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ESTIMATING THE CO2 EMISSION AND REVENUE EFFECTS OF CARBON PRICING: NEW EVIDENCE FROM A LARGE CROSS-COUNTRY DATASET

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ABSTRACT/RÉSUMÉ

Estimating the CO2 Emission and Revenue Effects of Carbon Pricing: New evidence from a Large Cross-country Dataset

This paper estimates the long-run elasticity of emissions and carbon-related government revenues to carbon pricing. It is based on the OECD Effective Carbon Rates database, the most comprehensive cross-country longitudinal database on direct and indirect carbon pricing. Econometric estimates suggest that a EUR 10 increase in carbon pricing decreases CO2 emissions from fossil fuels by 3.7% on average in the long term. In such a scenario, carbon-related government revenues would triple at global level, though over time they are expected to dwindle as additional increases in carbon pricing result in further reductions in emissions. Broadening carbon pricing to currently unpriced emissions contributes to two thirds of the effects on emissions and revenues. At the country-level, emissions and government revenues responses differ depending on countries' sectoral structure and fuel sources. Dynamic simulations based on these estimates reveal that even large effective carbon rates (about EUR 1000 per tonne by late 2030s) will not suffice to meet net-zero emission targets. A sensitivity analysis shows that this result is robust to large range of elasticity estimates. Reaching net-zero then calls for complementary policies aiming at broadening and raising carbon prices, and drastically increasing the substitution of clean energy sources for fossil fuels through innovation and reallocation.

JEL codes: Q41, Q48, H23, C23, Q54

Keywords: Effective carbon rates; carbon price elasticity; carbon-related revenues; mitigation policy

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Estimation des émissions de CO2 et des effets sur les recettes de la tarification du carbone : nouvelles preuves issues d'un vaste ensemble de données transnationales

Ce document estime l'élasticité à long terme des émissions et des recettes publiques liées au carbone à la tarification du carbone. Il s'appuie sur la base de données des taux effectifs sur le carbone de l'OCDE, la base de données longitudinale transnationale la plus complète sur la tarification directe et indirecte du carbone. Les estimations économétriques suggèrent qu'une augmentation de 10 EUR de la tarification du carbone réduit les émissions de CO2 des combustibles fossiles de 3,7 % en moyenne à long terme. Dans un tel scénario, les recettes publiques liées au carbone tripleraient au niveau mondial, bien qu'avec le temps, elles devraient diminuer à mesure que des augmentations supplémentaires de la tarification du carbone entraîneraient de nouvelles réductions des émissions. L'élargissement de la tarification du carbone aux émissions actuellement non tarifées contribue à environ les deux tiers des effets sur les émissions et les recettes. Au niveau des pays, les réponses des émissions et des recettes publiques diffèrent en fonction de la structure sectorielle et des sources de combustibles des pays. Des simulations dynamiques fondées sur ces estimations révèlent que même des niveaux élevés des taux effectifs sur le carbone (environ 1 000 EUR par tonne d'ici la fin des années 2030) ne suffiront pas pour atteindre les objectifs de neutralité carbone. Une analyse de sensibilité montre que ce résultat est robuste à une large gamme d'estimations d'élasticité. Atteindre la neutralité carbone nécessite alors des politiques complémentaires visant à élargir et à augmenter les prix du carbone, et à augmenter considérablement la substitution de combustibles fossiles par des sources d'énergie propres par l'innovation et la réallocation.

JEL classification codes : Q41, Q48, H23, C23, Q54

Mots-clés : Taux effectifs sur le carbone; élasticité au prix du carbone ; recettes liés au carbone ; politique d'atténuation

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Estimating the CO_2 Emission and Revenue Effects of Carbon Pricing: New evidence from a Large Cross-country Dataset

By Filippo Maria D'Arcangelo[1], Mauro Pisu[1], Anasuya Raj[2], Kurt van Dender[2,3]

1. Introduction

1. This paper estimates the long-run responsiveness of CO2 emissions from fossil fuel use, and of the related government revenues, to carbon pricing. Global carbon emissions are still rising and not on track to reach the Paris Agreement goals of keeping the rise in global temperature from pre-industrial levels below 2 degrees Celsius (IPCC, 2022[1]). In addition, current and planned policies are still insufficient to keep countries' emission-reduction pledges by 2030 and 2050 (IEA, 2021[2]). Avoiding large increases in global temperatures requires more stringent policies to put global emissions on a steady downward path. To do so, countries have at their disposal a wide range of policies, including pricing and non-pricing measures (D'Arcangelo et al., 2022[3]).

2. Pricing instruments are an important component of decarbonisation strategies. They provide incentives to abate emissions in cost-effective ways and to innovate and invest in low-carbon technologies. In addition, carbon pricing generates revenues that can be put to socially productive use, e.g. supporting clean technology innovation, enhancing social policies to offset the potential regressive or affordability impact of climate change mitigation strategies, lowering distortionary taxes (such as the labour income tax wedge), or reducing public debt. Despite this, carbon prices remain low in most countries, with less than one tenth of CO2 emissions from energy use in OECD and G20 countries being priced at EUR 60 per tonne of CO2 or more in 2018 (OECD, 2021[4]) and fossil fuel subsidies still widespread (OECD, 2021[5]).

3. The decrease in emissions resulting from emission pricing instruments will gradually erode the base from which revenues are derived, causing them to decline eventually. The expected rise and then fall

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[1] OECD, Economics Department

[2] OECD, Centre for Tax Policy and Administration

[3] This working paper has been prepared under the framework of the OECD Horizontal Project on Climate and Economic Resilience. An earlier version of this paper was discussed at a meeting of Working Party No.1 (WP1) of the OECD Economic Policy Committee, which provided relevant feedbacks and comments. The authors thank Åsa Johansson and Douglas Sutherland for valuable suggestions and fruitful discussion. They are grateful to Luiz de Mello, Alain de Serres, Tim Bulman, Sebastien Turban, Hélène Blake for their comments. They thank Michelle Ortiz and Sisse Nielsen for their great help with the final preparation of the manuscript.

of carbon-related revenues poses challenges for fiscal policy. Reliable and comparable estimates of the responsiveness of CO_2 emissions to carbon prices can help address these challenges by establishing carbon pricing impacts on carbon mitigation and revenues.

4. Available evidence on the responsiveness of emissions to carbon pricing and carbon-related revenues is fragmented and difficult to compare across countries (see Section 2). Most estimates are limited to one sector or fuel and apply only to some countries. For example, a typical estimate might pertain to the impact of a carbon tax on CO_2 emissions in the road sector in a specific country. In addition, most evidence is on short-term elasticities, i.e. adjustments in emissions that take place in one year or less. Such estimates are insufficient to infer the long-run effect of rising carbon prices on government revenues and emissions at a sector, country and global level. This requires cross-country comparable estimates covering countries' entire energy bases and their related emissions.

5. This paper uses a rich dataset to provide comparable long-run responsiveness estimates of emissions to carbon pricing and carbon-related government revenues within a unified framework. As described in Section 3, this study leverages the OECD Effective Carbon Rates (ECRs) dataset (OECD, 2016[6]; OECD, 2018[7]; OECD, 2021[4]). This is a comprehensive and detailed dataset on effective prices applying to CO_2 emissions from energy use, which encompasses explicit carbon taxes, permit prices resulting from emissions trading systems and fuel excise taxes. The data covers about 80% of worldwide emissions from energy use from 44 OECD and G20 countries over three years (2012, 2015 and 2018).[4]

6. Section 4 discusses the regression technique used to estimate the effect of carbon pricing, as measured by ECRs, on emissions. The results suggest that a EUR 10 increase in ECRs decreases emissions by 3.7% on average in the long term. As the estimates are obtained by exploiting the variation of the data across countries and sectors, rather than the variation over time, they capture the emission responsiveness to carbon pricing after firms and people have fully adjusted to higher ECRs by adopting available clean technologies and exploiting existing substitution possibilities, i.e. they measure long-term emission responsiveness. These are likely to be lower bound estimates as they are based on historical data between 2012 and 2018 while abatement technologies and alternative energy sources are becoming increasingly available and cheaper. The data and the regression analysis used preclude confident inferences about short-term emission responsiveness and the length of time it takes for technology adoption and behavioural changes to take place.

7. Results indicate that the emission responsiveness to carbon pricing differs across sectors and fuels. For example, emissions from coal and other solid fossil fuels are more responsive to carbon pricing than emissions from all other fossil fuel categories; emissions from fossil fuels in the agriculture and fisheries sector are more than twice as responsive as those in the buildings sector. These differences are important to understand the effects of carbon pricing across sectors and fuels and to explain the variation of emission responsiveness across countries.

8. Based on these estimates, Section 5 discusses policy scenarios at an aggregate and country level to illustrate the effects on CO_2 emissions from fossil fuel use and related revenues of different carbon pricing floors. The richness of the estimates allows for a multitude of policy scenarios. This paper focuses on two types of reforms: 1) increasing ECRs on emissions already priced; 2) broadening the emission base to which ECRs apply. In these policy scenarios, the length of time it takes for emissions to fully adjust to a change in ECR is assumed to be around 10 years.

9. The policy-scenario analysis shows that carbon price floors can have sizeable effects on emissions despite the estimated mild responsiveness of emissions to carbon pricing. This is because emissions are generally still priced well below even moderate carbon floor levels and a large share of emissions is not

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[4] The estimation carried out in the current study focuses on CO_2 emissions from fossil fuel use and these are the only emissions discussed when presenting results from the analysis.

priced at all. For example, a EUR 60 per tonne of CO_2 global carbon price floor would decrease total CO_2 emissions from fossil fuel use by 17%. The industry and electricity sectors and coal use would account for most of the estimated emission reductions because of their large share in total emissions, low ECR (in most countries), and higher emission responsiveness than in other sectors. Broadening the emission base to which ECRs apply is a priority for countries with a large share of emissions still unpriced, such as Australia, Brazil, China, Colombia, Indonesia, Russia, South Africa and Türkiye.

10. The estimated modest emission responsiveness to carbon pricing, in combination with low average ECR levels, translates into initial large government revenue increases as ECRs rise. For example, a EUR 60 per tonne of CO_2 global carbon price floor would lift carbon-related tax revenues from an average of 1.3% of GDP (in 2018) across countries to an average of 2.5%. Countries with currently low carbon prices and high emission intensity would experience the highest increases in revenues as a percentage of GDP. These include China (from 0.6% to 4.3%), Estonia (from 3.1% to 5.3%), India (from 1.5% to 5.5%), Russia (from 0.6% to 5.9%) and South Africa (from 2.6% to 8.4% of GDP). Broadening the emission base would provide significant revenues to China, Indonesia, Russia and South Africa. In contrast, countries with already high taxation or low carbon intensity, such as Sweden, Norway and Switzerland, would experience lower increases in revenues.

11. Large reductions in emissions translate into lower revenue increases and eventually into revenue decreases. The policy simulations highlight how coal is especially exposed to tax-base erosion because of its high responsiveness to carbon pricing. The evolution of carbon-related revenue streams from coal with increasing carbon price floors is especially important for countries such as Australia, China, Estonia, Poland and South Africa, which still use it as their main energy source in the industry and electricity sectors.

12. One main message of the policy simulations is that, given current technologies and substitution possibilities, even significant carbon price hikes will not suffice to meet net-zero emission targets. Raising carbon prices on emissions already priced to a minimum of EUR 175 per tonne of CO_2 would decrease priced emissions by 40% globally (equivalent to a reduction of total emissions by just 18%). Broadening the scope of carbon pricing by introducing a carbon price floor of EUR 60 per tonne of CO_2 on unpriced emissions would reduce unpriced emissions by around 20% (equivalent to a reduction in total emissions by 12%). The two policies combined would then reduce total emissions by just less than 30%.

13. These are sizeable reductions in emissions but are far from sufficient to meet net-zero targets. These results point to the importance of additional policies – such as green technology support measures, regulations, standards – to complement emissions pricing measures. Indeed, these policies can reduce abatement costs and ease the substitution of clean energy sources for fossil fuels, increasing emission responsiveness to carbon prices. Policy simulations show that an emission responsiveness twice as large as the baseline estimate, combined with an ECR floor of EUR 40 on priced and unpriced emissions, would result in the same emission reduction as the baseline responsiveness estimates combined with an ECR floor of EUR 175 on priced emissions and EUR 60 on unpriced emissions.

14. To fulfil countries' net-zero emission pledges, lower abatement costs and increased availability of alternatives to fossil fuels are needed. With no improvement in emission responsiveness, only steep and persistent increases in ECRs, reaching above EUR 1 000 per tonne of CO_2 by late 2030s, will lead to emission reductions consistent with the net-zero target by mid-century. Complementary policies could significantly reduce the ECR necessary to attain net-zero targets. For instance, raising ECR floors by EUR 10 per year to EUR 220 in 2040 will contribute to meet the net-zero target if accompanied by a gradual increase in emission responsiveness to 5-fold the baseline estimate.

2. Literature review

CO_2 emission responsiveness to carbon pricing

15. Carbon pricing is a key policy tool to reduce emissions in a cost effective way. First, carbon pricing encourages emission cuts up to the point at which marginal abatement costs equal the carbon price. Second, carbon pricing decentralises abatement decisions, thereby overcoming the asymmetry of information between the government and polluters and encouraging emissions cuts at the lowest cost. Third, carbon pricing spurs innovation and investment in low-carbon technologies. Hicks (1932[8]) and recent empirical evidence (Aghion et al., 2016[9]; Calel and Dechezleprêtre, 2016[10]) suggest a positive relationship between carbon pricing and clean innovation.

16. A growing literature analyses the causal impact of carbon pricing on CO_2 emissions from fuel use. The general finding is that carbon pricing reduces emissions, though studies report a wide range of numerical estimates. Estimates differ across energy products, sectors, countries, time span (long run versus short run), time periods (pre- or post- financial crisis for example) and pricing instruments (carbon taxes, fuel excise taxes or permit prices). Moreover, measured outcomes differ: studies may present elasticities or semi-elasticities, but they may also present global reductions in emissions due to the introduction of a carbon pricing mechanism. These differences along with methodological choices and data sources make these estimates hard to compare (Box 1). For instance, short-run estimates of the elasticity of emissions to carbon pricing for the road sector range from -0.1 to -0.4.

Box 1. Short-run responsiveness of CO2 emissions to carbon pricing

17. Many studies focus on country-specific data as these allow for sharp causal identification by employing estimation methods such as difference-in-differences with or without matching, synthetic control analysis or regression discontinuity designs. The country-specific evidence has focused mostly on the road sector, where effective carbon prices (i.e. the combination of fuel excise and carbon taxes) are high in almost all countries. An increasing number of studies, however, has started to focus on other sectors. Many studies on carbon taxes focus on Scandinavian countries as they were amongst the first to introduce them (in the 1990s).

18. Green (2021[11]) provides a meta-review of ex-post quantitative evaluations of carbon pricing policies around the world since 1990. She finds that the majority of studies suggest that the aggregate emission reductions due to carbon pricing are generally between 0% and 2% per year, with however, considerable variation across sectors. The papers discussed below provide estimates of the CO_2 emission responsiveness to carbon prices. They may also provide short-run elasticity or semi-elasticity estimates. They are broadly classified according to the sector categorisation that is used in this paper (road, industry, buildings and electricity sectors).

19. For the road sector in Finland, Mideksa (2021[12]) and Lin and Li (2011[13]) find a carbon tax elasticity of carbon emissions of about -0.1 (i.e. a 1% increase in the carbon tax is associated with a decline in emissions of about 0.1%). In the road sector in the United states, Davis and Kilian (2011[14]) exploit data from 1989 to 2008, and find that a 10-cent per gallon increase in the gasoline tax (from an average of 38 cents in 2008) would reduce carbon emissions from vehicles by about 1.5% (equivalent to an elasticity of -0.06). Andersson (2019[15]) finds that the introduction of the Swedish carbon tax has led to a decline of carbon dioxide emissions from transport by almost 11%. The results in the study are consistent with an elasticity of CO_2 emissions from gasoline use to the carbon tax of the order of -0.4.

20. As regards manufacturing, Dussaux (2020[16]) finds that a further increase of the carbon tax in France from EUR 45 (the level of France's carbon tax at the time of the study) to EUR 86 per tonne of

CO_2 would induce a reduction in carbon emissions by 8.7%, which would imply a carbon tax elasticity of -0.1 and semi-elasticity of about -0.002 (i.e., a EUR 1 increase in the carbon tax is associated with a decline in CO_2 emissions of 0.2%). Dechezleprêtre et al. (2018[17]) analysed the impact of the European Union emissions trading system (EU ETS) on emissions using installation-level carbon emissions for France, the Netherlands, Norway, and the United Kingdom. They find that the EU ETS lowered carbon emissions in the order of 10% between 2005 and 2012. In the Swedish industry sector, Brännlund et al. (2014[18]) find that the CO_2 tax improved firms' carbon intensity performance.

21. The results of Arimura and Abe (2019[19]) indicate that the introduction of the Tokyo Cap-and-Trade program (Tokyo ETS) was followed by a 6.7% reduction in greenhouse gas emissions from office buildings over 3 years, with half of the reduction due to an electricity price increase and the other half due to the Tokyo ETS.

22. Leroutier (2022[20]) finds that the UK Carbon Price Support (CPS) – a carbon tax implemented in the UK power sector in 2013 – induced emissions from the UK power sector to drop by 20-26% per year on average between 2013 and 2017.

23. Finally, the evidence available to date generally points to lower emissions due to higher taxes or emissions trading systems, but some studies find no effect, or even the opposite effect. Explanations have focused on the lack of competition (Leslie, 2018[21]), the presence of many tax exemptions or low prices (Lin and Li, 2011[13]), and free allowances in the case of the EU-ETS system (Joseph and Bel, 2015[22]).

24. Emissions' responses to carbon prices may differ over the short and long term. Short-run responses are typically assumed to realise within a year, whereas long-run responses after three to ten years. Short-run responsiveness are expected to be lower than long-run responsiveness, as firms and individuals adjust their behaviour gradually over time. The meta-analysis in Labandeira et al. (2017[23]) confirms that for most energy products demand elasticities to energy prices are larger (in absolute value) in the longer run than in the shorter run.

25. One way to obtain long-run elasticities is to explicitly model the forward-looking behaviour of firms and households within a structural model. This typically limits the scope of the approach to a single market. For example, Donna (2021[24]) studies the Chicago urban transport using such a model. An alternative approach, used in this paper, involves exploiting the cross-country and cross-sector variation in emissions and carbon prices.

26. The present study differs from most of the existing literature as it provides long-run CO_2 emission responsiveness empirical estimates that are comparable across countries and based on disaggregated data at sub-sector and fuel category levels. Moreover, the measure of carbon pricing used in this study is more comprehensive than in most previous studies as it accounts for both taxes (carbon and fuel excise taxes) and emissions trading systems.

27. The estimation method of the present paper is similar in spirit to the study of Sen and Vollebergh (2018[25]) who focus on 20 OECD countries. They find that on average a 10% increase in the carbon price per tonne of CO_2 lowers CO_2 emissions by 3.5% (implying an elasticity of -0.35) or a EUR 10 increase in the carbon price per tonne of CO_2 reduces CO_2 emissions by 7.3% (implying a semi-elasticity of -0.0073). This paper goes beyond their analysis, by including more countries, using a longer estimation period and providing disaggregated elasticity and semi-elasticity estimates at a sector and fuel category level.

Estimates of government revenues from carbon pricing

28. Few estimates of government revenues from emission pricing instruments are available to date. For the fiscal year 2020-21, Fetet and Postic (2021[26]) find that the revenues generated from carbon taxes

and emissions trading systems (ETS) amounted to USD 56.8 billion globally (corresponding to around 0.07% of world GDP in 2020). Marten and van Dender (2019[27]) calculate that in 2015 the revenues generated from effective carbon rates (which include fuel excise taxes in addition to carbon taxes and emission permits) exceeded 1% of GDP in many OECD and G20 countries. They suggest that a carbon price floor of EUR 30 per tonne of CO_2 could more than double such revenues. As regards the United States, Marron et al. (2015[28]) report estimates from the US Congressional Budget Office indicating that a tax of USD 25 per tonne of CO_2 could raise revenues amounting to 0.7% of GDP. Pomerleau and Asen (2019[29]) conclude that in the United States a carbon tax levied on all energy-related carbon emissions at a rate of USD 50 per tonne of CO_2 and an annual growth rate of 5% would generate USD 1.87 trillion (about 9% of US 2020 GDP) in additional federal revenue over the next 10 years. The IMF (2019[30]) assesses the revenue impact from carbon pricing set at USD 35 and USD 70 for a large number of countries based on estimates from previous studies. These results show a hump-shaped impact on revenue but do not provide sectoral and fuel disaggregation.

29. A recent OECD (2021[31]) study uses the elasticity estimates in Sen and Vollebergh (2018[25]) and finds sizeable revenue gains from carbon pricing. Introducing a EUR 60 per tonne of CO_2 price floor would generate revenues of about 1.5% of GDP on average across G20 countries, with, however, large differences across countries. For France, Germany, Italy and the United Kingdom, revenues would amount to 0.2-0.3% of GDP whereas for China, India, Indonesia, Russia and South Africa they could exceed 2% of GDP as the current average ECR in these countries is low.

3. Effective Carbon Rates

30. This study relies on the OECD Effective Carbon Rates (ECRs) database (OECD, 2019[32]; OECD, 2021[4]), which provides a breakdown of CO_2 emissions from energy use and corresponding effective carbon rates for each country by sector and fuel. Effective carbon rates measure how explicit carbon taxes, emissions trading systems (ETSs) and fuel excise taxes put a price on CO_2 emissions from energy use.[5] These are pricing instruments that either set an explicit price per unit of CO_2 (e.g. tonnes) or that set a price on units of fuel, which is then proportional to resulting emissions.[6] A key feature of ECRs is that the common methodology enables comparisons over time and across sectors, fuels and countries.

31. The database covers six sectors that together span all energy uses. Sectors are broken down into energy users, interchangeably referred to as sub-sectors in this paper (Table 1). Fuels are grouped into 10 categories (Table 2).

32. The ECR database spans three years: 2012, 2015 and 2018. In 2018, it covers 44 OECD and G20 countries.[7] Taken together, these countries represent about 80% of worldwide CO_2 emissions from energy use. A preliminary update of the database was conducted in 2021 for G20 countries (OECD, 2021[31]). CO_2 emissions in the ECR database are based on energy use data from the International Energy Agency's World Energy Statistics and Balances (IEA, 2020[33]).

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[5] Effective Carbon Rates do not account for fossil fuel support (except when delivered through preferential excise or carbon tax rates), so they are always greater than or equal to zero.

[6] In the latter case, rates are typically expressed in common commercial units (e.g. as a price per kilogram for solid fuels, per litre for liquid fuels, per cubic metre for gaseous fuels). These can be converted into a price per energy unit (e.g. GJ) using calorific factors from the IEA World Energy Statistics and Balances (IEA, 2018[58]) and then into a price per tonne of CO_2 using IPCC emissions conversion factors (Intergovernmental Panel on Climate Change's Guidelines for National Greenhouse Gas Inventories (IPCC, 2006[57]), volume 2). More precisely, such calculations make use of the fact that CO_2 emissions are constant per unit of fuel (e.g. one litre of diesel produces on average around 2.76 kilograms of CO_2). This applies to fuel excise taxes but also to many carbon taxes. See OECD (2019[32]), Chapters 1 and 3, for further details.

[7] As at June 2021, these 44 countries comprise all OECD and G20 countries excluding Costa Rica and Saudi Arabia.

Table 1. Categorisation of energy use by sector and user

Sector	Definition	Energy users (sub-sectors)
Road	All energy used in road transport.	Road
Electricity	All fuels used to generate electricity for domestic use (rather than the amount of energy generated from each fuel). Note that fuels used in the auto-generation of electricity are classified under industrial production.	Main activity producer electricity plants
Industry	All energy used in industrial processes, in heating (incl. inside industrial installations) and in the transformation of energy, including fuels used for auto-generation of electricity in industrial installations.	Adjusted losses in energy distribution, transmission and transport; Adjusted energy industry own use; Adjusted transformation processes; Auto-generation of electricity; Chemical and petrochemical; Construction; Food and tobacco; Industry not elsewhere specified; Iron and steel; Machinery; Mining and quarrying; Non-ferrous metals; Non-metallic minerals; Paper, pulp and print; Sold heat that is not auto-generated; Textile and leather; Transport equipment; Wood and wood products
Buildings	All energy used for commercial and residential heating.	Commercial and public services; Final consumption not elsewhere specified; Residential
Off-road	All energy used in off-road transport (incl. pipelines, rail transport, domestic aviation and maritime transport).	Domestic aviation; Domestic navigation; Pipeline transport; Rail; Transport not elsewhere specified
Agriculture & fisheries	Energy used in agriculture, fisheries and forestry. Energy used in on-road transport in this sector is included in the road transport sector.	Agriculture; Fishing

Source: OECD (2016[6]).

33. In 2018, about 60% of carbon emissions from energy use in the 44 OECD and G20 countries covered by the OECD ECRs database were unpriced. In addition, less than one fourth of priced emissions had an ECR greater than EUR 60 per tonne of CO_2 (Figure 1). Only three countries (Norway, Luxembourg and Switzerland) priced more than half of their CO_2 emissions from energy use at EUR 60 or more, while almost three quarters of these 44 countries priced the majority of their emissions above zero but below EUR 30 per tonne of CO_2.

Table 2. Fuel category breakdown

Energy type	Fuel category	Energy Products
Fossil fuels	Coal and other solid fossil fuels	Anthracite; Bitumen; Bituminous coal; Brown coal briquettes; Oven coke; Coking coal; Gas coke; Lignite; Oil shale; Patent fuel; Peat; Peat products; Petroleum coke; Sub-bituminous coal
	Fuel oil	Fuel oil
	Diesel	Gas/diesel oil excluding biofuels
	Kerosene	Jet kerosene; Other kerosene
	Gasoline	Aviation gasoline; Jet gasoline; Motor gasoline
	LPG	Liquefied Petroleum Gas
	Natural gas	Natural gas
	Other fossil fuels	Additives; Blast furnace gas; Coal tar; Coke oven gas; Converter gas; Crude oil; Ethane; Gas works gas; Lubricants; Naphtha; Natural gas liquids; Other hydrocarbons; Other oil products; Paraffin waxes; Refinery feedstocks; Refinery gas; White and industrial spirit
Other combustible fuels	Non-renewable waste	Industrial waste; Non-renewable municipal waste
	Biofuels	Bio jet kerosene; Biodiesels; Biogases; Biogasoline; Charcoal; Municipal waste (renewable); Non-specified primary biofuels and waste; Other liquid biofuels; Primary solid biofuels

Note: Energy products are defined as in IEA (IEA, 2020[33]), World Energy Statistics and Balances.
Source: OECD (2019[32]).

Figure 1. Proportion of CO_2 emissions priced at different price levels

Effective carbon rates in EUR per tonne of CO_2

Note: Effective carbon rates as of 1 July 2012 for 41 OECD and G20 countries, 1 July 2015 for 42 OECD and G20 countries and 1 July 2018 for 44 OECD and G20 countries.

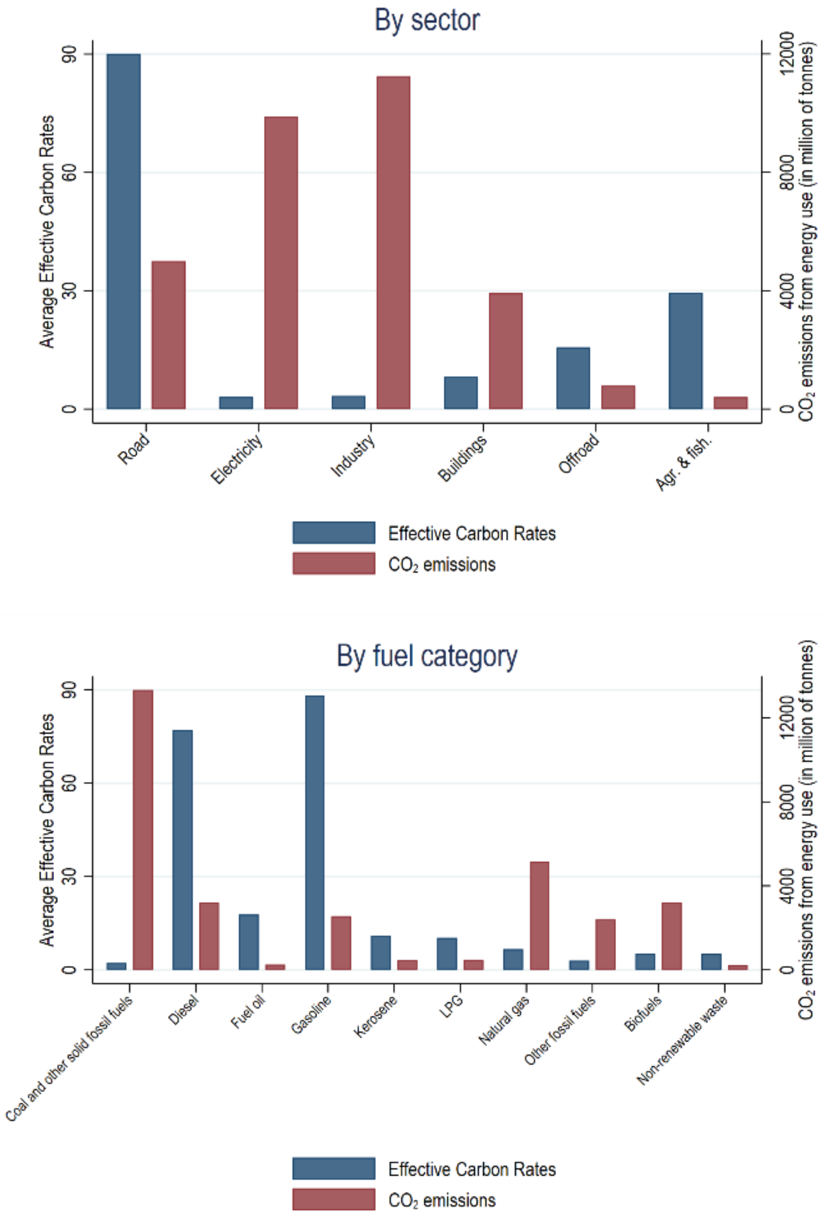
Source: Data from OECD (2021[4]). Database: https://stats.oecd.org/Index.aspx?DataSetCode=ECR.

34. Carbon pricing varies across sectors (Figure 2, top panel). In 2018, ECRs are highest in the road sector (at EUR 90 per tonne of CO_2 on average). They are lowest in the industry and electricity sectors (respectively at EUR 3.1 and 3.4 EUR per tonne of CO_2 on average), which account for the largest shares of emissions from energy use (32% and 36% of total emissions respectively). The ECR in the buildings sector (heating for residential and commercial buildings) is generally low but with large differences across countries. Only four countries (Korea, France, Switzerland and the Netherlands) price a majority of these emissions at EUR 30 per tonne of CO_2 or more while more than ten countries do not price at all more than 80% of these emissions.

35. Carbon pricing also varies across fuel categories. As can be seen in Figure 2 (bottom panel), in 2018, ECRs are highest on gasoline (at EUR 88 per tonne of CO_2 on average), closely followed by those on diesel (at EUR 77 per tonne of CO_2 on average), in line with the high ECR rates of the road sector (where gasoline and diesel are the main energy sources). CO_2 emissions from energy use principally stem from coal and other solid fossil fuel use (representing 43% of the total), followed by emissions from natural gas use (16%), from diesel use (10%), biofuel use (10%) and gasoline (8%). The average ECR of emissions from coal and other solid fossil fuel use is, however, the lowest, at EUR 2.2 per tonne of CO_2. This is both due to the large share (69%) of these emissions being unpriced, and to the low average ECR when this is applied (EUR 7 per tonne of CO_2).

Figure 2. Effective carbon rates and CO_2 emissions from energy use vary by sector and by fuel category

ECR, emissions-weighted average (left axis); CO_2 emissions from energy use, total (right axis), 2018



Note: Effective carbon rates as of 1 July 2018 for 44 OECD and G20 countries. CO_2 emissions are calculated based on energy use data for 2018 from IEA (2020[33]), World Energy Statistics and Balances.
Source: Data from OECD (2021[4]).

4. Empirical analysis

Data used for estimation

36. This section presents the data used for the empirical analysis and the policy scenario analysis. This data differs from the original OECD ECR database described in Section 3 in several ways, which can be summarised as follows (1Part IAnnex A provides details on the data cleaning). First, the empirical analysis relies on ECR yearly averages computed at the country-user-fuel category level. Relatedly, aggregated user categories were created in the industry sector in order to ensure stable coverage over the years. Second, some ECR and emission outliers are dropped. Third, seven countries (Canada, Colombia, Indonesia, Israel, Latvia, Lithuania and the United States) are excluded from the regression analysis, either because changes in the ECR methodology make data incomparable over time for these countries or because they only appear in some vintages. Including data on these countries, when they are available, in the empirical analysis does not alter the main results (as shown in Table A.1 in the Annex).Hence, these countries are included in the policy scenarios discussed in Section 5. Finally, the analysis focuses on CO_2 emissions from fossil fuels as emissions from biofuel combustion and non-renewable waste are excluded on account of data limitations.[8]

37. The clean dataset used in the empirical analysis is henceforth referred to as the “Full sample” and include also observations for which the ECR is zero. The “Restricted sample” instead include only observations (i.e. country-user-fuel averages) for which the ECR was positive in at least one of the three years considered. As further explained below in the Annex, including in the analysis observations that were never priced biases estimates downward because of simultaneity bias and reverse causality issues. Table 3 presents the breakdown of emissions by sector and fuel category in the Full sample.

Table 3. Fuel category share of emissions and average effective carbon rates by sector, 2018

Emissions-weighted averages of effective carbon rates, Full sample

Sector	Fuel category	Emission share (in %)	Average ECR (EUR per tonne of CO_2)	Average ECR of priced emissions (EUR per tonne of CO_2)
Road	Diesel	56	114.5	122.9
	Gasoline	41.4	128.3	128.3
	Natural gas	2.6	2.3	14.6
	Miscellaneous emissions	<0.1	0.4	1.1
Electricity	Coal and other solid fossil fuels	86.7	3	3.3
	Natural gas	11.3	7.5	13.1
	Miscellaneous emissions	2	15.1	15.8
Industry	Coal and other solid fossil fuels	53.9	1.7	2
	Other fossil fuels	25.2	2.6	3.2
	Natural gas	16.3	6.4	11.8
	Diesel	2.7	42.5	50.9
	Miscellaneous emissions	1.9	16.9	20.2
Buildings	Natural gas	42.8	19.4	25.5

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[8] Biofuels and waste products cannot always be identified in the form in which they are consumed (and thus emit). Biofuels are often consumed after blending with fossil fuels, but they are reported separately on the IEA energy balances (IEA, 2018[58]), which are employed to obtain effective carbon rates. In addition, beyond OECD countries, reliable consumption data on primary biomass may not be available. Moreover, hardly any emissions from these two categories are priced (priced emissions in these categories represent less than 0.8% of the data). See Table A.2 for further details.

	Coal and other solid fossil fuels	25.1	0.7	0.7
	LPG	16.4	3.3	5.8
	Diesel	11.1	58.7	59.8
	Kerosene	3.8	18	21.5
	Miscellaneous emissions	0.9	34.2	51.8
Off-road	Kerosene	38.8	7.6	19.6
	Diesel	30.2	46.8	50.8
	Natural gas	20.1	1.6	20.7
	Fuel oil	9.9	30.3	43.7
	Miscellaneous emissions	1	29.8	39.1
Agr. & fish	Diesel	69.5	50.1	61.1
	Coal and other solid fossil fuels	20.2	0.1	0.9
	Natural gas	4.2	12.9	20.2
	Miscellaneous emissions	3.4	16.4	27.8
	Gasoline	2.8	88	94.1

Note: Tax rates and permit prices applicable on 1 July 2018. CO_2 emissions are calculated based on energy use data for 2018 from IEA (2020[33]), World Energy Statistics and Balances. Energy categories that represent less than 2% of emissions within a sector are grouped into "miscellaneous emissions".
Source: OECD.

Empirical Framework

38. The empirical model regresses the natural logarithm of CO_2 emissions from fossil fuel use on carbon prices (ECRs) – as in Sen and Vollebergh (2018[25]) – and includes a rich set of fixed effects:

39. 40. $q_{cuft} = \beta \times ECR_{cuft} + \delta_{cut} + \delta_{uft} + \varepsilon_{cuft}$ 41. (1)

42. where q_{cuft} is the log of CO_2 emissions from fossil fuel use for country c, user u and fuel category f in the year t, ECR_{cuft} is the corresponding ECR averaged at the country-user-fuel category level in year t, δ_{cut} and δ_{uft} are fixed effects, and ε_{cuft} is the error term.

43. The parameter of interest, β, is the semi-elasticity of emissions with respect to the ECR. For example, $\beta = -0.005$ means that a EUR 1 increase in the ECR is associated with a 0.5% decrease in emissions. In other specifications, the semi-elasticity β varies across fuel categories or sectors to accommodate fuel and sector-specific responses.

44. One benefit of working with semi-elasticities is that they can facilitate the interpretation of policy scenarios, as changes in the ECR level translate into percentage changes in emissions. This is helpful to benchmark these results to national and international pledges as these express emission reductions in percentage and carbon price increases in absolute terms.[9] Moreover, semi-elasticities permit to keep unpriced emissions (i.e. those with ECR equals to zero) in the regression analysis, which instead would drop out of the sample if working with elasticities because of the logarithmic transformation. Unpriced emissions account for a large share of total emissions and the analysis below investigates how they affect results. This approach provides the basis for including unpriced emissions in the policy scenarios and for comparing the effects of base-broadening reforms with those that raise further ECRs on emissions already priced.

45. The identification of β hinges on the exogeneity of ECRs to fuel consumption and thus CO_2 emissions. For this reason, previous studies (Davis and Kilian, 2011[14]; Coglianese et al., 2017[34]; Bates and Kim, 2020[35]) assume conditional exogeneity of carbon pricing to emissions. The richness of the data

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[9] This is the case for example of the Nationally Determined Contributions (NDCs) established within the Paris Agreement framework.

used in this study ensures strong identification, allowing for a large set of fixed effects, denoted by δ_{cut} and δ_{uft}. These fixed effects capture many potential confounding factors, making additional controls redundant, as they would be collinear with such fixed effects. More specifically, these fixed effects include: δ_c, controlling for variables at the country level (e.g. geographical location of a country); δ_f, for fuel-specific factors (e.g. past supply-side investment decisions and sunk costs affecting the long-run supply of different fuels); δ_u, for user-specific factors (e.g. sub-sector energy intensity); δ_t, for common time shocks; δ_{ct}, for country-specific variables changing over time (e.g. GDP, population, terms of trade); δ_{cu} for country and user-specific variables (e.g. value added of subsectors, comparative advantages, technological levels of subsectors); δ_{uf} for fuel and user-specific variables (e.g. worldwide technology advancements in the use of a fuel in a specific sub-sector, unobserved country-invariant preference to tax the fuel in the sub-sector); δ_{ut} for time and user-specific variables (e.g. technological developments in different sub-sectors); δ_{cut} for country, user and time-specific variables (e.g. green policies enacted by specific countries in specific sub-sectors in a given year, prices of other inputs for the sub-sector varying across countries and over time) and δ_{uft} for user, fuel and time-specific variables (e.g. worldwide change in a specific use of a fuel in a subsector in a given year). 1Part IAnnex A details further the role of these fixed effects and the source of variation left to estimate β.

46. This set of fixed effects may still fail to control for some sources of bias. This is because governments may find it challenging to apply high carbon rates to small bases, as the revenue potential from such bases is small while the political and administrative costs of introducing new taxes or extending ETS coverage could be large. In addition, in some cases governments may apply low or no carbon prices to small bases to encourage their growth. For example, many countries apply a low tax rate to liquefied petroleum gas (LPG) and natural gas in the road sector (see Table 3) to encourage their use. For these reasons, zero ECRs could follow from the emissions base being small and from the political and administrative costs expected to follow from pricing them. If political and administrative costs mostly apply to small bases, then both factors contribute to biasing the estimate of β downward. The Annex documents two phenomena that are consistent with the presence of potential reverse causality and simultaneity bias caused by observations with ECR equal to zero. Moreover, the analysis shows that unpriced emissions are concentrated in fossil fuel producing countries.

47. The present paper addresses the potential reverse causality and simultaneity issues in different ways as described in 1Part IAnnex A. This includes restricting the estimation sample to observations with always positive ECRs and to switchers (i.e. those that switch from zero to positive ECR) and dropping from the dataset the use of LPG in the road sector. The instrumental variable approach of Sen and Vollebergh (2018[25]) to address the simultaneity bias proved unfeasible in this study when estimating sector-specific and fuel-specific semi-elasticities, which are key to the policy scenario analysis below. The Annex provides additional details on the instrumental variable approach and points to the weakness of instruments in this study.

Econometric results: semi-elasticity estimates

48. This section reports results from three alternative specifications for the Full and Restricted samples: 1) a baseline model yielding emission responsiveness estimates to ECR common to all countries, fuels and users (Table 4); 2) a model allowing for sector-specific responsiveness estimates (Table 5); 3) and a model allowing for fuel-specific responsiveness estimates (Table 6). The last two models are at the core of the policy scenario analysis in the next section. Together with semi-elasticity estimates, the tables report the elasticity at the group sample mean to facilitate comparisons with the existing literature.[10]

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[10] Elasticities are obtained by multiplying the estimated semi-elasticity with the relevant sample mean. With constant semi-elasticities β, the elasticity $\left(E = \frac{\partial q}{\partial \text{ECR}} \frac{\text{ECR}}{q}\right)$ can be calculated as $E = \beta \times ECR$.

49. Table 4 reports the results for the baseline model, which assumes a homogeneous responsiveness of emissions to ECRs across sectors and fuels. Columns (1) and (2) show the estimated semi-elasticity and elasticity for the Full sample and columns (3) and (4) for the Restricted sample. The point estimate implies that a EUR 10 increase in the ECR decreases emissions by 2.8% in the Full sample and by 3.7% in the Restricted sample. Both estimates are statistically significant at the 1% confidence level. The lower semi-elasticity of the Full sample can be ascribed to the downward bias that observations with zero ECRs may cause (as discussed in the Annex).

Table 4. Emission responsiveness to ECR: baseline

Estimated semi-elasticities (multiplied by 100) and elasticities

	Full sample		Restricted sample		Restricted sample
	Semi-elasticity (1)	Elasticity at mean (2)	Semi-elasticity (3)	Elasticity at mean (4)	(5)
ECR	-0.279***	-0.099***	-0.369***	-0.152***	-0.366***
	(0.078)	(0.03)	(0.084)	(0.03)	(0.083)
ECR * Switcher dummy					-0.034
					(0.229)
Switcher dummy					-0.319
					(0.464)
Constant	5.591***		5.579***		5.580***
	(0.024)		(0.031)		(0.031)
Observations	5766		4899		4899
N° country-sector-fuel	2092		1772		1772
user×fuel×year fixed effects (δ_{uft})	✓		✓		✓
country×user×year fixed effects (δ_{cut})	✓		✓		✓

Note: *p ≤ 0.1, **p ≤ 0.05, *** p ≤ 0.01. The dependent variable is log-emissions, the independent variable is ECR. The Switcher dummy identifies those observations (i.e. country x fuel category x sub-sector) that switch in the sample period from unpriced to priced emissions (i.e. it is equal to one for those observations with a positive ECR in one year and zero ECR in the previous year; it is zero otherwise). Standard errors clustered at user×fuel×time level and country×user×year level are in parenthesis. Respectively 293 and 378 singletons were dropped in the Full and Restricted samples. Estimates in columns 1 and 3 can be interpreted as follows: a EUR 1 increase in ECR decreases emissions by 0.28% (column 1) or 0.369% (column 3). Estimates in columns 2 and 4 can be interpreted as follows: at the sample mean, a 1% increase in ECR decreases emissions by 0.1% (column 2) or 0.15% (column 4).
Source: OECD.

50. At the sample mean (EUR 35 in the Full sample and EUR 41 in the Restricted sample) the semi-elasticity estimates translate into elasticities of about -0.10 for the Full sample and -0.15 for the Restricted sample, i.e. a 1% increase in ECR translates into a 0.15% decrease in emissions in Restricted sample. As regards the elasticity estimates (Table 4, columns 2 and 4), the estimate in the Restricted sample is 1.5 times above that in the Full sample. This reflects both the larger semi-elasticity estimates and the higher sample mean of the ECR in the Restricted sample (EUR 41 per tonne of CO_2) than in the Full sample (EUR 35 per tonne of CO_2).

51. The semi-elasticity estimates reported above are comparable to those in Sen and Vollebergh (2018[25]) for the 20 OECD countries they consider. With no correction for potential simultaneity and reverse causality issues, they find that a EUR 10 increase in the ECR decreases CO_2 emissions by 2.3% (against this study's estimate of 2.8% with the Full sample, Table 4, column 1). Using an instrumental variable approach to correct for these issues, they find that a EUR 10 increase in the ECR lowers emissions by 7.3% (against 3.7% with the Restricted sample Table 4, column 3). The rich fixed effect structure employed in this paper and the exclusion of observations with zero ECRs (i.e. the Restricted sample) help address simultaneity and reverse causality issues without resorting to instrumental variables, which proved unfeasible in this study as explained in more detail in the Annex. The difference between Restricted sample

estimates and Sen and Vollebergh (2018[25])'s instrumental variable estimates may be attributable to differences in the data used, with the present paper covering a larger number of countries (37 instead of 20), fuel categories (8 instead of 4), and years (3 instead of 1). However, the difference with Sen and Vollebergh (2018[25]) might also be due to remaining downward bias that the empirical approach employed in this paper is unable to correct. The policy simulations in Section 5 account for this possibility by building scenarios on a range of semi-elasticities (including higher values than those reported in Table 4) and shows broadly unchanged policy implications.

52. The behavioural response of firms and households may be different when governments start pricing emissions (i.e. raise ECRs from zero to some positive values) from when governments further increase already positive ECRs. This means that the emission responsiveness to ECRs may differ (because of behavioural changes) when the ECR is equal to zero.

53. Table 4 (column 5) tests for this possibility by adding to the baseline specification a switcher dummy and its interaction with ECRs, but results do not support the hypothesis of behavioural changes when ECR is raised above zero. The switcher dummy identifies those emissions that switch from being unpriced to being priced in any given year.[11] The point estimates of the coefficients of the additional variables are economically significant but they are estimated imprecisely and are not statistically significant. The low precision of these estimates may be attributable to the low number of cases in which unpriced emissions start to be priced (254 or about 3.6% of all observations in the Full sample). Additional tests (not reported here) indicate constant semi-elasticities across all values of ECRs above zero as the square of the ECR in the regression equation is not statistically significant. These tests, taken together, support the choice of employing constant semi-elasticities for all ECR values.

54. Table 5 shows the estimated semi-elasticities and elasticities by sector. In both the Full and Restricted samples, the responsiveness of emissions to ECRs differs across sectors, ranging from very low in the off-road transport sector to high in the agriculture & fisheries and industry sectors. However, some of these parameters are not significantly different from zero. Allowing for sector-specific responsiveness increases the number of parameters to estimate, reducing the precision of estimates. For example, in the electricity sector, the point estimate for the semi-elasticity is the second highest in absolute terms (a EUR 10 rise in the ECR decreases emissions by 4.5%) but not statistically different from zero.[12] Sector specific issue could confound estimates. In the electricity sector, the large fixed costs and long-lived capital of the electricity sector may dampen the response to higher ECR, especially if the increase in ECR is small. ECRs applying to electricity are often too low to induce fuel switching. Moreover, in the electricity sector, ECRs consist mostly of ETS prices and in some cases free permits, which could weaken responses to higher ECR. Unobserved heterogeneity not entirely being controlled for by the fixed effects structure could also result in large confidence intervals. Cross-country differences in fuel-specific environmental policies other than ECRs (such as renewable portfolio mandates) could be one source of this heterogeneity. Country differences in the power generation mix can be another. This may apply to the off-road transport sector as well, which is composed of very different subsectors, such as aviation, maritime, or pipeline transport.[13]

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[11] This dummy is equal to one for those observations with a positive ECR in one year and zero ECR in the preceding one; it is zero otherwise.

[12] The elasticity of CO_2 emissions to effective carbon rates in the electricity sector is low as compared to existing studies. The relatively high semi-elasticity estimate and low elasticity at the mean can be reconciled through the low average ECR in the electricity sector. Indeed, the semi-elasticity considers the effect of a EUR 1 increase in the ECR, which represents an almost 10% increase in the average ECR and is much larger than a 1% increase in the average ECR, which is what the elasticity at the mean focuses on.

[13] When allowing for country-specific semi-elasticities in the electricity and off-road sector, estimates differ substantially by country, supporting these arguments. However, the precision of these country-specific estimates is low.

55. The difference in estimated semi-elasticities in the Restricted sample and the Full sample in Table 5 is due to the large impact of removing observations with a zero ECR on some sectoral estimates.[14] For instance in the road sector, where the difference between the two estimates is largest, the elasticity estimate in the Full sample is close to zero (-0.018), suggesting a very low response of CO_2 emissions to carbon pricing in this sector. This contrasts with the studies on short-term tax elasticities of CO_2 emissions in the road sector, which generally report much higher and statistically significant values, as reviewed in Section 2. The elasticity for the road sector in the Restricted sample (-0.44) is markedly higher than in the Full sample and statistically different from zero, in line with that literature. A possible explanation of the difference between the Full and Restricted sample estimates is that many countries do not tax natural gas in the road transport sector (which is used in the form of compressed natural gas or liquefied natural gas) so as to encourage its use. Despite its lower taxation, however, natural gas use in road transport has remained limited because of difficulties in fuel storage and lack of recharging stations.

56. Table 6 shows estimates of semi-elasticities and elasticities by fuel type. These are to be interpreted as own-price elasticities as they are estimated by controlling at least partly for the ECR of other fuels through the set of fuel-subsector-year fixed effects, as described above. Because of data limitations, this paper does not estimate cross-price elasticities, e.g. the effect of increasing the carbon price of diesel on CO_2 emissions from natural gas use.[15]

Table 5. Emission responsiveness to ECR by sector

Estimated semi-elasticities (multiplied by 100) and elasticities

	Full sample		Restricted sample	
	Semi-elasticity	Elasticity at mean	Semi-elasticity	Elasticity at mean
	(1)	(2)	(3)	(4)
Road	-0.018	-0.022	-0.439***	-0.592***
	(0.137)	(0.167)	(0.135)	(0.182)
Electricity	-0.566	-0.0740	-0.452	-0.067
	(0.387)	(0.051)	(0.511)	(0.076)
Industry	-0.282**	-0.080**	-0.369***	-0.119***
	(0.108)	(0.031)	(0.112)	(0.036)
Buildings	-0.187	-0.076	-0.282	-0.131
	(0.184)	(0.073)	(0.182)	(0.085)
Off-road	-0.044	-0.017	0.017	-0.07
	(0.195)	(0.075)	(0.207)	(0.085)
Agriculture & fisheries	-0.719***	-0.229***	-0.907***	-0.382***
	(0.163)	(0.052)	(0.238)	(0.100)
Constant	5.577***		5.607***	
	(0.021)		(0.027)	
Observations	5766		4899	
N° country-sector- fuel	2092		1772	
user×fuel×year fixed effects (δ_{uft})	✓		✓	
country×user×year fixed effects (δ_{cut})	✓		✓	

Note: *p ≤ 0.1, **p ≤ 0.05, *** p ≤ 0.01. The dependent variable is log-emissions, the independent variable is ECR. Standard errors clustered at user×fuel×time level and country×user×year level are in parenthesis. Respectively, 293 and 378 singletons dropped in the Full and Restricted samples. Estimates in columns 1 and 3 can be interpreted as follows: in the Road sector, a EUR 1 increase in ECR decreases emissions by 0.02% (column 1) or 0.4% (column 3). Estimates in columns 2 and 4 can be interpreted as follows: in the Road sector at the sample mean, a 1% increase in ECR decreases emissions by 0.02% (column 2) or 0.6% (column 4).
Source: OECD.

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[14] This is for the most part driven by natural gas, which has a mass of observations with zero ECR and low emissions.

[15] Not every fuel category has observations for each sector in each year. This results in a heavily unbalanced panel, the size of which is insufficient to estimate with precision these cross-elasticities.

Table 6. Emission responsiveness to ECR by fuel category

Estimated semi-elasticities (multiplied by 100) and elasticities

	Full sample		Restricted sample	
	Semi-elasticity	Elasticity at mean	Semi-elasticity	Elasticity at mean
	(1)	(2)	(3)	(4)
Coal and other solid fossil fuels	-1.460***	-0.140***	-1.192***	-0.114***
	(0.458)	(0.044)	(0.440)	(0.042)
Diesel	-0.550***	-0.334***	-0.537***	-0.327***
	(0.099)	(0.060)	(0.103)	(0.063)
Fuel oil	-0.101	-0.021	-0.100	-0.021
	(0.157)	(0.033)	(0.165)	(0.035)
Gasoline	-0.104	-0.123	-0.218*	-0.257*
	(0.110)	(0.130)	(0.113)	(0.133)
Kerosene	-0.353	-0.128	-0.624**	-0.233**
	(0.258)	(0.090)	(0.285)	(0.102)
LPG	-0.308**	-0.079**	-0.330**	-0.085**
	(0.139)	(0.036)	(0.161)	(0.041)
Natural gas	-0.028	-0.006	-0.206*	-0.041
	(0.175)	(0.035)	(0.168)	(0.034)
Other fossil fuels	0.641	0.046	-0.333	-0.024
	(0.875)	(0.062)	(0.802)	(0.057)
Constant	5.607***		5.588***	
	(0.023)		(0.030)	
Observations	5766		4899	
N° country-sector- fuel	2092		1772	
user×fuel×year fixed effects (δ_{uft})	✓		✓	
country×user×year fixed effects (δ_{cut})	✓		✓	

Note: *p ≤ 0.1, **p ≤ 0.05, *** p ≤ 0.01. Dependent variable is log-emissions, independent variable is ECR. Standard errors clustered at user×fuel×time level and country×user×year level in parenthesis. Respectively 293 and 378 singletons were dropped in the Full and Restricted samples. Estimates in columns 1 and 3 can be interpreted as follows: for coal and other solid fossil fuels, a EUR 1 increase in ECR decreases emissions by 1.5% (column 1) or 1.2% (column 3). Estimates in columns 2 and 4 can be interpreted as follows: for coal and other solid fossil fuels, a 1% increase in ECR decreases emissions by 0.14% (column 2) or 0.11% (column 4).
Source: OECD.

57. The policy scenario analysis (Section 5) builds mostly on sector-level estimates as these implicitly allow for fuel switching within a sector, contrary to fuel-level estimates. For this reason, in the policy scenario analysis, estimates with fuel-specific semi-elasticities result in higher emission reductions. For example, when the ECR of diesel used in the road sector increases, the diesel-related emissions decline, but this reduction may be partly offset by an increase in the use of gasoline. The fuel-specific estimates cannot take into account this substitution and as a result may overestimate the decline in total emissions.

58. Fuel-level estimates indicate that emissions from coal use are more responsive to ECRs than those from other fuel categories. A EUR 10 per tonne of CO_2 increase in ECR being associated with a decline in coal emissions by 14.6% in the Full sample and 11.9% in the Restricted sample. These high and statistically significant semi-elasticities are not surprising. First, coal has high emission intensity, meaning that an ECR equal to EUR 10 per tonne of CO_2 implies a larger price increase per unit of energy used than for less carbon-intensive fuels, such as natural gas. Second, a low initial ECR means that an increase by EUR 10 per tonne of CO_2 is a relatively large price increase for coal than most other fuels. While estimates for coal demand are scarce, evidence from China points to similar emission elasticities to pricing (-0.37 in Zhang et al. (2011[36])) and fuel demand elasticities (-0.22 in Cattaneo et al. (2011[37])) to the coal's emission elasticity estimates reported in Table 5 (columns 2 and 4).

59. As regards emissions from fuel categories other than coal, the estimated semi-elasticities are highly heterogeneous in addition to be lower than for coal. For example, the Restricted sample estimates suggest that an increase in the ECR of gasoline use by EUR 10 can be expected to reduce emissions by 2.2%, which is less than half than the effect for diesel use (5.4%).[16]

60. Two further estimates in the Restricted sample merit commenting on. First, the point estimate of the semi-elasticity for "Other fossil fuel" is large on average but its precision is low. This category collects a large selection of diverse fossil fuels (see Section 3 for details), which are subject to very different policies to encourage or reduce their use. Grouping them together introduces unobserved within-category heterogeneity, reducing the precision of the estimate. Second, the estimated semi-elasticity for fuel oil is not statistically different from zero, but precisely estimated (it has a small confidence interval). This might be because of sectoral heterogeneity. When allowing for the semi-elasticity of fuel oil to vary across users, the estimated coefficients are negative for the road and electricity sectors.

5. Policy scenario analysis

61. The policy scenario analysis consists of three parts. In the first part, it fixes the conditions of the latest available year (2018) and builds scenarios simulating different changes in the ECR. This first part of the analysis shows and compares policy simulations based on sector-specific and fuel-specific semi-elasticity estimates. The second part performs a sensitivity analysis of the policy scenarios using different emission responsiveness estimates. The third part perform dynamic policy simulations to 2050 based on time-varying emission responsiveness.

62. The policy scenarios of the first and second part of the analysis present outcomes in terms of CO_2 emissions as well as revenue that carbon pricing (i.e. carbon tax, fuel excises as well as auctions of permit prices) generates. The simulation exercise assumes that all permit prices are auctioned – i.e. that the simulated reforms would be accompanied by a total phase-out of free permits.

63. The policy scenarios build on the results obtained with the Restricted sample shown in Table 5 and Table 6. The majority of simulations consider the introduction of ECR floors at different values (up to EUR 175 per tonne of CO_2). Consistent with the results in Table 4 (column 5) the policy simulations assume a constant semi-elasticity of emissions across ECR values (also including those outside the estimation sample). While there is no guarantee that the model extrapolations perform well for ECR levels well above those observed in-sample, considering ECR levels outside the estimation-sample range is relevant as most estimates of the social cost of carbon are well above 100 EUR (National Academies of Sciences, Engineering and Medicine, 2017[38]) and many studies conclude only high carbon prices will help to meet net-zero emission targets by mid-century (High-Level Commission on Carbon Prices, 2017[39]; Kaufman et al., 2020[40]).

64. The policy scenarios include emissions with a zero ECR in 2018, even though they are not used in the econometric estimation. Excluding these observations from the policy scenarios would have the drawback of ignoring a non-negligible share of emissions (60% in 2018) that governments could well choose to price. This would underestimate emission reductions in countries with a large share of unpriced emissions, such as Australia, Brazil, Indonesia, South Africa, or Russia. The underlying assumption behind the inclusion of observations with a zero ECR is that they have the same responsiveness as emissions with a positive ECR. The results in Table 4 discussed above corroborate this assumption.

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[16] Notice that, because the average ECR for emissions from diesel use (EUR 68 per tonne of CO_2) is around half of that for emissions from gasoline use (EUR 139 per tonne CO_2), the elasticity at the mean is roughly the same for the two fuels. This is because a EUR 10 per tonne of CO_2 represents a 14% increase in ECR on average for diesel and a 7% increase in ECR on average for gasoline.

65. The scenario analysis reintroduces the countries originally excluded from the estimation because of data limitations – i.e., Canada, Colombia, Indonesia, Israel, Latvia, Lithuania, and the United States (see 1Part IAnnex A). Their inclusion in the scenario analyses is based on the assumption that the behavioural response averaged across all the other countries included in the estimation sample is a good predictor of the behavioural response for these countries too. Table A.1 shows that including these countries in the estimation sample (where data are available) does not alter the estimates in a significant way.

66. The simulations in the first part of this section abstract from long-run general equilibrium effects caused for instance by improvements in energy efficiency and development of low-carbon energy sources that higher ECRs might entail (Aghion et al., 2016[9]; Popp, 2002[41]). For example, an increase in fossil fuel taxation in the electricity sector could be passed through to firms and households, affecting their production and consumption choices. However, characterising these general equilibrium effects requires modelling the full economy (Golosov et al., 2014[42]; Barrage, 2019[43]), which is beyond the scope of this analysis. Another important and potentially disruptive trend that the model is not able to capture, as this is not observed in the data used for the estimation, is the progressive electrification of sectors coupled with cleaner electricity generation.[17] Simulations of an increase of ECRs in road transport based on the empirical estimates reported above cannot show a fast take-up of electric vehicles as such variation is not yet observed in the data. Yet, the electrification of road transport and other sectors will gradually raise the responsiveness of fossil fuel demand to carbon pricing as clean electricity generation become increasingly widespread. The second and third part of the policy analysis go towards taking into account these effects by assuming higher semi-elasticities (and thus easier substitution of clean energy sources for fossil fuels) than those estimated above and used in the first part of the policy analysis.

67. Finally, the simulations reported below and the estimates on which they are based do not take into consideration the possibility of carbon leakage (i.e. emissions shifting from one country to another), which could affect the changes in CO_2 emissions and revenues that countries would experience. However, since the policy scenarios are applied simultaneously to all the considered countries, carbon leakage would not take place among these countries.

Scenarios based on the estimated emission responsiveness to ECR

68. This subsection first considers emissions and revenues in alternative scenarios focusing on the introduction of different carbon price floors. Box 2 provides concrete examples of carbon price floors. The carbon price floors are devised to capture two related but distinct choices policy makers face: 1) increasing ECRs on emissions already priced; 2) enlarging the emission base to which ECRs apply. In the parlance of public finance, the first relates to increasing tax rates, the second to broadening the tax base.

69. For emissions already priced, the policy scenarios below considers ECR floors varying by EUR 5 increments between EUR 0 (i.e. no ECR floor) and EUR 175 per tonne of CO_2. For unpriced emissions the ECR floors vary between EUR 0 and EUR 60. Total CO_2 emissions from fossil fuel use and revenues are indexed to 100 at 2018.

Box 2. Carbon price floors in practice: the Netherlands and the United Kingdom

70. Governments are increasingly discussing the introduction of carbon price floors. The Netherlands, for example, as part of its 2020 Climate Agreement, implemented a new carbon levy for industry on 1 January 2021. The new carbon levy complements the carbon price from the European Union Emissions Trading System (EU ETS) and implements a domestic price floor for Dutch industrial

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[17] This a policy objectives in many jurisdictions. For instance, the European Union's Fit for 55 proposals aim at replacing internal combustion engine vehicles with electric ones.

emissions. The price floor is planned to increase gradually over time from EUR 30 per tonne of CO_2 in 2020 to EUR 125 per tonne of CO_2 in 2030.

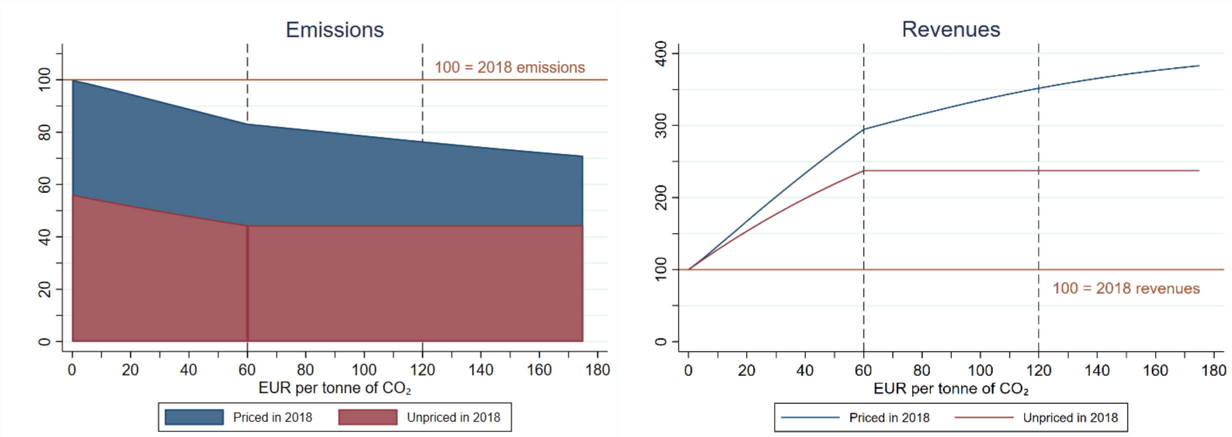
71. In 2013, the United Kingdom introduced a carbon price floor (CPF) for the electricity-sector fossil fuel emissions covered by the EU ETS (and now covered by the UK ETS). The CPF consists of two elements: the ETS allowance price and a carbon price support (CPS) mechanism, which is charged on top of permit prices. In 2013, in the electricity sector, the CPS was at GBP 9 per tonne of CO_2 emissions and rose to GBP 18 in 2015. In 2018, the average effective carbon rate in that sector was about EUR 26 per tonne of CO_2.

Source: Anderson et al. (2021[44]) and Hirst (2018[45]).

72. One of the main messages from this exercise is that, given the semi-elasticity estimates reported above, meeting net zero targets would require a substantially higher ECR floor than those envisaged in these policy simulations. An ECR floor of EUR 175 per tonne of CO_2 on emissions already priced combined with a EUR 60 ECR floor on unpriced emissions in 2018, would reduce total emissions from fossil fuel use by around 29% compared with the 2018 level (Figure 3, left panel). More than half (60%) of this decline would come from emissions already priced in 2018.

Figure 3. Aggregate effects of an ECR floor on emissions and revenues

CO_2 emissions from fossil fuel use and revenues changes, indexed to 100 in 2018



73.

Note: Simulations of a global ECR floor by EUR 5 increments. The maximum ECR floor for emissions unpriced in 2018 is EUR 60 per tonne of CO_2. Beyond EUR 60, the price floor on emissions already priced in 2018 keeps on rising until EUR 175, while that for unpriced emissions in 2018 remains at EUR 60. Semi-elasticities are allowed to differ by sector. An ECR floor of 0 corresponds to 2018 policies.
Source: OECD.

74. The decline in emissions would be accompanied by revenue increases, at least for the ECR floor range considered. With an ECR floor of EUR 175 on emissions already priced in 2018 and EUR 60 floor on unpriced emissions in 2018, carbon-related government revenues would raise almost four-fold compared with the 2018 levels. Broadening the base, i.e. applying a EUR 60 carbon price to unpriced emissions would increase revenues by about 2.5 times. Across all the range in the carbon pricing floors considered in the simulations below, at least half of the revenue increase would come from starting to price previously unpriced emissions (Figure 3, right panel). The rate of the increase in revenues declines as the ECR floor rises, since higher ECRs progressively erode the emissions base. However, for the range of ECR floors considered this "base erosion effect" is always lower than the "price increase effect".

75. The analysis below further explores the effect of introducing ECR floors, by presenting four alternative policy scenarios:

- Scenario 1: Floor 60. A global ECR floor of EUR 60 per tonne of CO2 is introduced on emissions already priced in 2018. This scenario simulates the effects of introducing a minimum carbon price globally, which would be equivalent to raising positive ECRs to EUR 60. Fuels with an ECR higher than 60 remain at their 2018 level.
- Scenario 2: Floor 120. A global floor of EUR 120 per tonne of CO2 is introduced on emissions already priced in 2018. This scenario is similar to the previous one, the only difference being a higher ECR floor.
- Scenario 3: Homogeneous ECR across fossil fuels in a sub-sector. Each country sets a homogeneous ECR for each fuel user (i.e. sub-sector) on both emissions already priced and unpriced in 2018 equal to the ECR applied to the fuel category with the highest ECR for that sector in 2018 ,. This scenario involves base broadening and simulates the effect of establishing the same price for all fuels within each sub-sector while preserving differences across countries and sub-sectors. Setting a homogeneous ECR across fuels within a sub-sector encourages the use of fuels with lower carbon content and higher fuel-efficiency.
- Scenario 4: Base broadening Floor 60: A global floor of EUR 60 per tonne of CO2 is introduced on all emissions including those unpriced in 2018. This scenario captures the effect of broadening the emission base to which ECRs are applied using a benchmark carbon price floor.

76. In each Scenario, the change in ECRs differs greatly across sectors, fuel categories, and countries, depending on 2018 ECR levels. The industry and electricity sectors experience by far the largest increase in average ECR. Table 7 provides further detail on the simulated changes in ECRs across different fuel categories for residential users (a category of fuel users in the buildings sector) in Italy and Türkiye. Table 8 shows that compared to 2018 policies, Scenario 3 (Homogeneous ECR) would result in the largest average increase in ECRs, 259%, followed by Scenario 4 (Base Broadening), 247%, Scenario 2 (Floor 120), 188%, and Scenario 1 (Floor 60), 73%.

Table 7. Hypothetical ECRs for residential users in different scenarios

ECR for residential users, average over country-user-fuel category

	ECR in 2018	ECR in Scenario 1 Floor 60	ECR in Scenario 2 Floor 120	ECR in Scenario 3 Homogeneous ECR	ECR in Scenario 4 Base Broadening Floor 60
Italy					
Diesel	159.7	159.7	159.7	159.7	159.7
Kerosene	142.1	142.1	142.1	159.7	142.1
LPG	72.0	72.0	120.0	159.7	72.0
Natural gas	87.4	87.4	120.0	159.7	87.4
Türkiye					
Coal and other solid fuels	0	0	0	172.3	60
Kerosene	0	0	0	172.3	60
LPG	172.3	172.3	120.0	172.3	172.3
Natural gas	5.1	60.0	120.0	172.3	60

Note: The table shows for residential users (a category of fuel users in the building sector) in Italy and Türkiye the ECR in the four scenarios. Scenario 1: A global ECR floor of EUR 60 per tonne of CO_2 is introduced on emissions already priced in 2018. Scenario 2: A global floor of EUR 120 per tonne of CO_2 is introduced on emissions already priced in 2018. Scenario 3: A homogeneous ECR for each user is introduced, equal to the maximum observed in the 2018 data, taken over the country and sub-sector, on priced and unpriced emissions in 2018. Scenario 4: A global ECR floor of EUR 60 per tonne of CO_2 is introduced on priced and unpriced emissions in 2018. ECRs are averaged over country-user-fuel category. Tax data presented in this table was last updated in February 2020.
Source: OECD.

Figure 4 compares 2018 sectoral emissions and revenues with those resulting from the four policy scenarios. The comparison is based on the estimated sector-specific semi-elasticities (Table 5, column 3). The main message of this analysis is that the impact of higher ECRs varies greatly across sectors. The electricity and industry sectors would experience the largest emission reductions but also the largest revenue increases as they currently face low ECRs. In the industry, road, buildings, and agriculture and fisheries sectors, the most promising policy for reducing emissions is setting a homogeneous ECR across fuels. In all sectors other than the road and off-road transport sector, broadening the emissions base would result in substantial emission reduction and revenue increases. In all scenarios, revenues increase the most in the industry and electricity sectors, both in absolute and relative terms.

Table 8. Average ECR by policy scenario

Emission-weighted averages

	2018	Scenario 1 (Floor 60)		Scenario 2 (Floor 120)		Scenario 3 (Homogeneous ECR)		Scenario 4 (Base Broadening)	
	ECR	ECR	Increase (%)	ECR	Increase (%)	ECR	Increase (%)	ECR	Increase (%)
Total	19.4	33.6	73%	55.8	188%	69.7	259%	67.3	247%
Road	88.7	97.8	10%	133.9	51%	130.4	47%	100.1	13%
Electricity	3.1	20.6	565%	41.2	1229%	46.2	1390%	60	1835%
Industry	3.8	17.4	358%	34.3	803%	65.7	1629%	60.3	1487%
Buildings	12.7	25.1	98%	44.1	247%	72.3	469%	63.5	400%
Off-road	15.7	34.8	122%	68.2	334%	34.6	120%	60.8	287%
Agriculture & fishing	31.9	40.4	27%	68.3	114%	78.1	145%	66.9	110%
Coal and other solid fossil fuels	2.2	18.3	732%	36.7	1568%	58.4	2555%	60	2627%
Diesel	77.1	85	10%	118.1	53%	121.8	58%	93.4	21%
Fuel oil	17.8	40.2	126%	79.8	348%	49	175%	60.2	238%
Gasoline	83.1	94.7	14%	135.3	63%	113	36%	95.3	15%
Kerosene	11.1	41.5	274%	81.8	637%	40.2	262%	60.8	448%
LPG	10.3	19.8	92%	34.2	232%	59.9	482%	62.7	509%
Natural gas	6.6	19.9	202%	37.8	473%	48.9	641%	61.2	827%
Other fossil fuels	3.0	16.1	437%	32.2	973%	72.5	2317%	60	1900%

Note: The table shows the emission-weighted average ECR over CO_2 emissions from fossil fuel use in the 44 countries present in the ECR database by sector and fuel categories in the 2018 policy baseline and the four scenarios, as well as the % increase in ECR implied by these scenarios. Scenario 1: A global ECR floor of EUR 60 per tonne of CO_2 is introduced on emissions that already have an ECR above zero in 2018. Scenario 2: A global floor of EUR 120 per tonne of CO_2 is introduced on emissions that already have an ECR above zero in 2018. Scenario 3: A homogeneous ECR for each user is introduced equal to the maximum observed in the 2018 data, taken over the country and sub-sector, on emissions that already have an ECR above zero in 2018. Scenario 4: A global ECR floor of EUR 60 per tonne of CO_2 is introduced on all emissions including those unpriced in 2018.
Source: OECD.

Policy scenarios by sector

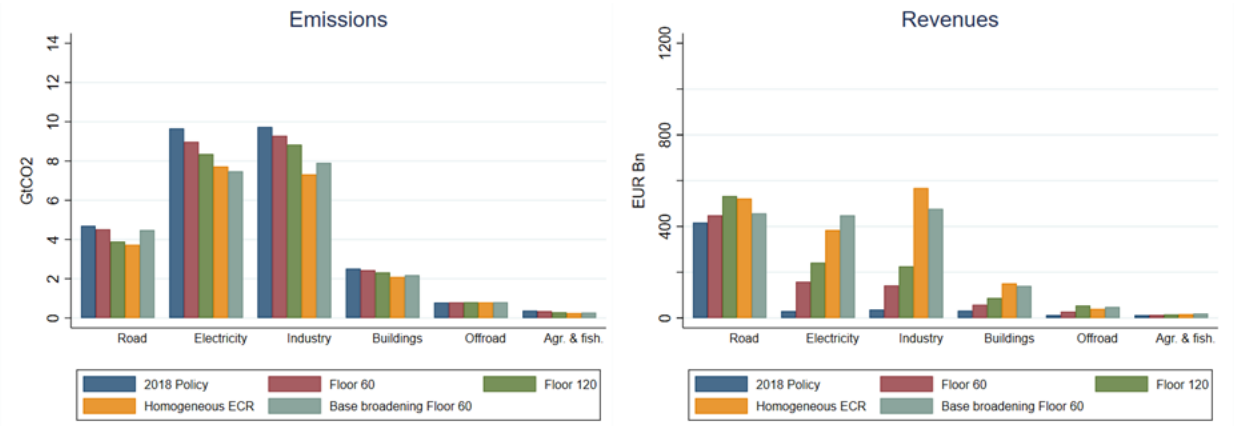
77. In the electricity sector, emissions would decline by 7% in the Floor 60 Scenario and by 13.5% in the Floor 120 Scenario. These reductions are largely attributable to the large increases in ECRs, especially in countries with low effective carbon rates and large emissions in the electricity sector, notably China and the United States.

78. In the Homogenous ECR Scenario, emissions from electricity sector would decline by 20%. In certain countries natural gas is the main fuel used for power generation and is priced at moderate (Luxembourg, Belgium) or high levels (Switzerland). In many countries diesel makes up a small share of emissions in this sector (less than 6%) but faces high ECRs (up to EUR 174 in Israel for example). By pricing previously unpriced emissions in many countries at levels going from EUR 4 to EUR 174, the Homogenous ECR Scenario results in larger increases in the ECR than the Floor 120 and Floor 60 scenarios. Finally, the Base Broadening Scenario also has an important effect at the aggregate level compared to the Floor 60 scenario, with emissions declining by 22%.

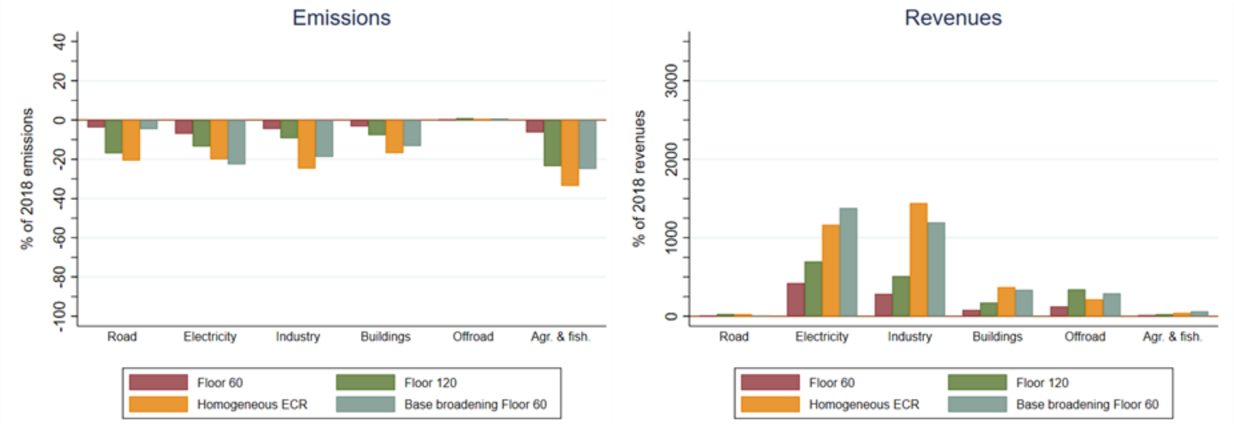
79. In the industry sector, the reductions in emissions are considerable. They are lower than those for the electricity sector in the Floor 60 and 120 Scenarios but larger in the Homogeneous ECR and Base Broadening Scenario. This underlines the importance of broadening the emission base in the industry sector. Emission decreases are largest in the Homogenous ECR Scenario (25%), followed by the Base Broadening Scenario (19%) and Floor 120 and 60 Scenarios (9% and 4.5% respectively) (Figure 4, Panel B).

Figure 4. Higher ECRs lower emissions and increase revenues differently across sectors

Panel A. Emissions and revenues, total by scenario and sector



Panel B. Difference in emissions and revenues compared to policies in 2018, % by scenario and sector



Note: Panel A. Left: emissions from fossil fuel use in gigatonne of CO_2; Right: revenues in EUR billion. Panel B. Left: emission change in the scenarios with respect to emissions in 2018; Right: revenues change in the scenarios with respect to revenues in 2018. Semi-elasticities are allowed to differ by sector. Source: OECD

80. In the Floor 60 and Base Broadening scenarios, impacts on road transport emissions and revenues are smaller than on electricity and industry sectors. Indeed, in both cases the simulated increase in road sector ECRs is markedly smaller than in industry and electricity as ECRs are generally already high, with an emission-weighted average of nearly EUR 90 per tonne of CO_2 in the road sector against around EUR 3 in industry and electricity sectors (Table 8). Moreover, in the road sector, a vast majority of emissions are already priced. The road transport's emission reductions would be larger in the Homogeneous ECR Scenario (21%) than in the Floor 120 Scenario (17%), the Base Broadening Scenario (4.6%) and the Floor 60 Scenario (3.7%). This is due to top ECRs in road transport being often very high (up to EUR 305 per tonne of CO_2), leading to large increases in the average ECR when applying the top ECR across all fuel types. This suggests that equalising carbon pricing in road transport can be more effective in reducing emissions than introducing relatively low ECR floors for that sector.

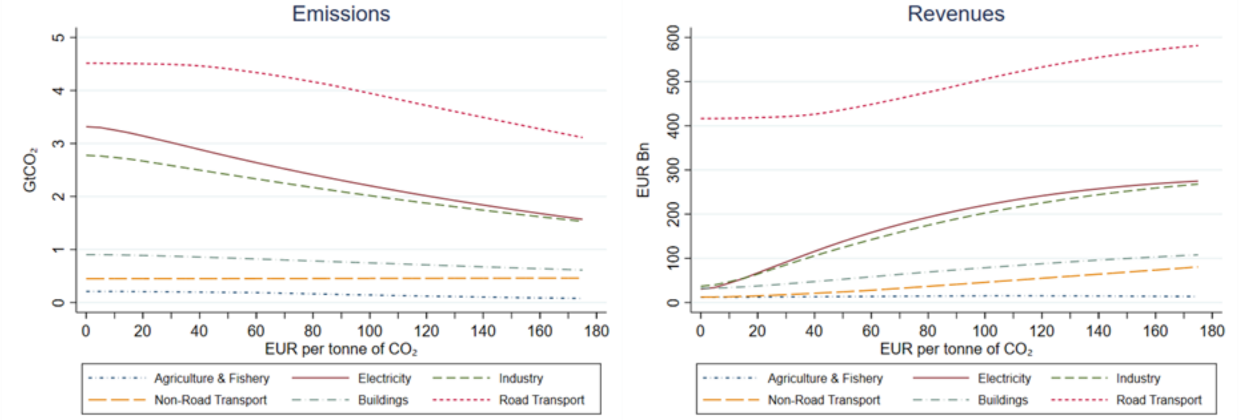
81. Extending carbon pricing would be most effective to reduce emissions in the agriculture and fisheries sector. This is shown by the significantly larger emission reductions in the Base Broadening scenario (25%) and Homogeneous ECR (36%) than in the Floor 60 scenario (6.3%), reflecting the fact that a large share of emissions is unpriced in these sectors.

82. Figure 5 provides further results on emissions and revenues by sector based on the introduction of an ECR floor ranging from zero to EUR 175 per tonne of CO_2. This exercise considers only emissions already priced in 2018 and provides a decomposition by sector of the decline in priced emissions at aggregate level (shown with the blue line in Figure 3, left panel).

83. The introduction of any ECR floor would have the largest absolute impacts on the CO_2 emissions from fossil fuel use in the electricity and industry sectors. Despite the large contraction of the emissions base, carbon-related revenues from these sectors would increase for all range of ECR floors considered (Figure 5, right panel). In the road sector, already high ECRs imply that there would be almost no effects on emissions and revenues up to a EUR 40 ECR floor. The agriculture and fisheries sector is responsive to changes ECR, and increasing ECRs in this sector would be effective in reducing emissions. In most countries, however, fuel use of this sector is limited compared to other sectors. Hence, its impact on total emission reduction and revenues would be small.

Figure 5. Effects of ECR floors on emissions and revenues by sector

Emissions and revenues, total



Note: Simulations of a global ECR floor applied to all emissions priced in 2018, by EUR 5 increments. Left panel: emissions from fossil fuel use in gigatonne of CO_2. Right panel: revenues in EUR billion. Semi-elasticities are allowed to differ by sector.
Source: OECD.

Policy scenarios by fuel category

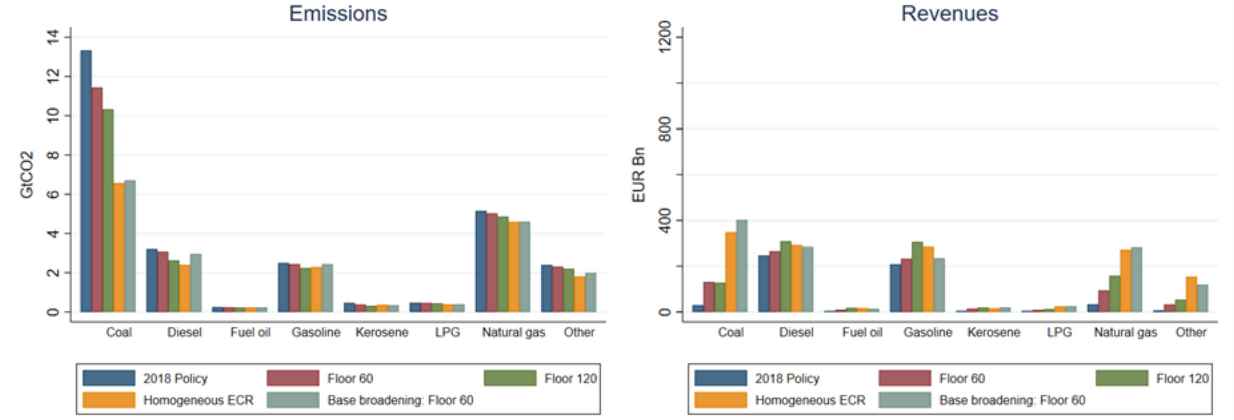
84. Figure 6 compares 2018 emissions and revenues by fuel category with those resulting from the four scenarios. The comparison is based on the estimated fuel-specific semi-elasticities (Table 6, column 3). Overall, in these simulations emission reductions are larger and revenue increases smaller than in simulations based on sector-specific estimates. As mentioned above, the difference is due to fuel–specific estimates not capturing the substitution across fossil fuels within a sector.

85. The main message of this analysis is to underline the importance of pricing emissions from coal and other solid fossil fuels use to reduce worldwide CO_2 emissions. This is because of coal's high responsiveness to carbon pricing and its low ECR in most countries. Pricing coal emissions would generate large government revenues even at low ECR levels. In all scenarios, higher ECRs for coal emissions would generate the largest absolute revenue increases as a result of the steep hike in their average ECR (Figure 6, Panel A). In 2018, the average ECR of coal was just EUR 2.2 per tonne of CO_2 (Table 8).

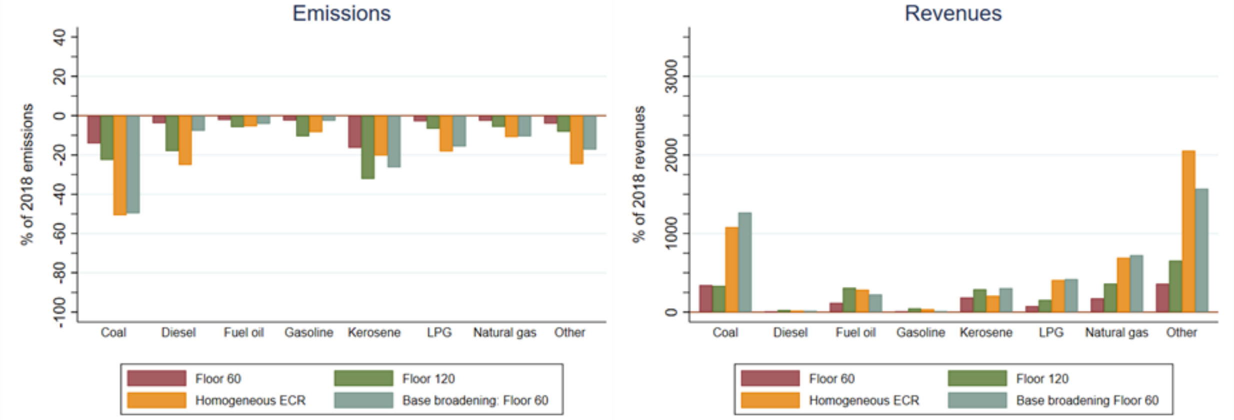
However, steady and sustained emission reductions as ECR rises would quickly erode the emission base, leading revenues from coal emission to decline even for moderate ECR levels (from EUR 80).

Figure 6. Higher ECRs lower emissions and increase revenues differently across fuel categories

Panel A. Emissions and revenues, total by scenario and fuel category



Panel B. Difference in emissions and revenues compared to carbon pricing policies in 2018, % by scenario and fuel category



Note: Panel A. Left: emissions in gigatonne of CO_2; Right: revenues in EUR billion. Panel B. Left: emission change in the scenarios with respect to the emissions in 2018; Right: revenues change in the scenarios with respect to revenues in 2018. Semi-elasticities are allowed to differ by fuel category. Here, “coal” stands for the fossil fuel category “coal and other solid fossil fuels” and “other” for “other fossil fuels” (see Table 2).
Source: OECD.

86. Emissions from coal and other solid fossil fuels, which account for a large share of emissions (almost 50% in the data considered for the policy scenarios), would decline by 14% in the Floor 60 scenario and by and 23% in the Floor 120 scenario (Figure 6, Panel B). The large drop in emissions from coal and other solid fossil fuels results from a combination of high responsiveness to ECR (a EUR 10 increase in the ECR induces a 12% decrease in coal emissions, higher than for other fossil fuels) and the large increase in the average ECR applying to coal emissions given its low starting value. In these two scenarios, only emissions from kerosene would experience similar emission reductions (in percentage) to coal, although they account for a significantly smaller share of total emissions than coal (less than 2%).

87. In the Floor 120 Scenario, CO_2 emissions from diesel and gasoline use would decline by 18% and 11% respectively. This is similar to the one estimated for the road sector (Figure 4), reflecting the high reliance of road transport on diesel and gasoline and their low level of substitutability.

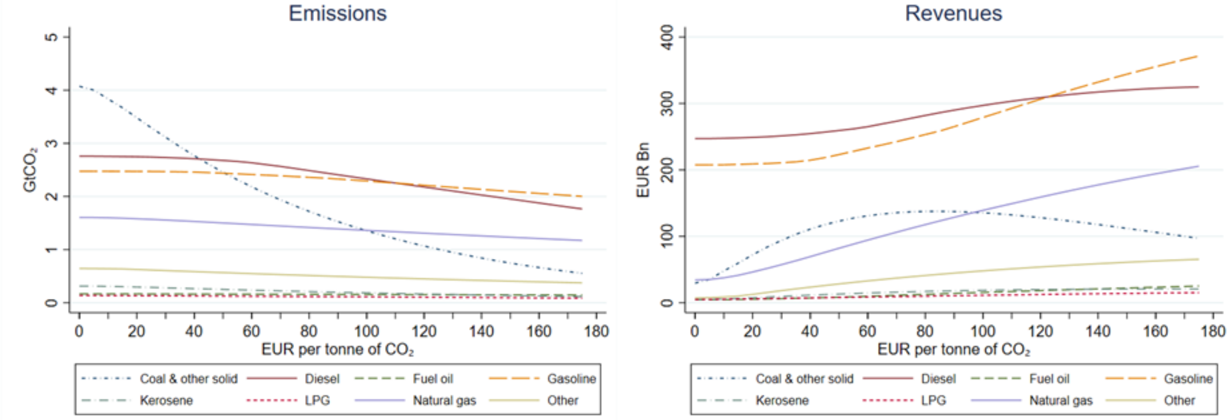
88. The emission reductions in the Homogeneous ECR Scenario are generally higher than in the Floor 60 Scenario, on account of the large differences in rates within a sector. Across all fuels, the Base Broadening Scenario leads to lower emissions and higher revenues across fuels than the Floor 60 Scenario, with the lowest gain for gasoline, the use of which is already priced in most countries and sectors (99% of gasoline emissions were priced in 2018 in the data used for the policy scenarios).

89. Figure 7 provides further results on emissions and revenues by fuel category based on the introduction of an ECR floor ranging from zero to EUR 175 per tonne of CO_2. This exercise considers only emissions already priced in 2018. Even a relatively small ECR floor would significantly reduce emissions from coal and other solid fossil fuels and thus total emissions. This is due to the low ECRs on coal emissions in large economies, such as the United States and China, combined with the large contribution to total emissions of these countries, especially in the industry and electricity sectors.

90. At an ECR floor of EUR 40, coal would stop being the largest source of carbon emissions from fossil fuels. This is because emissions from natural gas, gasoline and diesel would decline less (as they are less responsive to ECR changes) than coal emissions. Since emissions from coal are currently subject to low pricing, revenues would increase sharply even for moderate ECR increases. However, revenues from pricing CO_2 emissions from coal are estimated to peak at EUR 80 per tonne of CO_2 and decrease thereafter as the base narrows. In contrast, the lower responsiveness of the other fuels to ECRs would imply a slower reduction in emissions and sustained increase in revenues, especially from diesel, gasoline, natural gas even for an ECR of EUR 175 per tonne of CO_2.

Figure 7. Projected effects of an ECR floor on emissions and revenues by fuel category

Emissions and revenues, total



Note: Simulations of a global ECR floor applied to all emissions priced in 2018, by EUR 5 increments. Left panel: emissions in gigatonne of CO_2. Right panel: revenues in EUR billion. Semi-elasticities are allowed to differ by fuel category. Here, “coal & other solid” stands for the fossil fuel category “coal and other solid fossil fuels” and “other” for “other fossil fuels” (see Table 2).
Source: OECD.

The impact of higher ECR floors on emissions and revenues varies across countries

91. Higher ECRs have different effects on emissions and revenues across countries for two main reasons. First, low ECR floors do not affect (or affect little) countries with a high average ECR. The share of unpriced emissions in a country is important in this respect. Second, the sectoral composition of emissions determines the country-level responsiveness of emissions and of carbon-related government revenues to ECRs.

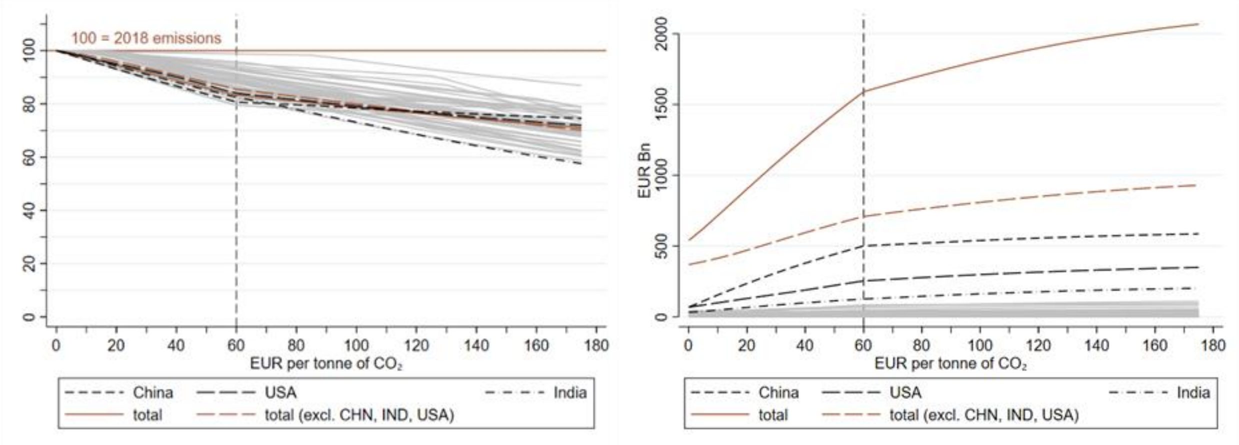
92. Figure 8 shows the impact of ECR floors varying between EUR 0 and 175 per tonne of CO_2 (with EUR 5 increments). Base broadening is captured by considering an ECR floor of up to EUR 60, applied to

the emissions unpriced in 2018 (as in Figure 3). The estimates are based on sectoral semi-elasticities (Table 5, column 3).

93. Overall, countries with the largest emission reductions and revenue gains, for a given ECR floor, are those in which the electricity and industry sectors are the predominant source of emissions, consistent with the sectoral responses shown in Figure 5. Figure 8 highlights three major economies – China, India, and the United States – that would play a major role in reducing total emissions from fossil fuel use. These countries have large industry and electricity sectors, the emissions of which face low ECRs and often no pricing at all. China and India rely on coal as a source of energy more than most other countries. For these reasons, an ECR floor would reduce markedly the CO_2 emissions from fossil fuel use of these countries while increasing carbon-related government revenues. Other countries where carbon pricing could be particularly effective in reducing emissions from fossil fuel use and increasing revenues include the Czech Republic, Estonia, Korea and Poland. Countries with large shares of unpriced emissions in 2018, such as Brazil, Indonesia and Russia, would experience a sharp increase in revenues from the introduction of a modest ECR floor on these emissions.

Figure 8. Projected effects of different ECR floors on emissions and revenues by country

Emissions and revenues, indexed

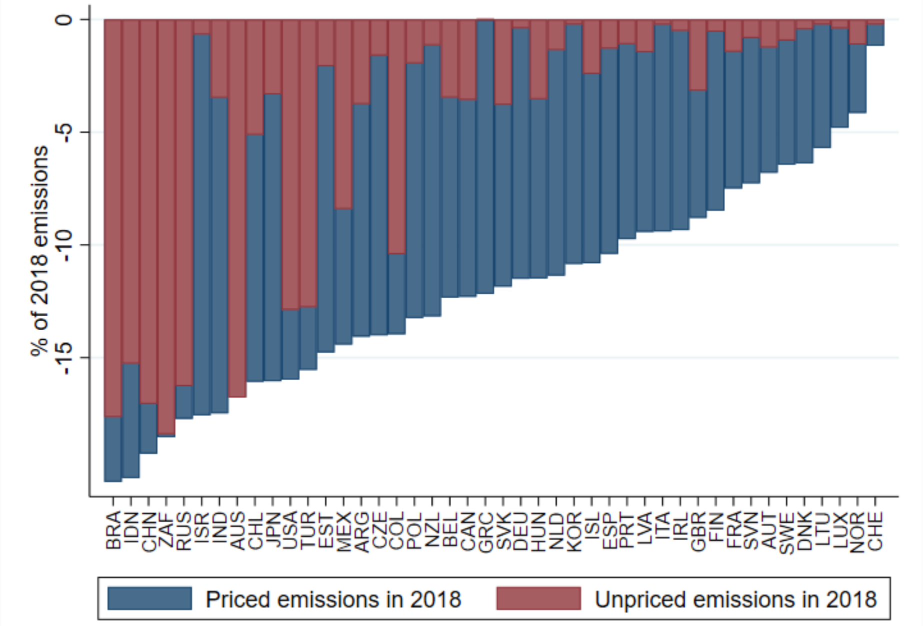


Note: Simulations of a global ECR floor, by EUR 5 increments. The maximum ECR floor for emissions unpriced in 2018 is EUR 60. Beyond EUR 60, the price floor on emissions already priced in 2018 keeps on rising until EUR 175, while that for unpriced emissions in 2018 rises up to EUR 60. Left panel: emissions in gigatonnes of CO_2. Right panel: revenues in EUR billion. Semi-elasticities are allowed to differ by sector.
Source: OECD.

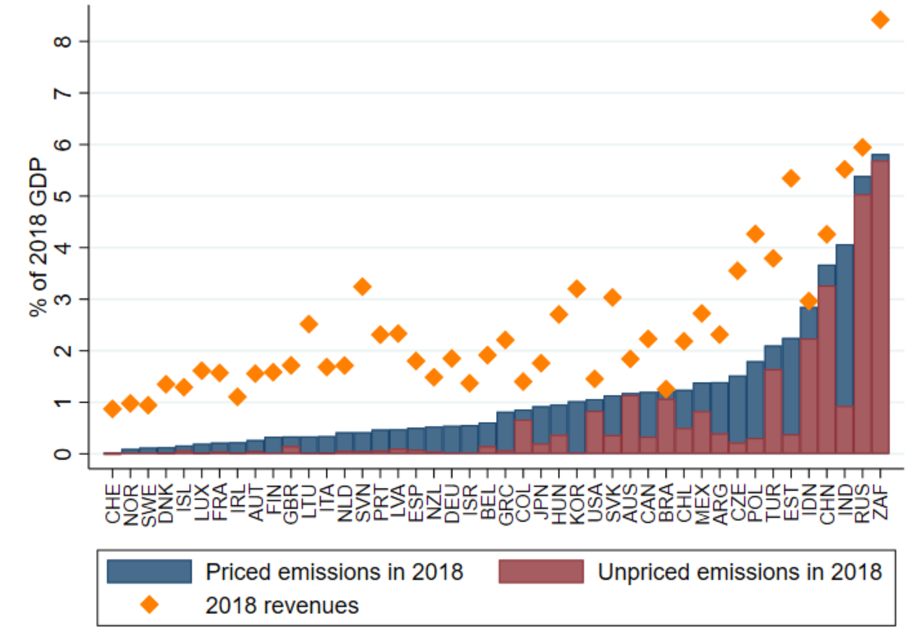
94. Figure 9 shows the effect by country on emissions and revenues of introducing an ECR floor of EUR 60 per tonne of CO_2 (Base Broadening Scenario) and identifies the contribution of two components: 1) raising ECRs on emissions already priced in 2018; and 2) broadening the ECR emission base. In the median country in terms of emissions-reductions (Greece), total emissions (priced and unpriced) would decline by about 12% compared with 2018 levels. Broadening the emission base would account for most of the emission reduction in countries with a large share of emissions that are still unpriced, such as Australia, Brazil, China, Indonesia, Russia, South Africa, Türkiye and the United States.

Figure 9. Impacts of a EUR 60 ECR floor on emissions and carbon-related revenues

Panel A. Change in fossil-fuel emissions and contributions from priced and unpriced emissions (% of 2018 total emissions); sector-specific estimates



Panel B. Revenues change, contributions from priced and unpriced emissions, and total revenues from fossil-fuel emissions after policy change (% of 2018 GDP); sector-specific estimates

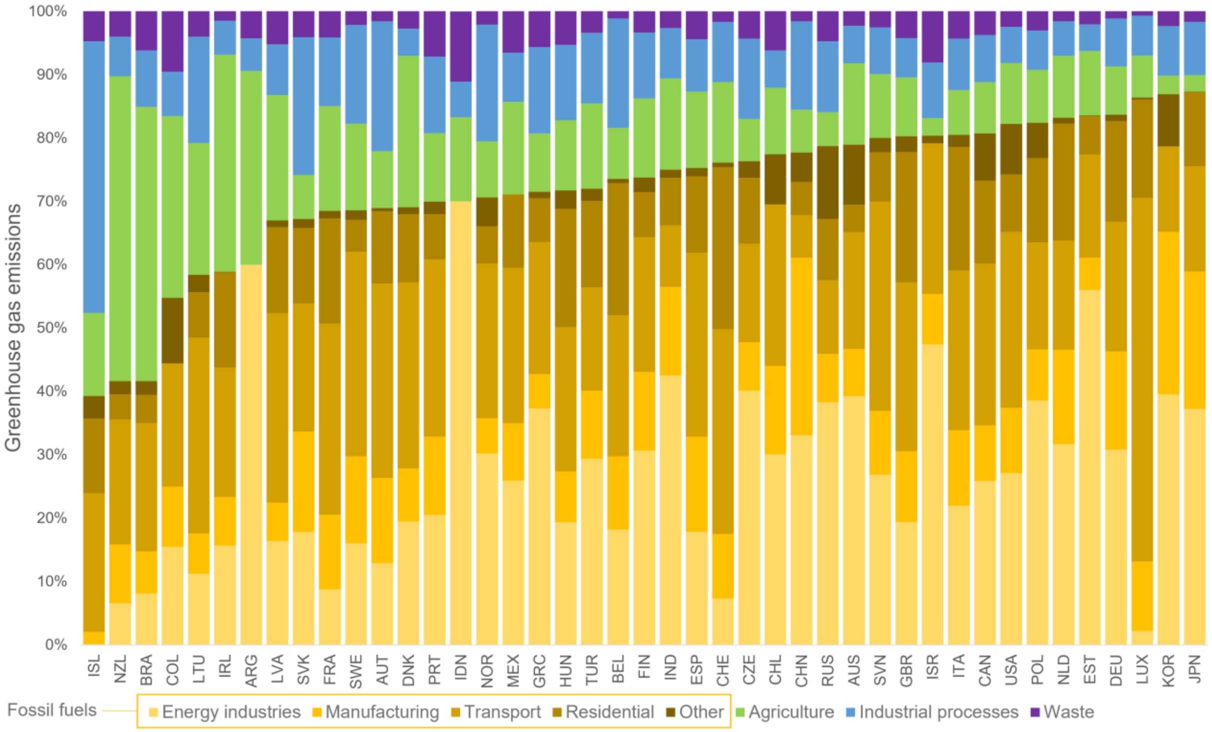


Note: Blue bars represent the contribution of emissions already priced (in 2018) to the change in emissions and revenues from introducing a carbon price floor of EUR 60 per tonne of CO_2 on all emissions from fossil fuel use. Red bars represent the contribution of unpriced emissions in 2018. Emissions are CO_2 emissions from fossil fuel use and revenues are revenues levied on these emissions only.
Source: OECD.

95. The median country (Belgium) in terms of increase in revenues as a percentage of 2018 GDP would collect about 0.6% of 2018 GDP of additional carbon-related revenues (as shown by the bar in Figure 9, panel B). This would raise total carbon-related revenues to 1.9% of 2018 GDP (as shown by the diamond in Figure 9, panel B). India, Russia and South Africa are the countries with the largest increases

in carbon-related revenues, as a large share of emissions still face low prices and coal is still one of their main energy sources. China, Indonesia and Türkiye would also record large increases in carbon-related government revenues, mostly driven by base broadening, and so would Estonia and Poland, mostly due to higher ECRs on priced emissions. Countries like Brazil, in which fossil fuels account for a low share of total GHG emissions (Figure 10), because for instance of a large agricultural sector, would not attain large carbon-related revenues as a percentage of GDP (1.2% of 2018 GDP in the case of Brazil) despite the steep increase in the average ECR. In these countries, the emission base to which ECR applies is small, relative the size of the economy, and hence they can raise less carbon-related revenues as a share of GDP than other countries.

Figure 10. Share of total emission, by sector



Source: OECD, Environment Database

Scenarios based on alternative values of emission responsiveness to ECR

96. The policy simulations presented above are based on a responsiveness of emissions to ECR given current technologies. These fix the substitution possibilities between fossil fuel energy sources and low (or zero) carbon alternatives. However, emission responsiveness may change over time.

97. Most countries have made ambitious pledges to curb emissions and have implemented or are considering a mix of climate policies to this end (D’Arcangelo et al., 2022[3]). These include carbon pricing but also non-pricing measures, such as infrastructure investments to better integrate intermittent energy sources into the electricity grid along with targeted and untargeted technology support for low-carbon energy sources. Such measures can over time ease the substitution of low carbon energy sources for fossil fuels by lowering abatement costs. Moreover, increased awareness of the effects of not reaching the net zero emissions by 2050 target may change citizens’ and businesses’ attitudes, making them more

responsive to carbon pricing.[18] In contrast, if the "low-hanging fruits" are picked first (see Bloom et al. (2020[46]) for a more general argument on "ideas getting harder to find") and marginal abatement costs increase, emission responsiveness could diminish over time. Yearly cross-sectional estimates, not reported here, suggest that the responsiveness of emissions to ECRs has more than doubled between 2012 and 2018, lending support the hypothesis that emission responsiveness is increasing over time.

98. To sketch the potential effect of various factors on emission responsiveness, the policy simulations below are based on a wide range of semi-elasticities, from 0.1 to 1.9 times the baseline estimates (Table 5, column 3). For comparison, the United States Congressional Budget Office (Gecan, 2021[47]) calibrates energy-related emission responsiveness to emission prices within a theoretical model and finds that, after 10 years, they have tripled in the electricity sector and declined by 25% in the transportation sector. Such an exercise also provides a sensitivity analysis to the policy simulations of the previous section.

99. Overall, these simulations enrich the policy implications discussed above without altering the main message: increasing ECRs can have a considerable effect on emissions, but meeting countries' emission reduction targets would still require large increases in ECRs from current levels. The rise in ECRs would initially generate sizeable carbon-related government revenues that could be used to fund new policies or lower other taxes.

100. Easing the substitution of low carbon energy sources for fossil fuels would help to achieve a certain emission reduction at lower ECR levels, thus limiting the economic costs of the climate transition. This suggests that cost-effective emission reduction strategies will have to rely on policy mixes that raise ECRs and at the same time ease the substitution of clean energy sources for fossil fuels (D'Arcangelo et al., 2022[3]).

101. Figure 11 shows the level of total emissions for different ECR floors (varying between EUR 0 and 175 per tonne of CO_2 for emissions already priced in 2018 and between EUR 0 and 60 for emissions unpriced in 2018) and assuming different degrees of responsiveness of emissions to ECRs. The baseline (yellow solid line) builds on the 2018 policies (it shows the same curve as in Figure 3, left panel). For comparison, the estimates obtained by Sen and Vollebergh (2018[25]) lie at the top of the range considered in Figure 11.

102. When assuming the baseline emission responsiveness to ECRs, meaningful emission reductions will necessitate extremely high ECR floors. In the simulations considered here, keeping the baseline semi-elasticity at the estimated level, an ECR floor of EUR 175 on emissions priced in 2018 and of EUR 60 on unpriced emissions would cut emissions by 29% (to about 20 gigatonnes of CO_2) as compared to 2018 levels. The intercepts of the curves indicate the emissions implied by alternative emission responsiveness values with the same ECRs as in 2018. For instance, with a semi-elasticity about twice as large (×1.9) as the baseline estimate, emissions would decline by 5% (to 26.3 gigatonnes of CO_2) at 2018 ECR levels.

103. Figure 11 highlights how improvements in the ease of substitution away from fossil fuels can contribute to reduce emissions at a much lower ECR floor than without such improvements. For instance, an ECR floor of about EUR 175 per tonne of CO_2 on priced emissions combined with a floor of EUR 60 on unpriced emissions and the baseline responsiveness would yield the same reduction in total emissions as an ECR floor of EUR 60 (applied to priced and unpriced emissions) and an emission responsiveness that is 1.6 times the baseline. An ECR floor of EUR 40 (applied to priced and unpriced emissions) and an emission responsiveness that is 1.9 times the baseline would also obtain the similar emission reductions.

104. If emission responsiveness to ECR increased, revenues would still increase but at lower rates. Even for semi-elasticities that are 1.9 times above the baseline value, total revenues would not start

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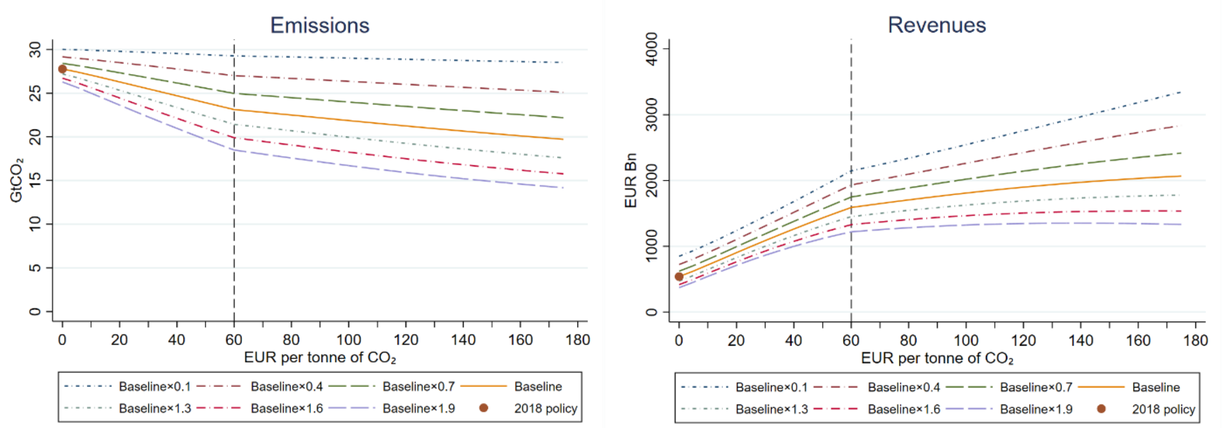
[18] According to surveys from the Pew Research Center, the share of citizens responding "yes" to the question of whether they see climate change as a threat to their country has risen across the world between 2013 and 2018: https://www.pewresearch.org/fact-tank/2019/04/18/a-look-at-how-people-around-the-world-view-climate-change/.

declining at an ECR floor value as high as EUR 175. With a semi-elasticity equal to 1.9 times the baseline estimate, keeping carbon-related revenues at the 2018 level would require an ECR floor of around EUR 30 only.

Figure 11. Higher responsiveness of emissions to ECR decreases emissions and revenues at each carbon price level

Emissions and revenues for different ECR floors, total



Note: Simulations of a global ECR floor by EUR 5 increments. The maximum ECR floor for emissions unpriced in 2018 is EUR 60. The price floor on emissions already priced in 2018 keeps on rising until EUR 175. Left panel: emissions in gigatonne of CO_2; Right panel: revenues in EUR billion. Panel B. Semi-elasticities are allowed to differ by sector

Source: OECD.

Scenarios based on time-varying responsiveness to ECR

105. This subsection presents dynamic policy simulations to 2050 assuming gradually increasing emission responsiveness to carbon pricing as well as gradually increasing carbon price floors. The estimated emission responsiveness to carbon pricing reported above necessarily reflects the abatement costs, technologies and substitution possibilities available in the period (2012-2018) used for the econometric analysis. For this reason, they are ill-fitted to model net-zero emission pathways to 2050 in view of the likely development and deployment of clean technologies over the medium and long terms.

106. The simulations below abstract from possible complex non-linear effects of carbon pricing on emissions. For example, high carbon prices could generate a sudden drop in abatement costs sometime in the future due to the development and deployment of new clean technologies (Acemoglu et al., 2012[48]). Though such non-linear effects are likely to realise over long term horizons, they are difficult to pinpoint with accuracy and simulating them would have required imposing additional and rather arbitrary assumptions. Therefore, the simulations below assume a linear increase in emission responsiveness to carbon prices.

107. Available analyses modelling paths to net zero typically rest on theoretical models that allow for improvements in the availability and costs clean technologies and in the degree of substitution among energy sources. In these models the effect of carbon prices on emissions arises from the behavioural response of firms and individuals to carbon pricing and other climate policies, as well as various socio-economic factors.

108. These models differ along many dimensions (Box 3) but a common characteristic is the sensitivity of CO_2 prices to assumptions concerning the fast rise in carbon capture and storage or direct carbon removal activities – either through technological developments or the use of natural carbon sinks. For instance, one such model for France (Quinet, 2019[49]) assumes land use sinks will remove between 75

and 95 $MtCO_2e$ by 2050 (equivalent to 17-22% of GHG emissions in 2050). Other models (IEA, 2021[50]; CCC, 2020[51]) also assume large behavioural changes, such as decreasing demand for certain goods or activities (e.g. meat consumption).

109. These assumptions are key to the determination of the carbon price level consistent with meeting climate-change mitigation goals. The 90 mitigation pathways to limit the increase in temperature to below 1.5°C compared to pre-industrial levels reported by the IPCC (IPCC, 2022[1]) yield shadow carbon price estimates (i.e., undiscounted mitigation costs) ranging between USD 135–6 050 per tonne of CO_2e in 2030 and between USD 245–14 300 per tonne of CO_2e in 2050. Such a broad range reflects different assumptions about technological developments and the effectiveness of other policies. These shadow carbon price estimates, however, do not imply that explicit carbon prices (i.e. carbon taxes and permit prices) should necessarily be as high. The IPCC report discusses findings for some sectors and countries that imply moderate explicit carbon prices of the order of USD 25 per tonne of CO2e in 2030-40 if combined with other policies, such as regulations and/or standards.

110. The Net-Zero Emissions by 2050 Scenario of the International Energy Agency (IEA, 2021[50]) highlights the role and timing of technologies and actors to achieve global net-zero emissions by 2050. These include: behavioural changes and avoided demand, energy efficiency, hydrogen-based mitigation, electrification, bioenergy, wind and solar, other fuel shifts and carbon dioxide removal (through carbon capture, utilisation and storage, or direct removal technologies). The report presents price paths for different jurisdictions – ranging from 2019 USD 75 per tonne of CO2 in 2025 to 2019 USD 250 in 2050, for advanced economies, and from 2019 USD 19 in 2025 to 2019 USD 200 in 2050, for emerging market and developing economies – depending on assumptions concerning the adoption of non-pricing policies and technological developments.

111. The French and United Kingdom governments use approaches giving rise to shadow-price pathways. Following the Commission presided by Alain Quinet, the shadow price ("valeur tutélaire du carbone") put forward for France is of EUR 250 per tonne of CO_2 in 2030 and EUR 500 in 2040 (Quinet, 2019[49]). The United Kingdom's Climate Change Committee (CCC, 2020[51]; CCC, 2020[52]) uses "exploratory scenarios", which also include "judgements on the achievable and sensible pace of decarbonisation in the face of uncertainty". Analysis from the 2019 report (CCC, 2019[53]), suggests shadow prices ("carbon values") by 2050 of between GBP 300 and 450 per tonne of tonne of CO_2e. These ranges reflect differences in the models used and their assumptions relating to learning-by-doing and behavioural effects in addition to the models' coverage of the land use land use change and forestry sector.

Box 3. Approaches to model net zero emission pathways

Integrated assessment models

112. The most common models used to assess alternative emissions pathways are Integrated Assessment Models (IAM). IAMs combine insights from different disciplines (e.g. climate science, economics, engineering) into a consistent framework and make predictions on energy–economy–land–climate systems under different scenarios. According to Box 5 in IPCC (IPCC, 2022[1]) IAMs can be declined into two broad categories:

- IAMs based on cost–benefit analysis (CBA). These models identify the optimal emissions trajectory minimising the discounted flows of abatement expenditures and monetized climate-change damages. Their key metric is the social cost of carbon (SCC) – the economic cost caused by an additional tonne of CO_2 emissions or its equivalent (Nordhaus, 2014[54])..
- IAMS based on cost-effectiveness analysis (CEA). The models identify emissions pathways that minimise the total costs of achieving a specified emission reduction – such as net zero emissions by 2050. The marginal abatement cost of carbon is determined by the target in question, resulting in a path for the shadow price of carbon. Detailed process IAMs, which

include a detailed representation of energy and land systems but not climate damages, are based on the CEA approach.

Energy-economic models

113. Energy-economic models, such as Kaufman et al. (2020[40]), rely on predetermined (exogenous) paths to net zero in 2050. This approach allows the modellers to choose higher or lower initial rates of emissions reduction based on different considerations, such as declining abatement costs over time, technology lock-in effects, managing the risk of climate tipping points. These models estimate the CO_2 prices consistent with reducing emissions following the desired pathway under a given set of assumptions about future technologies, prices, behaviour and other policy measures. Also using these models, near term projections can rely on historical data on the economy and energy systems, whereas long-term projections (i.e. to 2050) incorporate uncertain technology forecasts.

114. The policy simulations below aim at showing the order of magnitude of the increases in ECRs and improvements in emission responsiveness required to put emission on a downward path and meet net-zero targets. They are based on the following assumptions:

- The emissions' adjustment to a change in ECR takes 10 years. Based on the baseline estimates reported above, a EUR 10 increase in ECR reduces emissions by 3.7%. This reduction in emissions is spread over ten years (with emissions decreasing linearly over time).
- ECR floors increase exogenously and linearly every year up to 2040. The increase in ECR might not coincide with the optimal carbon pricing schedule. If marginal abatement costs increase over time, it might be better to frontload the ECR increase. The opposite is true if climate change damages increase over time. Similarly, the effects of accumulating emissions in the atmosphere ("stock effects") are not considered.
- Emissions' responsiveness to carbon pricing is assumed to increase linearly and exogenously over time. This captures diminishing abatement costs from new technologies easing the substitution away from fossil fuels or changes in attitudes and behaviours. There is no explicit feedback between carbon pricing and responsiveness.

115. The results of these simulations are shown in Figure 12. The lower panel shows the path of total CO_2 emissions from fossil fuel use (considering the 44 OECD and G20 countries present in the Effective Carbon Rates 2021 database). The top two panels show the evolution of the ECR floors and of the emission responsiveness to carbon pricing assumed in the different scenarios. The level of unabated emissions consistent with the net-zero target (shown in Figure 12) is 1.36 Gt CO_2. This is equivalent to 80% of total unabated emissions from energy use (1.7 Gt CO_2) consistent with the net-zero 2050 target (IEA, 2021[50]).[19]

116. Absent any improvements in emission responsiveness, Figure 12 shows that only steep and persistent increases in ECRs, reaching above EUR 1 000 per tonne of CO_2 by late 2030s, can reduce emissions by mid-century to levels consistent with the net-zero target. Only combining steady increases in ECRs with policies to markedly increase the emission responsiveness to carbon pricing can put emissions on a downward path consistent with meeting the net-zero target. For instance, raising the ECR floor by EUR 10 per year (to 220 in 2040) will require raising emission responsiveness by about 5 times the baseline estimate reported above (a 12% yearly increase with respect to current estimates). Raising the ECR floor by EUR 5 per year (to 110 in 2040) will instead require significantly larger improvements in the emission responsiveness (to 10 times the baseline estimate by 2050).

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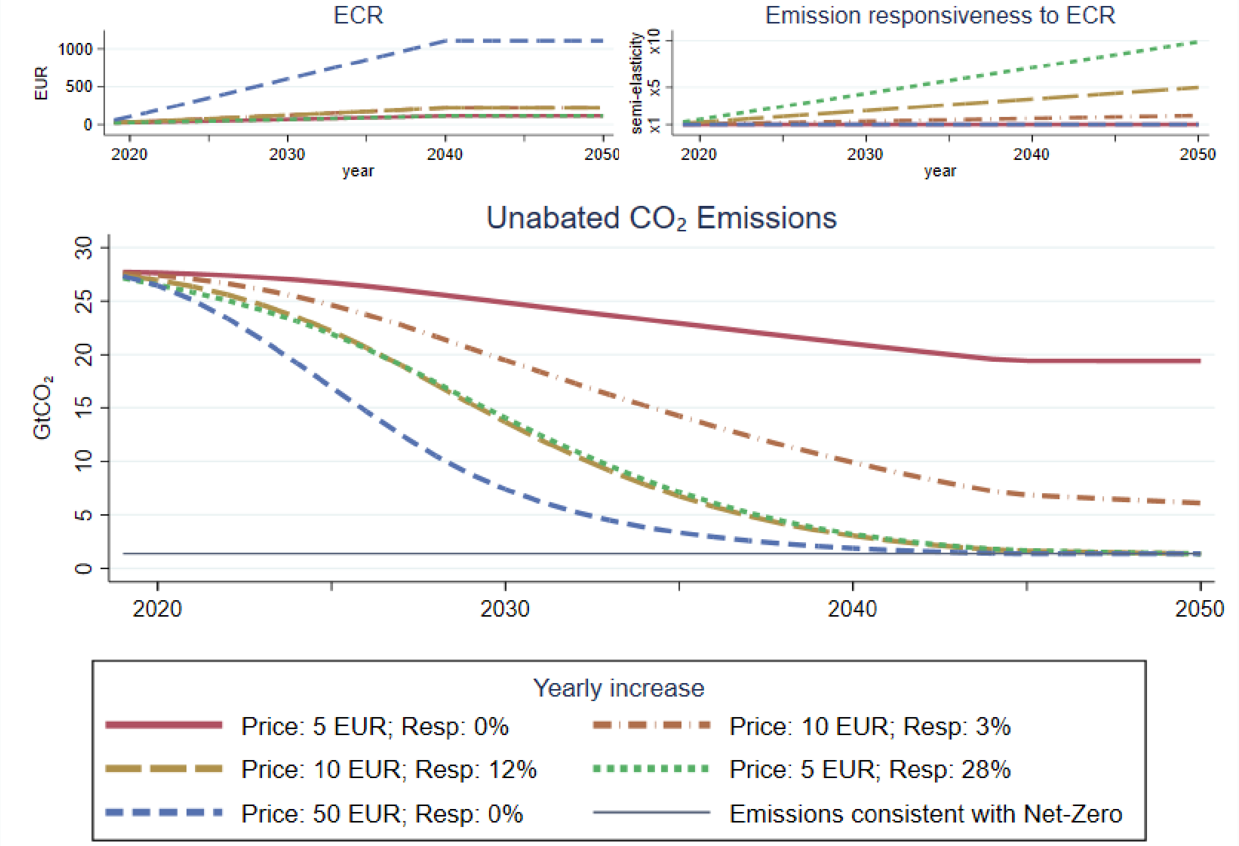
[19] 80% is the share of the 2018 total CO_2 emissions from energy use generated by the 44 OECD and G20 countries considered in this study.

Figure 12. CO2 emissions paths with emission responsiveness and carbon price floors adjusting over time



Note: The top two Panels show the evolution of ECR floors and emission responsiveness over time resulting in the CO_2 emission paths shown in the lower Panel. Simulations consider the 44 OECD and G20 countries present in the Effective Carbon Rates 2021 database.
Source: OECD.

117. Moderate increases in the ECR and no or moderate improvements in emission responsiveness will not be sufficient to reduce emissions in line with climate goals (Figure 12). Raising the ECR floor by EUR 5 per year (to EUR 110 in 2040) with no improvements in emission responsiveness will reduce emissions by less than half of what is need to reach the global net zero target. More sizeable increases in the ECR floor (EUR 10 per year, to 220 in 2040) accompanied by moderate improvements in the emission responsiveness (i.e. 3% per year, resulting in a 70% increase by 2050) will lead to a larger reduction in emissions, yet still insufficient to meet the net-zero target.

Annex A. Data and Methods

118. This section discusses the details of the empirical strategy, including the steps undertaken to clean the dataset and the identification of the empirical model.

119. The paper considers emissions from fossil fuel use, i.e. all fuel categories, with the exception of non-renewable waste and biofuels. Emissions from LPG in the road sector are also dropped due to potential endogeneity issues described below. Due to data constraints, the sample for the main elasticity estimates is restricted to 37 countries.[20] Canada, Colombia, Indonesia, Israel, Latvia, Lithuania, and the United States are excluded from the estimation sample because the data are not comparable or missing. They are included in the scenario analysis, as explained in Section 5. Table A.1 shows how results do not depend on removing these countries, and are not driven by results observations from India and China, two influential countries in terms of emissions. The estimates presented in Table 4, Table 5 and Table 6 are not statistically different when the countries discussed here are included or excluded.

120. Finally, we windsorise extreme values: these are observations above the 99.5 percentile for effective carbon rates and below the 0.5 percentile for CO_2 emissions from energy use. Taken together, the CO_2 emissions in the final sample used for the estimation represent about 68% of CO_2 emissions from energy use in the original database and about 55% of total CO_2 emissions from energy use. Table A.2 presents the share of each dropped category of data, as well as explanations as to why they were dropped from the final sample.

Table A.1. Results are robust to country inclusion or removal

	Full sample			Restricted sample		
	Baseline (1)	No China and India (2)	Every country (3)	Baseline (4)	No China and India (5)	Every country (6)
Baseline model	-0.280***	-0.320***	-0.320***	-0.369***	-0.386***	-0.406***
	(0.078)	(0.079)	(0.073)	(0.083)	(0.085)	(0.078)
Constant	5.591***	5.430***	5.702***	5.579***	5.403***	5.673***
	(0.024)	(0.025)	(0.021)	(0.031)	(0.032)	(0.027)
Observations	5766	5407	6528	4899	4609	5518
N° country-sector-fuel	2092	1972	2445	1772	1676	2057
user×fuel×year fixed effects (δ_{uft})	✓	✓	✓	✓	✓	✓
country×user×year fixed effects (δ_{cut})	✓	✓	✓	✓	✓	✓

Note: *p ≤ 0.1, **p ≤ 0.05, *** p ≤ 0.01. Standard errors clustered at user×fuel×time level and country×user×year level in parenthesis. Column (2) and (5) exclude observations from China and India; Column (3) and (6) include all the countries in the ECR database. The difference in the main coefficients for each sample is not statistically different.

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[20] Argentina, Australia, Austria, Belgium, Brazil, Switzerland, Chile, China, the Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, the United Kingdom, Greece, Hungary, India, Ireland, Island, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, New Zealand, Poland, Portugal, Russia, the Slovak Republic, Slovenia, Sweden, Türkiye, South Africa.

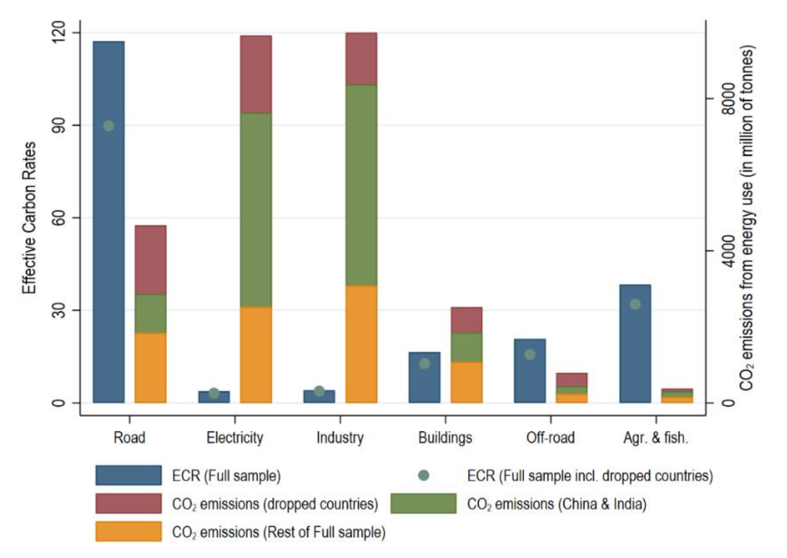
Table A.2. Data dropped from the estimation

Type of data	Detail	Share of emissions in ECR database, 2012	Share of emissions in ECR database, 2015	Share of emissions in ECR database, 2018	Reason
Fuel	Other combustible fuels (biofuels and non-renewable waste)	11%	10.8%	10.9%	According to IPCC guidelines, biofuels are not included in national total emissions. Moreover, hardly any emissions from these fuel categories are priced (92% of these emissions are unpriced). Finally, for the low share of priced emissions in these two categories, the conversion factors are not always consistent, so the data may not be comparable across countries or years.
	LPG in the road sector	0.15% (1% in the road sector)	0.16% (1% in the road sector)	0.15% (0.96% in the road sector)	Endogeneity issue: explained in the text
Country	Canada	2%	2%	2%	Data is not comparable between 2012-2015 and 2018 as the methodology regarding sub-national level trading schemes changed from 2018 onwards
	Colombia	n.a.	n.a.	0.3%	Data is only available for 2018
	Indonesia	2.2%	2.1%	2.2%	Predominance of unpriced emissions would provide misleading results for the restricted sample
	Israel	0.24%	0.21%	0.19%	Not all data is comparable between 2015 and 2018
	Latvia	n.a.	0.04%	0.05%	Data is not available for 2012
	Lithuania	n.a.	n.a.	0.06%	Data is only available for 2018
	United States	17.8%	17.7%	17.3%	Data is not comparable between 2012-2015 and 2018 as the methodology regarding sub-national level trading schemes changed from 2018 onwards

Note: “n.a.” not available
Source: OECD

121. Figure A.1 shows the average ECR and total emissions by sector considered in the analysis, contrasting the Full sample employed in the estimation and the one used in the scenario analysis, which includes all the countries in the 2018 ECR database. As can be seen when comparing this figure to Figure 2 from Section 3, average effective carbon rates are higher when restricting to the Full sample as compared to the original ECR database, especially in the road and agriculture and fisheries sector. This mostly stems from US observations being dropped in the Full sample. Relative magnitudes of effective carbon rates and CO_2 emissions remain the same as those illustrated in Figure 2. Indeed, in 2018 in the Full sample the ECR was highest in the road sector at EUR 117 per tonne of CO_2 and lowest in the electricity and industry sectors, respectively at EUR 3.8 and EUR 4.1. These two sectors account for the largest share carbon emissions from energy use (35.6% and 39%), with China and India being responsible for the majority of these emissions (67% in the electricity sector and 61% in the industry sector). The lowest emissions from fossil fuel use are in the off-road and agriculture and fisheries sectors.

Figure A.1. Average ECR (left axis) and total CO_2 emissions (right axis) by sector in the samples used for the analysis, 2018



Note: Effective carbon rates as of 1 July 2018 in the Full sample and in the Full sample including dropped countries (Canada, Colombia, Indonesia, Israel, Latvia, Lithuania and the United States); i.e. the sample used for the scenario analysis. CO_2 emissions from fossil fuel use.
Source: OECD.

Details on the empirical methods

122. This section explains in detail how the fixed effects reinforce this assumption, what variation is left in the data to identify the semi-elasticity, and how the paper address potential simultaneity problems. As explained in Section 4 the empirical model is:

123. $$q_{cuft} = \beta \times ECR_{cuft} + \delta_{cut} + \delta_{uft} + \varepsilon_{cuft}.$$ 124. (2)

125. The semi-elasticity β is identified if ECR is orthogonal to the error term. The three-way fixed effects δ_{uft} control for unobserved heterogeneity at the user-fuel-time level. These fixed effects absorb the fuel price fluctuations at the global level due to supply shocks. For example, coal experienced relatively higher global prices in 2018 than gasoline or oil, because of unexpected supply shortages and demand increases, while also experiencing a ratcheting up of ECR driven by rising EU-ETS permit prices. Failing to control for these global market developments would attribute the decrease of emissions from coal to a rising ECR

instead of the global market situation. These fixed effects also help to identify emission changes along the fuel demand curve, instead of a mix of the demand and supply curves, by allowing the supply to vary at the user-fuel level. Insofar as this user-fuel supply is global and thus exogenous for a country-user, variations in emissions can be attributed to changes in the demand for fossil fuels and β can be interpreted as a semi-elasticity.

126. Importantly, these fixed effects partial out the effect of all country-invariant prices, such as the global price of the fuel in a given year, as well as the global price of potential substitutes. For example, all global price indexes of fuels, such as the Brent oil price or the Henry Hub gas price, subsume into these fixed effects. As explained below, these fixed effects also help to retrieve unbiased estimates even if governments exhibit heterogeneous unobserved preferences over the 'tax base' (i.e. emissions) by controlling for their country-invariant component. For instance, motor fuels taxes are common in most countries because of historical and practical reasons. As recognized in Sen and Vollebergh (2018[25]), failing to control for these 'tax base' effects might introduce selection bias due to endogeneity of priced and unpriced categories.

127. The three-way fixed effects δ_{cut} control for unobserved heterogeneity at the country-user-year level. Importantly, these fixed effects take into account idiosyncratic differences in fuel demand caused by business cycle fluctuations at the country-user level. Failing to include these fixed effects could bias the estimates towards zero if the users facing the highest effective carbon rates are experiencing an increase in their base. For example, despite high taxation, emissions in the road transport sector rose in most countries during the period covered by this study. These fixed effects also help to control for unobservable changes in production technology, as well as sector-specific mitigation policies that might affect emissions beyond prices. Both country-time and user-time fixed effects are subsumed by δ_{cut}, allowing to control for factors like the size of the economy, as well as global trends in the sector that might affect emissions.

128. Overall, the rich set of fixed effects controls for a number of unobserved confounders that at the same time reduce the variation in ECR used to identify the parameter of interest (β). It is thus important to clarify what variation is left in the data that is used to estimate β. After controlling for the user and the fuel category with δ_{uft}, cross-country differences in the ECR determine variation in country-level emissions. Emissions of each user-fuel category pair should be lower in countries with higher ECR. After controlling for the country and the user with δ_{cut}, differences in the ECR across different types of fuel categories determine the fuel mix and then emissions of each sector-country pair. Emissions from fuels of each sector-country pair should be lower for fuel categories with higher ECR.

129. Table A.3 shows an analysis of variance of ECR. Results show that the variation in ECR is mostly cross-sectional and attributable primarily (column 1) to differences across fuels, secondly across country and user, and only minor to time variation.

Table A.3. Variation in ECR by source

Analysis of variance, ECR

	Partial SS (1)	Df (2)	MS (3)	F (4)
Model	9457025	61	155033	79.68
Country	2371070	36	65863	33.85
User	1934245	16	120890	62.13
Fuel category	3672622	7	524660	269.66
Year	44286	2	22143	11.38
Residual	11668046	5,997	1946	
Total	21125071	6,058	3487	

Note: (1) Sum of Squares; (2) degrees of freedom; (3) mean square error; (4) F statistics.
Source: OECD

130. Because the fixed effects δ_{cut} control for country-user level energy demand shocks and δ_{uft} control for sector-fuel category global supply shocks, estimation of the parameter of interest β relies on the remaining variation in emissions and ECR across countries and across fuels. Changes over time provide an additional, if minor, source of within-country and within-user variation. Therefore, the differences in ECR levels and emissions reflect long-standing structural differences across countries and fuel categories, such as differences in fuel demand reflecting past investment decisions that favoured certain types of fuels. They also reflect past investments in fuel efficiency, which are a determinant of final fuel demand. Thus, the estimated semi-elasticities can then be interpreted as long-run semi-elasticities to allow for the technical transformation and the time to install new capital that follows changes in ECR.

Addressing simultaneity problems

131. A simultaneity problem might arise if governments have unobserved preferences for pricing (or not) emissions from certain fuels and/or in certain sectors. One way to address this problem is through an instrumental variable approach. Sen and Vollebergh (2018[25]) use the ECR in neighbouring countries as instrument, based on the idea that effective carbon rates are spatially correlated across countries. This is either because of tax competition causing a 'race to the bottom', or because countries engage in carbon pricing policy mimicking. Assuming that ECRs in neighbouring countries do not affect domestic fuel consumption, a distance-weighted average of neighbouring countries' ECR can be a valid instrument of a country's ECR.

Table A.4. Robustness check: IV-regressions for sector-specific estimates

	Full sample			Restricted sample		
	OLS	Leave-one-out	Distance-weighted ECR	OLS	Leave-one-out	Distance-weighted ECR
	(1)	(2)	(3)	(4)	(5)	(6)
Road	-0.018	-0.941***	0.355***	-0.439**	-1.121	0.483***
	(0.137)	(0.000)	(0.00)	(0.135)	n.a.	n.a.
Electricity	-0.566	-0.249***	-23.449	-0.452	-0.313***	-25.892***
	(0.387)	(0.000)	n.a.	(0.511)	0.00.	0.000
Industry	-0.282**	0.037	3.045	-0.369***	-0.313	3.473
	(0.108)	(0.364)	n.a.	(0.112)	(0.242)	(14.907)
Buildings	-0.190	-0.183	2.676	-0.282	-0.253	2.396
	(0.183)	(0.331)	(2.439)	(0.182)	(0.364)	(2.109)
Off-road	-0.044	0.666*	-0.226	0.017	0.602	-1.153
	(0.195)	(0.325)	(1.424)	(0.207)	(0.364)	(1.444)
Agriculture & fisheries	-0.719***	-0.621**	1.297	-0.907***	-1.031***	0.597
	(0.163)	(0.253)	(1.187)	(0.238)	0.171	(2.683)
Observations	5766	5766	5766	4899	4899	4899
Nº country-sector- fuel	2092	2092	2092	1772	1772	1772
user×fuel×year fixed effects (δ_{uft})	✓	✓	✓	✓	✓	✓
country×user×year fixed effects (δ_{cut})	✓	✓	✓	✓	✓	✓
Kleibergen-Paap rank LM test (p-value)		0.3173	n.a.		0.3173	0.093

Note: *p ≤ 0.1, **p ≤ 0.05, *** p ≤ 0.01. Standard errors clustered at country×user×fuel×time level in parenthesis. Respectively, 293 and 378 singletons dropped in the Full and Restricted sample. "n.a.": not available, the weighting matrix of the 2-step GMM estimator used to deal with the instruments and the large number of fixed effects is not well-defined, resulting in undetermined standard errors.

132. Unlike the work of Sen and Vollebergh, this study allows for sector-specific and fuel-specific elasticities, which are key to the policy scenario analysis. This drastically weakens the validity of Sen and

Vollebergh's instrumental variable approach because of weak instruments. Table A.4 shows results from this IV approach (columns 3 and 6) as well as a leave-one-out IV approach. The tests we conduct cannot reject the hypothesis of weak identification, risking of introducing a large bias. Instead of resorting to an instrumental variable approach, potential simultaneity problems are addressed as follows

133. First, employing the fixed effects described above (δ_{uft}) controls for country-invariant unobservable governments' preference for pricing certain emissions and not others, due for instance to the political cost of introducing new taxes (e.g. due to the presence of well organised interest groups), its saliency (visible carbon prices tend to stoke strong opposition), or the associated administrative burden (which affects compliance rates).

134. Second, LPG in the road transport sector is excluded from the sample. In many countries, governments actively encourage its use, through low or zero tax rates, as LPG is considered a transitional fuel in the path to decarbonising the road sector. Despite these incentives, the share of transport fuelled with LPG remains low with respect to other fuels due to reasons other than its price, such as their more limited range or sparser refuelling networks. Indeed, LPG in the road sector exhibits a positive elasticity in a wealth of specifications, suggesting the presence of simultaneity problem in this case.

135. Third, together with the baseline specifications, the paper shows results on the subsample of observations with a strictly positive ECR (Restricted sample). Governments may set zero effective carbon rates on small bases (i.e. low emissions) as political costs are high while revenue potential is low and they use exemption policies to favour specific fuels or sectors. For this reason, removing exempted emission can be expected to ease the simultaneity problem. The rest of the Annex discusses in more detail the implications of removing these observations.

An analysis of unpriced emissions

136. There are different reasons why emissions from certain fuels are exempt from carbon pricing. In some cases, governments want to encourage their use, for example because they cause less harms to the environment than the alternatives. One such case is the use of natural gas in the road sector, which is untaxed in many countries. In some other cases, governments want to support the economy or some specific sector (OECD, 2020[55]; 2021[56]). For instance, countries whose economy heavily relies on fossil fuel production do not price emissions from fossil-fuel use or do so only lightly. Other countries provide fuel duty exemptions to specific sectors such as agriculture and fishery. These examples suggest that carbon pricing exemption is unlikely to be random, causing a sample selection issues and biasing estimates.

137. In the Full sample, a substantial share of unpriced emissions concerns fossil-fuel producing countries. Coal in China, Australia and South Africa and gas in Russia account for most of the share of emissions that are unpriced.[21] Table A.5 tests for differences in the proportion of unpriced emissions in fossil fuel producing and non-producing countries. A 'fossil fuel producer' country is defined to be one of the 10 largest producers of the associated fossil fuel by volume in 2018. Results show that fossil fuel producers exempt a larger share of emissions (66.9%), against a smaller share of non-producers (22.2%). This difference is significant at more than 1% confidence level. Industry and electricity sectors benefit from the largest exemptions and are the most relevant in terms of both observations and emission shares. The exemption to natural gas emissions in the off-road sector reflects the exemption of gas pipelines and transport. Because of these sector-country-fuel category differences, the fixed effects are not sufficient to control for a potential sample selection.

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[21] See Taxing Energy Use (OECD, 2019[32]) for further details and a precise breakdown of energy taxation by sector in these countries.

Table A.5. Fossil-fuel producing countries apply zero ECRs to a larger share of emissions than other countries

Test of difference in the average share of unpriced emissions in fossil fuel producing versus non-producing countries

		Producers	Non-producers	Difference	Standard error	P-value
		(2)	(1)	(3)	(4)	(5)
Emissions (Gt)	Unpriced	10.7	1.2			
	Total	16.0	5.4			
	Proportion	66.9%	22.2%	-44.7%	0.005	0.000

Note: Data from 2018. “Producers” countries are defined to be one of the 10 largest producers of the associated fossil fuel by volume in 2018.
Source: OECD.

138. As highlighted above, countries could also choose to exempt emissions in some sector because the corresponding base is small. Hence, fuel category-user combinations with a relatively small base (thus relatively low emissions) could be more likely to face no carbon pricing. This can introduce simultaneity problems and bias estimates. This hypothesis is tested by comparing the average share of priced and unpriced emissions in a country’s total emissions.[22] The share of unpriced emissions in the agriculture & fisheries (0.09%), buildings (0.24%), and road sectors (0.24%) is smaller than the share of priced emissions (respectively, 0.22%, 0.46%, and 3.37%).[23] These results contrast with the economic intuition that the emissions are highest where the price is lowest (zero) and support the idea that the costs of introducing a new tax causes sample selection against small bases.

139. All this suggests that, focusing on observations already priced in 2018 could help to address the problems caused by non-randomness in exemption of emissions from pricing. Furthermore, it avoids the problem of potential non-linear responses of fuel demand to ECR at zero. For example, unobserved compliance costs associated with a new tax or an extension in ETS coverage could cause a response “jump” when ECR rises above zero. This would bias estimates away from zero, as the introduction of a low carbon rate would cause a large drop in fuel use.[24]

140. Table A.6 shows differences between the Full and Restricted sample, which is limited to observations with a positive ECR. Only the fuel categories with the largest differences between the two samples, either by number of observations (Column 7) or by share of emission calculated as share of the sector (Column 9) are reported below. Restricting the sample increases the average ECR from 35.2 (Column 3) to 43.3 (Column 5) EUR per tonne of CO_2 and reduces the number of observations from 5766 to 4693 (-18.8%) and the emissions covered by 29%.

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[22] Mathematically, the average over countries and years of $\frac{taxed\ emissions_{cuft}}{\sum_u \sum_f emissions_{cuft}}$ is compared to that of $\frac{untaxed\ emissions_{cuft}}{\sum_u \sum_f emissions_{cuft}}$.

[23] The difference is not statistically significant in the other sectors with the exception of electricity, although this difference becomes not significant when exclude fossil fuel producing countries are excluded.

[24] The presence of nonlinearities at zero caused by a newly introduced price on CO_2 emissions is tested, but the results are inconclusive (i.e. not statistically significant). In practice, the baseline model (Equation (1)) is re-estimated interacting ECR with a dummy variable taking value of 1 if a new price has been introduced for previously exempted emissions (254 observations).

Table A.6. Differences between the Full sample and the Restricted sample

Observations dropped and their emission share, major fuel categories by sector

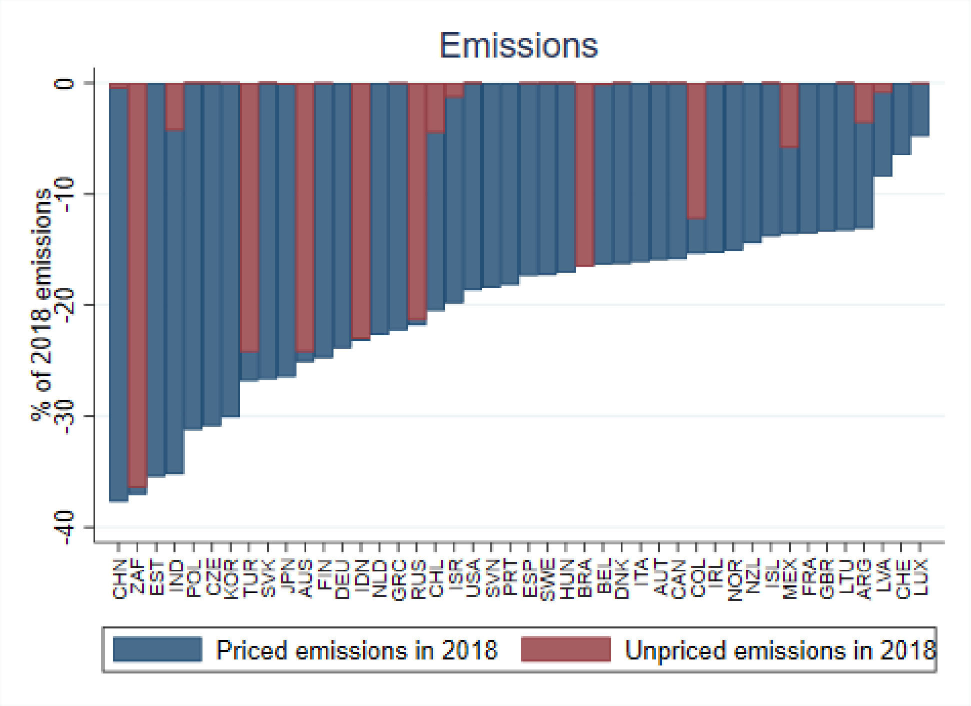
Sector	Fuel category	Full sample		Restricted sample		Difference		
		ECR mean (1)	N (2)	ECR mean (3)	N (4)	ΔN (5)	ΔN% (6)	Share of emissions (as sector total) (7)
Road	Natural gas	34.3	94	44.2	73	-21	-22%	-2%
Electricity	Coal and other solid	7.7	101	8.7	89	-12	-12%	-5%
	Natural gas	10.1	105	12.1	87	-18	-17%	-5%
Industry	Coal and other solid	11.1	427	13.6	361	-66	-15%	-6%
	Fuel oil	24.2	439	27.7	384	-55	-13%	0%
	Natural gas	18	543	21.0	463	-80	-15%	-7%
Buildings	Coal and other solid	7.3	142	9.2	112	-30	-21%	-4%
	LPG	24.4	212	27.8	186	-26	-12%	-6%
	Natural gas	26.4	214	32.6	173	-41	-19%	-8%
Off-road	Diesel	45.5	135	51.3	106	-29	-21%	-2%
	Kerosene	29	87	33.1	76	-11	-13%	-9%
Agr. & fish.	Coal and other solid	10.5	50	15.3	34	-16	-32%	-19%
	Diesel	41.1	143	50.0	117	-26	-18%	-15%
Total		35.2	5766	41.1	4899	-857	-15%	-18%

Note: Column (1): ECR by sector and fuel category in the Full sample (simple average); Column (2): observations in the Full sample; Column (3) ECR by sector and fuel category in the Restricted sample (simple average); Column (4): observations in the Restricted sample; Column (5): (4) – (2); Column (6): (5) / (3); Column (7): Share of emissions removed in the Restricted sample for the fuel category, as percentage of the sector total.
Source: OECD.

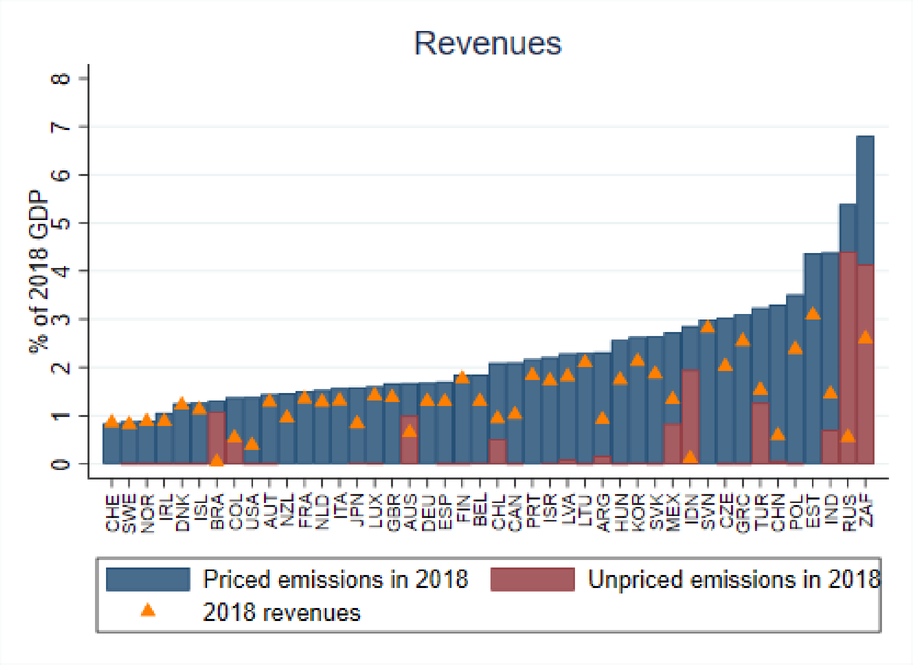
Robustness check. Estimates with fuel-specific semi-elasticities

Figure A.2. Projected effects on countries' carbon-related revenues of an ECR floor of EUR 60 and EUR 120

Panel A. Emission change, % of 2018 emissions, fuel-specific estimates



Panel B. Revenues, % of 2018 GDP per year, fuel-specific estimates



Source: OECD.

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