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Carbon pricing efficacy: Cross-country evidence

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Abstract
To date there has been an absence of cross-country empirical studies on the efficacy of carbon pricing. In this paper we present estimates of the contribution of carbon pricing to reducing national carbon dioxide (CO2) emissions from fuel combustion, using several econometric modelling approaches that control for other key policies and for structural factors that are relevant for emissions. We use data for 142 countries over a period of two decades, 43 of which had a carbon price in place at the national level or below by the end of the study period. We find evidence that the average annual growth rate of CO2 emissions from fuel combustion has been around two percentage points lower in countries that have had a carbon price compared to countries without. An additional euro per tonne of CO2 in carbon price is associated with a reduction in the subsequent annual emissions growth rate of approximately 0.3 percentage points, all else equal. While it is impossible to fully control for all relevant influences on emissions growth, our estimates suggest that the emissions trajectories of countries with and without carbon prices tend to diverge over time.

Keywords:
carbon dioxide emissions; carbon pricing; carbon tax; cross-country; emissions trading; fossil fuel policies; growth rates; renewable energy policies

JEL Classification:
O57; Q43; Q48; Q50; Q58

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1. Introduction

Effective policies to reduce greenhouse gas emissions are vital in order to make substantial progress in addressing climate change. The first tool in the economist's toolkit for reducing greenhouse gas emissions is for a price to be charged per unit of emissions. That carbon pricing can make an important contribution to reducing emissions has been established in individual case studies for countries such as Sweden (Andersson 2019). Yet to our knowledge there is an absence of large-*n* international studies on the effect of carbon prices on national emissions.

In this paper we use a longitudinal dataset for 142 countries to estimate the contribution of carbon pricing to reducing carbon dioxide (CO_2) emissions. We employ econometric techniques that control for other relevant factors, including other policies such as feed-in tariffs and renewable portfolio standards. We focus on emissions from fuel combustion, which account for approximately 80% of global human-induced CO_2 emissions and have been the main target of carbon pricing (IEA 2017).

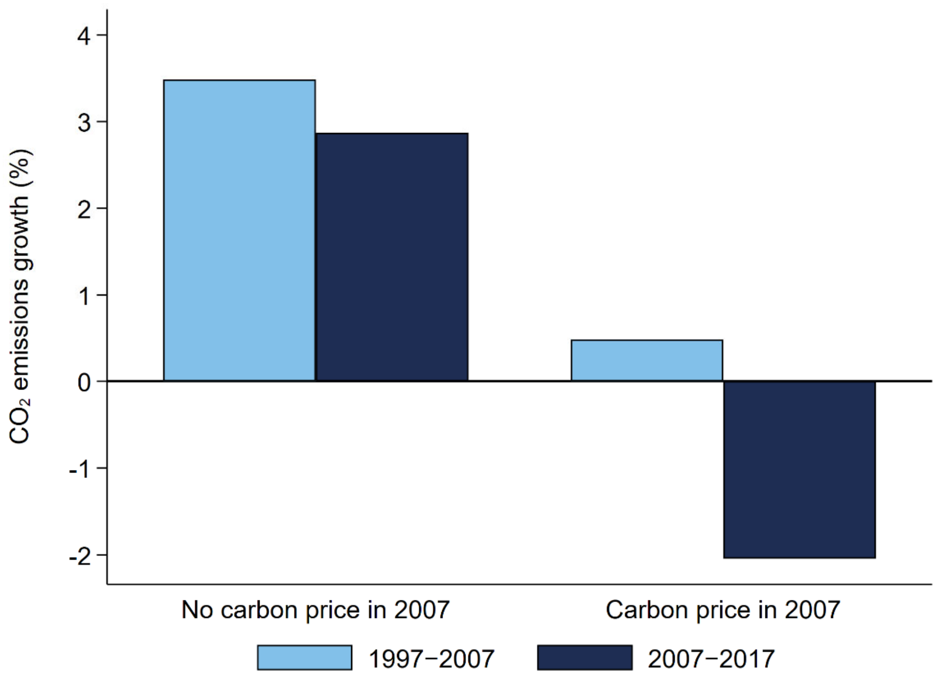
From a conceptual viewpoint, carbon pricing should promote emissions reductions by incentivising polluters to internalise external costs into their decisions (Aldy and Stavins 2012). Theory anticipates a downward-sloping demand curve for emissions, meaning that the quantity of emissions should be lower when the price of emissions is higher. As a result, the imposition of a carbon price via either an emissions tax or emissions trading scheme should induce some abatement activity relative to what would have been the case without the carbon price intervention.

Carbon pricing is typically considered to be a less invasive policy intervention than direct regulations given that it leaves decisions on how abatement activities will be undertaken to the market (Mankiw 2009). A carbon price provides a signal to equate marginal abatement costs across polluters, and can theoretically incentivise abatement across diverse sources at the lowest possible overall cost (Schmalensee and Stavins 2017). Abatement opportunities that are cheaper than the carbon price are incentivised, while abatement opportunities that are more expensive than the carbon price are not.

Carbon pricing has been implemented in a growing number of countries (OECD 2018). The first carbon tax was introduced in Finland in 1990. By 2019, 47 countries had a carbon price at either the national or subnational level, covering around 20% of global greenhouse gas emissions (World Bank 2019a). Among these countries, 25 had a carbon tax, with 40 having or participating in an emissions trading system (ETS) under international, national, or subnational initiatives (World Bank 2019a). Some countries, such as Sweden, have both a carbon tax and participate in an ETS. Recent adopters include Singapore and South Africa, which both introduced carbon taxes in 2019. However geographical coverage of carbon pricing remains far from universal, with the policy instrument facing technical and/or political barriers to implementation in some countries (Rabe 2018).

Figure 1 plots the decadal growth in CO_2 emissions from fuel combustion over 2007–2017 against the previous decade's growth rate in this variable. For countries without a carbon price in 2007, both of these decadal growth rates were close to 3% per annum. In contrast, there was a substantial reduction in the average emissions growth rate for countries that had a carbon price in 2007: their emissions grew at an average annual rate of 0.5% over 1997–2007, then fell by an average of 2% per annum over the subsequent ten years. Our econometric investigations will examine whether a negative association between carbon pricing and emissions growth holds after the consideration of key covariates.

Figure 1. Average annual CO_2 emissions growth rate, %



Notes: Emissions are from fuel combustion. The columns on the left show the annual average for countries without a carbon price in 2007. The columns on the right show the annual average for countries with a carbon price in 2007. 137 countries for which data are available for both 1997–2007 and 2007–2017 are included. Of these, 30 countries had carbon prices in 2007. The association is similar when using an earlier reference year. Data: International Energy Agency (2019); World Bank and Ecofys (2018).

Our analysis assesses the average experience across a large sample of countries. The results indicate that countries that have adopted carbon prices as part of their overall policy suite have tended to subsequently have slower emissions growth rates (or faster emissions reduction rates) relative to otherwise similar countries. Levels estimates indicate that subsequent per capita emissions levels are also lower than would otherwise be expected to be the case. While it is impossible to control for all other policies and relevant factors, our paper opens the way for further research into what have been and are the most effective policy designs for reducing CO_2 emissions. Information on what has worked and what has not may be able to inform policy approaches for achieving the large-scale emissions reductions that are needed in order to limit global warming to 2ºC.

2. Literature review

Analysing the effectiveness of carbon pricing is well known to be a challenging task (Sumner et al. 2011; Meckling et al. 2017; Haites 2018). This is in part because carbon pricing schemes have different coverages and intensities across jurisdictions. It is also difficult to fully separate out the effects of carbon pricing from those of other climate and energy policy instruments, such as energy-sector regulations or support schemes for renewables (Somanathan et al. 2014; Narassimhan et al. 2018). It is rare that carbon pricing is the only lever that policymakers pull.

Case study research in North America has reached varying conclusions on the effectiveness of carbon pricing. Murray and Rivers (2015) concluded that British Columbia's carbon tax reduced greenhouse gas emissions by 5–15% by 2012 compared to what they would have otherwise been. Martin and Saikawa (2017) found that California's cap-and-trade programme has had the largest impact on power-sector emissions among a range of policies, and noted the difficulty of separating out the effects of individual policies. Murray and Maniloff (2015) estimated that the Regional Greenhouse Gas Initiative (RGGI) in the north-east of the US reduced power sector emissions by 24% over 2009–2012, after separating out the effects of other factors such as recession, lower natural gas prices, and other environmental policies. However Schmalensee and Stavins (2017) concluded that the impact of the RGGI is likely to have been small given that the cap has rarely been binding.

Case study research for countries in other regions has also reached somewhat mixed conclusions on the environmental effectiveness of carbon pricing (Somanathan et al. 2014). Bullock (2012) concluded that the effectiveness of New Zealand's emissions trading scheme is somewhat unclear, but that the scheme likely had little in the way of short-run impacts. There is evidence that carbon taxes have helped to reduce emissions in Finland, although results are mixed for some other countries such as Norway (Bruvoll and Larsen 2004; Lin and Li 2011; Sumner et al. 2011). Sweden's large transport-sector carbon tax has been found to have played an important role in spurring emissions reductions in that sector (Andersson 2019).

For the EU, Bel and Joseph (2015) concluded that emissions reductions have mainly been due to weak economic growth rather than the EU ETS. Aydin and Esen (2018) found that energy and transport taxes in EU countries have had a significant emissions-reducing effect when these taxes have been sufficiently high. However it is challenging to measure the effects of EU policies without bringing in other countries for comparison.

A study by Haites et al. (2018) summarised the emissions outcomes under ten greenhouse gas ETSs and carbon tax regimes across 12 jurisdictions over 1991–2015. They found that there were emissions reductions in six of the carbon tax jurisdictions, although suggested that this may be largely due to other policies in at least three of the cases. They also found that actual emissions fell in six cases where there was an ETS, noting that attribution of these emissions reductions to the adoption of an ETS is rare in the literature. Narassimhan et al. (2017) analysed carbon pricing in 15 regions, noting the potential for emissions reductions even with modest carbon prices, especially in cases where it is known that policy stringency will increase over time.

Among studies that seek to explain differences in levels and growth rates of CO_2 emissions across countries, some use country fixed effects to control for a range of country-specific factors, including time-invariant policies (Narayan and Narayan 2010; Martínez-Zarzoso and Maruotti 2011; Sadorsky 2014; Burke et al. 2015; Presno et al. 2018). However the roles of various time-varying policies are typically not examined in these analyses.

There is a related literature examining the effects of various policies on other energy-sector outcomes. Feed-in tariffs have been found to be a significant contributor to renewable energy adoption in some (Baldwin et al., 2017; Carley et al. 2017) although not all (Aguirre and Ibikunle 2014; Best and Burke 2018a) international studies. Evidence suggests that feed-in tariffs have played a particularly important role in promoting less mature technologies (Johnstone et al. 2010; Polzin et al. 2015). Longer durations of contracts and higher tariff rates both contribute to greater effectiveness (Dijkgraaf et al. 2018). Carley et al. (2017) found that the existence of feed-in tariffs has been an important predictor of future renewable energy growth, but noted that researchers face identification challenges in estimating this effect. For example, the introduction of feed-in tariffs could be more likely in countries that have higher expectations for growth in renewable energy installations.

Recent studies by Best and Burke (2018a; 2020) find evidence that the adoption of carbon pricing is associated with a subsequent tilting of national energy mixes towards lower-emission energy sources such as wind power and away from higher-emission energy sources such as coal. However the effects of carbon pricing on CO_2 emissions from fuel combustion have yet to be examined in a cross-country setting. Given the importance of the topic, the current paper is an early contribution to what may well be a growing literature.

3. Data

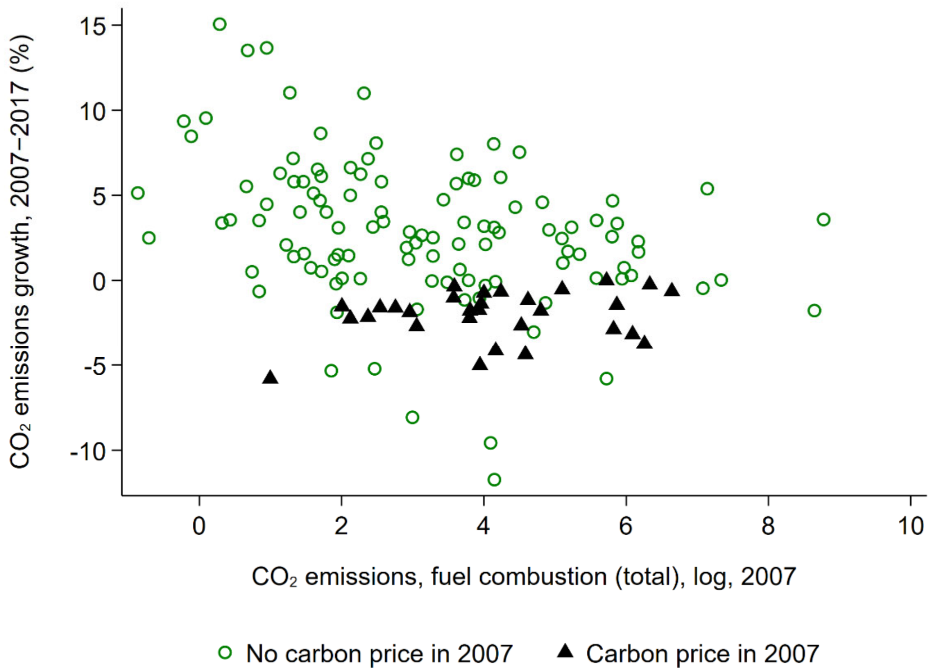
Before describing our methods, we first introduce the data to be used in the study. CO_2 emissions from fuel combustion are sourced from the International Energy Agency (IEA 2019). These data cover 142 countries that together accounted for about 96% of the global population as of 2017, the final year in our sample. However individual regressions will use data for fewer than 142 countries due to missing values for some explanatory variables; the number of countries in the reported regressions ranges from 104 to 137. The sample of 104 countries still covers over 92% of the world's year-2017 population and all of the world's top-twenty emitters. The overall sample excludes some quite small emitters, both those with a carbon price (such as Liechtenstein) and ones without (such as Tonga). In terms of population, the largest countries omitted from the overall sample are Uganda and Afghanistan.

Figure 2 displays a negative relationship between the initial level of log CO_2 emissions and the subsequent growth rate of these emissions.[1] The relationship is consistent with convergence in the level of emissions across countries, which is an important consideration

[1] 'Initial' refers to the year that is at the start of the growth period.

for the modelling of emissions trajectories over time. A per-capita version of Figure 2, available through the online code, also shows a negative relationship between the initial level and the subsequent growth rate.

Figure 2. CO_2 emissions growth, annual average, %, for 2007–2017 against log CO2 emissions in 2007



Notes: Emissions are from fuel combustion and include road-sector emissions. Regressions in section 5 control for population size. Data: International Energy Agency (2019); World Bank and Ecofys (2018).

Our analysis will use several variables that measure the existence, strength, and extent of carbon pricing (OECD 2016; ESMAP (Energy Sector Mangement Assistance Program) 2018; World Bank and Ecofys 2018). These include both continuous measures and a binary measure. Subnational schemes such as those adopted in the US and Japan are included. Estimates using a binary carbon pricing variable that does not include subnational schemes are available in the online code, with similar results being obtained.

A key feature of our methods is the inclusion of controls for other potentially relevant policies. This includes the use of binary variables for renewable portfolio standards (Carley et al. 2017; REN21 2017) and feed-in tariffs (REN21 2018). Some countries, such as Germany, have used feed-in tariffs for decades (since 1990 in Germany's case). We also use continuous measures of policies, although these are only available for more recent years. These include fossil fuel subsidies (Coady et al. 2015), the net gasoline tax of each country (Ross et al. 2017), and scores for each country's overall renewable energy and energy efficiency policy suites (ESMAP 2018). The renewable energy policies score covers indicators such as the existence of incentives and regulatory support for renewable energy. The energy efficiency policies score covers indicators such as energy labelling systems and energy codes for buildings.

Descriptions of each policy variable are presented in Table 1. Other than fossil fuel subsidies, each of the policies encourage reduced use of fossil fuels, via either increasing the use of low-carbon energy sources or encouraging the conservation of energy. Negative coefficients should thus be expected for these variables in our regressions. The inclusion of continuous policy variables is a relative strength of our study, as some prior cross-country policy analysis for various energy-sector outcomes have heavily relied on the use of binary policy measures (Carley et al. 2017; Best and Burke 2018a).

Table 1. Carbon pricing and other policy variables

Variable	Source	Description
Carbon price, binary	WB	A binary variable with a value of one for countries that had implemented carbon pricing in the year. 37 countries had implemented carbon pricing instruments in 2012. The variable includes implementation in subnational jurisdictions (such as in the US and Japan). This variable does not include other taxes such as fuel excise taxes. The variable also does not account for voluntary or internal carbon pricing initiatives of firms or other entities.
Duration-adjusted carbon price	WB, author calc.	The binary carbon price variable from above, multiplied by the proportion of the analysed period that a carbon price was in operation.
Effective carbon price rate, continuous	OECD, WB, author calc.	Average emissions trading system (ETS) rate plus average CO_2 tax, in 2012 euros per tonne of CO_2. This does not include other taxes such as general gasoline taxes. Average rates are weighted by the share of CO_2 emissions covered at each rate by each instrument, taking into account all CO_2 emissions from fuel combustion. There are 30 countries listed by the OECD (2016) with positive rates for 2012. For countries not listed by the OECD, we assign a value of zero if the World Bank and Ecofys (2018) did not identify the country as having a carbon price in 2012. We exclude the country if the World Bank and Ecofys identify the country as having a carbon price in 2012. We calculate the weighted average of road and non-road effective carbon price rates, using sector weights from the OECD (2016).
Effective carbon tax rate	OECD, WB, author calc.	The carbon tax component of the effective carbon price rate, as described above. This continuous variable is calculated by the OECD

		(2016) as the product of the value of the carbon tax and the proportion of emissions covered by the tax. We calculate the weighted average of road and non-road effective carbon taxes, using sector weights from the OECD (2016).
Effective emissions trading system (ETS) rate	OECD, WB, author calc.	The emissions trading system (ETS) component of the effective carbon price rate, as described above, using data from the OECD (2016). This is the price of emissions trading permits multiplied by the proportion of emissions that are covered by the ETS. Countries that introduced carbon prices during 2013–2015 are included using average first-year prices adjusted to 2012 prices by deflating by each country's consumer price index and then converting to euros. We use the ETS rates directly from the OECD (2016), then we calculate the weighted average of road and non-road effective ETS rates using sector weights from the OECD (2016).
Carbon price score	RISE	A variable for carbon pricing and monitoring in 2012. The pricing component is effectively a binary variable for implementation of a carbon tax or ETS. The monitoring component is a binary variable based on existence of an emissions monitoring, reporting, and verification system. The two components are equally weighted. We divide the scores by 100.
Net gasoline tax	Ross	The net gasoline tax is estimated using the price gap between the local retail price and a benchmark international price (e.g. the 2012 value is used for Table 3). We take an average of monthly values. Values are in 2015 US dollars per litre.
Fossil fuel subsidies	IMF, IEA author calc.	Pre-tax subsidies for fossil-fuel energy and electricity in million US dollars for 2013, divided by total fossil fuel use in thousand tonnes of oil equivalent. Fossil fuel subsidies are for 2013.
Feed-in tariff, binary	REN21	A binary variable for feed-in electricity policies in each year. The variable has a value of 1 for the year of first introduction and onwards; 0 otherwise. Table R12 in the REN21 (2018) report notes that nine countries are known to have discontinued feed-in tariff policies. We produce robustness tests that exclude these nine countries in the online code.

Renewable portfolio standard, binary	CAR, REN21	A binary variable for quota systems that require a specified percentage of electricity generation to be from renewable sources. For years up to 2010, we use data available from the study by Carley et al. (2017). We extend the series to 2016 by reference to Table R21 in the 2017 Global Status Report (REN21 2017). 1 = existence of a renewable portfolio standard. The variable switches back to zero for schemes that are identified as ending. Carley et al. (2017) identified schemes ending in Denmark in 2001 and Japan in 2012. REN21 (2017) identify the scheme in Italy as ending in 2012.
Renewable policies score	RISE	A score for national policy and regulatory frameworks for renewable energy in 2012. Renewable energy policies scores are an equally-weighted combination of seven indicators (legal framework for renewable energy, planning for renewable energy expansion, incentives and regulatory support for renewable energy, attributes of financial and regulatory incentives, network connection and use, counterparty risk, and carbon pricing and monitoring). We exclude the indicator on carbon pricing and monitoring, as we assess carbon pricing separately. We divide the scores by 100.
Efficiency policies score	RISE	A score for national policy and regulatory frameworks for energy efficiency for 2012. Energy efficiency policies scores are an equally-weighted combination of 13 indicators. We exclude the indicator on carbon pricing and monitoring, as we assess carbon pricing separately. We divide the scores by 100.

Data sources: CAR: Carley et al. (2017); IEA (2019); IMF: (Coady et al. 2015); OECD: Organisation for Economic Cooperation and Development (2016); REN21 (2017; 2018); RISE: ESMAP (2018); Ross: Ross et al. (2017); WB: World Bank and Ecofys (2018). Notes: Policies may be linked, such that revenue from carbon pricing may be used to fund initiatives such as energy efficiency programs. Whilst this has important budgetary implications, policy effects of different policies can still be assessed separately, as a given policy should invoke the same response regardless of financing method.

The continuous carbon pricing variable used in this paper is based on the effective carbon price rates for CO_2 emissions from fuel combustion in the road and non-road sectors in 2012, using data from the OECD (2016). We calculated a weighted average of the effective carbon price rate for all fuel combustion using the share of CO_2 emissions from fuel combustion from each of these two sectors as weights. The effective carbon price rate is calculated separately for both carbon taxes and ETSs, then summed.

An example will help. In 2012, New Zealand had an ETS with a carbon price of 1.33 euros per tonne of CO_2 (and no carbon tax). For the road sector, the OECD (2016) calculated the effective ETS carbon price rate in 2012 as 1.08 euros per tonne of CO_2, equal to the 2012 ETS price multiplied by the ETS coverage of the road sector of 81%. The effective carbon price rate for the non-road sector was 0.66 euro per tonne of CO_2. The non-road sector accounted for 67% of emissions (OECD 2016), so we calculated a weighted average of the effective carbon price rate in 2012 across both road and non-road sectors as 0.67 * 0.66 + 0.33 * 1.08 = 0.8 euro per tonne of CO_2.

The effective carbon tax variable from the OECD (2016) has non-zero values for 10 countries in 2012, as shown in Table 2. These countries had an average effective carbon tax rate of 8.2 euros per tonne, with a median of 7.9 euros per tonne. The average effective ETS rate among 30 countries with non-zero values was 2.3 euros per tonne, while the median was 2.5 euros per tonne. There is variation in the effective ETS rates across EU countries, as effective rates are weighted with respect to the share of CO_2 emissions covered in each country (and differences exist in the CO_2 emissions profiles of different EU countries).

Table 2. Descriptive statistics

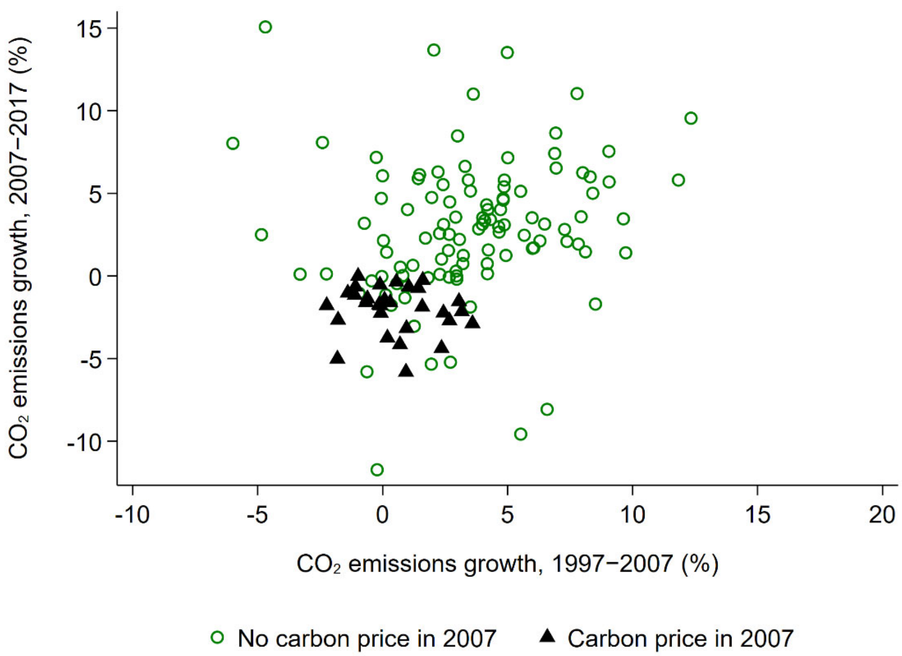
Variable	Obs	Min	Mean	Max	S.D
Policy variables					
Carbon price, binary	142	0.00	0.26	1.00	0.44
Carbon price, binary, duration adjusted	142	0.00	0.28	1.00	0.44
Effective carbon price rate	134	0.00	1.12	27.31	3.37
Effective carbon tax rate	134	0.00	0.61	26.15	2.91
Effective emissions trading system (ETS) rate	134	0.00	0.51	5.13	1.12
Effective carbon price rate, for countries with non-zero prices	30	0.46	5.03	27.31	5.64
Effective carbon tax, for countries with non-zero carbon taxes	10	0.10	8.20	26.15	7.47
Effective ETS rate, for countries with non-zero ETS rate	30	0.07	2.30	5.13	1.25
Road-sector effective carbon price rate (countries with non-zero prices)	9	1.08	26.39	107.92	34.0
Road-sector effective carbon tax (countries with non-zero carbon tax)	7	2.41	33.39	107.92	35.9
Road-sector effective ETS rate, for countries with non-zero ETS rate	3	1.08	1.25	1.55	0.26
Non-road effective carbon price rate, for countries with non-zero prices	30	0.42	4.37	16.79	3.25
Non-road effective carbon tax (countries with non-zero carbon taxes)	10	0.13	4.31	12.99	3.59
Non-road effective ETS rate, for countries with non-zero ETS rate	30	0.12	2.94	5.90	1.55
Carbon price score	112	0.00	0.23	1.00	0.39
Net gasoline tax (2015 USD per litre)	131	-0.90	0.47	1.77	0.60
Fossil fuel subsidies (2013 USDm divided by KTOE)	132	0.00	0.13	1.89	0.23
Feed-in tariff (binary)	142	0.00	0.47	1.00	0.50
Renewable portfolio standard (binary)	142	0.00	0.12	1.00	0.33
Renewable policies score	112	0.00	0.40	0.81	0.20
Efficiency policies score	112	0.00	0.32	0.76	0.20
Emissions growth rates in the current period					
CO_2 growth rate per year (2012–2017)	142	-0.14	0.02	0.21	0.05
Road-sector CO_2 growth rate per year (2012–2017)	142	-0.15	0.03	0.16	0.05
Non-road CO_2 growth rate per year (2012–2017)	142	-0.17	0.01	0.29	0.06
Emissions growth rates in the previous period					
CO_2 growth rate per year (2007–2012)	141	-0.11	0.02	0.17	0.05
Road-sector CO_2 growth rate per year (2007–2012)	141	-0.13	0.03	0.25	0.06
Non-road CO_2 growth rate per year (2007–2012)	141	-0.12	0.02	0.29	0.06
Structural indicators					
Initial CO_2 emissions (million tonnes)	142	0.47	215.48	8,820	869
Initial GDP per capita (PPP constant 2011 international $)	136	706.37	20,901	120,366	20228
Initial population (million)	139	0.03	48.80	1350.00	160
GDP per capita growth (2012–2017)	135	-0.09	0.02	0.08	0.03
Population growth (2012–2017)	139	-0.04	0.01	0.06	0.01
Initial energy intensity (MJ/$2011 PPP GDP)	138	1.37	5.91	24.32	3.83
Initial coal share	142	0.00	0.12	0.73	0.18
Initial oil share	142	0.03	0.37	1.00	0.22
Initial natural gas share	142	0.00	0.20	0.94	0.23
Transition economy, binary	142	0.00	0.19	1.00	0.39

Notes: Variables are for 2012 unless otherwise specified. Fossil fuel subsidies are for 2013. Energy-type shares are proportions of total primary energy supply. Emissions are for all of fuel combustion unless otherwise specified. The annual average growth of emissions is calculated as the difference of logged emissions at the start and end of the growth period, divided by the number of years in the growth period. Obs = number of observations; S.D is the standard deviation.

Our models will also control for structural variables that may be relevant for emissions. This includes lagged measures of log gross domestic product (GDP) per capita, log population, and the log energy intensity of GDP (log of the energy intensity level of primary energy in megajoules per unit of GDP) from the World Bank (2019b). We also include the lagged shares of energy supplied by each of the fossil fuels, using data from the IEA (2019). These serve as indicators of the structure of the energy system, and help to control for influences from drivers included in the Kaya identity.[2] Reforms by transition economies also likely contributed to emission reductions, so we include a binary variable for these countries based on the IMF (2000) classification.

Other key controls include the contemporaneous growth rates of GDP per capita and population in order to control for scale effects (Burke et al. 2015). Causation would run from GDP to emissions, since emissions are a by-product of economic growth.[3] We do not control for contemporaneous measures of the growth of energy intensity or the share of fossil fuels in the energy mix, as these are key channels through which carbon pricing might have its influence. One control that we do include is the historical emissions growth rate, with the idea being that this variable helps to control for potential persistence effects in emissions growth rates over time. Indeed, Figure 3 indicates that countries with a carbon price in 2007 generally had relatively low emissions growth in both the prior decade and the subsequent decade.

Figure 3. Growth in CO_2 emissions from fuel combustion, annual average, %, for 1997–2007 and 2007–2017



Notes: Emissions are from fuel combustion and include road-sector emissions. Data: International Energy Agency (2019); World Bank and Ecofys (2018).

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[2] The Kaya Identity decomposes CO_2 emissions into four factors: population * GDP per capita * the energy intensity of GDP * the carbon intensity of energy.

[3] Controlling for economic growth also removes effects of carbon pricing that transpire via a change in the GDP growth rate. Computable general equilibrium studies sometimes find small adverse effects of a carbon price on GDP growth (Li et al. 2014, for example), although this would depend on how a carbon pricing scheme is designed. As will be noted, a negative and significant effect remains when the GDP per capita growth control is omitted.

4. Methods

4.1 Roadmap to our modelling approaches

We use three modelling approaches, with our models seeking to explain either annual average growth in emissions or per capita levels of emissions in each country, *c*. A key feature of our models is the inclusion of a large suite of control variables, including multiple policy measures. This helps to isolate the effect of carbon pricing on emissions relative to what would have been the case without carbon pricing. The three approaches are:

- Cross-sectional growth-rate regressions (described in section 4.2).
- Fixed-effects growth-rate panel regressions (section 4.3).
- Fixed-effects panel estimations for levels of emissions per capita (section 4.4).

The first two approaches use emissions growth rates, calculated as the period-differenced logs divided by the number of years. Examining the effect of lagged variables on subsequent emissions growth over multi-year periods has a number of advantages. These include avoiding issues related to unit roots, as trending behaviour is more likely among annually-measured contemporaneous variables in levels. Use of growth rates and lagged explanators also helps to reduce the risk of reverse causation (Stern et al. 2017; Best and Burke 2018b).

Our long list of controls will help us to minimise the chance of omitted variable bias, although we emphasise that it is difficult to comprehensively account for all differences across countries. As one example, a waning of political support for coal-fired power stations may have implications for current emissions trends, but can be difficult to quantify. Likewise, it is not practical to fully control for all regulations due to unavailability of consistent data. We note, however, that the energy efficiency policies control (ESMAP 2018) incorporates some energy-sector regulations, including the use of minimum performance standards for light vehicles.

4.2 Cross-sectional growth-rate analysis

Our first model is a cross-sectional growth-rate regression for a dependent variable in five-year differences, as shown in equation (1). Medium- or long-term growth models have been used in other energy-sector papers (Csereklyei and Stern 2015; Burke and Csereklyei 2016; Stern et al. 2017), studies that focus on economic growth (Barro 2015), and studies estimating production function parameters (Chirinko et al. 2011). We apply this model to both total CO_2 emissions from fuel combustion and also to both road and non-road emissions:

$$(\ln E_c^{2017} - \ln E_c^{2012})/5 = \alpha + \boldsymbol{P'}_c\boldsymbol{\beta} + \gamma \ln E_c^{2012} + \delta \Delta \ln E_c^{2007-2012}/5 + \boldsymbol{K'}_c\boldsymbol{\theta} + \varepsilon_c \quad (1)$$

Equation (1) estimates the effect of carbon pricing and other policy variables (P_c) on subsequent emissions growth. Other explanatory variables include the initial level of emissions (E_c) to control for possible convergence effects (Barro 2015; Cseresklyei and Stern

2015; Best and Burke 2017), prior-period growth in emissions to control for potential persistence effects, and a vector of variables related to the Kaya Identity (K_c).

An advantage of using a five-year period is that some effects of carbon pricing are likely to be delayed. It can take years to propose, build, and connect new renewable energy generation to electricity grids, for example. A five-year period captures both short- and some medium-term effects, while avoiding the analysis of noisy shorter-term fluctuations. The reason for focusing on the five years to 2017 is that the continuous carbon price measure is available from only 2012, and 2017 is the most recent year for which emissions data were available at the time of writing. Key control variables, such as the energy efficiency policies scores, are also only available for fairly recent years.

The first carbon price variable that we use is the effective carbon price rate in euros per tonne CO_2 in 2012, based on OECD (2016) data (see Table 1). The OECD (2016) data also indicate that an additional three countries introduced a carbon price during 2013–2015. We use the carbon price in the year of adoption for these three countries.[4] We also explore the use of a binary carbon pricing variable and also a carbon price score obtained from ESMAP (2018). The ESMAP score measures both the implementation of carbon pricing and the monitoring of emissions, as described in Table 1. In additional estimates we use a binary carbon pricing variable that is weighted by the number of years that carbon pricing was in place during the time window. This is referred to in Table 4 with the label "Duration-adjusted carbon price".

4.3 Panel growth regressions

Our second modelling approach uses a panel of growth rates. We use periods of one, two, and three years. Equation (2) shows the model for a three-year period:

$$(\ln E_c^t - \ln E_c^{t-3})/3 = \alpha + \boldsymbol{P'}_c^{t-3}\boldsymbol{\beta} + \gamma \ln E_c^{t-3} + \boldsymbol{K'}_c\boldsymbol{\theta} + I_c + I^t + \varepsilon_c^t \qquad (2)$$

The dependent variable is the average annual growth rate of CO_2 emissions from fuel combustion. Binary carbon pricing variables are used because the continuous variable from the OECD (2016) is only available from 2012. Other independent variables include the values of other policies and emissions at the start of each three-year period. The *K* vector includes both the initial levels of the structural variables and the contemporaneous rates of growth in GDP per capita and population, as in equation (1) also. A difference is that lagged emissions growth is not included in equation (2) in order to avoid the direct inclusion of a lag of the dependent variable in a panel setting. Country and year fixed effects are included to control for time-invariant and commonly time-varying factors that are relevant for emissions growth rates.

The panel growth regression approach is similar to the panel approaches used by Barro (2015) and others when studying economic growth. Five-year growth periods are commonly examined in the economic growth literature. We use growth periods of one to three years, as five-year periods would overly curtail the number of time periods we could include in our

[4] We obtain similar results when excluding these countries (see robustness tests in the online code). We also present robustness tests using a binary carbon pricing variable for different periods (such as three or four years), finding similar results.

sample due to data constraints for our key explanatory variables. Using shorter time windows also increases the sample size. Our panel analysis covers the full time-frame over which carbon pricing has been in operation.

4.4 Panel regressions in levels

Our third approach is similar to the panel estimator used by Carley et al. (2017) in their study of the effects of renewable energy policies on renewable energy usage. The model is specified in levels rather than growth rates. Specifically, we seek to identify the effect of carbon pricing on the log of per capita emissions of CO_2 from fuel combustion. The effects of lagged dependent variables are not explicitly modelled. We produce results with each of the independent variables lagged by one, two, or three years in order to study various lagged effects:

$$\ln E_c^t = \alpha + \boldsymbol{P'}_c^{t-lag}\boldsymbol{\beta} + \boldsymbol{K'}_c\boldsymbol{\theta} + I^t + I_c + \varepsilon_c^t \text{ , lag = 1, 2, or 3} \qquad (3)$$

Possible reverse causation from the outcome variable to policies can be tested by the application of a Rothstein (2010) falsification approach. We find that the log of emissions per capita lagged one, two, or three years does not have a significant association with subsequent carbon price implementation. This suggests that reverse causality is perhaps not a major problem in equation (3). These results are in Appendix Table A.1.

5. Results

5.1 Cross-sectional growth-rate results (2012–2017)

We first present results using the continuous carbon price measure (Table 3). Column (1) displays a negative association between carbon pricing and the subsequent CO_2 emissions growth rate, with a one euro increase in the effective carbon price rate per tonne of CO_2 emissions being associated with a 0.3 percentage-point reduction in the annual rate of emissions growth. This effect is significant at the 1% level. The large size of this effect is evident when considering that a ten euro increase – which is well below the maximum effective carbon price rate of 27 euros – would be associated with a lowering of the annual emissions growth rate of about 3 percentage points below what would otherwise be expected.

Some significant and negative effects for the other carbon price measures are also found in the other columns of Table 3. In column (2), a one euro increase in the effective carbon tax rate is associated with a reduction of 0.2 percentage points in the subsequent annual emissions growth rate. A negative and significant coefficient is also found for the effective ETS rate in column (2). Tests of parameter equality indicate that the coefficients for the carbon tax and ETS variables are not statistically different from one another. This is not unexpected, as either type of carbon price raises the cost of emitting and so should induce a similar level of abatement activity.

Columns (3)–(6) of Table 3 include the additional policy controls. Doing so reduces the sample size, as they are unavailable for some countries. The effective carbon price rate again has a significant coefficient at the 1% level in column (3), with a similar magnitude to column (1). Column (4) finds negative point estimates for both the effective carbon tax and the effective ETS rates, although the result for the effective ETS rate is not significantly different from zero.

Columns (5)–(6) of Table 3 control for the feed-in tariff and renewable portfolio standard binary variables in place of the continuous renewable policies score variable.[5] Negative and significant estimates for the effective carbon price rate and the effective carbon tax are again obtained. The coefficients for the other policy variables are insignificant. This may relate to cross-correlations between variables (see Appendix Table A.2) and/or inexact measurement of these variables. Our estimation sample for these regressions is also not overly large (104 countries).

Contemporaneous economic growth is found to have a positive coefficient in Table 3. This is expected given that emissions are a by-product of economic production. A percentage point increase in average annual GDP per capita growth is associated with a 0.7 percentage point increase in average annual emissions growth over the five-year horizon in columns (1)–(2). Controlling for contemporaneous economic growth helps to account for the effects of the economic slowdown in Europe following the global financial crisis.

Table 4 uses the alternative carbon pricing measures. The carbon pricing score from ESMAP (2018) has a negative association with subsequent emissions growth in column (1), significant at the 5% level. However the coefficient for this variable becomes insignificantly different from zero when controlling for other policies in column (4). The coefficient for the binary carbon pricing variable in column (5) indicates that annual emissions growth is on average about two percentage points lower in countries with a carbon price than in countries without, all else equal. Column (6) uses the duration-adjusted binary variable, which has a value of one for countries with a carbon price in 2012, zero for countries that did not have a carbon price during 2012–2017, and the fraction of years for countries that introduced a carbon price during the five years to 2017. A similar coefficient is again obtained.[6]

[5] The feed-in tariff and renewable portfolio standard variables are not included in the same regressions as the renewable policies score variable given the similarity of these measures.

[6] The online code also includes regressions that control for the feed-in tariff and renewable portfolio standard variables instead of the renewable energy policies score variable. The carbon price coefficients in Tables 4–5 remain similar.

Table 3. Continuous carbon price results, average annual CO_2 growth rate, 2012–2017

	Dependent variable: Average annual CO_2 growth rate (2012–2017)					
	(1)	(2)	(3)	(4)	(5)	(6)
Effective carbon price rate	-0.003***		-0.003***		-0.002**	
	(0.001)		(0.001)		(0.001)	
Effective carbon tax rate		-0.002***		-0.003***		-0.002**
		(0.001)		(0.001)		(0.001)
Effective ETS rate		-0.006**		-0.004		-0.003
		(0.003)		(0.003)		(0.003)
Initial log CO_2	-0.017	-0.017	-0.005	-0.005	-0.008	-0.008
	(0.030)	(0.030)	(0.033)	(0.033)	(0.034)	(0.034)
Initial log GDP per capita	0.016	0.018	0.007	0.007	0.012	0.012
	(0.029)	(0.028)	(0.032)	(0.032)	(0.032)	(0.032)
Initial log population	0.017	0.018	0.003	0.003	0.008	0.008
	(0.030)	(0.030)	(0.033)	(0.033)	(0.033)	(0.033)
Initial log energy intensity	-0.004	-0.003	-0.026	-0.026	-0.019	-0.019
	(0.027)	(0.027)	(0.030)	(0.030)	(0.029)	(0.029)
Initial coal share	-0.039	-0.035	-0.059	-0.058	-0.047	-0.047
	(0.074)	(0.073)	(0.082)	(0.082)	(0.082)	(0.082)
Initial oil share	-0.060	-0.060	-0.116*	-0.116*	-0.108	-0.108
	(0.064)	(0.064)	(0.067)	(0.067)	(0.067)	(0.067)
Initial natural gas share	-0.040	-0.041	-0.089	-0.089	-0.082	-0.082
	(0.050)	(0.050)	(0.058)	(0.058)	(0.058)	(0.058)
Transition, binary	0.005	0.007	0.005	0.005	0.004	0.004
	(0.009)	(0.009)	(0.012)	(0.012)	(0.012)	(0.013)
CO_2 growth, previous	0.061	0.048	0.013	0.009	0.004	0.003
	(0.116)	(0.117)	(0.135)	(0.136)	(0.139)	(0.140)
GDP per capita growth	0.680***	0.678***	0.869***	0.866***	0.875***	0.874***
	(0.186)	(0.186)	(0.206)	(0.206)	(0.207)	(0.208)
Population growth	0.944**	0.912**	1.042**	1.029**	1.141**	1.137**
	(0.398)	(0.402)	(0.498)	(0.504)	(0.510)	(0.517)
Net gasoline tax			-0.011	-0.010	-0.016	-0.016
			(0.010)	(0.011)	(0.011)	(0.011)
Fossil fuel subsidies			0.029	0.029	0.028	0.028
			(0.025)	(0.025)	(0.025)	(0.025)
Efficiency policies score			0.036	0.037	0.028	0.028
			(0.024)	(0.024)	(0.024)	(0.025)
Renewable policies score			-0.044	-0.044		
			(0.027)	(0.027)		
Feed-in tariff, binary					-0.009	-0.009
					(0.008)	(0.008)
Renewable portfolio standard, binary					-0.009	-0.009
					(0.007)	(0.007)
Observations	126	126	104	104	104	104
R^2	0.518	0.522	0.586	0.587	0.583	0.583

Notes. ***, **, * show statistical significance at 1, 5 and 10 per cent level respectively. The effective carbon price rate, carbon tax, and ETS are continuous variables from the OECD (2016). Robust standard errors are in brackets below the coefficients. Coefficients for constants are not shown. The average annual rate of CO_2 growth is the differenced logs divided by the number of years. The explanatory variable for previous CO_2 growth is for the five-year period 2007–2012. GDP per capita growth is contemporaneous (2012–2017). The dependent variables include road-sector emissions. Fossil fuel shares are the proportions of total primary energy supply. An interaction between emissions trading and renewable energy policy is not significant. An interaction between the lagged coal share and the continuous carbon price is also not statistically significant (see the online code).

Table 4. Use of alternative carbon price variables, average annual CO_2 growth rate, 2012–2017

	Dependent variable: Average annual CO_2 growth rate (2012–2017)					
	(1)	(2)	(3)	(4)	(5)	(6)
Carbon price score	-0.021**			-0.011		
	(0.010)			(0.010)		
Carbon price, binary		-0.039***			-0.021*	
		(0.011)			(0.013)	
Duration-adjusted carbon price			-0.041***			-0.026**
			(0.012)			(0.012)
Initial log CO_2	-0.013	-0.013	-0.014	-0.005	-0.003	-0.002
	(0.032)	(0.028)	(0.028)	(0.033)	(0.033)	(0.033)
Initial log GDP per capita	0.012	0.017	0.020	0.004	0.005	0.006
	(0.031)	(0.026)	(0.026)	(0.032)	(0.030)	(0.030)
Initial log population	0.013	0.015	0.017	0.004	0.002	0.002
	(0.032)	(0.028)	(0.028)	(0.033)	(0.032)	(0.032)
Initial log energy intensity	-0.009	-0.007	-0.005	-0.026	-0.027	-0.027
	(0.031)	(0.025)	(0.025)	(0.030)	(0.029)	(0.029)
Initial coal share	-0.033	-0.053	-0.049	-0.041	-0.060	-0.060
	(0.079)	(0.072)	(0.072)	(0.083)	(0.085)	(0.084)
Initial oil share	-0.070	-0.086	-0.083	-0.100	-0.114	-0.116*
	(0.067)	(0.063)	(0.063)	(0.068)	(0.069)	(0.068)
Initial natural gas share	-0.040	-0.058	-0.061	-0.073	-0.085	-0.090
	(0.056)	(0.050)	(0.051)	(0.057)	(0.059)	(0.059)
Transition, binary	0.005	0.007	0.010	0.002	0.003	0.006
	(0.012)	(0.009)	(0.009)	(0.012)	(0.012)	(0.012)
CO_2 growth, previous	0.059	0.001	0.008	0.042	-0.001	-0.003
	(0.137)	(0.118)	(0.116)	(0.137)	(0.143)	(0.140)
GDP per capita growth	0.768***	0.589***	0.605***	0.875***	0.853***	0.861***
	(0.195)	(0.198)	(0.194)	(0.222)	(0.211)	(0.207)
Population growth	1.243**	0.821**	0.832**	1.023**	1.009*	1.004*
	(0.488)	(0.408)	(0.405)	(0.502)	(0.509)	(0.506)
Net gasoline tax				-0.011	-0.009	-0.008
				(0.011)	(0.011)	(0.011)
Fossil fuel subsidies				0.028	0.030	0.030
				(0.026)	(0.026)	(0.026)
Efficiency policies score				0.032	0.034	0.037
				(0.024)	(0.023)	(0.023)
Renewable policies score				-0.048*	-0.044	-0.049*
				(0.027)	(0.028)	(0.027)
Observations	110	134	134	108	108	108
R^2	0.531	0.527	0.531	0.581	0.587	0.590

Notes. ***, **, * show statistical significance at 1, 5 and 10 per cent level respectively. The carbon price score is from ESMAP (2018). The carbon price (duration adjusted) is based on the report from the World Bank and Ecofys (2018) and is multiplied by a fraction to represent the proportion of the five-year period that a carbon price was in operation. Robust standard errors are in brackets below the coefficients. Coefficients for constants are not shown. The average annual rate of CO_2 growth is the differenced logs divided by the number of years. The explanatory variable for previous CO_2 growth is for the five-year period 2007–2012. GDP per capita growth is contemporaneous (2012–2017). The dependent variables include road-sector emissions. Fossil fuel shares are the proportions of total primary energy supply.

5.2 Cross-sectional growth-rate results for road and non-road emissions (2012–2017)

We now separately explore the effects of carbon pricing on road and non-road sector emissions growth, with the results shown in Table 5. Explanatory variables for the log of the initial level of emissions and for lagged growth in emissions are for the corresponding sectors. The carbon pricing variables are also measured with respect to the relevant sector. We are thus focusing on the effect of carbon pricing in a sector on emissions in the same sector. We exclude the net gasoline tax variable given its overlap with the carbon pricing variable for the road sector, although carbon pricing results are similar when the net gasoline tax variable is included (see the online code).[7]

For the road sector, the coefficient for the continuous carbon pricing variable in column (1) of Table 5 is negative and significant at the 1% level. The coefficient for the carbon tax variable is also negative and significant in column (2). The coefficient for the effective ETS rate is estimated imprecisely, likely to be because only three countries had an ETS that covered road-sector emissions. Other policy variables are mostly insignificant.

For the non-road sector, column (5) displays a coefficient for the effective carbon price rate of –0.004. This implies that a one euro increase in the effective carbon price rate per tonne of CO_2 emissions is associated with a reduction of 0.4 percentage points in the annual emissions growth rate of non-road emissions. The association is statistically significant at the 5% level. The carbon pricing variable has a negative but insignificant coefficient in column (7) once the additional controls are included (and with the smaller sample). The coefficient for the effective carbon tax rate is statistically significant in columns (6) and (8). The coefficients for the effective ETS variable are negative but not statistically different from zero.

Comparing columns (1) and (5) of Table 5, the point estimate for the carbon pricing coefficient is smaller in absolute value terms for the road sector than for the non-road sector. A test of the equality of the carbon pricing coefficients in the two columns reveals that they are statistically different from one another at the 10% level. A smaller absolute magnitude for the road sector is expected given that sensitivity to prices tends to be relatively low for road-sector activity (Havranek et al. 2012; Burke and Nishitateno 2013).

[7] The net gasoline tax is measured as the gap between the local and the international benchmark prices. This gap will be affected by whether a carbon price is in place.

Table 5. Sectoral results, average annual CO_2 growth rate, 2012–2017

	Dependent variable: average annual CO_2 growth rate (2012–2017) for:							
	Road sector				*Non-road sector*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Effective carbon price rate	-0.001***		-0.001***		-0.004**		-0.003	
	(0.000)		(0.000)		(0.002)		(0.002)	
Effective carbon tax rate		-0.001***		-0.001***		-0.003*		-0.003*
		(0.000)		(0.000)		(0.002)		(0.002)
Effective ETS rate		-0.007		-0.011		-0.005		-0.003
		(0.008)		(0.009)		(0.003)		(0.003)
Initial log CO_2	-0.003	-0.003	-0.003	-0.002	0.013	0.013	0.024	0.024
	(0.014)	(0.014)	(0.019)	(0.019)	(0.023)	(0.023)	(0.025)	(0.025)
Initial log GDP per capita	0.000	-0.001	0.004	0.004	-0.016	-0.015	-0.028	-0.028
	(0.014)	(0.014)	(0.019)	(0.019)	(0.023)	(0.023)	(0.024)	(0.025)
Initial log population	0.002	0.002	0.003	0.002	-0.012	-0.012	-0.023	-0.024
	(0.014)	(0.014)	(0.019)	(0.019)	(0.024)	(0.024)	(0.026)	(0.026)
Initial log energy intensity	-0.013	-0.013	-0.018	-0.017	-0.028	-0.028	-0.052*	-0.053*
	(0.011)	(0.011)	(0.016)	(0.016)	(0.025)	(0.025)	(0.029)	(0.029)
Initial coal share	-0.047**	-0.048**	-0.061**	-0.064**	-0.106	-0.104	-0.119	-0.120
	(0.021)	(0.022)	(0.030)	(0.031)	(0.081)	(0.081)	(0.090)	(0.091)
Initial oil share	-0.080**	-0.081**	-0.095**	-0.097**	-0.131**	-0.130**	-0.178**	-0.178**
	(0.035)	(0.036)	(0.041)	(0.041)	(0.062)	(0.063)	(0.069)	(0.070)
Initial natural gas share	-0.030	-0.031	-0.065**	-0.067**	-0.094	-0.093	-0.124*	-0.125*
	(0.022)	(0.023)	(0.028)	(0.029)	(0.059)	(0.059)	(0.073)	(0.074)
Transition, binary	-0.020*	-0.020*	-0.020	-0.020	0.019	0.020	0.018	0.018
	(0.012)	(0.012)	(0.015)	(0.015)	(0.014)	(0.014)	(0.019)	(0.019)
CO_2 growth, prev.	-0.033	-0.034	-0.034	-0.037	0.057	0.056	0.035	0.037
	(0.107)	(0.107)	(0.109)	(0.110)	(0.121)	(0.122)	(0.144)	(0.144)
GDP per capita, growth	0.707***	0.710***	0.805***	0.811***	0.562**	0.559**	0.784***	0.785***
	(0.216)	(0.217)	(0.241)	(0.241)	(0.220)	(0.221)	(0.224)	(0.226)
Population, growth	0.320	0.322	0.672	0.692	1.451***	1.432***	1.658***	1.675***
	(0.464)	(0.466)	(0.524)	(0.532)	(0.491)	(0.496)	(0.557)	(0.578)
Fossil fuel subsidies			-0.030	-0.030			0.072**	0.072**
			(0.027)	(0.027)			(0.033)	(0.033)
Efficiency policies score			0.018	0.019			0.051	0.051
			(0.024)	(0.024)			(0.032)	(0.032)
Renewable policies score			-0.059**	-0.059**			-0.049	-0.049
			(0.025)	(0.026)			(0.043)	(0.043)
Observations	126	126	105	105	126	126	105	105
R^2	0.396	0.397	0.462	0.463	0.372	0.373	0.479	0.479

Notes. ***, **, * show statistical significance at 1, 5 and 10 per cent level respectively. Emissions in columns (1)–(4) are for the road sector (both the dependent variable and relevant explanatory variables). The carbon price variables are also for the road sector only. Emissions in columns (5)–(8) are for the non-road sector. The carbon price variables are also for the non-road sector only. Robust standard errors are in brackets below the coefficients. Coefficients for constants are not shown. The average annual rate of CO_2 growth is the differenced logs divided by the number of years. The explanatory variable for previous CO_2 growth is for the five-year period (2007–2012). GDP per capita growth is contemporaneous (2012–2017). Fossil fuel shares are the proportions of total primary energy supply. A net gasoline tax coefficient is statistically significant in robustness tests that include the gasoline tax in column (1) and when the gasoline tax variable replaces the effective carbon price rate in column (1) (see the online code).

5.3 Panel results: emissions growth

We next present panel results for growth rates of emissions from fuel combustion, using a binary carbon pricing variable as at the start of periods of one, two, and three years from 1990–2017. We use the binary variable due to unavailability of data for the continuous carbon price measure for early years of the sample. The one-year estimates in column (1) of Table 6 suggest that countries with carbon prices have emissions growth rates that are approximately four percentage points lower, all else equal. The magnitude is smaller (in absolute value terms) when other policies are controlled for in column (2). The carbon pricing coefficients are also slightly smaller when using two- and three-year growth periods, as in columns (3)–(5). While there is significance at the 1% level in each of the first five columns, the coefficient in column (6) for three-year growth periods is not significant. This may relate to the smaller sample.

Column (2) of Table 6 finds a negative coefficient, significant at the 10% level, for the net gasoline tax variable. An increase of 1 USD per litre in net gasoline tax is estimated to be associated with annual CO_2 emissions growth rates being 3.6 percentage points lower, on average and all else equal. This is consistent with the potential for carbon prices and gasoline taxes to make complementary contributions to emissions reduction. Countries with higher net gasoline taxes also tend to have lower *levels* of CO_2 emissions from the road sector (Burke and Nishitateno 2013) in addition to this estimate of having lower subsequent *growth rates* of overall CO_2 emissions.

The binary feed-in tariff variable has negative and significant coefficients in Table 6. This is expected given that feed-in tariffs for renewable electricity encourage a transition away from fossil fuels toward renewable energy. There are also negative and significant effects for the renewable portfolio standard variable. That we obtain more statistically significant estimates for the policy controls in these panel estimates is likely to be due to the larger sample size.

Table 6. Panel results: Average annual CO_2 growth over 1-, 2-, and 3-year periods

	Dependent variable: Average annual CO_2 growth rate for periods of:					
	1 year 1990–2016 (1)	*1 year 2003–2016 (2)*	*2 years 1991–2017 (3)*	*2 years 2003–2017 (4)*	*3 years 1990–2017 (5)*	*3 years 2005–2017 (6)*
Carbon price, binary	-0.040***	-0.033***	-0.036***	-0.029***	-0.033***	-0.011
	(0.008)	(0.008)	(0.007)	(0.007)	(0.007)	(0.010)
Initial log CO_2	-0.171***	-0.224***	-0.124***	-0.198***	-0.131***	-0.216***
	(0.050)	(0.068)	(0.024)	(0.048)	(0.029)	(0.066)
Initial log GDP per capita	0.154***	0.229***	0.109***	0.190***	0.124***	0.249***
	(0.050)	(0.064)	(0.030)	(0.046)	(0.032)	(0.068)
Initial log population	0.244***	0.305***	0.183***	0.270***	0.201***	0.333***
	(0.062)	(0.087)	(0.038)	(0.073)	(0.041)	(0.096)
Initial log energy intensity	0.048	0.017	0.004	-0.005	0.020	0.028
	(0.050)	(0.061)	(0.026)	(0.044)	(0.030)	(0.052)
Initial coal share	0.069	0.043	-0.031	0.170	0.028	0.148
	(0.146)	(0.207)	(0.094)	(0.145)	(0.103)	(0.190)
Initial oil share	0.120	0.135	0.007	0.134	0.059	0.085
	(0.139)	(0.155)	(0.082)	(0.117)	(0.093)	(0.160)
Initial natural gas share	0.032	-0.028	-0.021	0.029	0.003	0.027
	(0.118)	(0.127)	(0.082)	(0.105)	(0.083)	(0.142)
GDP per capita growth	0.540***	0.527***	0.652***	0.670***	0.662***	0.842***
	(0.088)	(0.116)	(0.090)	(0.128)	(0.117)	(0.176)
Population growth	0.878***	0.747***	1.111***	0.957***	1.114***	1.257***
	(0.247)	(0.275)	(0.240)	(0.263)	(0.230)	(0.379)
Net gasoline tax		-0.036*		-0.024		-0.017
		(0.021)		(0.015)		(0.020)
Feed-in tariff, binary		-0.016*		-0.017**		-0.017**
		(0.008)		(0.008)		(0.008)
Renewable portfolio standard, binary		-0.023***		-0.016***		-0.022***
		(0.008)		(0.006)		(0.006)
Observations	3,416	1,627	1,712	869	1,173	503
Countries	137	130	137	130	136	130
R^2 (within)	0.201	0.179	0.343	0.295	0.423	0.386
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Notes. ***, **, * show statistical significance at 1, 5, and 10 per cent level respectively. Robust standard errors are in brackets below the coefficients. Fixed effects include time and country fixed effects with standard errors clustered at the country level. Coefficients for constants and fixed effects are not shown. The average annual rate of CO_2 growth is the differenced logs divided by the number of years. For the three-year growth periods, there are nine non-overlapping periods, starting with 1990–1993 and ending with 2014–2017. Data for the net gasoline tax begin in 2003 and energy intensity was available up to 2015 at the time of writing; these are the reasons for the differences in time periods. The dependent variables include fuel combustion emissions (and include road-sector emissions). Fossil fuel shares are the proportions of total primary energy supply. GDP per capita growth and population growth are contemporaneous.

5.4 Panel results: per capita emissions levels

Table 7 presents panel results using log levels of emissions per capita (not growth rates). Column (1) uses explanatory variables lagged one year. Lag periods of 2 and 3 years are used in the subsequent columns. The table focuses on the full period for which carbon pricing has existed, starting in 1990.

The binary carbon pricing variable is found to have a negative and significant coefficient in each column of Table 7. The point estimates increase in magnitude (in absolute value terms) in each subsequent column, likely reflecting the accumulating effects of carbon pricing as more years pass. The results in column (3) indicate that carbon pricing is associated with emissions per capita being approximately 12% lower after three years (*ceteris paribus*).[8] This is equivalent to reductions of around 4% per annum on average, so is a slightly larger effect than obtained in most of the earlier estimates (although note that the control set is also smaller).

The control variables in Table 7 produce intuitive results. There are negative and significant effects for the feed-in tariff and the renewable portfolio standard variables, as expected. Lagged log GDP per capita has a positive coefficient, which is also as expected given that higher-income economies tend to have higher emissions levels (all else equal). The coefficients for the lagged energy-sector variables indicate that more energy-intensive and fossil fuel-reliant economies tend to have higher levels of emissions per capita, as expected.

Table 7. Panel results, log CO_2 emissions per capita

	Dependent variable: Log CO_2 emissions per capita		
Explanatory variable lag:	*Lag 1*	*Lag 2*	*Lag 3*
	1990–2016	*1990–2017*	*1990–2017*
	(1)	*(2)*	*(3)*
Carbon price, binary	-0.059***	-0.095***	-0.128***
	(0.010)	(0.011)	(0.016)
Log GDP per capita	0.822***	0.809***	0.773***
	(0.016)	(0.036)	(0.053)
Log energy intensity	0.705***	0.606***	0.504***
	(0.019)	(0.024)	(0.032)
Coal share	2.454***	2.161***	1.883***
	(0.129)	(0.140)	(0.149)
Oil share	2.579***	2.252***	1.949***
	(0.102)	(0.113)	(0.123)
Natural gas share	2.057***	1.768***	1.524***
	(0.091)	(0.076)	(0.081)
GDP per capita growth	0.504***	1.144***	1.813***
	(0.052)	(0.105)	(0.186)
Population growth	-0.420**	-0.275	-0.136
	(0.151)	(0.279)	(0.374)
Feed-in tariff, binary	-0.030***	-0.039***	-0.046***
	(0.009)	(0.012)	(0.016)
Renewable portfolio standard,	-0.041***	-0.046***	-0.050***
binary	(0.007)	(0.008)	(0.009)
Observations	3,416	3,413	3,277
Countries	137	137	137
R^2 (within)	0.760	0.674	0.598
Fixed effects:			
Time	Yes	Yes	Yes
Country	Yes	Yes	Yes

Notes. ***, **, * show statistical significance at 1, 5 and 10 per cent level respectively. Driscoll-Kraay standard errors are in brackets below the coefficients. Coefficients for constants are not shown. The dependent variables include road-sector emissions. Fossil fuel shares are proportions of total primary energy supply. Explanatory variables are lagged by the same number of years within each column. For GDP per capita growth and population growth, the starting year is indicated by the lag length. The lag lengths are identified in the column headings. Energy intensity was available up to 2015 at the time of writing.

[8] $\exp(-0.128) - 1 = -12\%$.

5.5 Robustness tests

An additional robustness test available through the online code finds that a binary carbon pricing variable has a negative and significant coefficient when added to the regression in column (1) of Table 3. The continuous coefficient remains significant at the 1% level, with a magnitude that is slightly closer to zero at –0.002, while the binary carbon pricing variable has a magnitude of –0.024 which is significant at the 5% level. This is indicative of both a ‘regime’ effect and a ‘level’ effect of carbon pricing. A ‘regime’ effect is where the mere existence of a carbon price has an impact on emissions, holding the actual level of the carbon price fixed.

Further robustness tests for Table 3 indicate that the effects of carbon pricing are robust to including a range of other controls including political, ideological, social, governance, and policy variables. The additional controls include measures of political globalisation from the KOF Institute (Gygli et al. 2019), of the economic policy orientation of the ruling party (Cruz et al. 2018), of climate change awareness (Gallup 2009), and of government effectiveness (Worldwide Governance Indicators 2016). The coefficients for these variables are never significant at the 5% level. These variables might well be more important as explanators of the adoption of carbon pricing and other policies (Rabe 2018) than of emissions growth rates. Carbon pricing results are also similar when excluding the contemporaneous GDP per capita growth variable (see the online code).

Robustness tests for one-year growth periods in Table 6 are also available through the online code. One of these tests excludes countries that had a feed-in tariff in place that was subsequently ended, finding similar coefficients for both the carbon pricing and feed-in tariff variables. We also produce similar results when excluding Australia, whose Emissions Reduction Fund Safeguard Mechanism was classified as a carbon price from 2016 (World Bank and Ecofys 2018) despite involving quite minimal compliance requirements to date.[9]

The coefficients for the binary carbon pricing variable are also negative in separate regressions for emissions growth in the electricity and industry sectors. For the electricity sector, the binary carbon pricing coefficient is –0.06 (significant at the 1% level) without policy controls and –0.035 (insignificant) when policy controls are added, although doing so reduces the sample size. For the industry sector, the coefficient is –0.06 (significant at the 5% level) and then –0.02 (insignificant) when policy controls are added.

6. Discussion and conclusion

We have presented the first large-*n* study on the effect of carbon prices on CO_2 emissions growth rates. Using several econometric modelling approaches and controlling for a range of variables thought to be relevant for emissions, our results provide empirical support to the contention that carbon pricing helps to reduce emissions below levels that would otherwise be observed. Countries with a carbon price have on average had annual CO_2 emissions growth rates that are about two percentage points lower than countries without a carbon price,

[9] The binary carbon-pricing variable has a value of 1 for Australia in 2014, 0 in 2015 due to abolishment of carbon pricing, and a value of 1 again in 2016 due to the introduction of the Emissions Reduction Safeguard Mechanism.

all else equal.[10] An increase in carbon price of one euro per tonne of CO_2 is on average associated with a reduction in the subsequent annual growth rate in emissions from fuel combustion of approximately 0.3 percentage points, all else equal.

Despite the generally low carbon prices that have been in place to date, the adoption of carbon pricing is statistically associated with quite a large reduction in emissions growth rates relative to the trajectories of otherwise similar countries. A reduction in an emissions growth rate of two percentage points per year adds up to very large differences over a decadal timeframe. It may well mean an absolute decline in a country's emissions rather than an increase, and would entail a substantial contribution toward meeting the Paris Agreement commitment of any country.

There are policy alternatives to carbon pricing, and there are numerous policies and instruments that serve as complements to carbon prices (Fay et al. 2015; Ball 2018). Our study focuses on the effects of carbon pricing within overall portfolios of policies. We also find evidence that other policies, such as feed-in tariffs and renewable portfolio standards, are associated with reductions in emissions, although these estimates are somewhat less statistically robust across specifications. In addition to emissions reductions, there are also other motivations for such policies, for example the stimulation of new investment in the energy sector or a reduction in local air pollution.

While we have controlled for a suite of policy variables, it is impossible to control for all relevant policies in each country in a study such as this. Our analysis thus remains somewhat exploratory. We cannot rule out the possibility that the negative coefficients for the carbon pricing variables reflect the effects of other policies or factors that we have been unable to adequately control for. It is also possible that part of the effect of carbon pricing on emissions reductions is a carbon leakage story, whereby some emissions are pushed to jurisdictions that do not have carbon prices. However, estimates of carbon leakage effects in the modelling literature are typically quite small (Elliott and Fullerton 2014). Carbon pricing may also in some cases lead to reductions in emissions in other countries, for example when emissions offsets are purchased to meet domestic compliance requirements or when there are demonstration effects between countries.

Future studies may be able to provide increasingly detailed examinations of the effects of carbon pricing, not only on emissions but also on other outcome variables. Additional controls may be able to be included. Future studies may also be able to access more detailed time-series information on carbon prices by sector or region, and may also be able to further consider interactions between policy variables. More in the way of detailed country case studies would also be of value, building off the work of Andersson (2019) for Sweden. Case studies are better able to uncover detailed information about what has worked in terms of scheme design in individual jurisdictions (Haites 2018; Rabe 2018; Arimura and Abe 2020; Hamamoto 2020). Future studies could also explore potential spillover effects of carbon pricing in one country to emissions in other countries.

[10] This is based on the average associations in regressions with the policy controls in Tables 4 and 6.

Even if there is (caveated) evidence that carbon pricing is associated with emissions reductions below what would otherwise have been the case, the overall contribution of carbon pricing has been limited by the political infeasibility of implementation in some countries. Technical challenges in the monitoring and enforcement of carbon prices also present barriers to adoption, especially in low-income countries where institutional capabilities remain underdeveloped. An important complement to our study would be cross-country empirical research on factors affecting carbon pricing uptake and stringency. This would supplement country case study analysis such as the work of Rabe (2018), which identifies strong political constituencies supporting fossil fuels as one factor that has hindered the adoption of carbon pricing.

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Appendix

Table A.1 Reverse causation test

	Dependent variable: Binary carbon pricing variable		
Explanatory variable lag:	*Lag 1*	*Lag 2*	*Lag 3*
	1990–2016	*1990–2016*	*1990–2016*
	(1)	*(2)*	*(3)*
Log CO_2 emissions per capita	-0.072	-0.065	-0.053
	(0.045)	(0.041)	(0.034)
Log GDP per capita	-0.008	-0.038	-0.051
	(0.060)	(0.066)	(0.070)
Log energy intensity	-0.044	-0.057	-0.061
	(0.041)	(0.043)	(0.044)
Coal share	-1.537***	-1.605***	-1.644***
	(0.257)	(0.267)	(0.256)
Oil share	-0.567***	-0.598***	-0.610***
	(0.137)	(0.141)	(0.152)
Natural gas share	-0.754***	-0.762***	-0.754***
	(0.134)	(0.150)	(0.169)
GDP per capita growth	-0.440***	-0.854***	-1.176***
	(0.095)	(0.185)	(0.290)
Population growth	-0.236	-0.499	-0.631
	(0.508)	(0.544)	(0.572)
Feed-in tariffs, binary	0.156***	0.162***	0.160***
	(0.016)	(0.014)	(0.021)
Renewable portfolio standards, binary	0.105***	0.135***	0.178***
	(0.026)	(0.025)	(0.024)
Observations	3,416	3,280	3,144
Countries	137	137	137
R^2 (within)	0.323	0.331	0.334
Fixed effects:			
Time	Yes	Yes	Yes
Country	Yes	Yes	Yes

Notes. ***, **, * show statistical significance at 1, 5 and 10 per cent level respectively. Driscoll-Kraay standard errors are in brackets below the coefficients. Coefficients for constants are not shown. Fossil fuel shares are proportions of total primary energy supply. Explanatory variables are lagged by the same number of years within each column. The lag lengths are identified in the column headings. Energy intensity was available up to 2015 at the time of writing.

Table A.2 Correlations between policy variables

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(1)	1.0											
(2)	0.9	1.0										
(3)	0.6	0.3	1.0									
(4)	0.4	0.2	0.6	1.0								
(5)	0.6	0.4	0.7	0.7	1.0							
(6)	0.6	0.4	0.8	0.8	1.0	1.0						
(7)	0.5	0.3	0.6	0.5	0.6	0.6	1.0					
(8)	-0.2	-0.1	-0.3	-0.3	-0.3	-0.3	-0.3	1.0				
(9)	0.3	0.2	0.4	0.4	0.5	0.5	0.4	-0.3	1.0			
(10)	0.4	0.2	0.5	0.4	0.5	0.5	0.6	-0.4	0.6	1.0		
(11)	0.4	0.3	0.5	0.5	0.6	0.6	0.5	-0.4	0.6	0.7	1.0	
(12)	0.3	0.2	0.3	0.3	0.2	0.3	0.2	-0.1	0.2	0.2	0.4	1.0

Notes. The variables are for 2012, consistent with the cross-sectional regressions. The variables are 1: effective carbon price rate; 2: effective carbon tax rate; 3: effective ETS rate; 4: carbon price score; 5: binary carbon price; 6: duration-adjusted carbon price; 7: net gasoline tax/subsidy; 8: fossil fuel subsidies; 9: binary feed-in tariff; 10: renewable policies score; 11: efficiency policies score; 12: binary renewable portfolio standard.