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Energy mix persistence and the effect of carbon pricing

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Abstract

Energy mix persistence is a defining characteristic of energy systems, for reasons including the long-lived nature of energy infrastructure and the role of local endowments. This persistence is evident in current energy-type use being strongly influenced by past use. Our analysis uses data for eight energy types and a large sample of countries, finding varying degrees of energy mix persistence. We also find evidence that carbon pricing appears to have played a key role in tilting energy mixes from coal toward renewable energy. Our estimates provide empirical support to policymakers seeking to implement carbon pricing to transition their energy systems in a lower-carbon direction.

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1. Introduction

Energy mixes have historically displayed substantial persistence, with the past energy mix having a considerable influence on the currently-prevailing energy mix. This is evident at a very macro level in Figure 1, which shows remarkable resilience in the share of fossil fuels in the global energy mix – this share having remained at around 80% for decades. This resilience is consistent with evidence that historical energy transitions have often taken decades to play out (Grübler 2012; Fouquet 2016a; Grübler et al. 2016; Sovacool and Geels 2016).

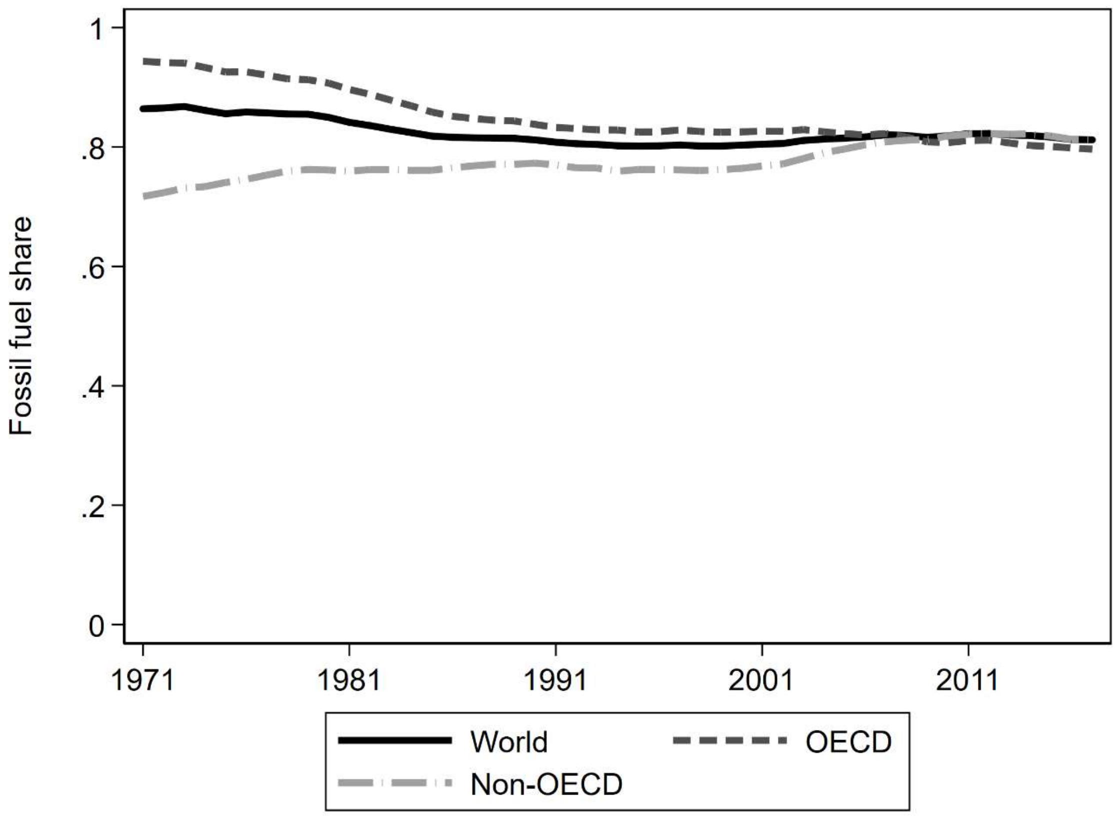

Figure 1. Fossil fuel shares of primary energy supply (% divided by 100) for global, Organisation for Economic Co-operation and Development (OECD), and non-OECD country groups, 1971–2017.

Source: IEA (2019).

Persistence of fossil fuel use is also evident in national-level data. Using data for 142 countries, Figure 2 shows that the coal shares of the primary energy mix in 2017 were strongly related to the corresponding shares 10 years earlier, despite strong growth in energy use in many countries. Most of the dots are close to the $y = x$ line, indicating a relationship close to 1:1. Persistence is less than 100%, as some countries had lower or higher shares in 2017 compared to 2007, as indicated by dots below or above the $y = x$ line. Reductions in the coal share of the energy mix were achieved in countries including Australia, Poland, and the United States. Some middle-income countries – such as India, Vietnam, and the Philippines – had higher coal shares in 2017 compared to 2007. Figure 2 also suggests that carbon pricing is associated with reductions in coal shares, as most countries with carbon prices in 2007 are below the $y = x$ line.

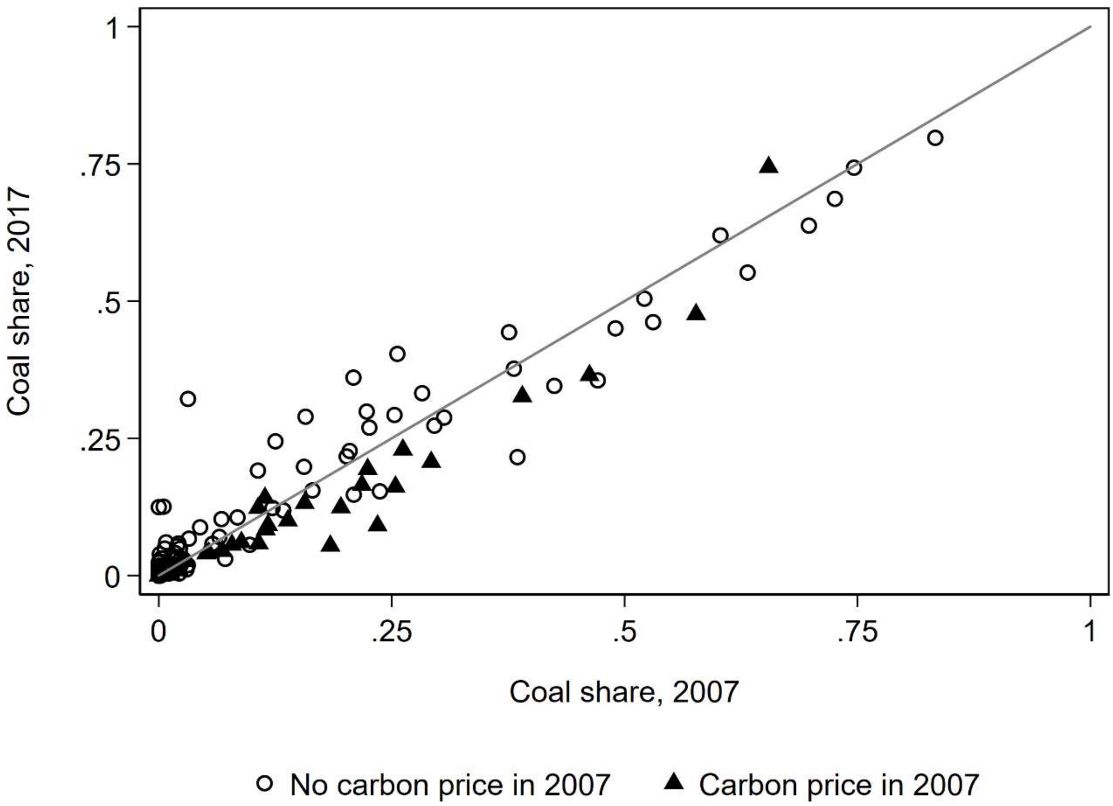

Figure 2. Coal share of primary energy supply (% divided by 100) in 2007 and 2017 for 142 countries.

Notes: A y = x line is shown. Countries with a coal share that increased during 2007–2017 are above the y = x line, while countries with a coal share that decreased during 2007–2017 are below the y = x line. Sources: World Bank and Ecofys (2018); IEA (2019).

In this paper we focus on the impact of a key policy approach – carbon pricing – on the energy mix, while controlling for energy mix persistence and other factors. We estimate various specifications, including cross-sectional regressions and a fixed-effects specification that controls for unobserved heterogeneity through the inclusion of country and time fixed effects. We find evidence that carbon pricing has been associated with a tilting of energy mixes away from coal. This is the case even though the levels at which carbon pricing has been applied have to date been generally quite low.

There is surprisingly little international evidence on the effect of carbon pricing on energy transitions, even though there is a long history of theoretical work indicating that carbon pricing should tilt energy mixes in a low-carbon direction (Goulder and Schein 2013). A previous study (Best and Burke 2018) found that a binary carbon pricing variable is positively associated with the adoption of modern renewables, although did not explore effects on the energy mix more broadly. The current paper is the first to estimate the effect of carbon pricing on overall national energy mixes in a cross-country context.

In the absence of large-scale carbon capture and storage, substantially reducing the fossil fuel share of the energy mix is necessary to reduce local pollution and address climate change (United Nations 2018). Switching to zero-carbon energy forms has been the primary mechanism for carbon dioxide emissions reductions in countries such as Sweden and France (Burke 2012). The results in this paper provide evidence on a policy channel via which countries have been able to make the transition to cleaner forms of energy.

Our results help to inform national and international debates on energy mix transitions. Australia is experiencing ongoing substitution from coal to an increasing share of renewables, a transition which had a temporary boost from a carbon price during 2012–2014 (O'Gorman and Jotzo 2014). Our findings support the contention that Australia's energy transition would likely have proceeded more quickly if the former system of broad carbon pricing had been maintained.

2. Energy mix persistence

Energy transitions typically take time, for technological, infrastructural, and institutional reasons (Fouquet 2016b). These can be mutually-reinforcing and lead to lock-in (Unruh 2000; Seto et al. 2016). Technology effects can occur due to increasing returns to adoption of a specific technology, as adoption leads to learning effects and cost reductions (Arthur 1989). Infrastructural effects are caused by the long-lived nature of energy infrastructure, which often spans half a century (Seto et al. 2016). Institutional effects can develop through establishment of vested interests and policy support for incumbent energy types, including the provision of subsidies (Granoff et al. 2016) or the avoidance of externality pricing. For example, fossil fuel subsidies have been high in some countries (Fouquet 2016b). Some countries also provide large subsidies for renewable energy (REN21 2017).

Natural endowments can also contribute to energy mix persistence. For example, countries with large fossil fuel endowments tend to persistently have energy mixes that are more fossil-fuel heavy. They are also less likely to adopt nuclear power or modern renewables (Burke 2010; 2013; Csereklyei et al. 2017; Ramalho and Santos 2018).

Persistence extends to non-fossil fuel energy sources also, for example nuclear energy. Figure 3 shows that France has had substantial persistence in the nuclear share of its energy mix, with large and similar nuclear shares in 2007 and 2017.[1] The figure also demonstrates that it is possible for major changes in energy mix shares to happen over a decadal horizon. For example, Lithuania closed its last nuclear power plant in 2009, while Japan scaled down its nuclear power program following the Fukushima disaster in 2011.

Wind and solar have become cost-competitive in recent years (REN21 2017), offering the potential to undermine the enduring dominance of fossil fuels. As for other energy types, persistence effects have been observed for renewables. Specifically, renewable energy use in previous periods has been found to be highly correlated to current use (Marques and Fuinhas 2011).

[1] The 1973 oil embargo motivated France to take a major shift toward nuclear, despite the substantial costs involved (Solomon and Krishna 2011; Sovacool 2016).

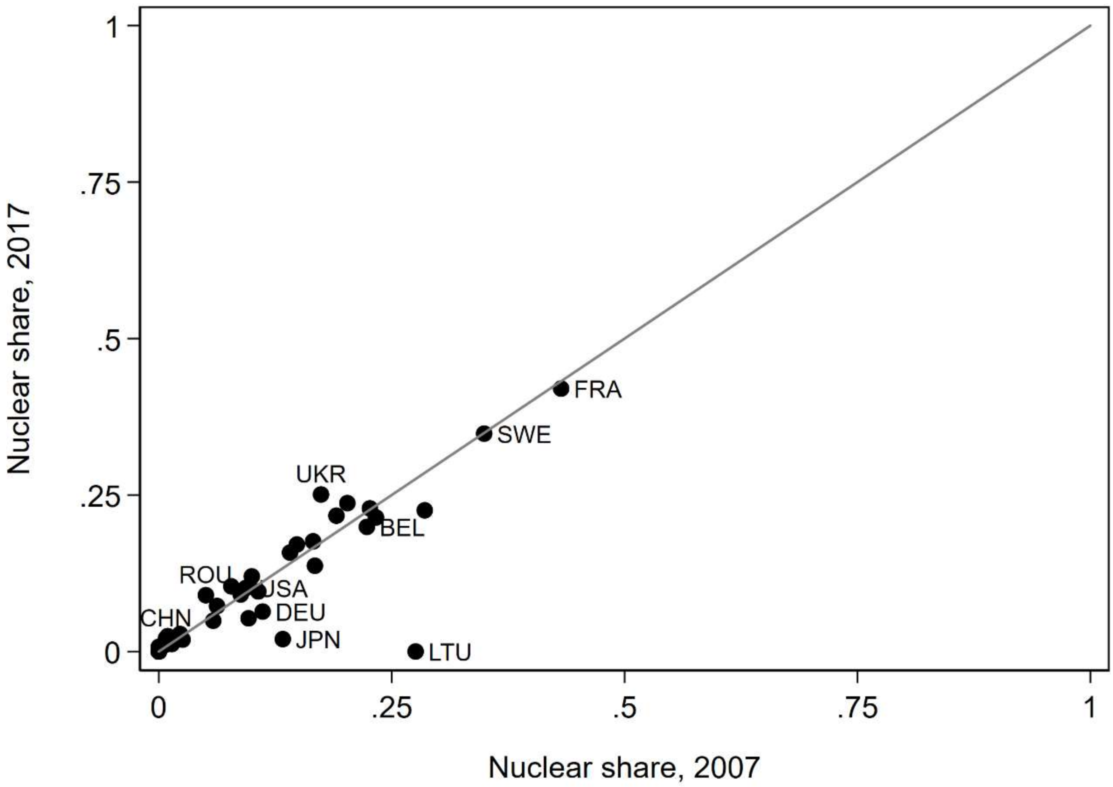

Figure 3. Nuclear share of primary energy supply (% divided by 100) in 2007 and 2017 for 142 countries.

Notes: A y = x line is shown. Countries with a nuclear share that increased during 2007–2017 are above the y = x line, while countries with a nuclear share that decreased during 2007–2017 are below the y = x line. Most countries are at the (0,0) position due to zero use of nuclear power. ISO 3166-1 alpha-3 country codes are shown for selected countries. Source: IEA (2019).

Previous analyses have often focused on issues such as convergence in energy intensity and aggregate energy use (Csereklyei and Stern 2016; Fallahi 2017). There is also evidence of convergence in electricity use in developing countries (Best and Burke 2017). Economic catch-up for developing countries has been associated with above-average growth in the use of coal and natural gas (Jakob et al. 2012; Burke 2013). However, the role of a principal policy instrument – carbon pricing – in influencing energy mix shares has not previously been comprehensively documented using national-level data.

3. Carbon pricing

Carbon pricing is a theoretically-compelling policy mechanism for reducing emissions. Carbon pricing works by encouraging cost-effective emissions abatement through the equating of marginal costs of abatement across abatement opportunities (Aldy and Stavins 2012). Carbon pricing also represents an opportunity to raise revenue and increase economic efficiency, potentially delivering a form of "double dividend" (Goulder 1995). Standard carbon pricing schemes set either a price for or a quantity of carbon dioxide emissions, via a tax or emissions trading system respectively.

The well-established theoretical literature on emissions pricing, going back to Arthur Pigou (1920) in the early 20th century, suggests that adoption of a non-zero price for emissions should lead to lower emissions relative to the scenario with no price (Mankiw 2009). In the context of energy, this would imply that a carbon price would lead to lower shares of high-carbon energy types (e.g. coal) and higher shares of substitute energy types that produce lower or zero emissions (e.g. renewables). The expected effects of carbon pricing on natural gas reliance are somewhat ambiguous, as a carbon price could either incentivise switching from coal to natural gas or from natural gas to renewables, depending on the setting. The former has been evident in the case of Great Britain (Wilson and Staffell 2018).

There are several channels via which carbon pricing could lead to lower coal shares of the energy mix. Carbon pricing may cause some coal power plants to be retired early (and the same is true for other coal-using equipment, such as smelters). Alternatively, some coal power plants may continue to be used, but at lower capacity factors. A carbon price could also reduce the number of new investments in coal power plants. We assess the combined effect of these channels.

There has been international momentum toward carbon pricing, although geographical coverage remains relatively limited (Hepburn 2017). To date most carbon prices have been applied in OECD countries, with the European Union's emissions trading scheme being the most famous example. A number of non-OECD countries such as China have adopted carbon pricing schemes of one form or another. Most recently, Singapore, South Africa, and Canada each introduced carbon taxes in 2019. The current context of rapidly falling costs for modern renewables presents an opportunity for policymakers to foster momentum in sustainable energy transitions, including through the adoption of mechanisms such as carbon pricing (Schmidt and Sewerin 2017).

4. Method and data

4.1 Models

Equation (1) displays our initial model. The approach analyses the effects of decade-lagged energy mix shares and carbon pricing on current energy mix shares:

$$S_c^j = \alpha^j + \beta^j S_{c,lag}^j + \theta^j P_c + \boldsymbol{N'}_c \boldsymbol{\delta}^j + \boldsymbol{R'}_c \boldsymbol{\gamma}^j + \boldsymbol{G'}_c \boldsymbol{\xi}^j + \boldsymbol{O'}_c \boldsymbol{\mu}^j + \varepsilon_c^j \quad (1)$$

The dependent variables are the primary energy mix shares for each energy type j for country c in 2017, S_c^j. Data are from the International Energy Agency (IEA 2019) and cover eight energy types, in total accounting for 99.98% of global total primary energy use. The remaining energy use is heat and traded electricity, the latter taking on a negative value for some net exporters of electricity. Standard errors will be robust to heteroscedasticity.

The first independent variable, $S_{c,lag}^j$, is the decade-lagged dependent variable, included to quantify persistence effects. Other explanatory variables are measured in the same lagged year. High values of β imply stronger persistence. Lower coefficients mean that the past is less important in explaining current use. The β coefficients can also be interpreted with respect to convergence and divergence: coefficients less than one indicate cross-country convergence, whereas coefficients greater than one indicate divergence and a potentially explosive autoregressive process. This becomes more evident when subtracting the lagged energy share from both sides, giving equation (2). We include all control vectors from equation (1) in the *X* vector in equation (2) to be concise.

$$S_c^j - S_{c,lag}^j = \alpha^j + (\beta^j - 1)S_{c,lag}^j + \theta^j P_c + \boldsymbol{X}'_c \boldsymbol{\chi}^j + \varepsilon_c^j \qquad (2)$$

A value of $\beta < 1$ in equation (1) corresponds to a negative coefficient for the lagged energy share in equation (2), which indicates a convergence process through a negative relationship between initial levels and subsequent growth. The inclusion of lagged energy mix shares implies that we are effectively assessing the impact of carbon pricing on the *change* in energy mix shares.

A key explanatory variable is P_c, a binary carbon pricing variable. This variable covers the existence of both emissions trading systems and carbon taxes enacted up to 2007. Further results will use shorter lags for carbon pricing and the other explanatory variables, including three- and five-year lags. The use of lags allows us to capture both immediate and some delayed impacts. However, short-term effects of very recently-introduced policies will not be fully captured by our estimates. This is less of a problem for our results with a three-year lag.

We also present estimates that use a continuous carbon pricing variable from the OECD (2016), which is measured as the average emissions trading system rate plus the average carbon dioxide tax for non-road energy use, in euros per tonne of carbon dioxide. The rates are weighted by the share of carbon dioxide emissions covered at each rate. This calculation produces ‘effective’ carbon rates based on the multiplication of the intensity of the measure (the carbon price level) and the breadth of the measure (the coverage of emissions).

A number of other controls are also included in equation (1). The *N* vector is made up of economic variables. These include private credit, measured as a proportion of GDP, as it has previously been found that stocks of financial capital are important for transitions toward capital-intensive energy types (Brunnschweiler 2010; Best 2017). There is also evidence that higher incomes make economies more likely to adopt modern renewables (Burke 2013), motivating us to control for log gross domestic product (GDP) per capita. Population growth is included to capture scale effects from this variable. We also control for the lagged fossil fuel share of the energy mix (coal plus oil plus natural gas).

Natural endowments, such as fossil fuel reserves and water and forest resources, are included in the *R* vector. We add the control variables selectively to maintain larger sample sizes, as explained in Section 5. In robustness tests available through the online code we also control for the growth in total primary energy use. We omit this variable from the main specifications given concerns about reverse causality from the energy mix to energy use.

Governance variables are included in *G*. This includes a measure of government effectiveness, as Best and Burke (2017) found that this governance attribute is important for some energy-sector outcomes. We also control for participation in political globalisation using a variable from Gygli et al. (2019) that reflects measures such as the number of treaties and treaty partners each country has, as well as the number of personnel contributed to UN Security Council missions as a percent of their population. More globally-engaged countries may be more likely to seek to address the problem of climate change, such as through making changes that affect their energy mix.

It is important to consider policies other than carbon pricing. For example, Baldwin et al. (2017) and Carley et al. (2017) found that the use of premium feed-in tariffs has stimulated renewable energy growth in some countries, as should be expected. We include other policies in the *O* vector in equation (1). Specifically, we include continuous variables for energy efficiency and renewable energy policies based on scores assigned by the World Bank (ESMAP 2018). We use the values of these variables in 2012 in the models with five-year lags, as they are not available for 2007. We also control for the net gasoline tax from 2012 and pre-tax values for total fossil fuel subsidies from 2013 (Coady et al. 2015; Ross et al. 2017). There is a trade-off between more controls and larger sample sizes, as some variables are unavailable for some countries. As a result, we only include the policy vector in one of the results tables.

We next employ a fixed-effects panel model with a three-year lag of the binary carbon pricing variable, the three-year lagged fossil fuel share, country fixed effects, and year fixed effects as the only explanatory variables. This approach facilitates analysis of more recently-introduced carbon prices and a larger dataset. A downside is that data unavailability prevents the inclusion of the full set of control variables, although the country and year fixed effects control for some unobserved heterogeneity.

We do not control for local energy prices due to data availability issues for our large sample. Local prices are in some cases correlated with endowments of natural resources, which are controlled for. For example, we include domestic coal reserves and wind resources as independent variables in one table of results. We do not pursue seemingly unrelated regression estimations, as doing so provides no additional benefit given that the same set of explanatory variables is used in each column. Our panel estimates use robust standard errors that are clustered at the country level. Further descriptions of variables are in Appendix Table A.1.

4.2 Identification

It is difficult to precisely evaluate the effects of carbon pricing, as controlled experiments for policy impacts at the macroeconomic level are not possible (Athey and Imbens 2016). Omitted variable bias is a possible threat. Reverse causality may also exist, as predictions of future fossil fuel use could affect the political feasibility of carbon pricing.

We address the identification challenge through a range of approaches. We include a comprehensive range of economic, environmental, governance, and policy controls. Doing so helps us to explain a high proportion of variation in our estimates (see the high R^2 values in

Section 5), which lessens concerns about omitted variable bias to some extent. Another key feature of our approach is the use of lags of the explanatory variables, which reduces the threat of reverse causation. We remove the lagged dependent variables in our panel estimates and instead control for the lagged fossil fuel share to avoid econometric issues associated with lagged dependent variables in a panel context.

An instrumental variable approach is one way to obtain causal estimates. For example, Aichele and Felbermayr (2012; 2013) assessed the impact of ratification of the Kyoto Protocol on carbon footprints and emissions, with their finding of a large impact of Kyoto ratification on emissions being reduced in absolute terms by including either a comprehensive control set or by using an instrumental variable approach. Their instrumental variable for Kyoto Protocol ratification was participation in the International Criminal Court.

We do not use an instrumental variable approach in our paper, as it is challenging to find a variable that affects carbon pricing while not potentially affecting energy mix shares in other ways. We include participation in political globalisation as a control variable rather than an instrument on the basis that this characteristic may indicate receptiveness toward contributing to global action to reduce climate change risk and be correlated with other policies. We considered OECD (2018) data on non-energy environmental taxes for use as an instrument, however the correlation with carbon pricing was quite low. As a result, our identification instead relies on inclusion of key variables as controls.

While we have aimed to be comprehensive, it is challenging to control for all relevant policies. For example, mechanisms that encourage coal use are often opaque, with coal in some countries being directly sold to government-owned utilities at low prices under long-term contracts (Ross et al. 2017). Our results should thus be interpreted with the caveat that there are likely to be other important variables that we have not controlled for. Nevertheless, we believe that our estimates provide useful results on whether countries that have adopted carbon prices have experienced a tilting of their energy mixes in a lower-carbon direction.

4.3 Data

We source energy data from the International Energy Agency (IEA 2019) and key control variables such as GDP per capita from the World Bank (2019). Private credit as a proportion of GDP is from the Global Financial Development Database (GFDD 2018). Solar resources are based on global horizontal irradiance (Breyer and Schmid 2010), wind energy potential is from a study by Lu et al. (2009), and fossil fuel reserves are from the US Energy Information Administration (US EIA 2018). Net gasoline taxes/subsidies were calculated by Ross et al. (2017), renewable energy and energy efficiency policy scores are from the World Bank (ESMAP 2018), and fossil fuel subsidies are as measured by the International Monetary Fund (Coady et al. 2015). Government effectiveness is an index from the Worldwide Governance Indicators (WGI 2016), while participation in political globalisation is from the KOF Institute (Gygli et al. 2019). Data definitions are in Appendix Table A.1.

The quantification of carbon prices is challenging owing to variations in scheme design, economic and geographic coverage, and fluctuations in effective carbon prices over time (World Bank and Ecofys 2018). Our main estimates use a binary carbon pricing variable based on a report by the World Bank and Ecofys (2018), with countries with sub-national pricing schemes being counted.[2] Countries with a carbon price are identified in Appendix Table A.2. For our continuous carbon pricing measure, there are 41 countries listed by the OECD (2016) for 2012. For countries not listed by the OECD (2016), we set the value to zero if the World Bank and Ecofys (2018) did not identify the country as having a carbon price in 2012.

5. Results

5.1 Persistence effects

We first focus on the size of decadal persistence effects in energy mix shares. There is strong evidence of energy mix persistence in Table 1, with the 10-year lags of energy mix shares being positive and significant at the 1% level in each regression. For example, an additional percentage point in the coal share of the energy mix in 2007 is associated with 0.9 additional percentage points in the coal share of the energy mix in 2017, after controlling for the other variables. This supports the observation made for Figure 2: the coal share of the energy mix is highly autoregressive on a decadal basis. Oil and natural gas are also highly related to past use, with approximately 0.9 percentage points in 2017 for each percentage point of the respective share in 2007 (*ceteris paribus*).

Modern renewables show a different kind of relationship with past use. Each percentage point of the wind plus solar share of the energy mix in 2007 is associated with 1.4 percentage points of wind plus solar share in 2017, *ceteris paribus*. This suggests divergence in reliance on these energy types across countries: early adopters have followed a path of faster wind and solar adoption. A large effect remains when excluding Denmark, the country with the largest wind share to date. This and additional results are available through the online code.

[2] Our use of a binary variable is similar to prior studies of feed-in tariffs (Carley et al. 2017). We also consider robustness tests such as using a binary variable restricted to only national-level carbon pricing schemes.

Table 1. Determinants of each primary energy mix share, 2017

	Dependent variable: Primary energy mix share, 2017							
	Biofuels and waste	Hydro	Coal	Oil	Natural gas	Nuclear	Wind and solar	Geothermal
Dependent variable, 10-year lag	0.875***	0.738***	0.928***	0.850***	0.915***	0.889***	1.445***	0.982***
	(0.035)	(0.058)	(0.033)	(0.052)	(0.040)	(0.090)	(0.485)	(0.055)
Carbon price	0.034***	-0.003	-0.029*	-0.018	-0.001	0.007	0.009**	-0.005
	(0.012)	(0.006)	(0.015)	(0.028)	(0.025)	(0.010)	(0.004)	(0.005)
Private credit, divided by GDP	-0.020	0.011	-0.014	0.007	-0.003	0.005	0.005	0.003
	(0.016)	(0.010)	(0.015)	(0.020)	(0.014)	(0.007)	(0.005)	(0.007)
Log GDP per capita	0.004	0.003	-0.018**	-0.003	0.012	-0.001	-0.001	0.001
	(0.007)	(0.003)	(0.007)	(0.012)	(0.012)	(0.001)	(0.001)	(0.002)
Government effectiveness	0.007	0.000	0.017**	-0.014	-0.003	-0.005	-0.001	0.000
	(0.007)	(0.005)	(0.008)	(0.014)	(0.012)	(0.003)	(0.002)	(0.003)
Political globalisation	0.000	0.000*	-0.001	0.001	0.000	0.000	0.000**	0.000
	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)
Population growth	-0.443	-0.401***	-0.347	-0.729	1.806***	0.205	-0.046	-0.024
	(0.338)	(0.146)	(0.248)	(0.484)	(0.414)	(0.197)	(0.063)	(0.066)
Fossil fuel share	-0.036	-0.021**	0.010	-0.040	0.071*	0.009	0.003	-0.008
	(0.029)	(0.010)	(0.015)	(0.029)	(0.038)	(0.006)	(0.004)	(0.008)
R^2	0.963	0.938	0.917	0.879	0.928	0.866	0.630	0.942

Notes: ***, **, * show statistical significance at 1, 5 and 10 per cent level respectively. Robust standard errors are in brackets below the coefficients. All countries are included if data are available. The sample covers 131 countries, except that the hydro regression has 130 countries because the hydro value for Israel is listed as a "non-publishable and confidential value" by the IEA (2019). Coefficients for constants are not shown. Independent variables are lagged 10 years. Population growth is over the 10 years to 2017. Shares are between 0 and 1. The eight energy types account for approximately 99.98% of global total primary energy use. The remainder includes a heat category and traded electricity, which may take on a negative value in the case of net electricity exports for some countries. The wind and solar category includes other energy types such as tide, wave, and ocean; wind and solar comprised approximately 99.3% of this category in 2016 at the global level. A robustness test in the online code shows that carbon pricing in 2007 is not significantly correlated with *past* fossil-fuel or renewable energy shares (as of 2002), helping to reduce endogeneity concerns. This robustness test used explanatory variables from 2002 (with the exception of the binary variable for carbon pricing in 2007), as lagged variables would lead to lower sample sizes.

5.2 Results for carbon pricing

In line with theoretical expectations, the binary carbon pricing variable in Table 1 has a negative association with coal use, the most carbon-intensive of the fossil fuels. There is significance at the 10% level for coal (p-value = 0.06), with having a carbon price as of 2007 being associated with a reduction in the coal share of the energy mix during 2007–2017 of approximately three percentage points, all else equal. This is a relatively large effect.

The binary carbon pricing coefficients in Table 1 are positive and significant for two of the renewable energy categories. This includes the wind and solar regression (at the 5% level) and the biofuel and waste regression (at the 1% level). On average, countries with carbon prices in 2007 adopted an additional 0.9 percentage points of wind and solar in their energy mix by 2017. This is a sizeable magnitude, being similar to the average global energy mix share of wind plus solar as of 2017. The carbon pricing coefficient for biofuel and waste (0.034) is even larger, although is smaller in relation to average reliance on biofuel and waste, which contributes around 10% of the global energy mix. The carbon pricing variable is not significant for hydro, perhaps because large-scale hydroelectricity use had already neared maximum feasible levels in most countries that have introduced carbon pricing.

Table 2 includes additional policy controls for a slightly smaller sample of countries, given data constraints. We use a five-year lag due to availability of the other policy variables and to capture more recent policy effects. The carbon-pricing coefficient is again negative and significant, this time at the 5% level for the coal share. The magnitude of the effect is similar to Table 1, with a reduction in coal share of approximately three percentage points over a five-year period for countries having a carbon price as of 2012. The magnitude of the carbon-pricing coefficient for the wind and solar regression is not statistically significant in Table 2. The coefficients for the other policy controls are mostly insignificant.

Table 3 uses the continuous carbon pricing variable, which measures the effective carbon price for all non-road energy. This is based on calculations by the OECD (2016) and represents explicit carbon taxes plus emissions trading system rates in euros per tonne of carbon dioxide emissions. The continuous carbon pricing variable has the advantage of accounting for the coverage of emissions and each country's prevailing per-unit emissions price, although data are available for only a smaller sample of countries. We again analyse the 5-year period to 2017, based on the availability of the continuous carbon pricing variable in 2012. We also introduce natural endowment controls. We drop the other policy variables to avoid encroaching on the sample size, and because they are mostly statistically insignificant in Table 2. The continuous carbon pricing variable has a negative and significant coefficient in explaining the coal share of the energy mix, with significance at the 5% level. A similar effect of carbon pricing is evident in a robustness test that includes energy use growth as an explanatory variable (see the online code).

The panel estimates in Table 4 focus on the effect of carbon pricing, while controlling for the lagged fossil fuel share and country and year fixed effects. Each column shows the effect of the binary carbon pricing variable at the start of nine three-year periods from 1990–1993 to 2014–2017. The results tell a similar story: there is a negative and significant coefficient for the (three-year lagged) carbon pricing variable in explaining the coal share of each country's energy mix. This time the statistical significance is at the 1% level. The magnitude of the coefficient is slightly smaller compared to Table 1, which used a longer lag. The effect of carbon pricing on the wind and solar share of the energy mix is also significant at the 1% level. There is again a positive and significant coefficient for carbon pricing in explaining the biofuels and waste share of the energy mix.

The results are robust in additional regressions available through the online code. This includes when we omit specific countries like Australia or China, or countries that only have sub-national carbon pricing schemes.

5.3 Endowment effects

In Table 3, the coefficients for most of the natural endowment variables are insignificant. This is because domestic abundance of natural resources has often already been accounted for via higher values of the lagged dependent variables. Some results of note are the positive and significant effects of water resources on the hydroelectricity share of the energy mix and forest area per capita on the biofuel and waste share of the energy mix. Negative effects of the oil reserves variable on the oil share, and similar for natural gas, are not unreasonable, as oil and gas-rich countries already had high dependence on these commodities at the start of the period. If the lagged dependent variables are excluded from the list of explanatory variables, the negative and significant effects of fossil fuel reserves are no longer evident. For example, the coefficient for natural gas reserves becomes positive and significant at the 1% level in the natural gas regression (see the online code).

Table 2. Determinants of each primary energy mix share, 2017, with extra policy controls, 5-year lags

	Dependent variable: Primary energy mix share, 2017							
	Biofuels/waste	Hydro	Coal	Oil	Natural gas	Nuclear	Wind/solar	Geothermal
Dependent variable,	0.899***	0.761***	0.947***	0.887***	0.930***	0.993***	1.302***	0.950***
5-year lag	(0.031)	(0.044)	(0.021)	(0.042)	(0.037)	(0.025)	(0.142)	(0.081)
Carbon price	0.004	-0.004	-0.029**	0.015	0.001	0.003	-0.003	-0.002
	(0.013)	(0.007)	(0.012)	(0.018)	(0.020)	(0.005)	(0.005)	(0.003)
Renewable energy	0.020	0.022*	0.031	-0.056	-0.009	-0.009**	0.005	0.008
policy score	(0.028)	(0.013)	(0.025)	(0.036)	(0.034)	(0.004)	(0.005)	(0.009)
Fossil fuel subsidy	0.015	0.006	-0.006	-0.019	0.018	0.000	-0.003*	-0.001
	(0.018)	(0.008)	(0.011)	(0.020)	(0.020)	(0.002)	(0.001)	(0.005)
Gasoline net tax,	0.004	-0.005	-0.015	0.015	0.003	-0.001	0.004*	0.001
USD per litre	(0.011)	(0.004)	(0.012)	(0.015)	(0.018)	(0.001)	(0.002)	(0.004)
Energy efficiency	-0.001	-0.012	0.009	0.026	0.006	0.002	-0.007*	0.000
policy score	(0.024)	(0.012)	(0.038)	(0.038)	(0.035)	(0.006)	(0.004)	(0.007)
Private credit,	-0.007	-0.003	-0.015	0.011	0.005	0.000	-0.003	0.002
divided by GDP	(0.015)	(0.006)	(0.017)	(0.018)	(0.016)	(0.004)	(0.005)	(0.002)
Log GDP per capita	0.007	-0.001	-0.014*	-0.006	0.013	-0.003	0.001	0.001
	(0.009)	(0.006)	(0.008)	(0.012)	(0.010)	(0.002)	(0.002)	(0.001)
Government	-0.001	0.007	0.019**	-0.004	-0.015	-0.001	0.001	-0.003*
effectiveness	(0.008)	(0.006)	(0.007)	(0.013)	(0.012)	(0.002)	(0.001)	(0.002)
Political globalisation	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)
Population growth	0.386	-0.352*	-0.182	-0.441	0.926	-0.089	-0.037	0.123
	(0.442)	(0.181)	(0.333)	(0.840)	(0.872)	(0.061)	(0.085)	(0.158)
Fossil fuel share	-0.025	-0.002	-0.024	-0.031	0.068	0.008	0.002	-0.006
	(0.022)	(0.014)	(0.019)	(0.034)	(0.045)	(0.007)	(0.005)	(0.008)
R^2	0.978	0.972	0.944	0.917	0.956	0.990	0.774	0.935

Notes: ***, **, * show statistical significance at 1, 5 and 10 per cent level respectively. Robust standard errors are in brackets below the coefficients. All countries are included if data are available. The sample covers 103 countries, except that the hydro regression has 102 countries, since the hydro value for Israel is listed as "non-publishable and confidential" by the IEA (2019). The sample size is less than Table 1 because the additional policy variables in Table 2 are unavailable for some countries. Coefficients for constants are not shown. Independent variables are generally lagged 5 years (i.e. at 2012) but the fossil fuel subsidies are for 2013 (Coady et al. 2015). Population growth is for the five years to 2017.

Table 3. Determinants of each primary energy mix share, 2017, continuous carbon price, 5-year lags

	Dependent variable: Primary energy mix share, 2017							
	Biofuels and waste	Hydro	Coal	Oil	Natural gas	Nuclear	Wind and solar	Geothermal
Dependent variable,	0.925***	0.743***	0.992***	0.921***	0.955***	1.005***	1.291***	0.949***
5-year lag	(0.034)	(0.029)	(0.034)	(0.038)	(0.029)	(0.023)	(0.155)	(0.081)
Carbon price	0.000	-0.001	-0.009**	0.002	0.007	0.000	0.000	0.000
(continuous)	(0.002)	(0.001)	(0.004)	(0.004)	(0.006)	(0.001)	(0.001)	(0.000)
Private credit,	-0.005	-0.002	-0.018	0.019	-0.005	0.003	-0.001	0.001
divided by GDP	(0.016)	(0.005)	(0.021)	(0.021)	(0.022)	(0.003)	(0.005)	(0.002)
Log GDP per capita	0.008	-0.008	-0.016*	0.005	0.006	-0.001**	-0.001	0.000
	(0.010)	(0.005)	(0.008)	(0.011)	(0.009)	(0.001)	(0.001)	(0.002)
Forest area per capita	0.739*	-0.505***	0.228	-0.786**	0.105	0.027	-0.096	-0.043
	(0.382)	(0.153)	(0.451)	(0.376)	(0.261)	(0.023)	(0.077)	(0.064)
Water reserves	-0.109	0.882***	-0.187	0.012	-0.060	0.012	0.157	-0.011
per capita	(0.341)	(0.194)	(0.395)	(0.433)	(0.298)	(0.038)	(0.108)	(0.059)
Coal reserves	-0.008	0.003	-0.014	0.018**	0.001	-0.002	-0.002	-0.002
per capita	(0.007)	(0.003)	(0.013)	(0.008)	(0.007)	(0.001)	(0.001)	(0.002)
Oil reserves	-0.003	0.003	0.007*	-0.020**	0.015	0.000	-0.001	0.000
per capita	(0.005)	(0.002)	(0.004)	(0.009)	(0.010)	(0.000)	(0.001)	(0.001)
Natural gas reserves	-0.002	0.000	0.000	0.004**	-0.005**	0.000*	0.000	0.000
per capita	(0.001)	(0.000)	(0.001)	(0.002)	(0.002)	(0.000)	(0.000)	(0.000)
Log wind	-0.003	0.000	-0.002	0.002	0.000	0.001	0.001	0.002
resources	(0.002)	(0.001)	(0.003)	(0.004)	(0.004)	(0.000)	(0.001)	(0.002)
Log solar	-0.019	-0.014	-0.024	-0.011	0.059	-0.001	0.003	0.005
resources	(0.022)	(0.009)	(0.034)	(0.038)	(0.050)	(0.006)	(0.005)	(0.004)
R^2	0.978	0.982	0.944	0.932	0.962	0.995	0.781	0.936

Notes: ***, **, * show statistical significance at 1, 5 and 10 per cent level respectively. Robust standard errors are in brackets below the coefficients. All countries are included if data are available. The sample covers 105 countries, except the hydro regression has 104 countries, since the hydro value for Israel is listed as "non-publishable and confidential" by the IEA (2019). Coefficients for constants are not shown. Independent variables are lagged 5 years. Solar and wind resources are not year-specific (Breyer and Schmid 2010; Lu et al. 2009). Shares are between 0 and 1. The eight energy types account for approximately 99.98% of global total primary energy use. The remainder includes a heat category and traded electricity, which may take on a negative value in the case of net electricity exports for some countries. The wind and solar category includes other types such as tide, wave, and ocean; wind and solar comprised approximately 99.3% of this category in 2016 at the global level. This table also includes the final four controls from the previous tables (government effectiveness, political globalisation, population growth and fossil fuel share); they are not shown to save space. Population growth is for the five years to 2017.

Table 4. Panel results

	Dependent variable: Primary energy mix share, three years after the carbon pricing variable							
	Biofuels and waste	Hydro	Coal	Oil	Natural gas	Nuclear	Wind and solar	Geothermal
Carbon price	0.024***	0.000	-0.021***	-0.001	-0.005	-0.009	0.008***	0.003
	(0.007)	(0.003)	(0.007)	(0.011)	(0.011)	(0.011)	(0.002)	(0.004)
Fossil fuel share	-0.580***	-0.023	0.203***	0.368***	0.128**	-0.073**	-0.014**	-0.009
	(0.059)	(0.026)	(0.046)	(0.070)	(0.050)	(0.031)	(0.007)	(0.016)
Country fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,258	1,257	1,258	1,258	1,258	1,258	1,258	1,258
R^2	0.522	0.013	0.132	0.158	0.158	0.044	0.361	0.040

Notes: ***, **, * show statistical significance at 1, 5 and 10 per cent level respectively. Shares are between 0 and 1. Coefficients for fixed effects and constants are not shown. The results include nine three-year periods, from 1990–1993 to 2014–2017. The carbon price is a binary variable at the start of each three-year period. The fossil fuel share is also measured at the start of each three-year period.

6. Conclusion and policy implications

In this paper we have presented evidence of substantial decadal inertia in energy mix shares. Despite this, carbon pricing has had a material association with switches towards lower-carbon energy sources, as theory would suggest. Countries that had carbon prices in 2007 or earlier have been estimated to have had coal shares of the primary energy mix that were approximately three percentage points lower by 2017 than they would otherwise have been, holding the other variables constant. The transition away from coal has involved a move toward renewables such as biomass, waste, wind and solar.

Significant coefficients for the binary carbon pricing variable are obtained despite generally low prevailing carbon price levels. As of 2019, implemented or scheduled schemes cover approximately 20% of global greenhouse gas, although this includes some schemes with very low prices (World Bank 2020). It has been estimated that only around 10% of global fossil fuel emissions are priced at a level that would limit global warming to 2°C (United Nations 2018). The effects of carbon pricing would likely be larger if carbon prices were higher and had broader sectoral coverage. There are examples of large carbon prices, such as Sweden's carbon tax on transport fuels that started at US$30 per tonne of carbon dioxide (CO_2) in 1991 and which has increased to over US$130 per tonne of CO_2 (Andersson 2019).

Our results are useful as an early contribution to what may well be an expanding literature on the empirical effects of carbon pricing. Our paper is the first to assess this impact in a cross-country context incorporating persistence effects in energy systems. However, we emphasise caveats related to challenges in the analysis of macroeconomic policy effects, including measurement issues for both carbon prices and other policy variables.

There is likely to be value in building on the research in this paper. In particular, there will be opportunities for future assessment of carbon-pricing impacts in recent adopters such as Singapore. It is also likely that more detailed cross-country data on carbon prices and other policy mechanisms will become available over time, enabling increasingly detailed investigations. Future studies could also investigate related outcomes, such as the effects of carbon pricing on new investments in electricity generating plants and on retirement decisions for aged plants.

Carbon pricing has been a politically challenging issue in Australia. Our results provide a reminder of the power of carbon pricing in helping to facilitate low-carbon energy transitions. Australia does currently have a market for offset permits, with some purchase requirements imposed on private-sector operators under what is known as a 'safeguard mechanism' (applied from 2016 onwards). However this approach has not involved large obligations for emitters. The offsetting approach is also subject to problems including the adverse selection of projects that are likely to be providing non-additional abatement (Burke 2016).

For countries that are yet to introduce a carbon price, one option is to start with a low price and to increase it over time (Tol 2017). Prior economic pricing reforms – such as Stockholm's road pricing scheme (Gu et al. 2018) – have become more popular once their effectiveness has been demonstrated. Another approach is to start with technology-specific policies that pave the way for carbon pricing when suitable constituencies are in place

(Morgan 2016; Meckling et al. 2017). There is ample scope for further research on optimal carbon pricing strategies in both developed- and developing-country contexts.

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Appendix

Table A.1. Description of variables

Variable	Source	Description
Energy shares	IEA	Share of primary energy supply for eight energy categories. Ranges from 0 to 1. Coal includes peat and oil shale.
Carbon price (binary)	WB/ EC	Carbon price implemented, binary variable. 30 countries had carbon prices in 2007. This includes countries with one or more sub-national pricing schemes.
Carbon price (continuous)	OECD	Average carbon tax plus average emissions trading system rate in euro per tonne of carbon dioxide for 2012 for all non-road energy. Average rates are weighted by the share of carbon dioxide emissions covered at each rate by each instrument. Data are available for 41 countries. We assign zero values for countries that did not have a carbon price in 2012 (World Bank and Ecofys 2018).
Renewable energy policy score	RISE	A score for national policy and regulatory frameworks for renewable energy in 2012. Renewable energy policy scores are an equally-weighted combination of seven indicators. We exclude the indicator on carbon pricing and monitoring, as we assess carbon pricing separately. We divide the scores by 100.
Fossil fuel subsidy	IMF	Pre-tax subsidies for fossil fuel energy and electricity in million USD for 2013, excluding externalities such as environmental damage, divided by total fossil fuel use in 2013 in thousand tonnes of oil equivalent.
Gasoline net tax	ROS	Net gasoline tax (subsidy) estimated using the price gap between the local retail price and a benchmark international price in 2012, average of monthly values, 2015 US dollars per litre.
Energy efficiency policy score	RISE	A score for national policy and regulatory frameworks for energy efficiency for 2012. Energy efficiency policy 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.
Private credit (% of GDP)	GFDD	Private credit by deposit money banks, proportion of GDP.

Log GDP per capita	WDI	Log gross domestic product per capita, purchasing power parity, constant 2011 international dollars.
Forest area per capita	WDI	Forest area, square kilometres per capita.
Water reserves per capita	WDI	Renewable internal freshwater resources per capita, million cubic metres.
Coal reserves per capita	EIA	Coal, recoverable reserves, thousand tonnes of oil equivalent per capita.
Oil reserves per capita	EIA	Oil, recoverable reserves, thousand tonnes per capita.
Natural gas reserves per capita	EIA	Natural gas, recoverable reserves, thousand tonnes of oil equivalent per capita.
Log wind resources	LU	Log wind energy potential for capacity factors greater than 20% with siting limited to exclude densely populated regions, forests, and areas under permanent ice cover (Lu et al., 2009). Wind resources are not year-specific.
Log solar resources	BR	Log mean global horizontal irradiance (kWh per metre squared per year), area weighted, 0-axis fixed tilted. Solar resources are not year-specific.
Government effectiveness	WGI	An index representing the quality of public services and the quality of policy formulation and implementation. This index is normally distributed with mean zero and standard deviation of one.
Political globalisation	KOF	An index from 0 to 100 for the degree of participation in political globalisation. This variable is based on the number of embassies, personnel contributed to UN Security Council missions as a percent of population, the number of treaties and treaty partners, along with many other components.
Population growth	WDI	The log of population in the end year (2017) minus the log of population in the start year, divided by the number of years. The start year is 2007 for Table 1 that assesses decadal outcomes and 2012 for Table 2 and 3 that use a five-year lag.
Fossil fuel shares	IEA	The sum of shares for coal, oil, and natural gas.

Sources: BR: Breyer and Schmid (2010), EIA: U.S. Energy Information Administration (US EIA 2018), GFDD: Global Financial Development Database (2018), IEA: International Energy Agency (2019), IMF: International Monetary Fund (Coady et al. 2015), KOF: KOF Institute (Gygli et al. 2019), LU: Lu et al., (2009), OECD (2016), RISE: ESMAP (2018), ROS: Ross et al. (Ross et al. 2017), WB/EC: joint report by World Bank and Ecofys (World Bank and Ecofys 2018), WDI: World Bank World Development Indicators (2019). WGI: Worldwide Governance Indicators (WGI 2016).

Table A.2. Selected data for countries with a carbon price in 2014

Country	Carbon price in 2007	Carbon price in 2014	Coal share in 2007
Australia	0	1	0.42
Austria	1	1	0.12
Belgium	1	1	0.08
Bulgaria	1	1	0.39
Canada	1	1	0.11
China	0	1	0.70
Croatia	1	1	0.07
Cyprus	1	1	0.01
Czech Republic	1	1	0.46
Denmark	1	1	0.23
Estonia	1	1	0.65
Finland	1	1	0.20
France	1	1	0.05
Germany	1	1	0.26
Greece	1	1	0.29
Hungary	1	1	0.11
Iceland	0	1	0.02
Ireland	1	1	0.16
Italy	1	1	0.09
Japan	0	1	0.23
Kazakhstan	0	1	0.49
Latvia	1	1	0.02
Lithuania	1	1	0.03
Luxembourg	1	1	0.02
Malta	1	1	0.00
Mexico	0	1	0.07
Netherlands	1	1	0.11
New Zealand	0	1	0.10
Norway	1	1	0.03
Poland	1	1	0.58
Portugal	1	1	0.11
Romania	1	1	0.25
Slovak Republic	1	1	0.22
Slovenia	1	1	0.22
Spain	1	1	0.14
Sweden	1	1	0.05
Switzerland	0	1	0.01
Ukraine	0	1	0.31
United Kingdom	1	1	0.18
United States	0	1	0.24

Notes: Values of 1 indicate that a country has a carbon price. Australia's carbon price was ended in mid-2014. Robustness tests available through the online code show that results are similar if Australia is excluded from the sample. Sources: World Bank and Ecofys (2018); IEA (2019).