2005	N/A	N/A	N/A	N/A	The carbon tax elasticity of demand for gasoline is three times larger than the price elasticity. Study remarks that there was a simultaneous shift to diesel cars but does not explicitly disaggregate where, why effects happened.
Rivers and Schaufele (2015)	Tax—BC	*Strong effect* on gasoline consumption	N/A	N/A	N/A	N/A	Higher carbon tax elasticity (compared to other taxes)
Lawley and Thivierge (2018)	Tax—BC	*Strong effect* on gasoline consumption	N/A	N/A	N/A	N/A	Higher carbon tax elasticity (compared to other taxes)
Xiang and Lawley (2019)	Tax—BC	*Strong effect* on per capita residential natural gas consumption	N/A	N/A	N/A	N/A	Higher carbon tax elasticity (compared to other taxes)
Bernard and Kichian (2019)	Tax—BC	*Weak effect* on diesel consumption	N/A	N/A	N/A	N/A	Higher carbon tax elasticity (compared to other taxes)

but do not explicate why; very likely, these are operational shifts (driving less, taking public transport for some trips) and low-carbon investment (buying a diesel car instead of a gasoline car); as Sweden and British Columbia have very low shares of electric cars and trucks in the investigated periods, we conclude that these results cannot be due to zero-carbon investment.

For the full decarbonization of energy systems, technological change is necessary, and here studies unanimously find insufficient effects—and generally no effect at all, especially on investment. Only one of the seven articles assessing effects on low-carbon investment find any effect at all: the other six articles conclude that there was no effect. Most critically, all seven articles presenting disaggregated results for zero-carbon investment conclude that the carbon pricing scheme had no effect. All five articles that present disaggregated effects on innovation/patenting activity show weak (4) or no (1) effects.

None of these studies investigated the most recent experiences: all except one focused on the time before 2015. Most studies mention low price for CO_2 and/or excessive allowance allocation as main explanations for the underperformance of the EU and NZ ETS to trigger new investment or innovation in low- or zero-carbon technology. Although the Nordic taxes were generally much higher than the EU ETS price, the identified effects are small in the Nordic countries too; authors often explain this with the excessive exemptions of carbon-intensive industries from the tax to ensure their international competitiveness. In British Columbia, a very high carbon tax elasticity is found to drive the observed emission reductions.

5 | DISCUSSION

The papers we review support three main findings. First, there is very little empirical evidence about the effectiveness of carbon pricing on technological change in general, and most of the papers that met our search criteria focused on one continent: Europe. Second, there is evidence that carbon pricing has triggered emission reductions, generally caused by fuel switches within existing assets and efficiency gains, although in the case of British Columbia the reason is not completely clear. Third, the limited empirical evidence that does exist shows a consistent pattern, across different countries, in terms of the effects of carbon pricing on the innovation and zero-carbon investment needed for technological change toward full decarbonization: there is no, or almost no, effect.

In the context of climate policies enacted a decade ago, to deliver near-term emission reductions needed for achieving the terms of the Kyoto Protocol, the lack of an effect on technological change may not have mattered. Then, the short-term emission reductions that carbon prices do appear to stimulate were of paramount importance. In the current context of the Paris Agreement, however, the desired immediate effect is technological change, as the prerequisite for eliminating emissions in the energy sector by mid-century. In this context, our results show existing carbon price schemes to have been an ineffective instrument.

An important emissions-reducing effect identified in a few, but not all, of the articles is an operational shift among existing assets. The articles on British Columbia find strong emission reductions, but do not say why; in all cases, as in Andersson (2019) for Sweden, it appears to be caused by operational shifts (e.g., taking the bus, driving less) and possibly low-carbon investment (e.g., replacing a gasoline car with a diesel car). Some articles mention a shift from coal to already existing gas power generation, as the carbon price affects carbon-intensive coal stronger than gas power, which pushed coal power out of the merit order and hence out of the market (Wilson & Staffell, 2018). This effect is currently identified as substantial in current gray literature, especially in European countries with large existing gas power fleets and increasing shares of renewables triggered by dedicated renewables support schemes (Agora Energiewende, 2020; Agora Energiewende & Sandbag, 2020; Sandbag, 2019). However, the same fuel-switch effect is currently also observed in the United States, where there is no carbon price (Bloomberg, 2019; IEEFA, 2020), raising questions of attribution: possibly, coal power is decreasing because of other reasons, including relative shifts in the recently volatile coal import and gas market prices. It seems that carbon pricing played a part in the "collapse of coal" in some industrialized countries in 2019, but policy-induced renewables deployment and gas price developments may have played large roles, too, and further research is needed. For the climate, operational shifts are helpful because they rapidly decrease emissions and increase the remaining carbon budget, buying time for full decarbonization. For the process of full decarbonization, however, such operational shifts are not useful: shifting from coal to existing gas power is not technological change, and it is neither sufficient nor necessary for full decarbonization.

Ten of the 19 articles we reviewed examine the effects on technological change, in terms of investments in lower- or zero-carbon investments or on innovation activity in lower- or zero-carbon technology. For R&D and patenting activity, most articles identify weak effects, and one concludes that there was no effect. Regarding investments, the evidence is clearer. Seven out of those 10 articles specifically take investment in low- or zero-carbon technologies as dependent variables. All seven of these conclude that the carbon price had no effect on zero-carbon investment, and six of them find no effect for low-carbon technology investment. Hence, there is no empirical evidence that carbon pricing has triggered investments in critically needed zero-carbon technologies, and some evidence that it has not.

The studies themselves describe three main reasons for the absence of mentionable observed effects on technological change, all of which are also commonly discussed in the broader literature (Haites, 2018). First, there have been design and implementation problems. Prominently, this is overallocation of certificates in emission trading schemes leading to a too low carbon price and excessive exemptions in carbon tax schemes. Second, contextual factors, such as other price developments, overshadowed the guiding effect of carbon pricing, masking or eliminating any price signal effect from the carbon price. Third, other policy instruments, especially renewable energy support schemes, triggered rapid innovation and deployment of zero-carbon technology by offering better conditions to investors than the parallel carbon pricing scheme and hence being the causal source of any observed technological change.

A core argument in the literature, including the reviewed articles, is that the carbon prices enacted to date are all inadequate in one way or another, and hence even if the carbon pricing systems we can observe have failed to have the desired effect, this does not preclude future carbon pricing policies being more effective. Our results do not challenge this argument, as we note that none of the carbon pricing schemes evaluated here was implemented according to textbook theory. And yet we also note that a policy may be both inadequate *and* the best possible implementation simultaneously. High carbon prices could, theoretically, be more effective, but are often politically very difficult to implement and maintain (see, e.g., Jenkins, 2014). There are many examples demonstrating the political difficulty of high carbon prices: the public rejection of a proposed carbon tax in Washington State; the yellow-vest protests in France protesting a carbon tax, and leading to a process designed to represent citizens' view in French climate policy that subsequently proposed over 100 climate policy measures to the government, which included a carbon border adjustment as the only pricing-based measure (CCC, 2020). There are also reasons why abiding by the need for a carbon price to be long-lasting and predictably rising over several decades may be impractical in the face of key uncertainties on the one hand, and democratic political systems on the other (see also Vogt-Schilb & Hallegatte, 2017). To us, the carbon price systems implemented around the world with all their often grave insufficiencies compared to the theoretical ideals are not necessarily political failures: maybe they are the best attainable output given the political difficulty of such schemes.

Carbon prices have the potential to transform by changing the relative costs of fossil and renewable energy. Ideally, the carbon price would change the rank ordering for any given application, making at least one renewable energy source less expensive than the least expensive fossil alternative. However, the cost barrier is not the only, and perhaps not the most important, barrier to the investments leading to technological transformation and full decarbonization. For example, although the relative cost of electric cars has fallen, they are still held back by lacking charging infrastructure (Patt, Aplyn, Weyrich, & van Vliet, 2019). Similarly for renewable electricity, the cost barrier is increasingly irrelevant: rapid learning triggered by technology deployment support in the last decades has brought the cost of several new renewables to or below cost parity with fossil fuels, also without a carbon price (IRENA, 2019). System and regime barriers, including both institutions (e.g., market design) and infrastructure (e.g., distribution and medium-voltage grids, electricity storage), remain high and are the critical obstacles to a transition—and carbon prices ignore these current main barriers. One could argue that with high enough carbon prices, there would be an incentive for market actors to fill these gaps, such as building the needed charging stations and power grids. But even here public sector leadership may still be crucial, first by addressing the regulatory barriers that often stand in the way, and second by directly supporting, or carrying out, the infrastructure adaptations needed for the entire system to change fundamentally, thereby also making the investments in renewable energy assets more technically and financially viable. Carbon prices without these additional policies may simply be ineffective at stimulating the needed investments. The empirical literature has not yet examined the effectiveness of carbon prices in interaction with other policies, and we see a clear need for further research on this important topic.

6 | CONCLUSION AND POLICY IMPLICATIONS

In this article, we have showed that there is no empirical evidence that carbon pricing triggers technological change, in terms of either increased innovation or zero-carbon investment, although it has had operational, short-term effects from fuel shifts and behavioral change. We found some evidence that existing carbon pricing schemes have not triggered technological change at all; all articles that analyzed the effect on zero-carbon investment conclude that there was no effect. This means that the effectiveness of carbon pricing remains a theoretical argument: in actual, existing carbon pricing schemes, technological change effects have been very modest, if at all empirically observable.

Our findings have important policy implications. First, it is important for decision makers to note that carbon pricing, however compelling the theoretical arguments for it are, does not have a track record of effectively triggering technological change. In contrast, there are many other policies that have proven to be effective—renewable energy support schemes (e.g., in several European countries, China) above all, but also more recent schemes such as support for electric vehicle deployment and infrastructure expansion, triggering both deployment and rapid cost reductions (e.g., Norway, California). Second, if carbon prices—even high carbon prices—do not trigger technological change and do not do it quickly, then there is a risk that relying mainly or solely on such schemes will increase the cost and decrease the speed of decarbonization – or simply not lead countries onto a path toward full decarbonization at all.

The intuitive attractiveness and apparent fairness of taxing emissions, in addition to the political capital already spent on introducing and reforming carbon pricing, makes it unlikely that policy-makers will abandon them, and our results do not suggest that they should. Rather, they suggest that carbon pricing alone, if not enacted in tandem with other instruments, will unlikely be enough for full decarbonization. Many nonprice barriers must be addressed, especially regarding infrastructure and the design of institutions and markets, and such barriers are ignored by the carbon pricing instrument. But many necessary policy measures will cost money, and here, carbon pricing may serve as a polluter pays-based revenue-raising instrument. The policies directly triggering the technological change will be other, but carbon pricing may be a source of the public funds these other policies require. This, our analysis of the track record of the effectiveness of carbon pricing schemes suggests, could be an important, empirically supported effect of carbon pricing on the urgently needed technological change for full decarbonization of society.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Johan Lilliestam: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration. **Anthony Patt:** Conceptualization; formal analysis; investigation; methodology. **Germán Bersalli:** Conceptualization; data curation; formal analysis; investigation; methodology.

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ENDNOTE

[1] Finland implemented a carbon tax in 1990, Norway and Sweden in 1991 and Denmark in 1992.

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