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RECESSIONS, THE ENERGY MIX AND ENVIRONMENTAL POLICY

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How do severe recessions, such as those brought about by the Global Financial Crisis or the COVID-19 pandemic, affect the composition of energy generation between green and dirty sources? Does creative destruction during recessions result in a sustained greening of the energy mix? The empirical analysis presented in this paper highlights that recessions and crises result in permanent, albeit small, increases in energy efficiency and in the share of renewables in total electricity. These effects are larger, however, when complemented with strong environmental policies – both market-based measures such as taxes on pollutants, trading schemes and feed-in-tariffs, and non-market measures such as emission and fuel standards and R&D investment and subsidies – that incentivise and hasten the transition towards renewable sources of energy.

Keywords: crises; recessions; energy mix; renewables.
JEL Codes: E32, E6, G01, O13, Q4, Q54, Q56.

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1 Introduction

This paper explores whether recessions and crises provide opportunities to green the energy mix on a durable basis. We investigate the response of the share of renewables in total energy to major historical recessions (including financial crises and pandemics), for a panel of 176 countries from 1965 to 2021. Our results show that recessions – while leading to permanent declines in energy demand and energy intensity – are also associated with sustained, though modest, medium-term increases in the composition of energy use in favour of renewables and away from dirty energy.

These modest overall effects, however, mask important cross-country variation, depending on the role of policy. We find that supportive policy in the form of more stringent environmental protection regulation (measured by the Organisation for Economic Co-operation and Development's Environmental Policy Stringency (EPS) index), including emission and fuel standards, taxes on pollutants, trading schemes for carbon, and R&D subsidies and public investment in renewables, are key to amplifying the effects of recessions on the energy mix. With stringent environmental policy, the greening of the energy mix in the wake of a recession is about double what it is on average in the sample as a whole.

Our paper contributes to the literature on the relationship between energy consumption and economic growth which, while documenting the cointegration among various energy variables and economic activity, has not reached a consensus on the direction of causality (Al-Iriani, 2006; Jokovak, 2018; Lee, 2006; Sharma, 2010; Soytas and Sari, 2003; Stern, 2000). This is as much the case for total energy consumption as it is for the composition of energy between renewables and non-renewables. Different studies, including Adams *et al* (2018) for sub-Saharan Africa, and Yasmeen *et al* (2022) for OECD countries, have arrived at different conclusions about how the various components of energy demand evolve during economic upturns and downturns.

Our paper takes a fresh look at the historical relationship between the business cycle and renewable energy by looking at major growth slowdown episodes, akin to the literature linking crises and emissions (Jalles, 2019). We use a much larger sample of countries over a longer period than previous studies. In addition, we focus on the impact of growth slowdowns on the trend evolution of the energy mix, rather than cyclical variations due to business cycle conditions. By focusing on major growth slowdowns and crises (including from major financial dislocations or pandemics), we improve the causal interpretation of the effect of economic activity on energy composition, as it is unlikely that the share of renewables affects the probability of the occurrence of a major slowdowns and crises (indeed, Granger causality tests reject the null that the energy mix affects the probability of such major dislocations).

Our investigation of the empirical relationship between the energy mix and recessions is not of course an exhaustive inquiry into the connections between growth and energy composition. Issues not covered in this paper include: how the effects of recessions differ from those of booms; whether higher or lower *trend* growth is favourable to the green energy share; differences in the causes of recessions, beyond the discussion in the paper of different measures of downturns (years of negative annual growth, peak-to-trough changes in GDP, crises, pandemics, etc), and how such differences influence the energy mix. The paper also does not provide direct firm-level evidence on creative destruction, but instead posits that the sustained greening of the energy mix in the aftermath of recessions is consistent with the creative-destruction narrative. The paper also does not delve into the optimal energy mix in a granular way from either an environmental perspective or a flexibility perspective (in response to changing demand conditions). These important issues are left for future research.

The remainder of the paper is structured as follows. Section 2 provides a brief overview of the literature on obsolescence and creative destruction, and provides intuition on how these trends interact with growth slowdowns and the use of renewables. Section 3 describes our data and empirical framework. Section 4 presents our results while Section 5 checks for robustness. Section 6 extends the analysis to assess the impact by type of economy and the role of supportive policy in the form of environmental protection stringency. The last section concludes.

2 Recessions, obsolescence, and policies

Recessions are associated with sharp declines in energy demand (Buechler *et al*, 2020). Lower demand in turn leads to excess electricity supply and, since the storage options for electricity are limited, power plants tend to be shut down. This is especially the case for dirty coal plants, because of their older technology and higher marginal cost of operation (including fuel costs).

Are such effects durable or ephemeral? After a crisis, will investment in old coal plants resume, or give way to investment in more efficient, greener plants? On the one hand, the disruption in financing during severe recessions may reduce innovation in new energy through less research and development, which is highly procyclical. On the other hand, recessions may give firms more reasons to improve their efficiency, leading to creative destruction.

The idea that units that embody the newest processes and product innovations are continuously being created, while outdated units are being destroyed, goes back to Schumpeter (1939, 1942)[1]. Industries undergoing continuous creative destruction can accommodate variations in demand in two ways: they can alter the rate at which production units that embody new techniques are created, or the rate at which outdated units are destroyed. The economic disruptions brought about by recessions act as a time of cleansing (see Caballero and Hammour, 1994), with faster obsolescence of outdated units amid lower demand and prices. In addition, the lack of demand created by recessions results in lower marginal costs of reallocating labour and capital (Davis and Haltiwanger, 1990; Aghion and Saint- Paul, 1998; Gali and Hammour, 1991; Hall, 1991).

A stark historical example of this effect was documented by Bresnahan and Raff (1991, 1993) in their study of the effect of the Great Depression on the motor vehicles industry. Using census panel data for the United States, they found that the large contraction in automotive production during the depression resulted in a permanent structural change. At the start of the Great Depression, the diffusion of mass-production techniques in manufacturing was small, with a substantial segment still based on skilled craftsmanship. But the plant shutdowns that occurred during the Great Depression because of lack of demand were concentrated in smaller, less-productive craftsmanship plants, while plants that had adopted the mass-production system maintained a competitive advantage that allowed them to survive. The result was a shakeout or 'cleansing' of the productive structure, as most plant shutdowns were permanent and the automotive industry that emerged afterwards was more reliant on mass-production and automation – a process that likely would have taken much longer without the destruction caused by the Great Depression. In addition, they noted that even during the deep process of plant shutdowns, a sizable number of new mass-production plants entered the industry. Similar evidence can be found from the Great Recession nearly eight decades later (see Pardo, 2016; Rembert, 2018).

[1] A rich body of research analyses the role of creative destruction in models of economic growth that embody technological progress (see, eg Johansen, 1959; Solow, 1960; Phelps, 1963; Sheshinski, 1967; Aghion and Howitt, 1992; Grossman and Helpman, 1991; Aghion *et al*, 2015).

Turning to the green energy sector, Peters *et al* (2012) found that when crises were triggered by energy shocks such as the 1970s and 1980s oil crises, they contributed to major improvements in the production of renewable sources of energy and energy efficiency. While this finding is not surprising, as the increase in the cost of fossil fuels would naturally boost energy efficiency and substitution toward renewables, they also argued that in times of crisis, countries tend to sustain economic output by supporting less energy-intensive activities.

The Global Financial Crisis also was associated with a significant increase in renewables (see UNEP, 2009; IEA, 2020). For example, researchers at the World Resource Institute found that *"U.S. solar electricity generation increased over 30 times from 2008 to 2015, and wind generation has increased over three times"*. Policy can be a powerful tool in boosting these underlying trends and assisting the transformation towards renewables (OECD, 2010). For example, the Climate Change Levy (CCL) introduced in the United Kingdom in 2001 is assessed to have had a strong negative impact on energy intensity and electricity use (see also Martin *et al*, 2011; Martin and Wagner, 2009). Similarly, in Spain, support for R&D and technological innovation is assessed to have led to higher investments in environmental protection, including in the use of renewable energy sources. Introduction of standards and charges for sulphur oxides in Japan during the 1960s and 1970s resulted in reductions in the levels of these pollutants and significant technological innovation. Ahmed (2020), using data for 20 OECD economies, found that more stringent environmental protection regulation (measured by the OECD EPS index) encouraged green innovation and provided an impetus for sustainable development. Wang *et al* (2022), using similar panel data techniques, found that environmental policies increased the renewable energy consumption in BRICS economies.

Bowen and Stern (2010) further argued that downturns provide a *"very good opportunity to undertake a necessary step change in the public spending component of environmental policies and to start working through a backlog of public investment to improve the environment"*. Drawing lessons from the Global Financial Crisis, Agrawala *et al* (2020) provided evidence that the implementation of timely and properly designed green stimulus measures can generate economic growth, create jobs and bring about environmental benefits. But they noted the trade-offs between competing economic, environmental and social policy objectives, underscoring the importance of proper policy design.

3 Data and estimation

The data on energy comes from the energy dataset maintained by *Our World in Data*, which is sourced from the *BP Statistical Review of World Energy*, with additional energy-consumption data from the SHIFT data portal, and electricity consumption and mix data supplemented from the EMBER global electricity dashboard. Data is available on overall primary energy use – a measure of energy as found in nature, for example blocks of coal, crude oil, natural gas, biofuels, nuclear, hydro, geothermal, solar or wind – and its subcomponents such as oil and coal, which is available for 176 countries from 1965 to 2021. In addition, we use data on the electricity shares generated from different sources, a measure of the energy mix – in particular electricity from fossil fuels, nuclear and renewable sources (including solar, wind, hydro) – which is available for a slightly smaller set of 172 countries over 1985–2021.

We analyse the impact of recessions – defined in the baseline as periods of negative annual real GDP growth – on overall energy use and the energy mix between green and dirty sources. While we use recession dummies (which capture periods of negative growth) in our baseline specification, we also check the robustness of our results using various other economic shocks. First, we look at the impact of financial crises from Laeven and Valencia (2020). Second, we explore the impact of pandemics using the data on major pandemic events – SARS in 2003, H1N1 in 2009, MERS in 2012, Ebola in 2014, and Zika in

2016 – from Furceri *et al* (2022). Third, instead of focusing just on periods of negative growth, we identify peaks and troughs, and thus peak-to-trough slowdowns, in economic activity using the Harding-Pagan algorithm applied to both annual real GDP and annual *per-capita* GDP. Finally, we test our results using changes in (log) GDP as opposed to negative-growth events.

The various economic data needed for our analysis is taken from the IMF's *World Economic Outlook* database, the World Bank's World Development Indicators and the Penn World tables. Environmental policy variables are taken from the EPS index dataset of the OECD (Botta and Kozluk, 2014). This data is the most comprehensive available source for policy measures across countries (28 OECD countries and a few large emerging market economies) and time (1990-2015). The dataset helpfully provides a breakdown by instrument type: (i) market-based measures, which include instruments such as taxation of emissions, trading schemes and feed-in tariffs; and (ii) non-market-based measures, including emission limits and R&D subsidies. The EPS varies from 0 (not stringent at all) to 6 (very stringent). Not surprisingly, the stringency of EPS is corelated with higher renewable shares in electricity generation and lower use of fossil fuels. In addition, EPS is strongly correlated with income levels, with more developed economies having higher environmental protection standards, on average.

To estimate the dynamic effects of recessions on energy use and mix, we use the local projection methods proposed by Jordà (2005) and estimate impulse response functions directly from local projections. Compared to the more traditional Vector Auto-Regression (VAR) approach, local projections allow for more flexible structural impulse response estimations by imposing weaker assumptions on the dynamics of the data. As a result, impulse responses from local projections have a lower bias than VARs (see Barnichon and Brownlees, 2019; and Li *et al*, 2022). Compared to VARs, the local projection method is also better suited to estimating nonlinearities in the dynamic response – in our context, how the response of renewable energy to recessions varies with the EPS index. We estimate the following specification:

$$\Delta e_{i,t+h} = u_i + \theta_h s_{i,t} + \sum_{\ell=1}^{2} \psi_{h,\ell} \Delta e_{i,t-\ell} + \sum_{\ell=1}^{2} \gamma_{h,l} s_{i,t-\ell} + \varepsilon_{i,t+h} \qquad (1)$$

where $e_{i,t+h}$ is the energy consumption variable, in country i at date $t+h$. This energy variable either enters the equation as the logarithm of energy use (in terawatt-hours) or as the share of different sources in total electricity in the case of the energy mix variables. u_i are country fixed effects, included to control for cross-country differences in energy consumption as well as unobserved country-specific time-unvarying characteristics. $s_{i,t}$ denotes the measure of growth slowdown, identified in most specifications as a dummy variable that takes the value of 1 during periods of negative GDP growth, or financial crisis, and zero otherwise. In the case of pandemics, we explicitly consider intensity of the event by using the number of cases normalised by population, and control for GDP growth which enters directly in the regression. We include lags of both the dependent variable and the recessions/crisis/shock variable to control for existing trends and provide robust estimates (see Montiel Olea and Plagborg-Møller, 2021). The baseline considers two lags, but the results are robust to different specifications of lags and leads.

Equation (1) is estimated for an unbalanced panel of 176 countries over the period 1965–2021, for each horizon (year) *h*=0,1, 2…8. The impulse response functions (IRFs) are computed using the estimated coefficient θ_h, with the associated confidence bands obtained using robust standard errors clustered at the country level. In the case of energy use, the θ_h coefficients can be interpreted as the change in consumption *h* years after the shock relative to a baseline of no growth slowdown. In the case of the energy mix variable, the coefficients capture the change in the share of renewables in total electricity *h* years after the recession relative to a baseline of no growth slowdown. We also estimate equation 1 for subsamples by income group – that is, advanced economies and emerging market and developing economies.

We do not include time dummies in our baseline specification because several major growth slowdown episodes and crises – including COVID-19 and the global financial crisis – are global in nature and time fixed effects would absorb their impact, which we want to explicitly capture. However, our baseline results are robust when we include both time dummies and a country-specific time $trend_i$ to capture trends in energy use or the share of renewables, as well as fluctuations in global fuel prices.

We use the smooth transition autoregressive model developed by Granger and Terävistra (1993) to test whether the effect of recessions on the share of renewables varies across different environmental policy regimes. This method allows the effect of recessions to vary smoothly across regimes by considering a continuum of states, thus making the IRFs more stable and precise than those obtained by estimating responses for each regime. Specifically, we estimate:

$$\Delta e_{i,t+h} = \mu_i + \theta_h^L F(z_{i,t}) * s_{i,t} + \theta_h^H (1 - F(z_{i,t})) * s_{i,t} \quad + \sum_{\ell=1}^{2} \psi_{h,\ell} \Delta e_{i,t-\ell} + \sum_{\ell=1}^{2} \gamma_{h,l} s_{i,t-\ell} + \sum_{\ell=1}^{2} \partial_{h,\ell} EPS_{i,t-\ell} + \varepsilon_{i,t+h} \qquad (2)$$

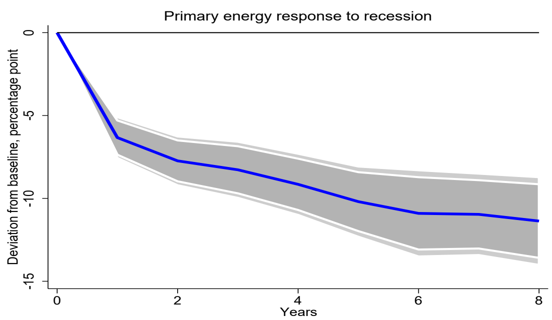
with $F(z_{it}) = \text{expfunction}\ (-\text{z}_{it})/(1 + \text{expfunction}\ (-\text{z}_{it}))$,

where z is the environmental protection stringency or its subcomponent, normalised to have zero mean and a unit variance (that is, $\frac{(EPS_{it} - \overline{EPS})}{sd\ (EPS_{it})}$, and $EPS_{i,t-\ell}$ is the corresponding lagged value of the measure). The weights assigned to each regime vary between 0 and 1 according to the weighting function $F(.)$, so that $F(z_{it})$ can be interpreted as the probability of being in each regime. The coefficients θ_h^L and θ_h^H capture the impact of recessions in cases of very low EPS ($F(z_{it}) \approx 1$) and very high EPS ($1 - F(z_{it}) \approx 1$), respectively.

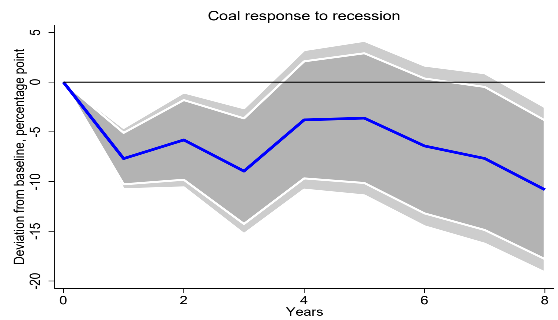
4 Results

Before moving to the core results on the effects of recessions on the energy mix, we present the results on the effect of recessions on energy use. As expected, and in line with previous research, we find that recessions are associated with a significant and permanent decline in energy use of about 10 percent (Figure 1). A similar pattern can be seen in specific sectors; coal and oil demand after a recession drops by around 5 percent and 8 percent respectively after five years, while electricity demand declines by around 7 percent. In addition to the effect on energy use, there is also a statistically significant reduction in energy intensity, defined as energy used per unit of GDP. Figure 2 shows that energy intensity declines durably after a recession. The initial decline in energy use is in line with the decline in output, resulting in no statistically significant change in energy intensity, but over time, as output recovers, energy intensity declines.

Figure 1: Impact of recessions on energy use



Note: Impulse response functions are estimated using a sample of 176 countries over the period 1965–2021 using equation (1). The graph shows the response and 95 and 90 percent confidence bands. The x-axis shows years after the event, with t=0 is the year of the recession.



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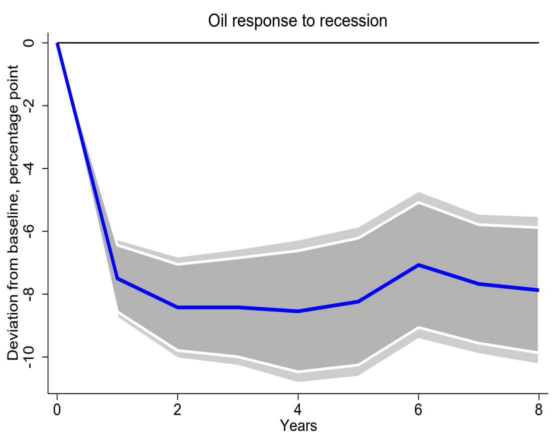

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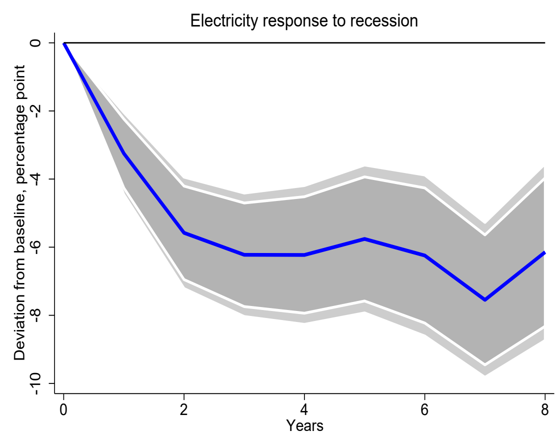

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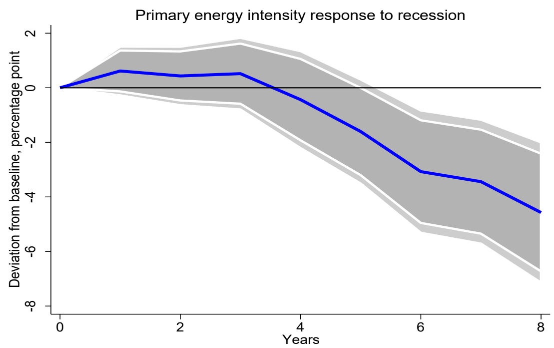
Figure 2: Impact of recessions on energy intensity



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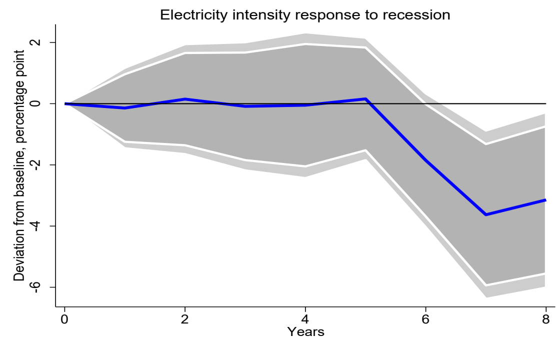

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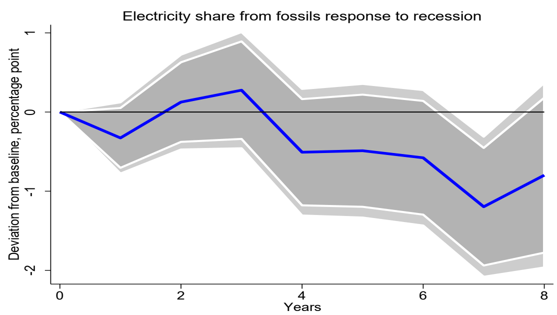
Having established the negative impact of recessions on energy use and intensity, we turn our attention to the energy mix and try to answer the following question: does the share of renewable energy increase durably after a recession? We find it does. Our main results, shown in Figure 3, suggest that after a typical major recession, during which GDP declines by 2.5 percent on average, the energy mix becomes greener, with the share of electricity generated from fossil fuels going down by about 1 percentage point after five years and the share of renewables going up by 2 percentage points. This effect is economically significant as it corresponds to about 40 percent of the standard deviation of the annual change in the share of renewable energy in our sample.

It is worth noting that the level of electricity generated by renewables (as opposed to the share) is resilient during recessions. And while overall energy intensity declines during recessions, renewables energy intensity actually increases. This reflects the fact that once built, renewables including hydro, wind and solar have very low marginal costs of operation and are generally used ahead of other sources of electricity. Renewables receive priority in the grid and are not asked to adjust their output to match a fall in demand for electricity. As a result, during recessions, when demand for energy is low and overall capacity utilisation falls, older power plants, primarily coal plants, are the first to be shut down given their high marginal cost of operation (fuel costs) and the relative inefficiency of the older technologies. Once demand recovers, investors choose not to restart these inefficient (and dirty) power plants and instead invest in newer and renewable technologies to meet the increase in demand for electricity. This is corroborated by the large increase in investment in renewable observed during the global financial crisis. Within renewables, the effects are larger for solar and hydro (Figure 4).

Figure 3: Changes in energy mix after recession



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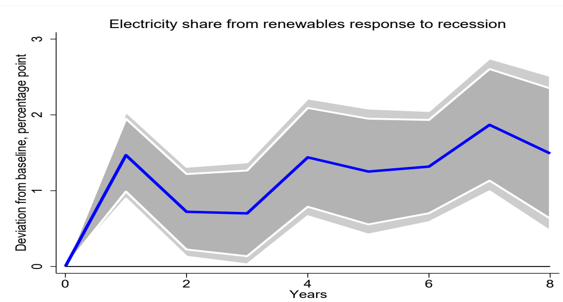

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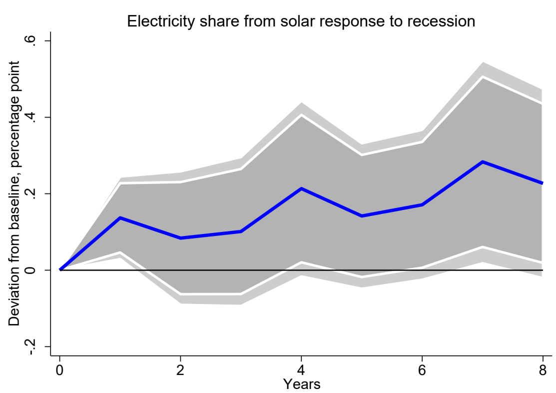
Figure 4: Impact of recession on renewables



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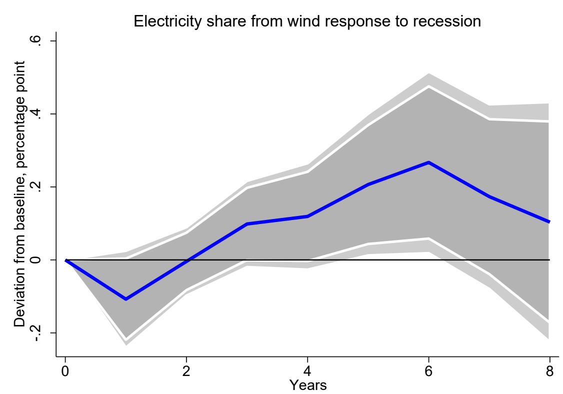

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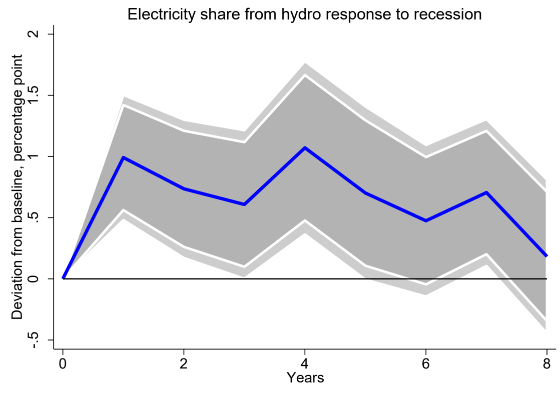

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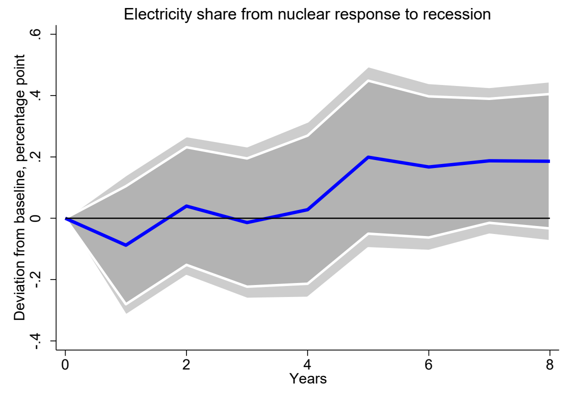

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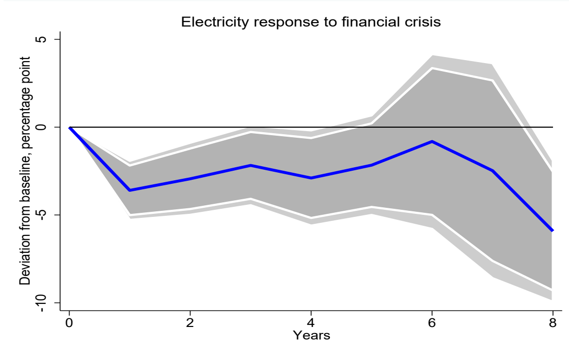
5 Robustness

Alternative measures of growth slowdowns

We check the robustness of our central result first by analysing different types of growth slowdown episodes. While Figures 3 and 4 are based on recession dummies in which annual growth is negative, in Figures 5 and 6, we look at the impact of financial crisis dummies, pandemics, peak-to-trough slowdowns (identified by the Harding-Pagan algorithm applied to both annual real GDP and annual *per-capita* GDP data) and simple GDP growth. Figure 5, top panel, shows that our results are similar in the case of financial crises to those obtained for recessions, with total electricity use declining by around 6 percent, and the share of renewables increasing by a little over 1 percent. Turning to pandemics (Figure 5 bottom panel), the impact takes longer to develop and is weaker. This can be explained by a lower initial energy demand from businesses being partially offset by higher demand from households due to lockdowns and increased work from home. Nevertheless, the impact on the energy mix remains positive, with an increase in the share of renewables.

We also look at the impact of growth slowdowns measured as the period after a growth peak to its trough. Our baseline results continue to hold, with a decline in overall energy demand and an increase in the share of renewables (Figure 6 top and middle panels). However, the results for the changes in the energy mix are somewhat weaker and less statistically significant, particularly for solar and wind energy. A likely explanation is that, in contrast to recessions and recoveries, prolonged periods of slow growth result in longer periods of lower investment generally, including in renewables, which are often more capital intensive and carry greater risk. Hydro, with its long gestation lag, is less affected. In addition, in the absence of the immediate shock from the recession (negative growth), the creative-destruction channel is likely to be weaker and more drawn out as well. As a final check, we also look at the impulse responses to GDP growth itself and find that the share of renewable energy is counter-cyclical (Figure 6, bottom panel).

Figure 5: Energy mix in the aftermath of financial crises and pandemics



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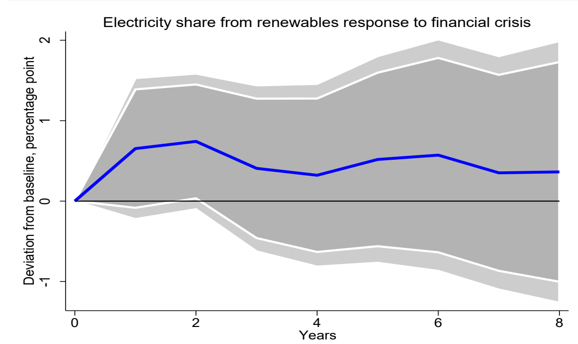

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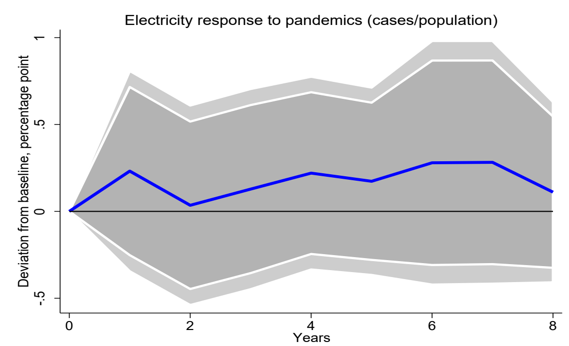

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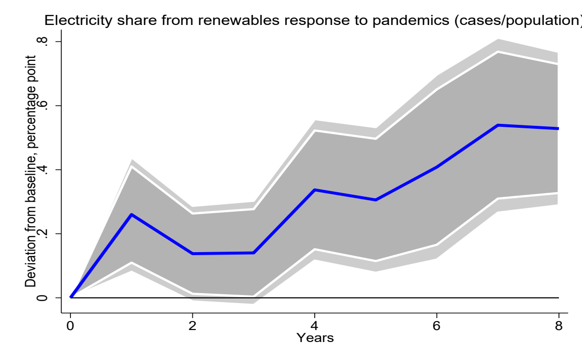
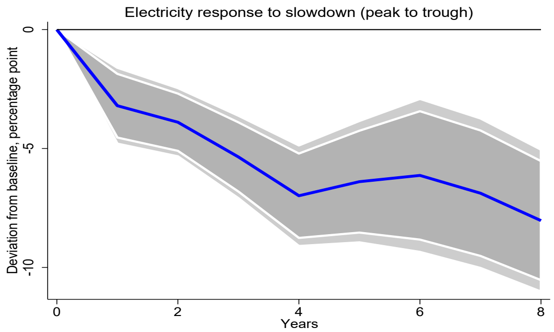
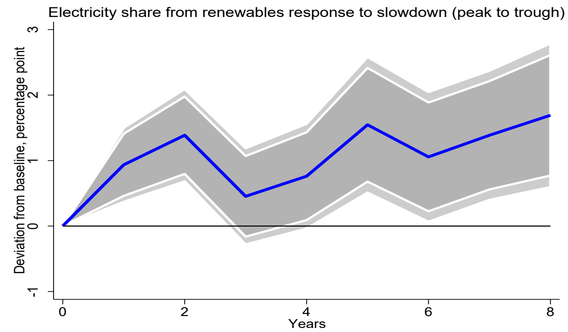


Note: Impulse response functions are estimated using a sample of 172 countries over the period 1985–2021 using equation (1). The graph shows the response and 95 and 90 percent confidence bands. The x-axis shows years after the event, with t=0 is the year of the recession.

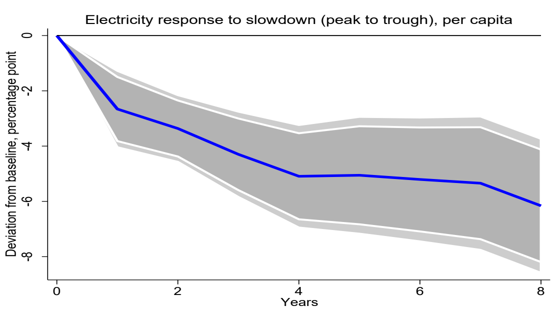
Figure 6: Energy mix in response to various types of economic slowdown



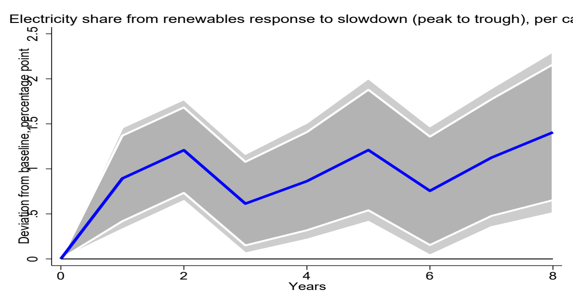
Note: Impulse response functions are estimated using a sample of 172 countries over the period 1985–2021 using equation (1). The graph shows the response and 95 and 90 percent confidence bands. The x-axis shows years after the event, with t=0 is the year of the recession.



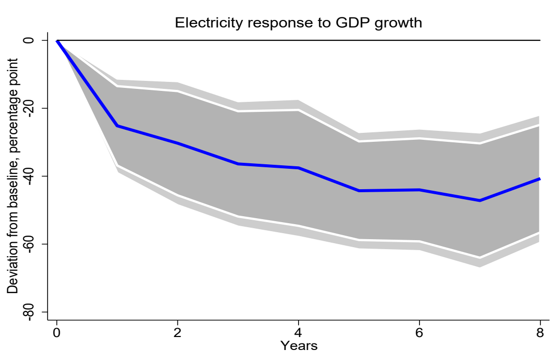
Note: Impulse response functions are estimated using a sample of 172 countries over the period 1985–2021 using equation (1). The graph shows the response and 95 and 90 percent confidence bands. The x-axis shows years after the event, with t=0 is the year of the recession.



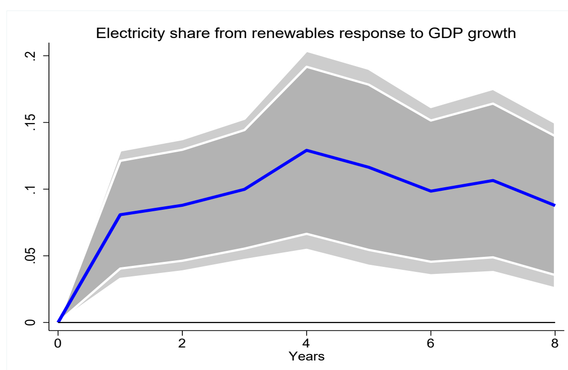
Note: Impulse response functions are estimated using a sample of 172 countries over the period 1985–2021 using equation (1). The graph shows the response and 95 and 90 percent confidence bands. The x-axis shows years after the event, with t=0 is the year of the recession.



Note: Impulse response functions are estimated using a sample of 172 countries over the period 1985–2021 using equation (1). The graph shows the response and 95 and 90 percent confidence bands. The x-axis shows years after the event, with t=0 is the year of the recession.



Note: Impulse response functions are estimated using a sample of 172 countries over the period 1985–2021 using equation (1). The graph shows the response and 95 and 90 percent confidence bands to changes in GDP growth (inverted).



Note: Impulse response functions are estimated using a sample of 172 countries over the period 1985–2021 using equation (1). The graph shows the response and 95 and 90 percent confidence bands to changes in GDP growth (inverted).

Alternative specifications

Our specification controls for lags of the shock and dependent variable – two lags of both the dependent variable and the recession dummy are included in the baseline. This said, our results are robust to alternative lag structures (up to eight lags of the dependent variable and the shock; up to eight leads of the shock). The baseline results continue to hold with these richer structures, which allow us to control better for pre-existing trends as well as the persistence of recessions.

As an additional robustness check, we control for lagged growth in our regression directly. The impulse responses and all our results continue to hold. While we do not include time dummies and country-specific trends in our baseline regressions, to avoid excluding global crises and pandemics from our analysis, all our results continue to hold if we include time dummies and are also robust to controlling for country-specific time trends. We conclude that our results are robust to controls for global shocks such as swings in fuel prices and technological changes that affect production costs, which are picked up by the time effects, but the effects are smaller than in the baseline (which reflect a combination of both global and country-specific recessions).

While we do not believe reverse causality drives our findings as the energy mix seems unlikely to affect the occurrence of a major recession, omitted variable bias where the omitted factors are correlated with major recessions and the energy mix remains a possibility[2]. To address this, we repeat the analysis to include the following set of additional controls: population growth, change in urbanisation, credit growth, investment growth, changes in the share of manufacturing in total value added, export growth. The inclusion of these controls does not affect our main results.

Another concern is that the results are picking up the effect of trends in the energy mix rather than the effect of the shocks *per se*. To address this, we checked the validity of the parallel trend assumption, that is, the assumption that the energy mixes in the treatment and control cases were following a parallel trend before the recession. We do this by running a placebo test where the impulse responses are computed by randomly assigning the date of the recession across the sample. Reassuringly, the impulse response functions obtained by attributing randomly recession dates do not point to any significant effect on the energy mix. In other words, the impulse response functions obtained in the baseline seem indeed to be capturing the effect of the shock rather than different energy-mix trends in countries experiencing a recession (treatment) and countries with no recessions (control)[3].

6 Country characteristics and environmental policy

Our baseline pools together all countries to provide the widest possible coverage. Although there is significant variance across counties in our sample, formal tests such as those proposed by Pesaran and Yamagata (2008) and Blomquist and Westerlund (2013) for slope heterogeneity do not reject the null of slope coefficient homogeneity. Nevertheless, we run the regressions separately for advanced economies and emerging market and developing economies (EMDEs) to ascertain whether the point estimates differ qualitatively between these two groups. The results suggest that the share of renewables in total electricity rises strongly in the case of advanced economies, but the results are weaker and quantitatively smaller in the case of EMDEs, though the difference is not statistically different across all horizons. One

[2] Granger causality tests suggest that lags of the energy mix do not predict the occurrence of major recessions.

[3] Intuitively, if the improvement in energy use and mix is driven by a trend and not any underlying dynamics associated with the shock (economic recession in the baseline), then we should find statistically significant results from assigning recession dates randomly.

possible explanation for these results is that most EMDEs lack the resources to make the costly investments in renewables-based energy and also have less stringent environmental-protection regulations, factors that can retard the use of greener sources of energy.

To formally test this point, we examine how the response of the share of renewable energy to recessions varies with the EPS index[4]. As noted earlier, comprehensive cross-country data on environmental-policy variables is only available for a limited set of relatively advanced economies and over a shorter period. We therefore begin our analysis by confirming that our baseline results hold for this more limited time sample: they do. Next, we introduce the environmental-policy variables into our baseline specification. In line with the literature highlighting the role of environmental policy stringency in accelerating environmental innovation (Ahmed, 2020; Hassan and Rousselière, 2021), Table 1 shows that both the overall EPS index and market and non-market EPS components are associated with a higher share of renewables in total electricity. In addition, the impact increases over time. In particular, we find that a unitary increase in the EPS indicator (such as took place in the United Kingdom in 2010 when various climate change policies were strengthened, including the introduction of feed-in-tariffs and inflation indexing of the CCL) is associated with a 3-5 percentage points boost in the share of renewable energy. This result has important implications as it suggests that climate polices can be effective in fostering the transition to a greener economy.

Next, we use the smooth transition autoregressive model in Equation 2 to assess formally the impact of EPS on the energy mix after a recession. Our headline result, shown in Figure 7, confirms that overall environmental protection stringency (EPS) can boost the transition towards renewable energy, with high EPS associated with an increase in the share of renewables in total electricity after a recession, while the effect is not statistically significantly different from zero in regimes with low levels of EPS. While on average, we find that a recession is associated with a 2 percentage points increase in the share of renewables, countries with high EPS see a much larger increase – essentially double at around 4 percentage points.

Digging deeper, we look at both market and non-market-based EPS. Market-based EPS measures comprise taxes on pollutants, trading schemes such as carbon trading, energy savings certificates and green energy certificates, and feed-in-tariffs for renewables. In contrast, non-market-based EPS include emission and fuel standards and R&D incentives and investments, including public investment (see Botta and Kozluk, 2014). We find that both market and non-market EPSs are associated with an increase in the share of renewables after a recession (Figure 8). These results are confirmed by looking more narrowly at specific measures (Figure 9). Higher emission and fuel standards are associated with a larger shift towards renewables after recessions. Particularly relevant for renewable electricity generation are feed-in-tariffs and trading schemes such as green certificates and white certificates[5].

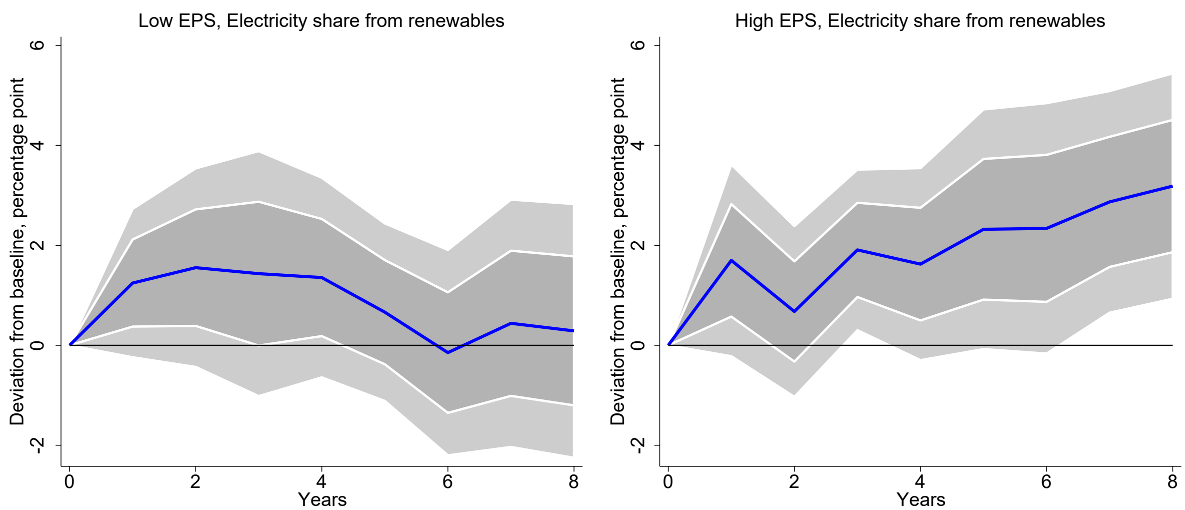
Finally, we look at the impact of non-renewable energy prices on the change in energy mix after a recession. Other things being equal, higher energy prices should tilt the balance in favour of renewables and make the energy mix cleaner over time. Given the global nature of oil prices, we use it as a proxy for overall energy costs and find that when recessions coincide with periods of high oil (and energy) prices,

[4] It is possible that a crisis triggers the adoption of more stringent EPS, which in turn affects the energy mix after the recession. We test for this and find that the effect of crisis on EPS is not statistically significant in our sample.

[5] A green certificate is an obligation, which can be traded, to source a given percent of electricity from green sources. White certificates are tradeable documents confirming energy saving, with more stringent policy associated with higher overall energy-saving targets.

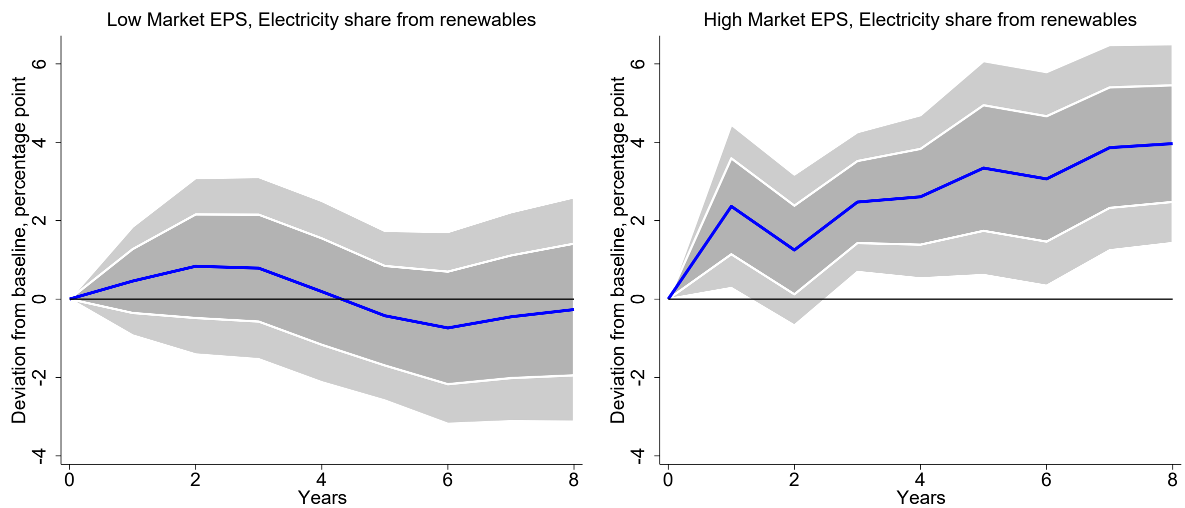
the impact is a quicker and more durable boost towards renewables (Figure 10). This is consistent with past experience, for example the oil shocks in the 1970s and 1980s, which contributed to major improvements in the energy mix and in energy efficiency.

Figure 7: Impact of environmental protection stringency (EPS) on post-recession energy mix

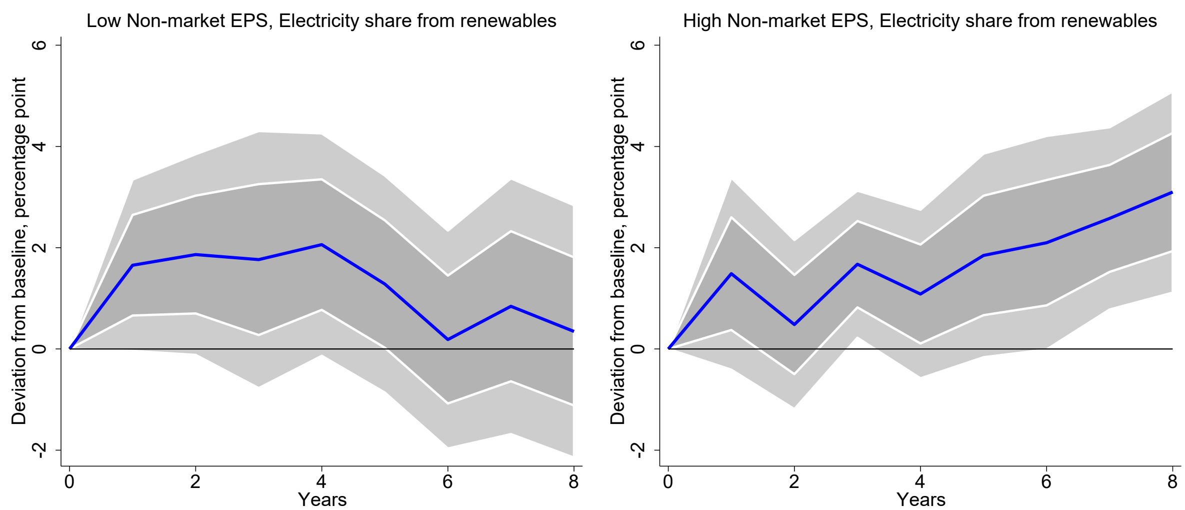


Note: Impulse response functions are estimated using a sample of 33 countries over the period 1985–2021 using equation (2). The graph shows the response and 95 and 90 percent confidence bands. The left panel denotes the low "regime" when $F(z_{it}) \approx 1$ and the right panel denotes the high `regime; when $(1 - F(z_{it})) \approx 1$. The x-axis shows years after the event, with t=0 is the year of the recession.

Figure 8: Impact on post-recession energy mix by type of EPS: market vs non-market measures

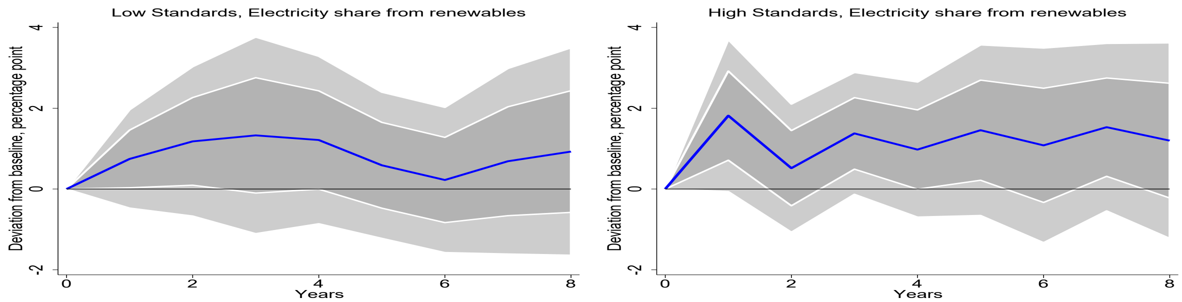


Note: Impulse response functions are estimated using a sample of 33 countries over the period 1985–2021 using equation (2). The graph shows the response and 95 and 90 percent confidence bands. The left panel denotes the low “regime” when $F(z_{it}) \approx 1$ and the right panel denotes the high ` regime; when $(1 - F(z_{it})) \approx 1$. The x-axis shows years after the event, with t=0 is the year of the recession.

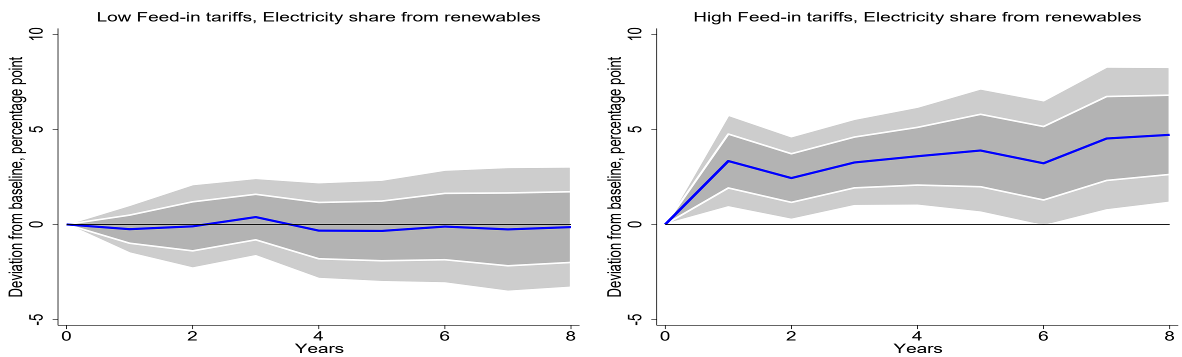


Note: Impulse response functions are estimated using a sample of 33 countries over the period 1985–2021 using equation (2). The graph shows the response and 95 and 90 percent confidence bands. The left panel denotes the low “regime” when $F(z_{it}) \approx 1$ and the right panel denotes the high ` regime; when $(1 - F(z_{it})) \approx 1$. The x-axis shows years after the event, with t=0 is the year of the recession.

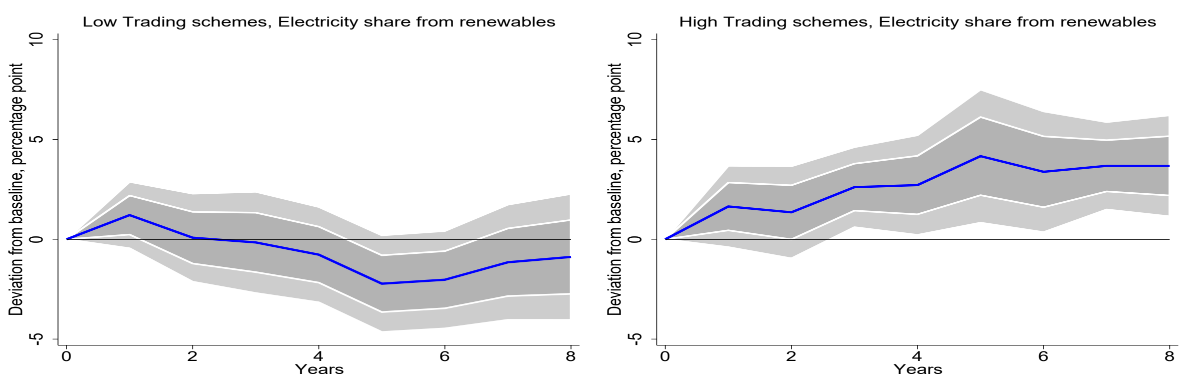
Figure 9: Post-recession energy mix by type of EPS: Standards, feed-in-tariffs, and trading schemes



Note: Impulse response functions are estimated using a sample of 33 countries over the period 1985–2021 using equation (2). The graph shows the response and 95 and 90 percent confidence bands. The left panel denotes the low "regime" when $F(z_{it}) \approx 1$ and the right panel denotes the high `regime; when $(1 - F(z_{it})) \approx 1$. The x-axis shows years after the event, with t=0 is the year of the recession.

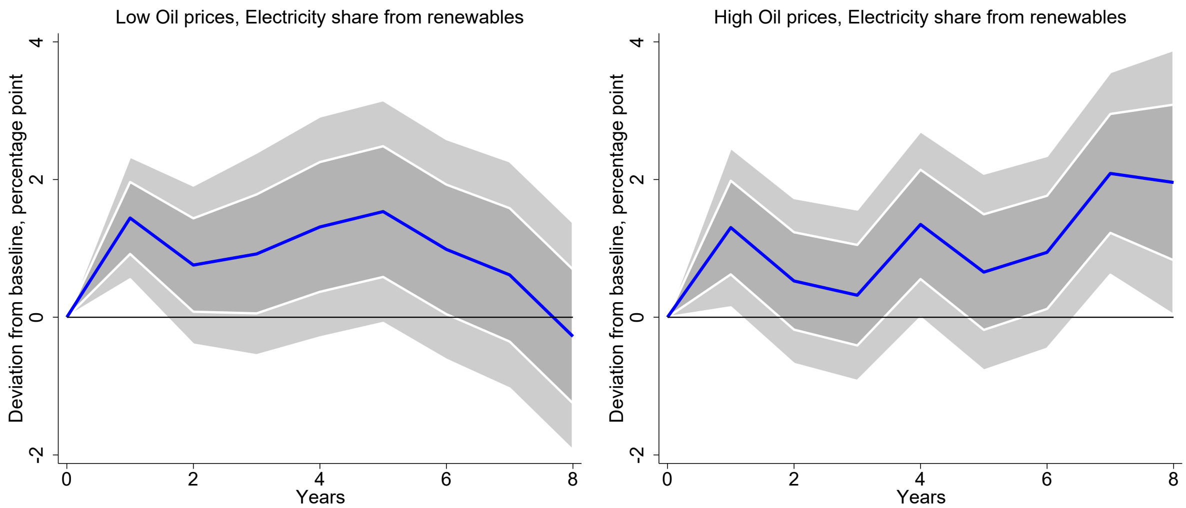


Note: Impulse response functions are estimated using a sample of 33 countries over the period 1985–2021 using equation (2). The graph shows the response and 95 and 90 percent confidence bands. The left panel denotes the low "regime" when $F(z_{it}) \approx 1$ and the right panel denotes the high `regime; when $(1 - F(z_{it})) \approx 1$. The x-axis shows years after the event, with t=0 is the year of the recession.



Note: Impulse response functions are estimated using a sample of 33 countries over the period 1985–2021 using equation (2). The graph shows the response and 95 and 90 percent confidence bands. The left panel denotes the low "regime" when $F(z_{it}) \approx 1$ and the right panel denotes the high `regime; when $(1 - F(z_{it})) \approx 1$. The x-axis shows years after the event, with t=0 is the year of the recession.

Figure 10: Impact on post-recession energy mix; role of world energy prices



Note: Impulse response functions are estimated using a sample of 172 countries over the period 1985–2021 using equation (2). The graph shows the response and 95 and 90 percent confidence bands. The left panel denotes the low "regime" when $F(z_{it}) \approx 1$ and the right panel denotes the high `regime; when $(1 - F(z_{it})) \approx 1$. The x-axis shows years after the event, with t=0 is the year of the recession.

Table 1: Electricity share from renewables after recession

VARIABLES	(1) 1 year	(2) 5 years	(3) 8 years	(4) 1 year	(5) 5 years	(6) 8 years	(7) 1 year	(8) 5 years	(9) 8 years
Recession	0.0138**	0.0136*	0.0174***	0.0147**	0.0153**	0.0212***	0.0145**	0.0149**	0.0165***
	(0.00606)	(0.00669)	(0.00530)	(0.00630)	(0.00679)	(0.00551)	(0.00584)	(0.00677)	(0.00551)
Lag 1	0.00321	0.00675	0.00463	0.00275	0.00774	0.00833	0.00258	0.00556	0.00464
	(0.00275)	(0.00546)	(0.00383)	(0.00270)	(0.00536)	(0.00503)	(0.00298)	(0.00599)	(0.00366)
Lag 2	0.00442	0.00741*	0.00466	0.00474	0.00786*	0.00716	0.00462	0.00803*	0.00614
	(0.00445)	(0.00402)	(0.00775)	(0.00459)	(0.00386)	(0.00902)	(0.00447)	(0.00426)	(0.00742)
Renewable share (Lag 1)	0.436***	0.365***	0.261	0.464***	0.445***	0.339*	0.441***	0.365***	0.251
	(0.103)	(0.113)	(0.180)	(0.103)	(0.125)	(0.195)	(0.105)	(0.113)	(0.177)
Lag 2	0.393***	0.427***	0.362	0.407***	0.448***	0.385	0.385***	0.402***	0.344
	(0.0848)	(0.128)	(0.232)	(0.0879)	(0.143)	(0.256)	(0.0829)	(0.122)	(0.225)
Overall EPS (Lag 1)	0.00290	0.0277***	0.0485***						
	(0.00449)	(0.00569)	(0.00982)						
Lag 2	0.0153***	0.0174***	0.0124*						
	(0.00538)	(0.00551)	(0.00660)						
Market EPS (Lag 1)				0.00507**	0.0239***	0.0378***			
				(0.00242)	(0.00635)	(0.00837)			
Lag 2				0.0120***	0.0176**	0.0164***			
				(0.00295)	(0.00651)	(0.00575)			
Non-market EPS (Lag 1)							0.00427	0.0207***	0.0343***
							(0.00423)	(0.00483)	(0.00625)
Lag 2							0.00957**	0.0148***	0.0141***
							(0.00460)	(0.00447)	(0.00387)
Constant	0.0177	0.00345	0.0380	0.0178	0.00615	0.0498	0.0182	0.00719	0.0401
	(0.0203)	(0.0487)	(0.0814)	(0.0216)	(0.0535)	(0.0883)	(0.0196)	(0.0475)	(0.0799)
Observations	708	692	627	708	692	627	714	698	633
R-squared	0.609	0.601	0.500	0.594	0.540	0.407	0.603	0.587	0.489
Number of countries	33	33	33	33	33	33	33	33	33

Dependent variable is the share of renewables in electricity generation. Robust standard errors clustered at the country level. *** p<0.01, ** p<0.05, * p<0.1

Table 2: Summary statistics

VARIABLE	Period		Full Sample			AEs			EMDEs			Unit	Source
	Start	End	Observations	Mean	Standard Deviation	Observations	Mean	Standard Deviation	Observations	Mean	Standard Deviation		
Energy Data													
Primary Energy	1965	2021	6,895	4.17	2.48	1,707	5.91	1.85	5,188	3.60	2.39	Terawatt-hours, logs	Our World in Data
Coal	1965	2021	3,244	3.34	2.79	1,607	3.70	2.57	1,637	2.99	2.95	Terawatt-hours, logs	Our World in Data
Oil	1965	2021	3,541	5.18	1.43	1,633	5.33	1.59	1,908	5.05	1.26	Terawatt-hours, logs	Our World in Data
Electricity	1985	2021	4,464	2.57	2.50	1,212	4.07	1.87	3,252	2.01	2.47	Terawatt-hours, logs	Our World in Data
Electricity share from													
Fossil Fuels	1985	2021	3,966	62.6%	33%	1,015	55.3%	32%	2,951	65.1%	33%	Percent	Our World in Data
Renewables	1985	2021	4,365	31.8%	33%	1,156	28.7%	30%	3,209	33.0%	33%	Percent	Our World in Data
Solar	1985	2021	4,365	0.5%	2%	1,156	0.7%	2%	3,209	0.4%	2%	Percent	Our World in Data
Wind	1985	2021	4,365	1.2%	4%	1,156	2.9%	7%	3,209	0.6%	2%	Percent	Our World in Data
Hydro	1985	2021	4,365	27.4%	31%	1,156	21.7%	29%	3,209	29.4%	32%	Percent	Our World in Data
Nuclear	1985	2021	4,365	5.5%	14%	1,156	15.7%	21%	3,209	1.8%	8%	Percent	Our World in Data
Shocks													
Recession	1965	2021	6,895	0.15	0.36	1,707	0.12	0.32	5,188	0.16	0.37	Dummy variable	IMF WEO
Financial Crisis	1965	2021	6,757	0.05	0.22	1,638	0.03	0.17	5,119	0.06	0.24	Dummy variable	Laeven and Valencia, 2020
Pandemics	1965	2021	6,391	0.15	0.91	1,565	0.16	1.04	4,826	0.15	0.86	Cases/population	Furceri et al, 2020
Peak to trough	1965	2021	6,895	0.24	0.43	1,707	0.21	0.41	5,188	0.26	0.44	Dummy variable	IMF WEO
Peak to trough, per capita	1965	2021	6,895	0.38	0.49	1,707	0.28	0.45	5,188	0.42	0.49	Dummy variable	IMF WEO
GDP growth	1980	2021	5,983	3.3%	6%	1,328	2.7%	3%	4,655	3.5%	6%	Percent	Penn Tables

8 Conclusions

This paper explores the historical relationship between growth slowdowns and energy use to identify systematic and permanent shifts inherent in the pattern of recoveries from recessions. The empirical analysis confirms that growth slowdowns, including those engendered by pandemics and financial crises, result in permanent increases in energy efficiency and a corresponding decline in the energy intensity of output, with a disproportionate impact on dirty energy. These effects are stronger in the presence of more stringent environmental policies that incentivise the shift towards renewable energy. Our results confirm that both non-market-based policies in the form of emission and fuel standards, R&D incentives and subsidies and public investments, as well as market-based measures such as trading schemes for carbon, renewable energy certificates and energy saving certificates, can be effective in boosting the transition towards renewables. As noted by the OECD, taxes and other environmental policy instruments can complement each other. And even though renewable sources of electricity are becoming cost-competitive with fossil fuels and nuclear power, and will soon no longer need subsidies, policies such as carbon pricing and more stringent climate policy can encourage demand for renewable energy and help to meet ambitious climate targets.

Although climate change and clean-energy policies can entail political costs in the form of opposition from both energy-using industries and the public at large, these costs can be mitigated if the design of environmental policies internalises political economy considerations and if complementary policies are deployed to protect vulnerable households. Although the transition to renewables might be socially less costly during boom times – it is easier for obsolete power plant workers and coal miners to find new jobs during a boom – it still requires measures that may be unpopular with voters (taxes or standards) to close a power plant during a boom when energy demand is high. And while recessions are events that are far from desirable and should be avoided through macro management policies, when they do occur, they provide a silver lining in the form of creative destruction, offering an opportunity to foster reforms to achieve a more resilient and greener recovery

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