Energy Economics 148 (2025) 108616

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

The evolution and implications of national energy cost shares

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ARTICLE INFO

Keywords:
Energy cost share
Energy income share
Energy subsidies
Energy Intensity
Energy price elasticity
Energy efficiency
carbon price

ABSTRACT

Energy cost share is a key indicator to assess the importance of energy in an economy, to highlight the potential exposure of energy-importing countries to international price shocks, and to understand the implications from introducing carbon pricing or energy subsidies reforms. We construct a global dataset to study the evolution of national energy cost shares over time and their relationship with energy prices. On these data we estimate a theoretically grounded econometric model and we obtain a wide set of findings that have important implications for policy. The main findings are that economies have a strong capacity to adapt to higher energy prices through technological innovation, but the time for this adjustment can be very long; the ability to reduce energy intensity in response to higher energy prices has improved over time; both energy efficiency policies and certain macroeconomic characteristics can help in facilitating the adjustment avoiding an excessive increase in energy cost share.

1. Introduction

A declining ratio of energy expenditure to GDP, known as energy cost share or energy income share, is widely considered a stylized fact in the energy literature, though long-run empirical studies have documented it only for Sweden and the UK over 1800–2009, and the USA in 1950–1998 (Csereklyei et al., 2016; Jones, 2002; Stern and Kander, 2012). Understanding the determinants of this long-run behaviour requires first of all an analysis of the relationship between energy cost shares and energy prices. At one end of the spectrum we have the possibility that a given change in energy prices translates directly into an equivalent increase in energy cost shares – which implies an elasticity of energy cost shares with respect to prices equal to 1. This is equivalent to assuming no response of energy demand to prices, which is not supported by the literature on price elasticities (Labandeira et al., 2017). At the opposite extreme of the spectrum, energy cost shares are posited to be constant in the long run, a hypothesis introduced by Bashmakov (2007) and consistent with earlier cross-country analysis in Newbery (2003) and other conclusions mainly based on OECD data.[1]

The interest of macroeconomists and policymakers in energy cost shares is motivated by several considerations, given the critical role of energy for economic activity and the daily lives of citizens. High energy costs have implications for economic growth and inflation, especially when they are the result of sudden supply shocks to the economy, as in the 2022 crisis (World Bank, 2022). Energy cost shares are therefore a key indicator to measure the economy's dependence on energy, the overall sustainability of economic growth, and its vulnerability to variations of its price. High energy costs, in Europe but also in many emerging markets and developing economies (EMDEs), have recently been under scrutiny with a number of policies introduced by governments to shield households and firms (Sgaravatti et al., 2021).

Energy cost shares are also important in the context of energy subsidies, which have several negative consequences related to distortions of relative prices, increasing energy consumption and environmental impacts, reduction of incentives for the adoption of alternative energy sources and energy efficiency, misallocation of resources towards those sectors benefitting the most from reduced energy prices, and increasing public deficit leading to higher levels of debt or higher taxation, with

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[1] This hypothesis has also been presented in terms of an *economically sustainable* range of energy cost shares, with these tending to rebound and move in the opposite direction if they approach either boundary of the range. The range has been estimated to be between 5.7% and 8.7% of GDP by (Bashmakov et al., 2024), for developed economies, including former centrally-planned countries of eastern Europe.

https://doi.org/10.1016/j.eneco.2025.108616
Received 12 July 2024; Received in revised form 31 March 2025; Accepted 13 May 2025
Available online 22 May 2025

related negative impacts on economic growth (Koplow and Dernbach, 2001; Plante, 2014; Yau and Chen, 2021).[2]

From a policy perspective, the response of energy cost shares to the variation in energy prices is relevant to understand how direct or indirect carbon pricing (Agnolucci et al., 2024a; Agnolucci et al., 2024b; Organisation for Economic Co-operation and Development OECD, 2022) can incentivize changes in technologies, capital stock, economic structure, and consumption behaviour, which enable the realization of climate targets. Like in the case of energy subsidy reforms, efforts to increase energy prices by introducing environmental taxes can be met with public reaction and political pushback in both EMDEs and advanced economies (AEs) (Lee, 1994, OECD, 2006, Skovgaard et al., 2019). Studying how energy cost shares respond to energy prices helps us understand to what extent an economy or a specific sector is affected by various policies related to energy pricing, taxation, or carbon pricing. But it also helps inform the design of pricing policies and additional measures that can support their implementation, such as measures aimed at compensating those who are worst impacted.

In this paper we conduct a comprehensive study of the global evolution of energy cost shares and its relationship with energy prices. We construct a new global dataset of annual time series of national aggregate measures related to the energy consumption of 142 countries, both EMDEs and AEs, over a period of 40 years, from 1980 to 2019. As a first step, we perform a descriptive analysis of these data and we identify three interesting empirical patterns: a complex relationship between energy cost shares and energy prices which depends on the time horizon of interest and the historical period considered; a substantial heterogeneity in the correlation between energy cost shares and energy prices across groups of countries depending on the income level; an important heterogeneity in the same correlation across different sectors of the economy.

In the second part of the paper, we develop an econometric model that is grounded in standard growth theory to shed light on the underlying determinants of those empirical patterns. Then, we extend the model to study the potential influence of national energy efficiency policies, as well as the importance of key structural characteristics of the economy. Finally, we offer a rich discussion of the wide implications of these findings for policies that aim at removing energy subsidies or introducing carbon taxes.

We obtain several interesting findings, which are robust to different technical changes, such as the dynamic specification of the model, the instruments set used in the GMM estimation, and the treatment of the global trend. First, we uncover that while the price elasticity of energy cost shares is high in the short run, it declines considerably over the long run buffering energy cost share from more than half of any energy price increase. Second, we find that the price elasticity of energy cost shares has declined substantially in more recent year. Using our theoretical framework we attribute this decrease to the impact of induced technological change that doubled the implied elasticity of substitution between energy and the other production inputs. Third, we obtain that energy cost shares decline only very gradually as the aggregate level of economic activity increases in the long run. Fourth, we calculate that it takes a long time for energy intensity to fully adjust to an increase in energy price, which is consistent with the decades-long lifetime of existing capital stock. Fifth, we obtain that energy efficiency policies can enhance and accelerate the structural adaptation to higher energy prices. Sixth, we estimate that higher economic growth, financial development, and human capital are associated with higher speed of adjustment and a stronger offsetting response of energy intensity.

The structure of this paper is the following. In Section 2, we describe our dataset and illustrate the historical empirical patterns in energy cost shares and prices. In Section 3, we explain the methodological aspects of our modelling approach. In Section 4, we present our main results on the relationship between energy cost share and energy price, as well as the influence of energy efficiency policies and a number of national economic factors on this relationship. In Section 5, we discuss the main implications of this econometric analysis for energy subsidy reforms and carbon pricing. In Section 6 we draw some general conclusions.

2. A new dataset on energy consumption

We build a new global dataset of annual time series on national aggregate measures related to energy consumption for a total of 142 countries, both developed and developing economies, covering a period of 40 years from 1980 to 2019. In this section, we first describe in detail how each variable is constructed, and then we present some interesting empirical patterns that emerge from a preliminary descriptive analysis of the data. These empirical patterns will serve as the starting point and the motivation for our econometric investigation.

2.1. Definition of the variables

National energy cost shares are calculated by dividing the product between total energy consumption and average energy price by the level of aggregate economic activity. Energy consumption and price data were collected for fuels consumed in most of the sectors of a given economy and aggregated to compute total energy consumption, and related energy price. Consumption for the following fuel is included in the dataset used in this study: coal, diesel, electricity, gasoline, kerosene, LPG, natural gas and other oil products. The following energy-consuming sectors are covered by this analysis: industrial, residential, public administration and services, and transport. Energy data were taken from the energy balances of International Energy Agency publications, as described in Appendix A. It is worth mentioning that biomass used in the energy system is not covered by this study, as data on its consumption are very limited while data on price are not included in the source we had access to in this study. This is a common limitation for empirical studies of energy demand using data from the International Energy Agency or similar data providers.

Annual retail prices for the fuels included in this study are sourced from the datasets collected by the International Monetary Fund and the World Bank, also described in Appendix A. These datasets contain information, disaggregated by fuel and by sector, on retail fuel prices, incorporating all taxes, including VAT or sales tax, and subsidies. As an example, in the case of gasoline, the price data used in this study is the average price 'at the pump'. The primary sources of this dataset are the IMF and World Bank country desk datasets. For cases where such data were not available, a number of other sources were used as discussed in Appendix A. Prices were converted into nominal US dollars per ton of oil equivalent (TOE) by using standard conversion factors. All monetary variables, such energy price and economic activity, are measured in international (Purchasing Power Parity or PPP) dollars.

The impact of energy efficiency *policies* is assessed using energy efficiency indices from the Regulatory Indicators for Sustainable Energy (RISE) dataset. This study uses the overall indicator for energy efficiency, as well as 11 detailed sub-indicators, which are comprised in the overall indicator. RISE indicators range from 0 to 100, with higher values indicating higher level of factors expected to lead to higher energy efficiency. These eleven sub-indicators include national energy efficiency planning (indicator $EnEff_1$ below), energy efficiency entities ($EnEff_2$), incentives and mandates for industrial and commercial end

[2] Empirical evidence overwhelmingly supports the existence of a long-run negative impact of public debt on GDP, and in many cases the impact becomes more pronounced as debt increases (de Rugy and Salmon 2020; Eberhardt and Presbitero, 2015.) Similarly, the impact of taxes on economic growth is highly non-linear, with negative impact of tax increases becoming increasingly negative as the tax rates increase (Gunter et al.2021)The impact is influenced not only by the overall level of the taxation but also the type of taxation (Arnold, 2008**,** Nguyen et al.2021).

users ($EnEff_3$), for public sector users ($EnEff_4$) and for utilities ($EnEff_5$), financing mechanisms for energy efficiency ($EnEff_6$), minimum energy efficiency performance standards ($EnEff_7$), energy labelling systems ($EnEff_8$), building energy codes ($EnEff_9$), measures for the transport sector ($EnEff_{10}$), and those relate to carbon pricing and monitoring ($EnEff_{11}$). Finally, this study assesses the heterogeneity of the relationship between energy cost shares and prices by using data related to the stage of economic development, the degree of financial development, the human capital index, the oil trading status, the degree of dependence on energy imports and the level of net energy consumption taxes, from the data sources mentioned in Appendix A.

2.2. Empirical patterns

We identify at least three key empirical patterns in the combined dynamics of energy cost shares and energy prices that are worth discussing. The first empirical pattern is what appears to be a close co-movement in these two variables, but in fact reveals some interesting complications when we distinguish different time horizons and different historical periods.

In Fig. 1 we plot the cross-country average of the energy cost share over the full 40-year period from 1980 to 2019, for the 90 countries that have data available during this period, alongside the average (consumption-weighted) real energy price.[3] As expected, there is a strong short-term positive co-movement between energy price and energy cost shares (Fig. 1a), but the strength of this co-movement varies over time, as previously observed in Hassler et al. (2021), Saunders et al. (2021), and Smulders and de Nooij (2003). In particular, it is very evident that the average cost share fell alongside the largely falling energy price in the first half of the period until year 2000. In the second half, apart from an initial, the average energy cost share decreased while the average energy price remained largely stable. This decoupling between the energy cost share and the energy price occurring in the second half of the sample is very much reflected in the correlation between the two variables, which fell from 0.91 in the first half of the sample (1980–1999) to only 0.55 for the remaining half (2000–2019).

Over the short term, when price increases cost share follows – as an example, average country cost shares increased by more than 50% between 1998 and 2008 driven by prices increasing by about 60% (Fig. 1a) – but even though end-use energy prices, in international (PPP) dollars, were significantly higher by 2008 than in the early 1980s, the corresponding cost shares were lower. In fact, a downward trend in the energy cost share relative to energy prices becomes evident, as shown in Fig. 1b. Given a price of approximately 1200 real international \$/TOE, energy cost shares decreased from 10.3% in 2005 to 8.7% in 2015. From the opposite perspective, energy cost share with a value near 9% was observed in 1986, 2001 and 2018 when energy prices were about 870, 1050 and 1300 international \$/TOE. Changes in energy intensity, driven mainly by changes in both energy efficiency and the structure of the economy, have counteracted the impact of rising prices. From Fig. 1b it emerges quite clearly that the correlation between the average energy cost share and energy price is undoubtedly positive in the short term, but maybe not over the long run.

The second empirical pattern that arises from our dataset is the hint that the relationship between energy cost shares and prices may be very heterogeneous across different groups of countries. As can be seen in Fig. 2, a positive but small correlation emerges between average national energy cost shares and energy prices in high-income countries, as highlighted in World Bank (2024). With a value of 0.20 for the correlation between average national cost shares and energy prices, this reflects the finding of roughly constant energy cost share for industrialized countries in Newbery (2003) and Bashmakov (2007), and updated in Bashmakov et al. (2024).

On the other hand, a much starker positive correlation is obtained in the case of lower-middle-income and low-income countries ('LMLI' in the figure), with a correlation between average national cost shares and energy prices equal to 0.43. It is also interesting to see that energy cost shares in medium and low income countries tend to be higher than in high-income economies.

The heterogeneity in the above relationship reflects the host of factors that can facilitate the decoupling of energy cost shares from the positive correlation pointed out in Fig. 1, including 1) technological progress, which is normally energy-saving; 2) changes in the composition of the economy, at least for some countries, in the direction of less energy-intensive economic activities; 3) different size of the response of energy consumption to changes in energy prices as conveyed by price elasticities; 4) impact of international trade[4]; 5) introduction of policies aimed at increasing energy efficiency, delivering energy security, or more recently fighting climate change.

In Fig. 3, the two largest countries (China and the US) reflect to varying degrees the global trend in Fig. 1a, with cost shares declining over the 1980–2000 timespan. The immediate price impact of major structural price reforms in China and India, followed by their long-run impact on national energy intensity and therefore on energy cost shares, is particularly clear. China displays a negative relationship between energy cost shares and prices for the great majority of the timespan covered by this study, resulting in a correlation of −0.46. Like in China, energy cost shares and prices completely diverged in India but only from 2005 onwards: when the energy price almost doubled in the 1990s the energy cost share also increased, resulting in an overall correlation of 0.53. On the other hand, Italy appears to have struggled to improve its energy intensity, as reflected by the energy cost share closely tracking the movement in price, as supported by the correlation being 0.99, whilst in Saudia Arabia the relationship between energy costs shares and prices was less strong, resulting in a correlation of 0.57.

The third empirical pattern emerging from the dataset is the considerable heterogeneity in the co-movement between energy cost shares and prices across economic sectors within any given country, particularly over the long term. This is most likely due to the different substitution possibilities across sectors, and possibly also to the varying strength of some relevant economic factors influencing the relationship between energy costs shares and prices (Agnolucci et al., 2017). This heterogeneity between sectors will also contribute to the heterogeneity observed at the country level (as depicted in Fig. 3), as the sectoral structure differs between countries. As an example, Fig. 4 shows the relationship between the energy cost share and price for the industrial,

[3] Note that the energy price here, though strongly influenced by the large fluctuations in international oil prices, is a consumption-weighted average of end-use pries in the 90 countries covered in the diagram. Notably, in real terms the international oil price around 2010 (in real US \$) was similar to the peak reached in 1979 / 1980, but the consumption-weighted average illustrated in Figure 1 indicates a substantial increase. This may be due to reduction in substitute, introduction of consumer taxes (excise duties and carbon pricing), and the impact of PPP adjustments in our dataset.

[4] As the period covered by this study is characterized by growing globalization and the rise of industrial activity in China decreasing energy cost share in some countries might have taken place through the relocation of energy intensive firms to countries with lower energy prices. This relates to the so-called pollution-haven hypothesis, though of course other factors affected both energy price, and relocation during the era of globalization (most obviously, labor cost differentials). OECD (2019) points out that trends in carbon emissions embodied in trade suggest that a subset of countries specialize in economic activities that are consistent with the existence of pollution havens, but it falls short of a proof, and evidence of 'carbon leakage' caused by carbon pricing to date is very tenuous as reviewed by the IPCC (IPCC, 2022, Chapter 14).. Increasing manufacturing exports from China during the period covered by the dataset used in this study is not correlated to increasing national energy cost shares, as shown in Figure 3a. OECD (2019)

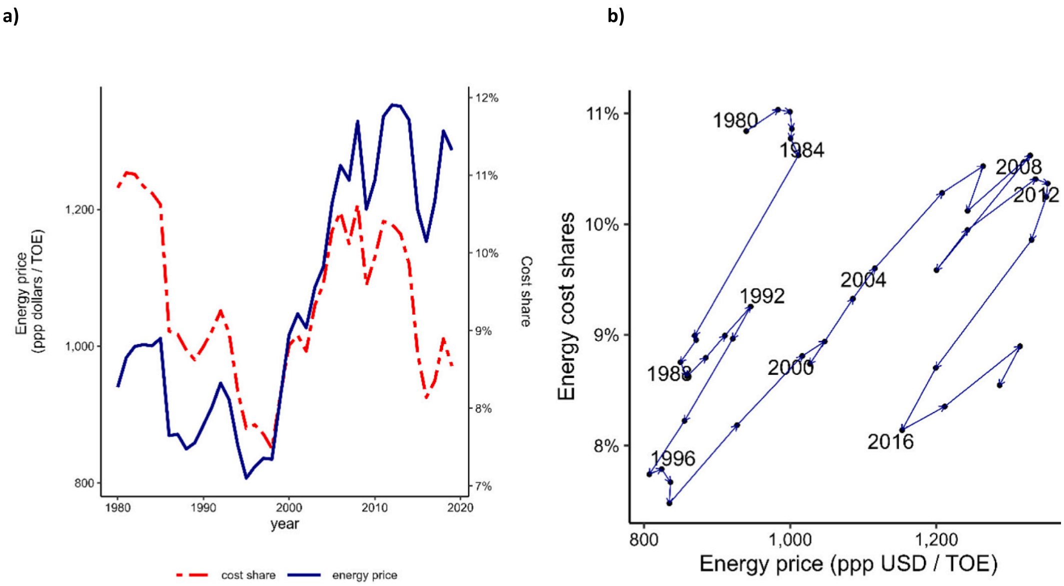

Fig. 1. Global end-use energy prices and cost shares. Energy prices are weighted by energy consumption across countries. Monetary figures are expressed in real international dollars. The data in these figures incorporate energy cost shares and prices for which data are available from 1980 to 2019 to ensure comparability between data points across the whole period. This comprises 90 countries, of which two thirds are non-OECD countries.

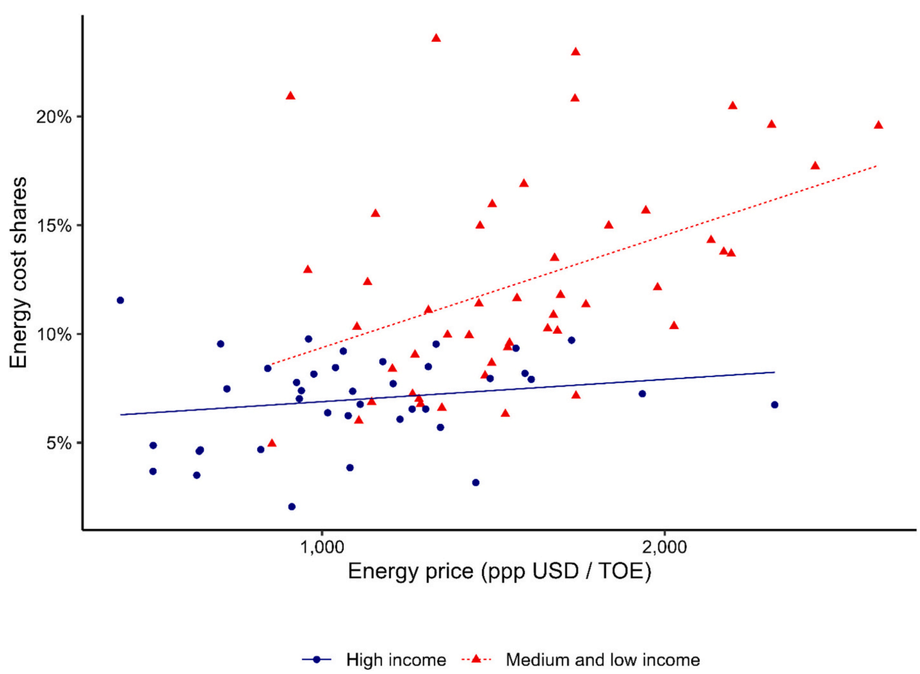

Fig. 2. Relationship between average national energy prices and energy cost shares. Each dot represents the combination of average cost share and average energy price across time for a specific country. This figure plots the same subset of countries as in Fig. 1. The value of the R2 for the two regression lines plotted in this figure is 0.04 and 0.19 for the high income, and the medium and low income countries, respectively.

transport, and residential sectors in China alongside the relationship for the whole economy. It becomes apparent that in the case of China, the negative correlation between the national energy cost share and price is largely driven by the industrial sector, which is the most important energy consumer.

3. Research approach

To investigate the underlying determinants of some of the empirical patterns described in the previous section we estimate a model of the energy cost share that is grounded in the traditional growth theory. In the following subsection, we use a simple model of the aggregate production function where energy enters as an input to derive its optimal demand as a function of energy price. The insights from this theoretical analysis will be useful in two respects, to underpin the specification of the econometric model that we will estimate on the data and to provide a theoretical framework to interpret our empirical results.

3.1. Theoretical framework

Consider an economy in which aggregate production is described by a standard CES function

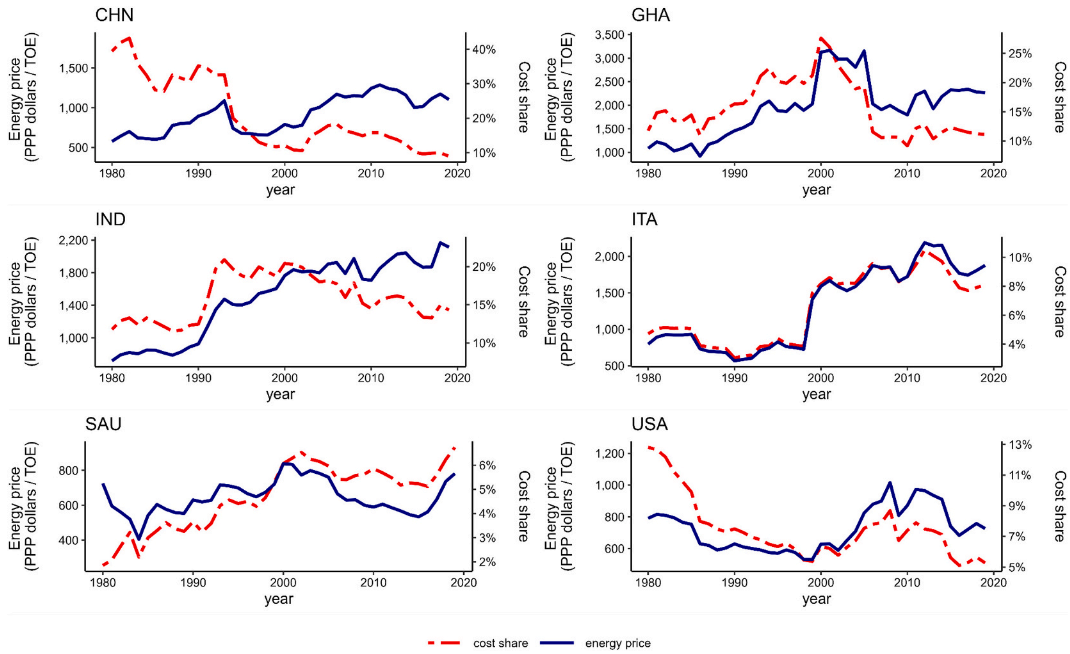

Fig. 3. Time pattern of energy price and cost share for selected countries. Monetary figures are expressed in international USD by using PPP conversion factors. The range in the vertical axis reflects the values of the specific time series being plotted.

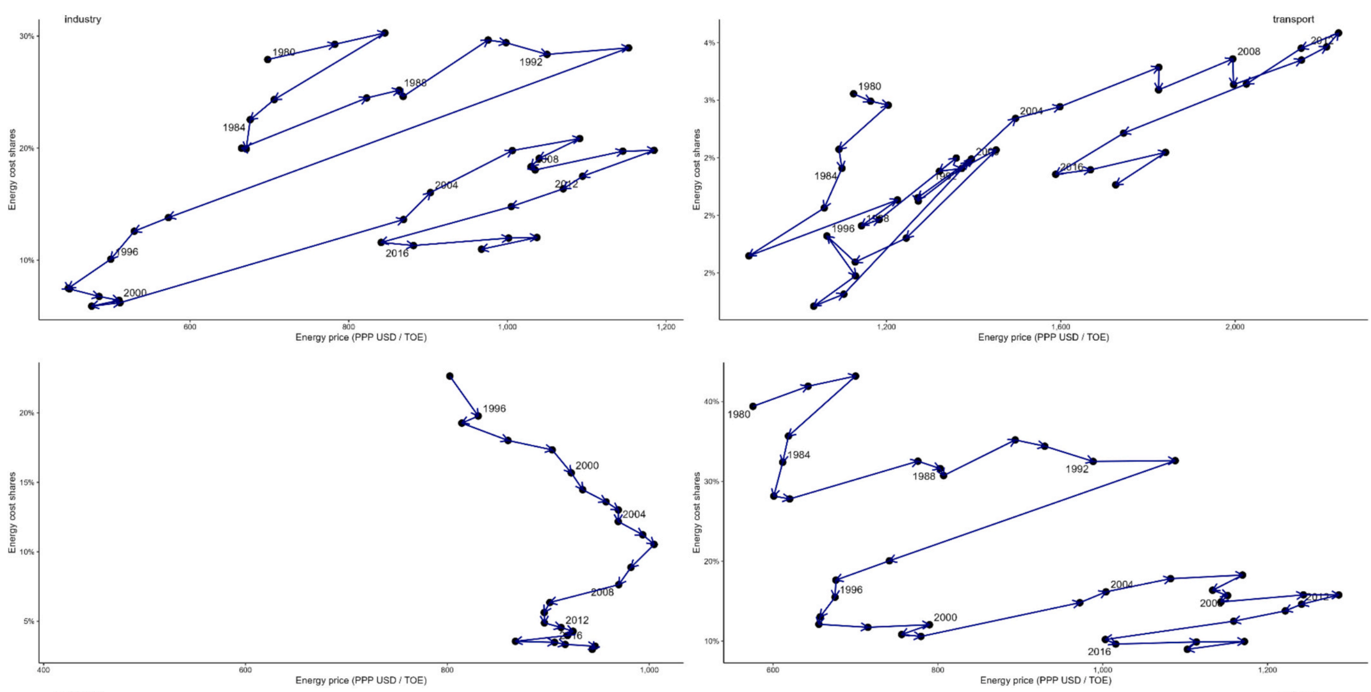

Fig. 4. Scatter plot of sectoral energy price and cost share in China. Monetary figures are expressed in international USD by using PPP conversion factors. The range in the axes reflect the values of the specific time series being plotted.

$$Y = \left[\alpha K^{\rho} + (1-\alpha)(AE)^{\rho}\right]^{\frac{1}{\rho}} \tag{1}$$

where we distinguish two inputs, energy E, which is multiplied by a factor A that captures energy-augmenting technological change, and a composite input that for simplicity we indicate with the stock of capital K. As usual, α is the share parameter in the production process and ρ is linked to the elasticity of substitution according to the relation $\rho = \frac{\sigma-1}{\sigma}$. By solving the profit-maximization problem of the firm, we obtain the optimality condition for the energy input

$$\frac{\partial Y}{\partial E} = \left[\alpha K^{\rho} + (1-\alpha)(AE)^{\rho}\right]^{\frac{1-\rho}{\rho}}(1-\alpha)(AE)^{\rho-1}A = p_E, \tag{2}$$

where p_E is the price of energy. From this condition we can derive a demand function for energy, which, after applying the logarithmic transformation, can be expressed in terms of the energy cost share as

$$ln\left(\frac{E}{Y}p_E\right) = \frac{1}{1-\rho}ln\left[(1-\alpha)A^{\rho}\right] + \theta_{SR}ln(p_E), \tag{3}$$

where $\theta_{SR} = 1 - \sigma$ is the short-run price elasticity of the energy cost share. The two inputs can be safely considered gross complements given that common estimates for the elasticity of substitution in the US fall around 0.20 (Hassler et al., 2021), while developing countries are expected to have even lower values due to outdated capital, energy-intensive industries, weaker regulations, and infrastructure limitations. Hence, we have that $0 < \sigma < 1$ and $\rho < 0$, which implies that energy-augmenting technological change is also energy-saving. Over the long run, it can be argued based on both theoretical grounds and empirical evidence that a prolonged period of high energy prices stimulates innovation in energy-saving technologies. A simple way to capture this induced technological change is to assume the following function for A

$$A = ap_E^{\gamma}, \tag{4}$$

where $\gamma > 0$. Plugging this definition of energy-saving technological change in Eq. (3), we obtain the long-run energy cost share as a function of energy price

$$ln\left(\frac{E}{Y}p_E\right) = \frac{1}{1-\rho} ln\left[\frac{(1-\alpha)}{a^{\rho}}\right] + \theta_{LR} ln(p_E) \tag{5}$$

where the long-run price elasticity of energy cost share is $\theta_{LR} = 1 - \sigma + (\sigma - 1)\gamma$. This last expression highlights the extent to which induced energy-saving innovation can reinforce the price elasticity of energy demand and thereby lower the price elasticity of energy cost share.

3.2. The econometric model

Following the theoretical framework above, we set up an econometric model for energy cost shares that is a re-parameterization of an energy demand equation. As suggested by Eq. (3), on the right-hand-side we include the current level of energy price plus deterministic components that captures all time-invariant factors specific to each country, including the level of energy-augmenting technology. Energy cost shares are expected to adjust to changes in prices only with a delay, and not immediately, as substitution across production inputs and consumption goods is subject to substantial frictions and adjustment costs. The consequence is that in any given period energy consumers achieve only a fraction of the change delivering their desired energy consumption. Bearing this in mind, we choose a dynamic structure that incorporates a partial adjustment model. Our baseline model then is the following

$$\ln\widetilde{cs}_{it} = \alpha + \mu_i + \beta_0 \ln\widetilde{cs}_{it-1} + \beta_1 \ln y_{it-1} + \sum_{j=0}^{T} \beta_{2j} \ln ep_{it-j} + \varepsilon_{it} \tag{6}$$

where $\ln\widetilde{cs}_{it}$ is the logarithm of the energy cost share for country i at time t in its demeaned version (indicated with a tilde), $\ln ep_{it}$ is the logarithm of the prevailing energy price, and $\ln y_{it}$ indicates the logarithm of the aggregate level of economic activity. The term μ_i is a fixed-effects component for country i, ε_{it} is an idiosyncratic error and the term α indicates a common intercept. All variables are transformed using the natural logarithm, as indicated by the term ln in the equation. The energy cost share is defined as the product of the energy price and energy consumption, divided by the level of economic activity, $cs_{it} = (ec_{it} \cdot ep_{it})/y_{it}$.

The lag order for the energy price is chosen by including up to three lags as suggested by the Akaike Information Criterion (AIC). As any change in the energy price immediately affect the energy cost shares before energy consumers can take any action to adjust consumption to the new desired level, one would expect the impact of energy prices on energy cost shares to be highest in the period when the change takes place and then to decrease as the energy consumers adjust consumption to the desired level. We include at least one lag of energy price to be able to capture this delayed response, but we exclude lags beyond three as coefficients become not statistically significant.

Current energy prices are largely exogenous to domestic demand factors as their dynamics is primarily driven by global commodity prices or by the fact that they are heavily regulated by national government policies. The energy demand of large energy consuming economies, such as US and China, may affect the global price of energy, but they represent a very small minority of the 142 countries included in the panel, so this potential source of endogeneity is negligible for the estimation of the common slope coefficients. Moreover, while demand factors dominate the variation in energy prices at higher frequencies such as monthly, our annual prices are likely to be driven in a significant part by supply factors.

The dependent variable is cross-sectionally demeaned (subtracting the cross-country mean for each year from cs_{it}) to control for cross-sectional dependence, underlying downward trends in energy cost shares as discussed in Section 2 and the impact of time-variant factors which have an impact on cost shares across countries, like the changing bundle of energy services, for example implied by the diffusion of air conditioning or other electronic equipment. The model is estimated for the whole set of countries in the dataset as well as for groups of countries identified based on the value of economic factors poised to influence the relationship between energy prices and cost shares. With the exception of income class, for which grouping is defined in World Bank (2024), the groups of countries have been obtained based on the median value of each factor across the countries included in the dataset. The precise definition of these variables is described in Appendix A.

We explore the influence of existing energy efficiency policies on the relationship between the energy price and the energy cost share by augmenting Eq. (1) with a set of energy efficiency indices developed by the World Bank (2022). These indices are part of the Regulatory Indicators of Sustainable Energy (RISE) dataset and are described in detail in Appendix A. One at a time, each of these indices is interacted with the level of energy price which mediates the impact of energy efficiency on cost shares. The part of the impact of energy efficiency on energy cost share that is independent of the level of energy price cannot be estimated in this framework as the energy efficiency indices are absorbed by the fixed effects due to their time-invariance. The elasticity of cost shares to the level of energy efficiency can however be computed only to the extent it interacts with the level of energy price. The new equation augmented with the efficiency index eff_i becomes

$$\ln\widetilde{cs}_{it} = \mu_i + \beta_0 \ln\widetilde{cs}_{it-1} + \beta_1 \ln y_{it-1} + \sum_{j=0}^{T} \beta_{2j} ep_{it-j} + \beta_3 \ln ep_{it} \cdot \ln eff_i + \varepsilon_{it}. \tag{7}$$

By definition, the long-term impact of the variables on the right-hand side of models (6) and (7) on energy cost shares is influenced by their short-term coefficients and the autoregressive coefficient β_0. The long-run elasticity of energy cost shares with respect to economic activity is $LR_y = \beta_1/(1-\beta_0)$, while the long-run elasticity with respect to energy price is $LR_{ep} = \sum_{j=0}^{T} \beta_{2j}/(1-\beta_0)$ in Eq. (6) but it is influenced by the value of energy efficiency in Eq. (7), namely $LR_{ep} = \left(\sum_{j=0}^{T} \beta_{2j} + \beta_3 \ln eff_i\right)/(1-\beta_0)$. As energy efficiency can alter the way in which energy costs shares respond to a change in the energy prices, the strength of this relationship can be assessed by computing LR_{ep} at the 25, 50 and 75 percentiles of the distribution of $\ln eff_i$. Similarly, the long-run elasticity of energy cost shares with respect to energy efficiency through the level of energy price, $LR_{eff} = \beta_3 \ln ep_{it}/(1-\beta_0)$, can be computed at the 25, 50 and 75 percentiles of the distribution of $\ln ep_{it}$.

Both Eqs. (6) and (7) above are estimated using the system

Table 1
Base model. Estimates of model (6). The numbers in parentheses indicate the standard error of the estimates. The symbols ***, ** and * indicate statistical significance at 1%, 5% and 10%, respectively.

	1980–2019	1980–1999	2000–2019
$\ln cs_{i,t-1}$	0.962$^{(***)}$	0.890$^{(***)}$	0.961$^{(***)}$
	(0.012)	(0.024)	(0.027)
$\ln ep_{i,t}$	0.825$^{(***)}$	0.848$^{(***)}$	0.781$^{(***)}$
	(0.022)	(0.017)	(0.038)
$\ln ep_{i,t-1}$	−0.825$^{(***)}$	−0.772$^{(***)}$	−0.779$^{(***)}$
	(0.027)	(0.027)	(0.045)
$\ln ep_{i,t-2}$	0.012		−0.010
	(0.017)		(0.030)
$\ln ep_{i,t-3}$	0.008		0.024
	(0.011)		(0.017)
$\ln y_{i,t-1}$	−0.002$^{(*)}$	−0.005	−0.003
	(0.001)	(0.003)	(0.002)
const	−0.261$^{(**)}$	−1.049$^{(***)}$	−0.205$^{(**)}$
	(0.121)	(0.298)	(0.228)
Long-run ECS elasticities			
LR_{ep}	**0.483**$^{(***)}$	**0.687**$^{(***)}$	**0.390**$^{(***)}$
LR_y	**−0.062**$^{(**)}$	**−0.042**$^{(*)}$	**−0.077**$^{(***)}$
Observations	4246	1864	2382
Units	133	129	133
Instruments	118	56	58
Hansen test (p-value)	0.86	0.58	0.35

Generalized Method of Moments (GMM) estimator (Arellano and Bond, 1991; Blundell and Bond, 1998) to overcome the bias in the estimation of dynamic panel models (Nickell, 1981). Panel OLS or fixed/random effects estimators lead to biased and inconsistent estimates due to the inclusion of the lagged dependent variable on the right-hand side of the equation, which is correlated with the demeaned error term. Compared to the difference GMM estimator (Arellano and Bond, 1991; Blundell and Bond, 1998), the system GMM estimator has better finite sample properties and increased efficiency.[5] An increase in estimation efficiency is obtained by using first differences of the dependent variable as instruments in addition to lagged levels, which are the only instruments in the case of the difference GMM estimator and which can easily prove to be weak.

We implement the forward orthogonal deviation transformation, which is an alternative strategy to the first differencing used in Arellano and Bover (1995), as it is resilient to missing data, therefore preserving sample size in panels with gaps. This transformation consists in subtracting the average of all future available observations from any given observation, instead of subtracting the previous observation from the current one, as implemented in the first-difference transformation. Standard errors are calculated by incorporating the small sample correction developed by Windmeijer (2005) for the two-step estimator, improving on the implausibly small standard errors, which would be otherwise computed. When generating the instrument sets in the system GMM estimator we use only the third and fourth lag of the cost shares to limit the number of instruments. In all cases, the number of instruments is smaller than the number of units in the panel, as discussed in Roodman (2009).

4. Results

We discuss the results of our investigation by focusing on three main aspects: 1) the magnitude of the response of energy cost shares to energy prices and its evolution over time; 2) the influence produced by the energy efficiency policies; 3) the role played by some key characteristics of the national economies in explaining an important part of the heterogeneity in the effects.

4.1. Response of energy cost shares to changing prices

The results of our analysis indicate a high degree of persistence in the energy cost share, with its level highly impacted by the current energy price and only marginally influenced by the past level of economic activity. Table 1 shows the results from the system GMM estimation of the cost share model (6) over the whole available sample period 1980–2019, as well as over the two subsamples, 1980–1999 and 2000–2019, suggested by the findings in Section 2. The AIC selects three lags for energy price in the first and third case, and one lag only in the second.

The initial response of the energy cost share mirrors the change in the energy price very closely: a 10% increase in the energy price translates into an approximate 8% increase in the energy cost share in the same year. Using the model estimated on the full sample period, indeed, the short-run (within the year) elasticity of the energy cost shares with respect to energy prices is 0.825, while the coefficient on the first lag of energy cost shares is 0.962, both statistically significant at 1% significance level. The short-run elasticity to the level of economic activity, on the other hand, is a mere −0.002 and statistically significant only at 10%.

A different story emerges if we consider the passage of time and look at the dynamic effects of the energy price. If we use our estimated model to simulate the dynamics of energy cost share in response to a permanent 10% increase in energy price, we obtain the following sequence of deviations from the starting point in the first four periods: 8.2%, 7.8%, 7.6%, 7.5%. As time goes by, this analysis shows that the impact of a price increase is partially absorbed to the extent that in the long run the increase in energy cost shares in response to a 10% increase in energy price is only 4.8%, as indicated by the estimated long-run price elasticity[6].

If we look at the definition of energy cost share as the product between energy price and energy intensity

[5] As typically is the case, a system approach to estimation gains from higher efficiency but tends to be more sensitive to misspecification. In our application this risk does not seem to be very serious given that our results are robust to changes in the dynamic specification and in the instrument set, as shown in Appendix B.

[6] The long-run price elasticity is calculated as the sum of the coefficients on all energy prices, current and lagged, i.e. 0.825, −0.825, 0.012 and 0.008, divided by the difference between one and the coefficient on lagged energy cost share, 0.962. For the general formula see Section 4.

$$cs_{it} = ep_{it}\frac{ec_{it}}{y_{it}} \tag{8}$$

it becomes clear that the extent to which an increase in energy prices raises energy cost shares depends on the offsetting behaviour of energy intensity, which is theoretically expected to decrease. The empirical literature confirms a negative relationship between energy price and energy intensity, see for instance Filipović et al. (2015), Verbič et al. (2017), Parker and Liddle (2016) Hang and Tu (2007), Adom (2015), and Metcalf (2008). These studies find an elasticity of energy intensity with respect to energy price that is negative but well above −1, namely −0.65 in the case of China, at most −0.63 in the case of Nigeria, and at most −0.30 in the case of the United States. An estimated price elasticity of energy intensity smaller than 1 in absolute value implies a positive but smaller than one price elasticity of energy cost share. Another way to assess the possible impact of energy price on energy cost share is to look at the literature on energy consumption. The meta-analysis in Labandeira et al. (2017) arrives at a short-term and long-term impact of prices equal to −0.21 and − 0.61 which matches well the values of 0.82 and 0.48 that we report for the elasticity of the cost share with respect to the energy price.

What is interesting to note is that the relationship between energy prices and costs shares is changing substantially over time. Using the year 2000 as a watershed suggested by the analysis in Section 2, we estimate the same model (6) in the two separate time segments of 1980–1999 and 2000–2019 and display the results in Table 1. After 2000, the short-run price elasticity of energy cost share decreases from approximately 0.85 to 0.78, which implies a fall of 43% in the long-run price elasticity, as this declines from 0.69 to 0.39. Such estimates tell us that after 2000 more than 60% of an increase in energy price is absorbed by an offsetting decrease in energy intensity, up from approximately 30% before that same year.

This substantial change in the price elasticity of energy cost shares can be explained using the theoretical framework that we developed in Subsection 3.1. If we take the definition of price elasticity of energy cost shares from Eq. (3) and plug in our short-run estimate of 0.82, we obtain an implied elasticity of substitution between energy and the other production inputs of 0.18. This value is perfectly in line with typical estimates existing in the literature, such as the 0.20 value estimated for the US economy (see Hassler et al., 2021). When we look at the estimated long-run elasticity in the two subsamples, we see that a value of 0.69 before 2000 implies an elasticity of substitution of 0.31, whereas a value of 0.39 after 2000 implies an elasticity of substitution of 0.61, which is almost double.

We can use our definition of energy-saving technological change that characterizes the long run production process and that is described in Eq. (4) to show that this doubling of the implicit elasticity of substitution between energy and the other production inputs can be sensibly explained by the action of induced technological innovation, which responded to a prolonged period of very high energy prices characterizing the second half of the sample. Using the formula for the long-run price elasticity of energy cost share from Eq. (5) and the implied elasticity of substitution of 0.18 obtained from the full sample, we can obtain the value of the parameter γ which is positive and equal to 0.50. Therefore, the increase in the elasticity of substitution implied by our estimates can be explained very well by the energy-saving technological innovation that in the second half of the sample was encouraged by energy prices that did not show any sign of abating.

As for the relationship with the aggregate level of economic activity, our model conforms with the theoretical assumption that energy demand responds proportionally one-to-one to current economic activity, but we include the lagged value to capture a potentially richer dynamic effect. From the full sample estimation, we obtain a very small negative coefficient: energy costs shares decrease by a tiny 0.02% in the year after the economic activity increases by 10%, and this effect is significant only at 10%. Also in the long run, economic activity continues to have a very small impact on energy cost shares: an increase of economic activity increasing by 10% leads to a decrease of only 0.6% in energy cost shares, this time with a statistical significance of 5%. It is worth noting, however, that after 2000 the long-run elasticity with respect to economic activity doubles in size to −0.08 and becomes strongly significant. This indicates that long-run energy cost shares would decline in the long-run by one percentage point if GDP increased by 12.5%.

The plausibility of these results can be assessed by drawing on the extensive literature on the relationship between economic activity and energy intensity.[7] A negative relationship between economic growth and energy intensity has been consistently observed over the past few decades by several authors, such as Azhgaliyeva et al. (2020), Deichmann et al. (2019), Filipović et al. (2015), and Verbič et al. (2017). This conclusion is in line with our finding that economic growth leads to a slightly declining energy cost share in the long run.

The results of our econometric analysis are robust to the set of instruments used in the GMM estimation procedure. Collapsing the set of instruments used in model (6) over the same three time periods produces negligible changes in the estimated coefficients (see Table 6 in Appendix B). The results are also robust to the use of alternative numbers of lags in the energy price. In the case of the estimation performed over the whole sample period, Table 5 in Appendix B shows that using one, two or three-year lags of energy price, in addition to the current energy price, has a very small impact on both the short-run and long-run price elasticity. Finally, we found that our results on the long-run elasticities remain stable also if we forgo the preliminary demeaning of the energy cost share variable, with and without the inclusion of a time fixed-effects (see Table 7 in Appendix B).

Our econometric results can also be used to obtain an estimate of how long it takes for the energy cost share to absorb the effects of an increase in the energy price. Given the existence of substantial adjustment costs due to the long and costly turnover of the energy-related capital stock, it is useful to provide an indication of the time required for the adjustment in the energy cost share to effectively take place. One measure of this adjustment timescale is the concept of *half-life*, which captures how many years it takes for half of the adjustment to the new long-run equilibrium to complete. From the estimates of the model fitted over the whole sample (Table 1), the half-life is computed to be 17.6 years: this means that it takes about 18 years for the energy cost share to absorb half the impact of a change in the energy price. Separating the two time segments, the half-life is 6.0 before 2000 and 17.3 after that year.

A half-life estimate of 17.6 years describes a very slow process of adjustment, with energy cost shares absorbing approximately 4% each year of the effects produced by a permanent energy price increase. Such a low speed of adjustment is not implausible, given that energy demand depends strictly on the existing capital stock, which has a lifetime that can easily reach many decades (Vogt-Schilb et al., 2018; Harmsen et al., 2021). This finding highlights the importance of implementing policies and incentives that facilitate the economy's adaptation to new energy price levels, shortening the adjustment period, and supporting firms and households during the process, especially addressing its relevant distributional effects.

4.2. *The impact of energy efficiency policies*

Energy efficiency policies are expected to decrease the level of energy costs shares as they reduce energy requirements. They can also alter the consumers' ability to respond and adapt to changes in energy prices. They can do this by facilitating the substitution among production inputs, therefore reducing the elasticity of energy cost shares with respect

[7] This is because the only difference between energy cost shares and energy intensity consists in the energy price appearing in the numerator of the former variable but not in the definition of the latter.

to energy prices. This subsection explores which energy efficiency policies may be best suited to reduce energy cost shares and the impact of energy prices on energy cost shares. Here, 11 types of energy efficiency policies and strategies contained in the RISE dataset (World Bank, 2022) are considered: frameworks for national energy efficiency planning (eff_1), energy efficiency entities (eff_2), incentives and mandates for industrial and commercial end users (eff_3), for public sector users (eff_4), and for utilities (eff_5), financing mechanisms for energy efficiency, (eff_6), minimum energy efficiency performance standards (eff_7), energy labelling systems (eff_8), building energy codes (eff_9), measures for the transport sector (eff_{10}), and those related to pricing and monitoring (eff_{11}), as well as an overall indicator built on the previous 11 sub-indicators.[8]

A number of results are evident from Table 2. First, energy efficiency reduces energy cost shares through its interaction with price. This is a result which holds across the 12 indices contained in RISE and the overall energy efficiency indicators, as testified by the negative coefficient on the interaction variable $eff_i \ln ep_{i,t}$. Secondly, this impact is limited, as evidenced by the similarity of the long run elasticity of energy cost shares with respect to energy price at the 25th, 50th and 75th percentiles of the RISE variables. More generally, the strength of the interaction between energy efficiency and energy prices is limited, as the value of the elasticity with respect to energy efficiency is also relatively stable along the distribution of the energy price. As an example, the long run elasticity with respect to incentives and mandates for industrial and commercial end users (eff_3), conditional on the price level, is -0.261 when assessed at the 25th percentile of the price distribution, -0.268 at the median and -0.274 at the 75th percentile.

Our findings show that the impact of energy efficiency policies on energy cost shares is statistically significant both in the short-run, as conveyed by the energy efficiency indicator interacting with the price, $eff_j \bullet ep_{i,t}$, and in the long-run as conveyed by the value of LR_{RISE} in Table 2a and Table 2b. It also emerges that policies targeting a specific sector and well-defined energy uses tend to have a statistically significant impact on energy cost shares. This applies to incentives and mandates for industrial and commercial end users (eff_3), building energy codes (eff_9), measures for the transport sector (eff_{10}) and those related to carbon pricing and monitoring (eff_{11}). Building energy codes influence mainly heating/cooling and lighting in both residential and commercial buildings, including renovated buildings and green or near zero-energy buildings. The 'transport sector' policies covered in this analysis include mainly those affecting the fuel economy of vehicles, demand for transport and modal shift, while those related to carbon pricing and monitoring incorporate both the coverage of existing carbon pricing mechanisms and whether associated MRV are in place. All indicators consider the need for regular reporting and updates based on the progress of best practices and technological development, therefore ensuring that their influence on consumers' behaviour is ongoing.

On the other hand, we find that policies with wider coverage and scope, such as the establishment of national energy efficiency planning (eff_1) or energy efficient entities (eff_2) do not appear to directly and significantly influence the energy cost shares. This may be a reflection of these higher-level policies creating the enabling environment for energy efficiency but do not directly impacting decisions of firms and households, whose change in behaviour needs to be incentivized by policy and regulatory instruments that directly target them. It is critical to note that these foundational policies and national plans are a prerequisite for other policies, but on their own, they are not likely to have an impact on the behaviour of energy users.

The analysis indicates that the impact of minimum energy efficiency performance standards (eff_7) and energy labelling systems (eff_8) on energy cost shares is not statistically significant. This might be because establishing a floor for the performance of new energy-using capital stock and signaling the relative consumption of equipment and appliances does not necessarily influence the way in which consumers respond to prices, once the minimum standard has been met by the manufacturers. It is also the case that changes in standards for new capital stock may only work through the systems slowly, according to the rate of capital stock turnover. In addition, standards and labels can only influence new purchases and hence can only diffuse with the rate of capital stock turnover.

Regarding the indicators related to incentive and mandates, only those affecting industrial and commercial end users (eff_4) have a statistically significant impact on energy cost shares. The impact of the indicator related to incentives and mandates for utilities (eff_6) is not statistically significant since power generation, transmission and distribution are not covered by the dataset used in this study, as our analysis focuses on the end use of energy rather than conversion and distribution. Similarly, as mandates affecting the public sector (eff_5) cover only a limited share of national energy consumption, it not surprisingly that their impact on costs shares is not statistically significant. Finally, our estimates indicate that energy cost shares are not significantly affected by the value of the indicator related to the financing mechanisms for energy efficiency. This might be because financing for energy efficiency is in most countries a relatively small, albeit growing, sector, therefore having only a limited impact on national energy consumption.

4.3. Heterogeneity due to national characteristics

The estimated impact discussed above may obscure important heterogeneities between countries resulting from economic factors that are very likely to influence the response of energy consumption to changes in energy prices (Choi et al., 2018; Labandeira et al., 2017; Liddle and Huntington, 2020; Churchill et al., 2023; Bettarelli et al., 2023; De Michelis et al., 2019; Rafiq et al., 2016; Peersman and Van Robays, 2012; Rafiq et al., 2016; Gelos and Ustyugova, 2017). Therefore, in this subsection we assess the role played by five distinct factors of macroeconomic importance in influencing the relationship between energy cost share and energy price: 1) the stage of economic development, 2) the level of financial development and human capital, 3) the oil trading balance, 4) the energy import dependence, and 5) the level of energy taxation. The precise definition of these variables is described in Appendix A.

In practice, we split our sample of countries in two separate groups depending on whether the country has a value for the relevant variable that is above or below the median value. On each of these two groups, we perform a separate estimation, and we repeat such exercise for each of the five economic factors above. The results are shown in Table 3.

Stage of economic development. The empirical results in Table 3 show that the long run elasticity of energy cost shares with respect to energy prices is substantially lower in high-income countries (about 0.19) than in other countries (about 0.49). As long-run elasticity is also non-statistically significant in high-income countries, we can conclude that these economies are better able to absorb most of the impact of higher energy prices on energy cost shares. This confirms the visual insights arising from Fig. 2 showing only very limited differences in energy cost shares as the energy price varies across UMHI countries. In addition, it takes about 12 years for the energy cost shares in high-income countries to absorb half of the initial deviation from the long-run equilibrium, compared to 18 years in the remaining countries. It is worthwhile to observe that this result could also be due to trade effects

[8] As an aside, it is worth mentioning that energy prices are likely to have an impact on energy efficiency levels and the introduction of energy efficiency policies. As an example, national governments might have a higher incentive to promote energy efficiency policies when prices are high. The correlation between the logarithm of the energy efficiency overall indicator in the RISE dataset and energy prices in 2019 confirms this, with a value of 0.14.

Table 2a
Models incorporating energy efficiency indices. The numbers in parentheses indicate the standard error of the estimates. The symbols ***, ** and * indicate statistical significance at 1%, 5% and 10%, respectively. Energy efficiency variables are defined as follows: *eff* indicates an overall indicator built on the 10 sub-indicators below; eff_1 indicates frameworks for national energy efficiency planning, eff_2 energy efficiency entities, eff_3 incentives and mandates for industrial and commercial end users, eff_4 incentives and mandates for public sector users, eff_5 incentives and mandates for utilities, eff_6 financing mechanisms for energy efficiency, eff_7 minimum energy efficiency, eff_8 performance standards energy labelling systems, eff_9 building energy codes, eff_{10} efficiency measures for the transport sector, and eff_{11} indicates carbon pricing and monitoring.

	eff	eff_1	eff_2	eff_3	eff_4	eff_5
$\ln cs_{i,t-1}$	0.9672(***)	0.9671(***)	0.9645(***)	0.9631(***)	0.941(***)	0.9662(***)
	(0.0145)	(0.0144)	(0.0151)	(0.0169)	(0.0155)	(0.0148)
$\ln ep_{i,t}$	0.8512(***)	0.8558(***)	0.8498(***)	0.8443(***)	0.8339(***)	0.8479(***)
	(0.0204)	(0.0188)	(0.0212)	(0.0232)	(0.0225)	(0.0208)
$\ln ep_{i,t-1}$	−0.8286(***)	−0.8341(***)	−0.8235(***)	−0.8175(***)	0.7919(***)	−0.8267(***)
	(0.0254)	(0.0234)	(0.0262)	(0.0279)	(0.0253)	(0.0259)
$\ln y_{i,t-1}$	−0.0009	−0.0022	−0.0019	−0.0019	0	−0.0022(*)
	(0.0015)	(0.0016)	(0.0016)	(0.0015)	(0.0014)	(0.0013)
$\ln eff_i \ \ln ep_{i,t}$	−0.0004(*)	−0.0001	−0.0005(*)	−0.0007(***)	−0.0004	0.0000
	(0.0002)	(0.0002)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
const	−0.3036(**)	−0.3006(**)	−0.3407(**)	−0.3382(*)	−0.5877(***)	−0.2976(*)
	(0.1466)	(0.1429)	(0.1517)	(0.1726)	(0.1738)	(0.1546)
LR_y	−0.027	−0.067	−0.054	−0.052	0.0000	−0.065
$LR_{ep\ (25\%)}$	0.648(***)	0.647(***)	0.684(***)	0.652(***)	0.685(***)	0.627(***)
$LR_{ep\ (50\%)}$	0.640(***)	0.646(***)	0.679(***)	0.647(***)	0.683(***)	0.627(***)
$LR_{ep\ (75\%)}$	0.637(***)	0.646(***)	0.676(***)	0.641(***)	0.681(***)	0.627(***)
$LR_{RISE\ (25\%)}$	−0.168(**)	−0.042	−0.194	−0.261(**)	−0.093	0
$LR_{RISE\ (50\%)}$	−0.172(**)	−0.043	−0.199	−0.268(**)	−0.096	0
$LR_{RISE\ (75\%)}$	−0.176(**)	−0.044	−0.203	−0.274(**)	−0.098	0
Observations	3920	3742	3788	3395	3009	3789
Units	114	109	110	98	87	110
Instruments	8	8	8	8	8	8
Hansen: p-value	0.45	0.56	0.518	0.493	0.88	0.666

Table 2b
Models incorporating energy efficiency indices. The numbers in parentheses indicate the standard error of the estimates. The symbols ***; ** and * indicate statistically significance at the 1%, 5% and 10% significance level, respectively. Energy efficiency variables are defined as follows: *eff* indicates an overall indicator built on the 10 sub-indicators below; eff_1 indicates frameworks for national energy efficiency planning, eff_2 energy efficiency entities, eff_3 incentives and mandates for industrial and commercial end users, eff_4 incentives and mandates for public sector users, eff_5 incentives and mandates for energy utility programs utilities, eff_6 financing mechanisms for energy efficiency, eff_7 minimum energy efficiency, eff_8 performance standards energy labelling systems, eff_9 building energy codes and eff_{10} indicates efficiency measures for the transport sector.

	eff_6	eff_7	eff_8	eff_9	eff_{10}	eff_{11}
$\ln cs_{i,t-1}$	0.9464(***)	0.9604(***)	0.9451(***)	0.9388(***)	0.9691(***)	0.9511(***)
	(0.0201)	(0.0165)	(0.0191)	(0.0153)	(0.0193)	(0.0178)
$\ln ep_{i,t}$	0.8434(***)	0.8299(***)	0.835(***)	0.7983(***)	0.8527(***)	0.7995(***)
	(0.0241)	(0.0257)	(0.0272)	(0.0299)	(0.0217)	(0.0344)
$\ln ep_{i,t-1}$	−0.8054(***)	−0.8028(***)	−0.7987(***)	−0.7518(***)	−0.8321(***)	−0.7615(***)
	(0.0312)	(0.0308)	(0.0326)	(0.0327)	(0.027)	(0.0401)
$\ln y_{i,t-1}$	−0.0030(*)	−0.0028(**)	−0.0015	0	−0.001	−0.0027
	(0.0015)	(0.0014)	(0.0015)	(0.0015)	(0.0015)	(0.0018)
$\ln eff_i \ \ln ep_{i,t}$	−0.0002	−0.0003	−0.0004	−0.0006(***)	−0.0005(*)	−0.0013(*)
	(0.0004)	(0.0002)	(0.0003)	(0.0002)	(0.0003)	(0.0007)
const	−0.5221(**)	−0.3634(**)	−0.4966(**)	−0.6373(***)	−0.2691	−0.4572(***)
	(0.2258)	(0.1824)	(0.2078)	(0.1735)	(0.1926)	(0.1602)
LR_y	−0.056(**)	−0.071(**)	−0.027(*)	0.000	−0.032	−0.055(**)
$LR_{ep\ (25\%)}$	0.693(***)	0.658(***)	0.635(***)	0.726(***)	0.610(***)	0.673(***)
$LR_{ep\ (50\%)}$	0.693(***)	0.654(***)	0.631(***)	0.720(***)	0.599(***)	0.655(***)
$LR_{ep\ (75\%)}$	0.692(***)	0.651(***)	0.629(***)	0.718(***)	0.595(***)	0.655(***)
$LR_{RISE\ (25\%)}$	−0.052	−0.104	−0.100	−0.135(**)	−0.222(*)	−0.365(***)
$LR_{RISE\ (50\%)}$	−0.053	−0.107	−0.103	−0.138(**)	−0.228(*)	−0.374(***)
$LR_{RISE\ (75\%)}$	−0.054	−0.109	−0.105	−0.141(**)	−0.233(*)	−0.383(***)
Observations	3061	3323	3111	2733	2567	2093
Units	89	96	90	81	74	61
Instruments	8	8	8	8	8	8
Hansen: p-value	0.188	0.181	0.194	0.782	0.39	0.04

Table 3
Models estimated for countries grouped according to their stage of economic development, financial development and human capital, oil trading status, energy import dependence and net energy taxes. The number in parentheses indicate the standard error of the estimates. The symbols ***, ** and * indicate statistical significance at 1%, 5% and 10%, respectively. The median value of the variable in the header of the table was used as the threshold for dividing countries into two groups, with the exception of the stage of economic development and oil exporting/importing status. The stage of economic development is based on the World Bank's income classification (World Bank, 2024), with the 'low' group including low income, lower middle income and upper middle income countries, and 'high' group including high income countries.

	Stage of economic development		Financial Development and Human Capital		Oil Trading Status		Energy Import Dependence		Net Energy Taxes	
Variable	High	Low	High	Low	Importers	Exporters	High	Low	High	Low
$\ln cs_{i,t-1}$	0.946 (***)	0.963 (***)	0.943 (***)	0.977 (***)	0.946 (***)	0.9703 (***)	0.871 (***)	0.974 (***)	0.953 (***)	0.962 (***)
	(0.012)	(0.014)	(0.015)	(0.018)	(0.019)	(0.016)	(0.039)	(0.013)	(0.019)	(0.014)
$\ln ep_{i,t}$	0.690 (***)	0.835 (***)	0.769 (***)	0.821 (***)	0.757 (***)	0.844 (***)	0.672 (***)	0.850 (***)	0.831 (***)	0.788 (***)
	(0.04)	(0.026)	(0.032)	(0.031)	(0.028)	(0.033)	(0.037)	(0.029)	(0.025)	(0.039)
$\ln ep_{i,t-1}$	−0.680 (***)	−0.817 (***)	−0.752 (***)	−0.810 (***)	−0.728 (***)	−0.832 (***)	−0.598 (***)	−0.845 (***)	−0.806 (***)	−0.773 (***)
	(0.039)	(0.029)	(0.032)	(0.038)	(0.033)	(0.036)	(0.042)	(0.031)	(0.030)	(0.041)
$\ln y_{i,t-1}$	−0.004	−0.000	−0.002	0.002	−0.005 (**)	0.001	−0.008 (*)	−0.001	−0.006 (**)	0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.004)	(0.002)	(0.002)	(0.002)
const	−0.127	−0.267(*)	−0.243	−0.171	−0.401(**)	−0.176	−1.034(***)	−0.075	−0.337(**)	−0.232
	(0.130)	(0.138)	(0.149)	(0.159)	(0.202)	(0.144)	(0.295)	(0.122)	(0.138)	(0.161)
LR_{ep}	**0.186**	**0.489** (**)	**0.306** (**)	**0.464** (*)	**0.545** (***)	**0.389** (*)	**0.577** (***)	**0.193**	**0.537** (***)	**0.406** (*)
LR_y	**−0.078** (**)	**−0.002**	**−0.041**	**0.101**	**−0.095** (***)	**0.040**	**−0.061** (***)	**−0.039**	**−0.125** (***)	**0.035**
Half- life	**12.37**	**18.49**	**11.70**	**29.92**	**12.56**	**22.99**	**5.01**	**26.21**	**14.43**	**18.04**
Observations	1792	2682	2304	2208	2806	1609	2100	2242	2374	2138
Units	51	81	66	67	83	46	63	65	68	65
Instruments	7	7	7	7	7	7	7	7	7	7
Hansen: p-value	0.22	0.61	0.56	0.75	0.81	0.98	0.67	0.85	0.57	0.82

(since high-income countries tend to be more open to trade, they can respond more quickly to changes in the energy price), easier access to technology, and capital stock enabling substitution possibilities between energy and other production inputs or consumption goods.

Financial sector and human capital. The results in Table 3 indicate that the long run elasticity of energy cost shares with respect to energy prices is lower in countries with higher level of financial development and human capital (0.31 rather than 0.46). The former group of countries is also quicker at adjusting to changes in energy prices: about 12 years to complete half of the adjustment process, as opposed to 30 years in countries with less developed financial sectors and lower levels of human capital. Human capital propels technological progress and complements R&D expenses (Barro, 2001; Hanushek and Woessmann, 2008; Vandenbussche et al., 2006) facilitating the adoption of energy efficiency technologies (Kim and Heo, 2013; Yao et al., 2020). Similarly, financial development facilitates access to finance, it reduces adoption costs and other barriers for investing in energy-efficient and renewable energy technologies (Sadorsky, 2010), fostering higher substitution possibilities between energy and other goods when the relative price of energy changes.

Oil trading status. As oil is for several countries a key feature of their economies and energy systems, it is not surprising that a country's oil trading status has an impact on the relationship between energy cost shares and prices. The long run response of energy cost shares to a doubling of energy prices is lower in oil exporting (about 0.39) than in oil importing countries (about 0.55), but the adjustment process is slower, i.e. 23 years compared to about 13 years in oil-importing countries. Part of the explanation for this result might be related to the fact that energy prices directly impact economic growth in oil exporting countries. When prices are high, the increasing opportunity cost of energy consumption can also contribute to explain the lower price elasticity of energy cost shares in oil exporting countries.

Energy import dependence. As a substantial amount of diversity is lost when merely categorizing countries as importers or exporters (De Michelis et al., 2019), we further examine the response of energy cost shares to changes in energy prices by considering the level of energy import dependence. Reflecting the results for oil trading status, energy cost shares in countries with high energy import dependence are more sensitive to changes in the price but adjust more quickly. Long-run price elasticity in countries with low energy import dependence is substantially lower, 0.19 rather than 0.58, and non-statistically significant; the adjustment process is however much slower, i.e. 26 years rather than 5. These results indicate that the response of countries with high energy dependence is more rapid, but the scope for adjustment is more limited, perhaps due to fewer options for alternative energy sources. On the other hand, countries with low energy import dependence are more able to absorb the long-run impact of energy price increases, as their energy mix and supply options are more likely to be diversified.

Impact of energy taxation. We also found that the level of net energy taxes influences the impact of energy prices on energy cost shares. Countries with relatively high levels of taxation are less able to substitute away from energy following a price increases, as 54% of the change in prices is passed through to cost shares. On the other hand, the adjustment is faster, as it takes about 14 years for energy cost shares to absorb half of the deviation from the long-run equilibrium. Countries with low levels of net energy taxation have a smaller long-run elasticity, 0.41, but their adjustment unfolds at a slower pace, as the half-life is 18 years. This result might be due to the fact that countries with high levels of net energy taxes are more energy efficient. As consumers in these countries operate close to the efficient substitution frontier, there are limited substitution possibilities available when price increases. On the other hand, countries with low levels of net energy taxation are not very likely to use energy efficiently (see, for example, Solarin, 2020) and more energy substitution possibilities are left available.

5. Implications for energy subsidy reform

The analysis in this paper indicates that the impact of energy price increases on energy cost shares is, as time goes by, partially absorbed: in the long run, the increase in energy cost shares to a doubling of energy prices is 48%. This means that the savings arising from removing energy subsidies are more than double the compensation which could be paid to energy consumers to keep their energy costs constant, a result confirming previous findings in the literature, e.g. Groot and Oostveen (2019).[9]

Our results indicate that the potential public budget savings arising from energy subsidy reforms have increased over time. In the first 20 years of our sample, up to 1999, a doubling of energy prices is correlated to a 70% increase in energy cost shares; in the last 20 years of the sample, from 2000 onwards, the same increase in energy prices results only in a 40% increase in cost shares. This means the conditions for the implementation of energy subsidy reforms have improved over time. As removing fossil fuel subsidies offers a fiscal gain exceeding the additional costs, this means that social protection spending in general, and social assistance, in particular, can be funded through the reduction in governmental spending allocated to energy subsidies. The introduction of compensatory measures is important, especially for the poorest households. Groot and Oostveen (2019) show that the vast majority of compensation should go to the lowest affluent households. Even though the great majority of subsidies is enjoyed by more affluent households, the poorest households are worst affected by the removal of subsidies without introducing social reforms (Vagliasindi, 2013).

The existence of fiscal savings allows also for the possibility of additional fiscal resources redirected to arguably more economically productive uses such as funding infrastructure, healthcare and education. It is in fact well known that energy subsidies have hidden costs in terms of resources which are not made available to other public expenditure items. Ebeke and Ngouana (2015) found that on average spending on health and education decreased by 0.6% for a 1% increase in energy subsidies. When diverting government funding from public goods such as infrastructure, healthcare, and education (Ellis, 2010), subsidies have additional negative impacts on productivity. This is because an efficient healthcare sector is likely to contribute to current labor productivity, while education is likely to maintain or increase productivity in the future workforce (Flochel and Gooptu, 2017).

Our analysis, however, points to two complications which need to be addressed to deliver the fiscal savings implied by the estimated long-run elasticity of cost shares with respect to prices. First, the short-run (within year) elasticity of energy cost shares is much higher, about 0.80 across the samples used in the estimation. This means that the impact of removing energy subsidies on the consumers' budget will be considerable immediately after the reform and, consequently, limited fiscal budget savings can be achieved if consumers are compensated for the additional costs on them. The size of additional costs in the short run also has implications for the timing of policy measures: it is important to promptly introduce compensation measures, as sizeable additional costs on consumers might turn public opinion against the reform. Therefore, it is necessary to ensure readiness for short-term assistance so that consumers are insulated from negative impacts.

The second complication is related to the fact that the adjustment process implied by the models estimated in this study is relatively slow. Our results indicate that half of the adjustment to the new long-run equilibrium may take more than a decade. Two policy implications arise from this finding. First, governments removing energy subsidies need to acknowledge the long-term need for compensation measures. Secondly, energy subsidies reforms are more likely to be successful if supported by cross-party agreement. This is because compensation measures required to tackle increasing energy costs will need to be in place after a new government forms. If they were abolished when a party in the opposition gains power, risks to the sustainability of the energy subsidy reform could materialize.

The introduction of energy subsidy reforms can be facilitated by introducing a set of policies increasing the speed of adjustment to the new long-run equilibrium or decreasing the long-run elasticities of energy cost shares with respect to energy prices. Our analysis shows that in countries with high per-capita income long-run increases in energy cost shares to rising prices are smaller, and in addition the adjustment to the new long-run equilibrium is quicker: this means that energy subsidy reforms can deliver higher public budget savings, allowing for measures to protect consumers from increasing costs, and that these savings become available more speedily. Our results, therefore, indicate that policy measures stimulating economic growth have the additional benefits of facilitating the introduction of energy subsidy reforms. The same aims of decreasing the long-run elasticities of energy cost shares and increasing the speed of adjustment can be achieved through policy measures increasing the level of financial development and stock of human capital in a country. These measures are helpful, as both factors are likely to facilitate energy efficiency technologies and substitution possibilities between energy and other goods by decreasing adoption costs and increasing technological progress.

Our results indicate that reducing dependence on energy imports is correlated with a lower impact of removing energy subsidies on energy cost shares, although at the cost of slowing the adjustment process. Reduction in energy import dependence is normally motivated in terms of improved trade balance and increased energy security. Our results indicate that the additional benefit of such policies is to facilitate the introduction of energy subsidy reforms. Finally, the introduction of energy taxes is not a policy option that helps government's intent on reducing the impact of reforming energy subsidies on energy costs shares. This may be because countries with high levels of energy taxes are already relatively energy efficient and, therefore, with limited residual substitution possibilities available to them. The opposite is likely to occur in the case of countries with high energy subsidies.

Energy subsidy reforms can also be facilitated through the introduction of energy efficiency policies. An extensive literature highlights the rationales for specific policies to improve energy efficiency, grounded in a wide range of market failures, along with a more systemic understanding of the extent to which energy consumption is subject to 'satisficing' behaviours (Grubb et al., 2014). The broad picture that emerges from our analysis is that only specific policies exert some influence on the way energy cost shares respond to energy price increases, which are brought about by subsidy reforms. Those targeting a specific sectors or energy uses are more likely to reduce the impact of changes in the energy prices on cost shares, while foundational policies such as the establishment of national energy efficiency planning or energy efficient entities are not able on their own to affect the response of consumers to changes in energy prices, although they are likely to be the prerequisite for other focused policies. Government planning to introduce energy efficiency policies to counteract the effects of price increases after the removal of energy subsidies needs to institute a comprehensive package. Introducing only national plans or generic mandates and objectives is not enough to enable consumers to increase their response to energy prices: decreasing the impact of energy price changes on energy cost shares requires targeted incentives prompting consumer to take

[9] This is essentially due to the fact that the financial resources committed to existing subsidies are equal to the unitary subsidy multiplied by the consumption which was observed before the reform (which can be assumed to continue in the immediate future), while the increased cost borne by consumers after the reform is equal to the change in price (which is equal to the change in unitary subsidy) multiplied by level of consumption observed after the reform. If energy consumption responds negatively to price increases, a reduction in consumption brought about by the price reform will deliver savings to the government even after paying targeted compensation to consumers. In terms of energy costs, this will manifest itself as an elasticity smaller than one with respect to energy price. If price elasticity of energy costs is 0.50, the savings arising from removing energy subsidies are double the compensation which could be paid to energy consumers to keep their energy costs constant. We estimate the elasticity of energy cost share which is approximately 0.50. Assuming the output is fixed, this is also the elasticity of energy costs, which means that a 100% increase in price leads to an increase in energy costs by 50%. But if output changes, and most likely falls in response to higher energy prices, energy costs must increase by less than 50%. Hence, the savings are more than double the extra energy costs.

conscious action beyond the minimum mandated standards.

The unambiguous policy implication is for the coevolution of targeted policies for energy efficiency along with a wider reform of energy pricing such as subsidy removal, consistent with the 'three pillars' approach to energy policy (Grubb et al., 2023). Broadly, the findings indicate that energy systems have the capacity to adapt to higher prices and other pressures *given enough time*, provided the price signals are sustained and are accompanied by other policy measures, notably those enhancing energy efficiency, to facilitate adjustment. Thus, effective and sustainable policy reform would require the combination of energy price reforms (through subsidy reduction or removal, or environmental/carbon pricing, or both) alongside measures to enhance energy efficiency and to improve the capacity for the energy system to absorb and respond to price increases, so as to contain impacts on the overall share of GDP devoted to energy.

6. Conclusions

We constructed a global dataset that describes the dynamics of national energy consumptions over a period of 40 years and we used it to identify some recent key empirical patterns about national energy cost shares. We then used an econometric model grounded in standard economic theory to shed light on the underlying determinants of such empirical patterns. Finally, we extended the model to study the role played by energy efficiency policies and some structural characteristics of the economy. Several conclusions, relevant for both economic analysis and policy design, can be drawn from this work.

First, as expected, energy cost shares and energy prices tend to move very closely together in the short term, as adjustment costs prevent any quick reduction in energy intensity. As time goes by, however, the economy shows the ability to adapt considerably in response to a sustained increase in energy prices. Over the long run, a 100% increase in energy prices ultimately leads to only a 48% increase in energy cost shares.

Second, the correlation between energy prices and energy cost shares has decreased over time and in particular since 2000 when energy prices rose and remained high for a prolonged period while energy cost shares exhibited a declining path. Our econometric model confirms that the price elasticity of energy cost share has declined in more recent years, to the extent that if we estimate our model separately on the first and second half of the sample, we obtain that before 2000 approximately 30% of an increase in energy price was absorbed by an offsetting decrease in energy intensity, whereas after 2000 this share rises to 60%. Using our theoretical framework we deduce that such change implies an increase in the elasticity of substitution between energy and the other production inputs from 0.31 to 0.61. As suggested by our theoretical framework, the mechanism that presumably has made such adjustment possible is the energy-saving technological change induced by the persistently high energy prices.

Nevertheless, the time it takes for energy intensity to fully adjust to changes in energy prices is long. After 18 years only half of this adjustment has taken place, which means 4% each year. This reflects heavy adjustment costs in the economy, which is not surprising considering the long lifetime of energy-using capital stock that can easily reach several decades.

There are, however, major differences across countries. In some countries, energy cost shares and energy prices have moved together throughout the timespan used in this study, while in others their comovement has been largely counteracted by a decreasing long-run trend in energy cost shares perhaps linked to technological change, policy interventions, modernization of the economy or structural changes. The same level of heterogeneity in the relationship between energy cost shares and energy prices can be found across sectors of the economy. Taken together, these two findings show that different countries or sectors within the same country can have varying abilities to counteract the impact of energy price increases on energy costs shares. Any long-term strategy to align energy prices with the full costs, i.e. subsidy removal and carbon pricing, need to consider varying ability of energy users to neutralize the impact of energy price increases when selecting the sectors that should be targeted first for policy intervention.

There are five broad conclusions relevant to policy. First, to the well-grounded economic argument for reducing energy subsidies we add the finding that removing subsidies offers a fiscal gain that exceeds the added costs to consumers; moreover, this gain will increase over time as the economy gradually responds to higher prices. Second, the full adjustment unfolds over long periods, typically one or more decades. Consequently, governments need to tackle the challenge of managing the transition towards higher energy prices and their impact on energy consumers, in particular those least able to afford the increased price of energy. Some of the fiscal gain could be used to compensate poorer households. Third, the same basic arguments apply to carbon pricing and other policies to internalize the damages associated with fossil fuel use. The economy can adjust over time to carbon prices, which helps align price signals in the economy with the growing imperative to tackle climate change. In this context, some of the fiscal surplus could also be used to accelerate the adoption of improved low carbon technologies, which in turn reduces the exposure of the economy to the impact of carbon pricing. Fourth, the introduction of energy subsidies reform can be facilitated through the introduction of a set of broader economic policies affecting the response of energy consumers to an increase in energy prices. Our analysis shows that policies stimulating economic growth, the level of financial development and human capital have all a role to play in increasing the speed of adjustment to the new long-run equilibrium and decreasing the size of the long-run response of energy cost shares with respect to energy prices. Finally, we have shown that energy efficiency policies might enhance and accelerate the structural adaptation to higher energy prices. Again, this reinforces a widely (if not universally) recognized conclusion, of the benefits of complementary policy packages, and in this case, specifically the benefits of targeted energy efficiency policies which more directly, and permanently, reduce the exposure to all forms of policies for economically appropriate energy pricing, whether subsidies, excise duties, or carbon pricing.

CRediT authorship contribution statement

Paolo Agnolucci: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Vincenzo De Lipsis:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Defne Gencer:** Writing – review & editing, Writing – original draft, Funding acquisition. **Abraham Lartey:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Michael Grubb:** Writing – review & editing, Writing – original draft, Visualization.

Acknowledgments

This paper was prepared as part of a collaboration between the World Bank's Macroeconomics Trade and Investment (MTI) Global Practice and the Energy Sector Management Assistance Program (ESMAP) of the Energy and Extractives Global Practice. The underlying research and analysis were funded by ESMAP's Energy Subsidy Reform Facility and MTI's Fiscal Policy and Growth Unit. ESMAP is a partnership between the World Bank and over 20 partners to help low- and middle-income countries reduce poverty and boost growth through sustainable energy solutions. The opinions expressed in this article are the authors' own and do not reflect the view of the World Bank. The authors would like to thank Dirk Heine for insightful advice provided.

Appendix A. Dataset used in this study

A.1. Energy consumption, energy prices and economic activity

In simple terms, energy cost shares are calculated by dividing the product of total energy consumption and corresponding average energy price by the level of economic activity. Therefore, this computation requires data on energy prices, energy consumption and economic activity. For the analysis performed in this paper, energy consumption and price data were collected for fuels consumed in most of the sectors of a given economy and aggregated to compute total energy consumption for each country and related energy price.[10] Table 4 summarizes the coverage of the dataset used in this study.

Table 4
Scope and coverage of the dataset used in this study.

Category	Included elements
Fuels	Coal, diesel, electricity, gasoline, kerosene, LPG, natural gas and other oil products.
Sectors	Industry, residential, public administration and services, and transport.
Geography and time period	142 countries, with observations up to a maximum of 40 years spanning the period from 1980 to 2019.

Real GDP in international (Purchasing Power Parity or PPP) dollars was computed using data from *International Monetary Fund (IMF)* (2023) by multiplying per capita GDP in real international dollars by the level of the population.[11] On the other hand, data on nominal GDP in US dollars was obtained from World Bank, 2022and rescaled following the procedure described in World Bank (2022). This variable is required to compute the ratio between real GDP in international dollars and nominal GDP in US dollars, which enables conversion of energy prices from current U.S. dollars to constant international dollars.[12] Data from energy balances published in IEA (2022) and Black et al., 2023 are used to determine the total amount of energy consumed in each country. These two sources provide fuel consumption data for the following sectors: 1) industrial[13], 2) residential; 3) services and public administration; and 4) transport[14]. The IEA dataset provides information on the consumption in each of the above for: 1) biomass; 2) coal; 3) diesel, 4) electricity; 5) gasoline; 6) kerosene; 7) LPG; 8) natural gas, 9) other oil products[15]. Biomass was not incorporated into the analysis due to the fact that prices were not available.

Annual retail prices for the fuels included in this study are sourced from the datasets underlying Parry et al. (2021) and Black et al., 2023. These datasets contain information, disaggregated by fuel and by sector, on retail fuel prices, i.e. average prices paid by final users and incorporating all taxes and subsidies, including VAT payments. As an example, in the case of gasoline, the dataset used in this study is the average price 'at the pump'. Annual average retail prices for coal, natural gas, and electricity are available disaggregated by main end-users, i.e. industrial and residential, while for other fuels, only economy-wide retail prices are available. This dataset incorporates information from IMF and World Bank country desk datasets. For cases where such data were not available, Parry et al. (2021) uses the average across third-party sources (including Eurostat, 2021, IEA (2020), World Bank, 2021, Global Petrol Prices, 2021 and Enerdata, 2021) combined with a number of ad hoc procedures.[16] Prices were converted into nominal US dollars per TOE by using conversion factors from World Bank (2023a) and *International Monetary Fund* (2023) and into real international dollars through a conversion factor, obtained from the ratio between GDP in real international dollars and nominal U.S. dollars computed from World Bank (2023a), as described above.

A.2. Energy efficiency policies

The impact of energy efficiency policies on the relationship between energy price and energy costs shares is assessed using energy efficiency indices from World Bank (2022). The Regulatory Indicators for Sustainable Energy (RISE) dataset includes a set of indices that assess policy and regulatory frameworks across countries to support the achievement of Sustainable Development Goal 7 (SDG7) on universal access to clean and modern energy. This study uses the overall indicator for energy efficiency, as well as 10 detailed sub-indicators, which are comprised in the overall indicator. Each indicator, ranging from 0 to 100, is obtained by weighting several binary responses to a set of questions about important aspects of energy efficiency. These include national energy efficiency planning (indicator $EnEff_1$ below), energy efficiency entities $(EnEff_2)$, incentives and mandates for industrial and commercial end users $(EnEff_3)$, the public sector $(EnEff_4)$ and energy utilities $(EnEff_5)$, financing mechanisms for energy efficiency $(EnEff_6)$, minimum energy efficiency performance standards $(EnEff_7)$, energy labelling systems $(EnEff_8)$, Building Energy Codes $(EnEff_9)$ and measures related

[10] A bottom-up approach to the construction of the national aggregates is required as there are no national energy prices in the dataset underlying Parry et al. (2021), hence one has to build national energy prices as an average of sectorial fuel prices weighted by the related fuel consumption, as described below.

[11] This required using series NGDPRPPPPC for real per capita GDP in international dollars and series LP for the level of population in IMF (2023).

[12] This ratio is used as a conversion factor to remove both the effect of inflation and the cross-country differences in terms of general price level. Current GDP in U.S. dollars (series NY.GDP.MKTP.CD) was obtained from World Bank (2023a).

[13] Industrial sector includes subsectors related to 1) cement; 2) construction; 3) food and forestry, 4) iron and steel; 5) machinery; 6) mining and chemicals; 7) non-energy use; 8) non-ferrous metals; 8) other manufacturing; 9) other industry. It excludes consumption related to energy transformation in Black et al. (2023) which encompasses the following IEA flows: 1) transformation processes; 2) transfers, including pipelines; and 3) energy industry own use; 4) distributional losses, and 5) a statistical difference.

[14] The transport sector includes fuel consumed for domestic shipping, railway, and road by both freight and passenger vehicles. Consumption from aviation is not incorporated in the transport sector due to limited availability of data for both jet fuel price and consumption.

[15] Detailed information on IEA flows incorporated in each item of the fuel taxonomy used here can be found in Black et al. (2023).

[16] As an example, missing data for natural gas and coal used in the industrial sector were filled by Parry et al. (2021) by using prices in the power generation sector. In case of missing data for both power and industry sectors, industrial fuel prices were computed by summing the supply cost and any known taxes, including import duties and pre-retail taxes.

specifically to the Transport Sector $(EnEff_{10})$, and those relate to carbon pricing and monitoring $(EnEff_{11})$.

Each RISE indicator reflects the policies but it does not capture 'quality' or the stringency of the regulations.[17] For this reason, the econometrically-estimated effect is likely to be lower than the actual effect associated with fully-enforced efficiency policies, as the estimated coefficient will reflect the average contribution across policies with varying degree of implementation. In addition, the policies included in the RISE indicators must be supported by other factors (such as strong institutions, open markets, access to finance, open flow of information, and a strong private sector) to have a marked impact on energy consumption. The fact that no information for these factors is used in this study, due to data availability, is likely to increase the 'noise' affecting the measurable impact of RISE scores. Another source of variation in the impact of a given RISE score is that some policies may be implemented only for specific regional areas or specific types of end-users, e.g. iron and steel firms in the industrial sector, which complicates the way in which these cases should be scored for the RISE indicators.

Here, we succinctly describe the most salient aspect of the 10 RISE indicators and introduce the *EnEff* descriptor to present the results. The detailed list of questions as well as the used weights can be found in World Bank (2023b).

1. The indicator '**National Energy Efficiency Planning**' $(EnEff_1)$ is related to the presence of legal frameworks, national action plans, energy efficiency goals and carbon reduction targets, their coverage and scope, the way in which these instruments have been arrived to, and whether the progress against their achievement is regularly reported.
2. The indicator '**Energy Efficiency Entities**' $(EnEff_2)$ measures the extent / impact of mandated certification/accreditation programs for energy efficiency activities, and the existence of bodies which set energy efficiency strategies and standards, and certify compliance with the standards, either directly or through third-party auditors.
3. The indicator '**Incentives & Mandates: Industrial and Commercial End Users**' $(EnEff_3)$ measures the existence of 1) energy-efficiency mandates for large energy users, including targets and mandatory audits, and whether these programs are supported by penalties for non-compliance, requirement for periodic reporting, as well as measurement and verification systems; 2) incentives for large energy users such as programs championing end users achieving significant energy savings measures, awareness programs or publicized case studies, and programs offering technical assistance to identify energy savings investment opportunities.
4. The indicator '**Incentives & Mandates: Public Sector**' $(EnEff_4)$ is related to the presence of energy savings obligations for public buildings and/or other public facilities, including financing mechanisms to support retrofitting, reporting mechanisms to track and enforce energy savings, specific policies or mandated guidelines for public procurement of energy-efficient products and services, guidelines to help identify energy-efficient options for procurement, and whether public entities are allowed to retain energy savings.
5. The indicator '**Incentives & Mandates: Energy Utility Programs**' $(EnEff_5)$ deals with energy efficiency programs associated to power generation, transmission and distribution networks, and demand-side management/demand-response, including mandated regulations for utilities to carry out energy efficiency activities, penalties for non-compliance and mechanisms for utilities to recover costs associated with or revenues lost from mandated energy efficiency activities. The indicators also include whether electricity tariffs are cost-reflective, metering mechanisms are in place to measure time-of-use and whether customers receive information comparing their consumption to other users or their own consumption across time.
6. The indicator '**Financing mechanisms for Energy Efficiency**' $(EnEff_6)$ reflects funding mechanisms for energy efficiency activities in the residential, commercial and industrial sectors, including the share of financial and/or non-financial institutions which offer credit lines for energy efficiency investments.
7. The indicator '**Minimum Energy Efficiency Performance Standards**' $(EnEff_7)$ measures the extent to which minimum energy performance standards have been adopted for domestic appliances, lighting equipment, industrial equipment and light vehicles, whether compliance with the standards is verified, enforced through penalties, and supported by periodical reporting, and whether standards are updated to reflect technological advances and changes in best practices.
8. The indicator '**Energy Labelling Systems**' $(EnEff_8)$ assess whether energy efficiency labeling schemes have been adopted for domestic appliances, lighting equipment, industrial equipment and light vehicles, whether they are mandatory or voluntary, and whether they are periodically updated to reflect technological advances and changes in best practices.
9. The indicator '**Building Energy Codes**' $(EnEff_9)$ describes the existence of heating/cooling strategy plans, targets for green (energy efficient) buildings, standards, regulations, energy efficiency codes for residential and commercial buildings, including renovated buildings and "near zero energy buildings". The indicator also relates to whether energy efficiency standards in new and renovated buildings are required to be regularly updated to reflect technological advances and changes in best practices, and whether compliance is supported by periodic reporting and credible verification systems.
10. The indicator '**Transport Sector**' $(EnEff_{10})$ is related to the presence of databases for transport efficiency metrics such as fuel consumption per mile driven, the existence of mandates or incentive programs supporting the reduction of transport demand or shifts to more energy-efficient modes for private, commercial and industrial transport, and whether there are requirement for periodic reporting to verify compliance with or progress of the programs.
11. The indicator '**Carbon pricing and monitoring**' $(EnEff_{11})$ is related to whether GHG emissions are covered by any carbon pricing mechanism and whether monitoring, reporting and verification system for greenhouse gas emissions are in place.

A.3. Economic factors affecting the response of energy cost shares to energy prices

Finally, this study employs multiple indicators of country characteristics to examine how the estimated impacts differ across factors that could potentially affect the response of energy cost shares to changes in energy prices. These include:

[17] As an example, the presence of governmental and/or independent bodies carrying energy efficiency planning work would lead to a similar increase in the RISE indicator related to 'energy efficiency entities', regardless of the stringency of standards, the extent of activities supporting energy consumers, and the extent to which compliance is promoted and enforced by third-party auditors.

1. The *stage of economic development* according to the World Bank's income classification (World Bank, 2024). Countries are classified as low-income, lower-middle-income, upper-middle-income, and high-income economies based on the level of per capita income.
2. The *degree of financial development* as measured by the index introduced by Svirydzenka (2016). This IMF database scores the development of financial institutions and markets based on their depth, access, and efficiency. The index ranges from zero to one, with the value of 1 indicating the highest level of financial development.
3. The *human capital index* developed by Kraay (2019). This World Bank dataset quantifies the contribution of health and education to the productivity of the next generation of workers. The index ranges from zero to one, with the value of one indicating that a child born today can expect to achieve full health (defined as no stunting, and survival up to at least age 60) and complete their education potential (defined as 14 years of high-quality school by age 18).
4. The *oil trading status*, as computed in Agnolucci et al. (2024a). A country is classified as energy exporting or importing based on whether the sum of the net exports of crude oil and natural gas liquids between 1990 and 2019 is positive or negative, respectively.
5. The degree of dependence on *energy imports* defined as net energy imports as a percentage of energy use, taken from the World Integrated Trade Solution (World Bank et al., 2024). Net energy imports are computed as energy use less production, measured in oil equivalents. A negative value indicates that the country is a net exporter.
6. The level of *net energy consumption taxes,* as computed in Agnolucci et al. (2024a). Energy consumption taxes net of energy consumption subsidies are measured by taking the difference between retail energy prices and supply costs for specific energy consumption sectors. National values are obtained by weighing the sectorial net energy taxes by the amount of energy in each sector.

Appendix B. Robustness checks

Table 5
Robustness to lags in the energy price. Estimates of the base model using the full sample and including one, two, and three lags for the energy price variable. The number in parentheses indicates the standard error. The symbols ***, ** and * indicate statistical significance at 1 %, 5 %, and 10 %, respectively.

	One lag	Two lags	Three lags
$\ln cs_{i,t-1}$	0.956 (***)	0.957(***)	0.962(***)
	(0.013)	(0.013)	(0.012)
$\ln ep_{i,t}$	0.822(***)	0.825 (***)	0.825(***)
	(0.022)	(0.022)	(0.022)
$\ln ep_{i,t-1}$	−0.800(***)	−0.833(***)	−0.825(***)
	(0.024)	(0.027)	(0.027)
$\ln ep_{i,t-2}$		0.030(*)	0.012
		(0.012)	(0.017)
$\ln ep_{i,t-3}$			0.008
			(0.011)
$\ln y_{i,t-1}$	−0.002	−0.003 (*)	−0.002 (*)
	(0.001)	(0.001)	(0.001)
constant	−0.310(**)	−0.308(**)	−0.2614(**)
	(0.136)	(0.136)	(0.121)
Long-run elasticities			
LR_{ep}	**0.494** (***)	**0.513** (***)	**0.483** (***)
LR_y	**−0.054** (**)	**−0.061** (**)	**−0.062** (**)
Observations	4512	4379	4246
Units	133	133	133
Instruments	116	117	118
Hansen: *p*-value	0.670	0.772	0.861

Table 6
Robustness to instruments used in the estimation. Estimates of the base model when collapsing the set of instruments used in the estimation, for the full sample and two subsamples. The number in parentheses indicates the standard error. The symbols ***, ** and * indicate statistical significance at 1 %, 5 % and 10 %, respectively.

	1980–2019	1980–1999	2000–2019
$\ln cs_{i,t-1}$	0.957(***)	0.905 (***)	0.934 (***)
	(0.012)	(0.048)	(0.0232)
$\ln ep_{i,t}$	0.824(***)	0.834 (***)	0.809 (***)
	(0.022)	(0.022)	(0.0411)
$\ln ep_{i,t-1}$	−0.804(***)	−0.7740 (***)	−0.7830 (***)
	(0.025)	(0.046)	(0.0478)
$\ln y_{i,t-1}$	−0.003 (**)	−0.0060 (*)	−0.006 (*)
	(0.001)	(0.003)	(0.0022)
constant	−0.285(**)	−0.819	−0.345
	(0.121)	(0.578)	(0.179)
Long-run elasticities			
LR_{ep}	**0.467** (***)	**0.625** (*)	**0.393** (**)
LR_y	**−0.085** (**)	**−0.061** (**)	**−0.083** (**)
Observations	4512	1864	2386

(*continued on next page*)

Table 6 (*continued*)

	1980–2019	1980–1999	2000–2019
Units	133	129	133
Instruments	7	7	7
Hansen: p-value	0.763	0.796	0.843

Table 7
Robustness to the use of demeaning used in the estimation. Results from model (6), from the same model without cross-sectionally demeaning the dependent variable, and from the same model without cross-sectionally demeaning but with a time fixed effect. The number in parentheses indicates the standard error. The symbols ***, ** and * indicate statistical significance at 1 %, 5 %, and 10 %, respectively.

	Cross-sectionally demeaned	No demeaning	No demeaning, time effect
$\ln cs_{i,t-1}$	0.962$^{(***)}$	0.945$^{(***)}$	0.964$^{(***)}$
	(0.012)	(0.035)	(0.018)
$\ln ep_{i,t}$	0.825$^{(***)}$	0.907 $^{(***)}$	0.918$^{(***)}$
	(0.022)	(0.036)	(0.020)
$\ln ep_{i,t-1}$	−0.825$^{(***)}$	−0.884 $^{(***)}$	−0.903$^{(***)}$
	(0.027)	(0.014)	(0.029)
$\ln ep_{i,t-2}$	0.012	0.060 $^{(}$0.012)	−0.005
	(0.017)		(0.016)
$\ln ep_{i,t-3}$	0.008	−0.007	0.005
	(0.011)	(0.014)	(0.012)
$\ln y_{i,t-1}$	−0.002$^{(*)}$	−0.005 $^{(**)}$	−0.003 $^{(**)}$
	(0.001)	(0.002)	(0.012)
constant	−0.261$^{(**)}$	−0.420	−0.268
	(0.121)	(0.420)	(0.240)
Long-run elasticities			
LR_{ep}	**0.483**$^{(***)}$	**0.400**$^{(*)}$	**0.399**$^{(**)}$
LR_y	**−0.062**$^{(**)}$	**−0.094**$^{(***)}$	**−0.069**$^{(**)}$
Observations	4246	4246	4246
Units	133	133	133
Instruments	118	118	154
Hansen: p-value	0.86	0.80	1.00

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2025.108616.

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