



The asymmetric effect of economic policy uncertainty on energy consumption

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Received: 8 September 2021 / Accepted: 23 April 2022 / Published online: 4 May 2022
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Abstract Assuming that economic policy uncertainty (EPU) can significantly affect economic activities, the paper explored the nature of its effect on energy consumption in G7 countries (Canada, France, Germany, Italy, Japan, the UK, and the USA) over the period 1997–2019 using a panel nonlinear autoregressive distributed lag model. The presence of an asymmetric effect of EPU on energy consumption was tested by decomposing EPU into negative and positive changes and placing it in a multivariate setting. The results reveal that the asymmetric effect of EPU on energy consumption is limited to the short run. However, if energy policy fails to manage uncertainty, it could become significant in the long run. Energy consumption is statistically significantly affected by economic institutions and income in both the short and the long run. Higher real income per capita boosts energy consumption in the short run, but like energy technology innovation, it reduces energy consumption in the long run. In contrast, more economic freedom, which was used as a proxy for institutions, increases energy consumption regardless

of the time frame. The results point to the energy policy challenges associated with energy consumption and sustainable energy practices.

Keywords Economic policy uncertainty · Energy consumption · Asymmetry · G7 · Nonlinear autoregressive distributed lag model

Introduction

Recent global events such as the global financial crisis, the Great Recession, and the COVID-19 global pandemic have considerably increased economic uncertainty and made economic decisions more difficult. Faced with discontinuities, turbulence, instability, and crisis situations, economic policy authorities are forced to change their policies, programs and measures more frequently. In doing so, as earlier studies have shown (Aizenman & Marion, 1993; Bloom, 2009, 2014; Rodrik, 1991), they themselves introduce uncertainty into economic life. The paper focuses on economic policy uncertainty (EPU), which refers to the uncertainty caused by economic policies, programs, and measures that change the general and business environment (see Baker et al., 2016). Empirical data shows that the EPU index, a common measure of EPU developed by Baker et al. (2016), has increased its value almost sixfold for the USA compared to 20 years ago (see the EPU index, 2021; <https://www.policyuncertainty.com/>).

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According to the same source, the global EPU index has also shown an upward trend since mid-2014 and is on average at the highest levels in the last 20 years.

Economic theory suggests that an increase in EPU may unfavorably affect economic activity as firms and households postpone investment and purchases, respectively (for a review, see Bloom, 2014 or Al-Thaqeb & Algharabali, 2019). Recent studies have empirically corroborated that this type of economic uncertainty has a considerable effect on the economic activities of households and firms, economic processes, and phenomena such as inflation expectations (Istiak & Alam, 2019), consumption or saving behavior (Levenko, 2020), oil prices (Hamilton, 1983), investment decisions (Rodrik, 1991), carbon emissions and environment (Adams et al., 2020; Al-Thaqeb & Algharabali, 2019), and tourism industry (Adedoyin et al., 2021). Therefore, it is plausible to expect that it will also affect energy consumption. Indeed, delaying the implementation of planned energy efficiency and conservation projects and activities as well as delaying the purchase of more efficient energy products and services due to uncertainty should have an impact on energy consumption. However, earlier studies on energy determinants did not pay much attention thereto, with a few exceptions (e.g., Barradale, 2010).

Several recent studies have explored the effect of EPU on energy consumption mostly within a carbon dioxide (CO₂) or growth function (Adams et al., 2020; Adedoyin & Zakari, 2020; Adedoyin et al., 2021; Liu et al., 2020; Pirgaip & Dinçergök, 2020; Wang et al., 2020). However, they did not consider the possibility that its effect is inherently asymmetric, meaning that its reduction and increase may not have the same effect on energy consumption. Only few recent studies have empirically tested and validated an asymmetric effect of EPU on selected economic variables (e.g., Bahmani-Oskooee & Maki-Nayeri, 2019, 2020; Bahmani-Oskooee & Saha, 2019; Foerster, 2014; Jones & Enders, 2016; Shahbaz et al., 2020). However, to the best of our knowledge, none has been done so for energy consumption. We hypothesize that the response of economic agents to uncertainty is asymmetric in nature. An increase in uncertainty may lower expectations of future income and growth, reduce risk-taking, and postpone plans for new energy investments. A decrease in uncertainty can encourage new economic activity, investment and purchases, and increase demand for energy.

The present paper aims to extend previous research by examining the asymmetric effect of EPU on energy consumption in G7 countries (Canada, France, Germany, Italy, Japan, the UK, and the USA) over the period 1997–2019. They are among the most industrialized, competitive, and richest countries in the world. In addition, G7 countries are known as the countries with sound economic institutions and a stable institutional framework. However, they are responsible for about 30% of the world's primary energy consumption and a quarter of the world's CO₂ emissions (British Petroleum, BP, 2020). Therefore, it would be interesting to find out whether the asymmetric effect of EPU plays a role when the decision on energy consumption is made in such a group of countries. The analysis relies on the estimation of the nonlinear autoregressive distributed lag (NARDL) model. It was recently proposed by Shin et al. (2014) to account for the asymmetric relationships among the variables under study. EPU is proxied by the EPU index of Baker et al. (2016). We believe that explicitly incorporating EPU in the energy equation can provide more relevant information for energy and environmental policy.

The paper makes three main contributions to the energy literature. First, it addresses the asymmetry in EPU and explicitly estimates its impact on energy consumption over time, thereby reducing the estimation bias. It also simultaneously accounts for nonlinearities and heterogeneity in the energy consumption-EPU relationship by using a recently developed NARDL model for panel data of G7 countries. Second, it further improves the estimates by including additional independent variables, i.e., economic institutions, energy innovation and income, in the energy consumption equation. Among them, little is known about the role of economic institutions, i.e., the rules of the game in North's terminology (North, 1981) in the energy field. Third, it identifies important energy policy challenges and implications with respect to policy-induced uncertainty, economic institutions, income, and energy innovations.

In the next sections, the relationship between energy consumption and EPU is briefly reviewed from the perspective of accumulated knowledge. Then, the data, the methodology and the empirical model are presented in "Data and methodology," the results are shown and discussed in "Results and discussion," and finally, conclusions with policy implications are drawn in "[Conclusions and policy implications](#)."

Economic policy uncertainty and energy consumption: a literature review

When examining the determinants of energy consumption in G7 countries, the literature has traditionally been focused on socioeconomic variables, particularly real income (expressed as gross domestic product (GDP) per capita or in growth terms). For example, Menegaki and Tugcu (2017) studied the short- and long-run causal relationship between sustainable economic welfare (proxied by the index), growth, and energy consumption. Soytas and Sari (2006) researched the association between energy consumption and income, while Banday and Aneja (2019) did the same for energy consumption, economic growth and CO₂ emissions. Sadorsky (2009) examined the role of oil price, GDP, and CO₂ per capita on renewable energy consumption.

However, the global financial crisis and the Great Recession have brought policy-related uncertainty and its detrimental effects on economic activity into focus of empirical research (Pirgaip & Dinçergök, 2020). Certainly, economic uncertainty is not an unknown concept in economics; for example, Keynes (1936) already established a link between uncertainty and economic activity, emphasizing that it determines the behavior of economic agents and financial markets in particular. Many other scholars, such as Rodrik (1991), Bloom (2009, 2014), Baker et al. (2016), among others, contributed a lot to a better understanding of the concept itself and its role in economics. They documented that even moderate levels of policy uncertainty can reduce private investment, output, and contribute to business cycles. Though, due to the lack of reliable measures of uncertainty and econometric techniques, the early studies were not able to accurately assess the impact of uncertainty.

A recent growing interest in studying the effect of uncertainty may be justified not only by the fact that EPU has been high in recent years (see the EPU index at: <https://www.policyuncertainty.com/>) but also by the availability of data on uncertainty. As noted above, Baker et al. (2016) constructed an EPU index that takes into account the frequency of words in newspaper articles concerning fiscal and monetary policy, the tax code set to expire and the prevalence of disagreement between economic forecasters about future inflation and government consumption. In addition to the aforementioned index used in this paper, several other measures

were employed in the literature to proxy for uncertainty. A popular example is the World Uncertainty Index (WUI) developed by the World Bank (WB, 2020). It counts how often the word “uncertain” or its variant appears in the country reports produced by the Economist Intelligence Unit. As Baker et al. (2016) pointed out, high uncertainty is usually associated with weak economic performance and growth prospects.

Previous literature primarily studied the effect of EPU on adverse emissions or economic growth. By investigating the 1999–2007 period, Barradale (2010) showed that an EPU reduction is an essential component of sound renewable energy policies that can promote renewable energy investment in the USA. Adedoyin and Zakari (2020) investigated the impact of EPU, energy consumption, and GDP on CO₂ emissions within the environmental Kuznets curve framework in the UK for the period 1985–2017. Using the ARDL bound test, they found out a statistically significant impact of EPU on CO₂ emissions in the short run and a controversial effect in the long run. They also detected one-way pairwise Granger causality running from energy consumption to EPU. The effect of EPU together with energy consumption and tourism on environmental degradation was also corroborated by Adedoyin et al. (2021) for the ten countries with the highest tourism revenues in the period 1995–2015.

Applying the ARDL approach, Adams et al. (2020) tested the effect of EPU, geopolitical risk, economic growth, and energy consumption on CO₂ emissions for ten resource-rich countries in the period 1996–2017. They provided evidence that an increase in EPU, measured by the WUI, worsens the environment in the short and the long run, but only statistically in the latter case. They also revealed bidirectional causality between EPU and energy consumption. Pirgaip and Dinçergök (2020) investigated the causal relation between EPU, energy consumption, and carbon emissions in G7 countries for the period 1998–2018. They detected different causality relationships among selected countries and underlined a possible harmful effect of higher EPU on the environment and energy conservation policies. Wang et al. (2020) also demonstrated that EPU, proxied by the WUI, unfavorably impacts green energy and renewable energy projects in the USA over the period 1960–2016. Liu et al. (2020) studied the impact of EPU on traditional and renewable energy firms’ investment in China from 2007Q1 to 2017Q4 by

using a panel regression model. Their results suggest that EPU has a stronger adverse effect on the former than on the latter.

The asymmetric effects of EPU have only recently been the subject of research interest. Foerster (2014) validated this effect on economic activity and found that an increase in uncertainty has a greater effect than its reduction. Jones and Enders (2016) tested the asymmetric effect of uncertainty on aggregate economic activity in the US. Bahmani-Oskooee and Maki-Nayeri (2019, 2020) assessed the asymmetric effect of EPU on domestic investment and consumer consumption in G7 countries, respectively, while Bahmani-Oskooee and Saha (2019) did that for stock prices in the same group of countries. Shahbaz et al. (2020) tested the asymmetric responses of renewables on economic growth in G7 countries during 199Q1–2015Q4. In a nutshell, all of them detected the asymmetric effect of EPU on selected economic variables. However, as already mentioned, the literature failed to investigate the asymmetric effect of EPU on energy consumption. This is particularly important as many strategic objectives at national, European, and global level are directly linked to energy consumption.

Data and methodology

Data

The present study uses a balanced panel dataset that covers the period 1997–2019 for G7 countries. The annual data includes primary energy consumption per capita as the dependent variable and a set of independent variables: the EPU index, the economic freedom index, real GDP per capita, and the energy

public research, development, and demonstration (RD&D) budget. Basic information on the data is given in Table 1. Energy consumption (*EC*) refers to the consumption of primary energy before conversion into final consumption fuels. It is measured in gigajoules per capita.

As mentioned earlier, the EPU index (*EPU*) is created through a search process that tracks the words related to EPU appearing in major newspapers. The higher the value of the EPU index, the higher the level of uncertainty. We employ the annual data, which are the averages of the quarterly data published on the web platform <https://www.policyuncertainty.com/>. Refer to this web page for details of the index. The economic freedom index (*EFI*) is designed to track 12 freedoms, organized into the following four broad pillars: rule of law, government size, regulatory efficiency, and open markets (Heritage Foundation, 2020). It reflects the effect of economic institutions. The value of the index is scaled from 0 to 100, with a higher value reflecting more freedom. Although the role of institutions in the energy-environment-growth nexus has been mostly ignored (Aminem & Menegaki, 2019), recent evidence (Cadoret & Padovano, 2016; Fredriksson et al., 2004) confirms their importance, whether advocating more or less government regulation of energy production, distribution and use. Although G7 countries have sound institutions, that can mitigate the adverse consequences of uncertainty, the index scores point to important differences in the economic freedom enjoyed by the private sector in these countries.

Real GDP is measured by the 2015 USD prices and expressed in per capita terms (*GDP*). As mentioned above, it is a commonly used variable in the energy-environment-growth nexus (e.g., Liu et al., 2019; Narayan & Smith, 2008). However, the

Table 1 Descriptive statistics

Variable	Symbol	Obs	Mean	Std. dev	Minimum	Maximum	Source
Primary energy consumption per capita (gigajoules per capita)	<i>EC</i>	161	210.90	96.13	103.14	418.73	BP(2020)
Real GDP per capita (US\$, 2015)	<i>GDP</i>	161	42,281.400	5525.947	32,882.030	60,695.550	OECD (2020)
Economic Uncertainty Index	<i>EPU</i>	161	139.09	79.45	37.60	542.77	Baker et al. (2016) For Japan: Arbatli et al. (2019)
Economic Freedom Index (0–100)	<i>EFI</i>	161	70.90	6.84	57.40	81.20	Heritage Foundation (2020)
Energy public RD&D budget, % GDP	<i>RD_D</i>	161	0.037	0.022	0.003	0.100	OECD (2020)

evidence is inconclusive regarding its effect on energy consumption. The energy public RD&D budget (RD_D), expressed as a percentage of total energy public RD&D in GDP, is a proxy for energy innovations. We assume that its higher values, i.e., more resources devoted to science and technology, reinforce RD&D activities and lead to new or improved energy-efficient technologies, innovative processes and materials. Recent studies (e.g., Fernandez et al., 2018) confirmed the important role that RD&D plays in reducing energy consumption by improving energy efficiency and conservation, and developing a clean energy future. All variables except the energy public RD&D budget are included in their natural log form in econometric analysis.

Model specification and estimation methodology

To estimate the impact of EPU and other explanatory variables on energy consumption, the following empirical function is set:

$$EC_{it} = f(EPU_{it}, EFI_{it}, GDP_{it}, RD_D_{it}), \quad (1)$$

where i refers to the country ($i=1, \dots, 7$), and t represents the period under investigation ($t=1997, \dots, 2019$).

The estimation methodology applied in this paper follows the common practice in panel data analysis. It is performed in three steps. The first includes data property analysis, i.e., the application of the unit root test in order to detect the order of integration of the variables, the slope homogeneity test to check for homogeneity in the panel data and multicollinearity analysis to detect a possible existence of the multicollinearity issue. The selection of a proper unit root test assumes the previously verified presence of cross-sectional dependence. Namely, if this issue is present, the estimates may be biased and statistical inference incorrect. Besides, the first generation panel unit root tests, which suppose cross-sectional independence, should not be applied (Pesaran, 2007). Hence, we tested for its presence the Lagrange multiplier (LM) test, developed by Breusch and Pagan (1980), for the case when the time-series dimensions (T) is larger than the cross-sectional dimension (N). Based on the evidence provided by this test, the Pesaran (2007) cross-sectional augmented panel unit root test (CIPS)

may be employed to examine whether the variables are stationary. To apply the ARDL model and have a consistent estimation, it is important that the order of variables does not exceed the integration of order one (Pesaran et al., 1999). Furthermore, the Swamy's test (Swamy, 1970), which is valid for a case when $N < T$, was applied to test for slope homogeneity in a panel of interest and the variance inflation factor (VIF) was used to check for the presence of multicollinearity.

In the second step, panel cointegration methodology should be applied if variables of interest have the same order of integration. Its purpose is to investigate the presence of cointegration, i.e., a stable, long-run equilibrium relationship among variables under investigation. The cointegration test developed by Westerlund (2007) can be applied since it handles the presence of cross-sectional dependence. The null hypothesis is that cointegration does not exist, while the alternative hypothesis is that some (not necessary all) panels are cointegrated.

In the third step, the panel NARDL model is used to explore the asymmetries that may be caused by changes in EPU in the short and the long run. We expect that positive and negative shocks related to EPU differently affect energy consumption bearing in mind their effect on expectations concerning future income and growth, risk-taking behavior, and investment and purchase plans. To that end, the values of the EPU index in the current period were compared with its values in the previous period to determine the direction and the magnitude of the change ($\Delta EPU_{it} = EPU_{it} - EPU_{it-1}$). In mathematical terms, the EPU series was split into two series based on the sign of ΔEPU as follows:

$$EPU_{it}^+ = \begin{cases} EPU_{it}, & \Delta EPU_{it} \geq 0 \\ 0, & \text{otherwise} \end{cases}, \quad (2)$$

$$EPU_{it}^- = \begin{cases} EPU_{it}, & \Delta EPU_{it} < 0 \\ 0, & \text{otherwise} \end{cases}, \quad (3)$$

In line with Shin et al. (2014), the panel NARDL (p, q, \dots, q) model adopted by this study is expressed as follows:

$$\begin{aligned}
 \Delta EC_{it} = & \alpha_{0i} + \alpha_{1i} EC_{it-1} \\
 & + \alpha_{2i}^+ EPU_{t-1}^+ + \alpha_{2i}^- EPU_{t-1}^- \\
 & + \alpha_{3i} EFI_{t-1} + \alpha_{4i} GDP_{t-1} \\
 & + \alpha_{5i} RD_D_{t-1} + \sum_{j=1}^{p-1} \beta_{ij} \Delta EC_{it-j} \\
 & + \sum_{j=0}^{q-1} \left(\gamma_{ij}^+ \Delta EPU_{it-j}^+ + \gamma_{ij}^- \Delta EPU_{it-j}^- \right) \\
 & + \sum_{j=0}^{q-1} \left(\delta_{ij} \Delta EFI_{it-j} + \theta_{ij} \Delta GDP_{it-j} + \sigma_{ij} \Delta RD_D_{it-j} \right) \\
 & + \mu_i + \epsilon_{it},
 \end{aligned} \tag{4}$$

where Δ refers to the difference operator. The residual (error) term is denoted by ϵ_{it} and μ_i stands for the fixed effects. The parameters α_1 - α_4 refer to the $k \times 1$ vector of the long-run coefficients, which are computed as follows: $EPU_i^+ = -\alpha_{2i}^+ / \alpha_{1i}$, $EPU_i^- = -\alpha_{2i}^- / \alpha_{1i}$. β_{ij} , γ_{ij} , δ_{ij} , θ_{ij} , and σ_{ij} represent the $k \times 1$ vectors of the short-run coefficients.

The error correction version of Eq. (4) is as follows:

$$\begin{aligned}
 \Delta EC_{it} = & \tau_i \varphi_{it-1} + \sum_{j=1}^{p-1} \beta_{ij} EC_{it-j} \\
 & + \sum_{j=0}^{q-1} \left(\gamma_{ij}^+ \Delta EPU_{it-j}^+ + \gamma_{ij}^- \Delta EPU_{it-j}^- \right) \\
 & + \sum_{j=0}^{q-1} \left(\delta_{ij} \Delta EFI_{it-j} + \theta_{ij} \Delta GDP_{it-j} + \sigma_{ij} \Delta RD_D_{it-j} \right) \\
 & + \mu_i + \epsilon_{it},
 \end{aligned} \tag{5}$$

where the error correction term (φ_{it-1}) refers to the long-run equilibrium of Eq. (4). The speed of adjustment is depicted by τ_i . If it equals 0, the variables do not have a long-run relationship. If it is negative and significant, the variables converge to the long-run equilibrium in case of any shocks.

The NARDL model was applied in this paper since it provides an error correction (EC) process that includes the asymmetries into long-run cointegration. It has become a commonly used model in empirical studies that captures the effects of positive and negative uncertainty. It does that in both the short and the long run in a nonlinear framework, but in a single equation (Shin et al., 2014). Model parameters were estimated by both the pooled mean group (PMG) estimator and the mean group (MG) estimator. The former incorporates a combination of pooling and

averaging of coefficients, while the latter is based on the estimation of N time-series regressions and averaging the coefficients (Blackburne & Frank, 2007). The Hausman test is used to test the presence of systematic differences between them. If the difference between PMG and MG estimations is not significant, the PMG estimator yields efficient and consistent estimates and should be preferred. As highlighted by Pesaran et al. (1999), it allows the short-run coefficients including the intercepts and error variances to be heterogeneous per country, whereas the long-run coefficients are constrained to be homogenous across the countries. We expect that the long-run relationship between energy consumption and a set of explanatory variables is homogenous across G7 countries, whereas the short-run effects of the latter are affected by specificities of each country.

Results and discussion

Preliminary testing

Firstly, we made a preliminary analysis that includes a descriptive analysis and a correlation analysis. Table 1 gives the descriptive statistics, while Table 4 in the appendix presents the correlation matrix.

Although the G7 group includes highly industrialized and rich countries, there are significant differences among them. The richest country is the US, while Japan and Italy have the lowest GDP/capita. The lowest average per capita energy consumption was recorded in Italy and the USA, and the highest one in Canada and the UK. Higher than average uncertainty is observed in Canada, France, the UK, and the USA. However, the highest levels of economic freedom are recorded in the UK and the USA, and lowest in Italy. Japan has the largest energy public RD&D as the percentage of GDP, while the UK has the smallest one.

Pearson’s correlation coefficients (Table 4) indicate that energy consumption is statistically significantly and positively correlated with EPU and economic freedoms, and negatively correlated with the GDP and energy public RD&D budget variables. The EPU variable is positively correlated with all other variables. Wang et al. (2020) also found a positive correlation between EPU and GDP/capita. Since the correlation between explanatory variables is not

so strong, the probability of a multicollinearity issue is not high. The average VIF of 1.22 (Table 5) corroborated that multicollinearity is not an issue in this paper.

Given the importance of testing for the presence of cross-sectional dependence, the Breusch-Pagan LM test is applied. Its results, reported in Table 2, indicate that the validity of the null hypothesis of cross-sectional independence should be rejected at the 1% significance level. Consequently, the second generation unit root test, the Pesaran CIPS test, is appropriate to be applied to detect stationarity of the series. Its results are placed in Table 6. According to them, the GDP per capita and economic freedom variables are of order one ($I(1)$), while energy consumption, EPU, and energy RD&D expenditure variables are of order 0 ($I(0)$).

The mixed order of variable integration, but not exceeding order $I(1)$, allows the panel (N)ARDL model to be applied. Moreover, the presence of cross-sectional dependence, tested with the modified Wald test for groupwise heteroskedasticity, suggests that the variables of interest follow a kind of dynamics common to all countries in the sample (Table 2). This is not unexpected; these are rich countries and leaders of global trends. Moreover, they are economically interconnected and some of them are regionally integrated. Thus, the spillover effects possibly contribute to cross-sectional dependence as well.

The heterogeneity of the parameters is confirmed by Swamy's homogeneity test statistics (Table 2). Therefore, the panel (N)ARDL model is an appropriate model as it takes into account inherent heterogeneity and non-stationarity in the panel data series. We also checked for the presence of cointegration between the variables of interest. For this purpose, we used the Westerlund (2007) cointegration test. A robust critical statistics is obtained by 100 bootstrap replications. The results of the panel Pa and Pt statistics, reported in Table 7, show that the null hypothesis of no cointegration for the panel as a whole can be

rejected but only at the 10% significance level. The lack of clear evidence for the existence of linear cointegration suggests the possibility of the existence of a nonlinear one.

Panel PMG NARDL estimation

As mentioned earlier, the paper adopts the approach of Shin et al. (2014) to capture asymmetric changes in EPU on energy consumption. However, for comparison purposes, first, a symmetric and then an asymmetric effect of EPU was tested. Both the MG and PMG estimators were applied. However, since Hausman statistics indicated that the PMG estimator is a more efficient estimator in both linear (symmetric) and non-linear (asymmetric) specifications, the paper focuses on examining the effect of EPU and other explanatory variables on energy consumption by using this estimator. Table 3 displays the result of PMG estimation of symmetric and asymmetric models addressing the estimated long- and short-run coefficients. It also provides the results of the Hausman test and the Jarque–Bera normality test. The latter indicates the residuals of the error terms are normally distributed and the coefficient estimates are efficient and unbiased. The error correction term (ECT) is negative and statistically significant at the 10% level in the NARDL specification. This suggests that there may be convergence of the system to its long-run equilibrium after a shock.

In a symmetric specification, EPU has no statistically significant effect on energy consumption in G7 countries in either the short or the long run. When an asymmetric effect is tested, no statistically significant effect can be observed in the long run either. However, its short-run impact is statistically significant at a 10% level. Accordingly, both positive and negative shocks in EPU increase energy consumption. Thereby, a negative shock has a stronger effect thereon. The Wald asymmetry test supports the

Table 2 Preliminary test results

Model	Mean VIF	Cross-sectional dependence test statistics	Heteroscedasticity test statistics	Homogenous slope test statistics
$\ln EC_{it} = f(\ln EPU_{it}, \ln EFI_{it}, \ln GDP_{it}, RD_D_{it})$	1.22	$\chi^2(21) = 160.452; p < 0.001$	$\chi^2(7) = 275.23; p < 0.001$	$\chi^2(36) = 23,408.44; p < 0.001$

Table 3 Panel (N)ARDL estimation results (dependent variable: $\Delta \ln EC$)

Variable	Time period	Symmetric ARDL model with EPU (1 1 1 2 2)		Asymmetric NARDL model with EPU (1 1 1 1 1 1)		Asymmetric NARDL model with WUI (1 0 0 1 1 2)	
		Estimated coefficient	Standard error	Estimated coefficient	Standard error	Estimated coefficient	Standard error
$\Delta \ln EPU$	Short run	-0.006	0.007				
$\Delta \ln EPU^-$				0.020*	0.010	0.008	0.019
$\Delta \ln EPU^+$				0.018*	0.010	-0.010	0.011
$\Delta \ln EFI$		0.191**	0.096	0.352*	0.199	0.430	0.138
$\Delta \ln GDP$		0.769***	0.129	0.857***	0.147	0.878***	0.151
ΔRD_D		-0.109	0.317	-0.216	0.494	0.151	0.286
Constant		1.814*	1.247	1.331*	0.797	1.561*	0.410
ECT_{t-1}		-0.274	0.191	-0.147*	0.088	-0.151*	0.080
$\ln EPU$	Long run	-0.009	0.012				
$\ln EPU^-$				0.038	0.032	0.194	0.760
$\ln EPU^+$				0.029	0.029	0.175**	0.480
$\ln EFI$		0.374***	0.142	2.200***	0.205	2.116***	0.104
$\ln GDP$		-0.266***	0.092	-1.256***	0.115	-1.338***	0.000
RD_D		-2.974***	0.752	-3.119***	1.117	-2.439***	0.692
Log likelihood		408.0231		425.563		413.1955	
Hausman test		$\chi^2(4) = 3.50; p = 0.477$		$\chi^2(5) = 8.06; p = 0.153$		$\chi^2(5) = 6.13; p = 0.2934$	
Jarque-Bera normality test		$\chi^2(2) = 1.978; p = 0.372$		$\chi^2(2) = 3.015; p = 0.222$		$\chi^2(2) = 2.041; p = 0.360$	
Number of observations		154		154		154	

Note: ***, **, and * denote 1%, 5%, and 10% levels of significance, respectively. Δ denotes the first difference of the variable. The numbers in the first row reveal the number of lags attributed to each variable in the long run model specification

hypothesis of the asymmetric effect of EPU in the short run ($\chi^2(1) = 9.70; p < 0.01$). Since it adversely affects economic activity, it would be expected that EPU would reduce energy consumption. However, the opposite effect has already been observed (Pirgaip & Dinçergök, 2020). EPU increases the cost of economic activities and decreases incentives to invest in energy efficiency. Firms delay investment projects (Bloom, 2009), including energy projects (Barradale, 2010), and consumers reduce their spending on new and more energy efficient appliances and services, especially when uncertainty is high (Bahmani-Oskooee and Maki-Nayeri, 2019, 2020). This in turn leaves firms and households with less efficient energy technologies, materials, buildings, vehicles, appliances, and the like, which increases energy consumption. A decline in uncertainty, on the other hand, raises expectations of future economic growth and boosts economic activity and new investment.

It also encourages the purchase of new products and services. This in turn increases energy consumption, i.e., it triggers the rebound effect by offsetting energy efficiency gains.

The asymmetric effect of EPU weakens over time and is limited to the short run. This finding is partially in line with Adams et al. (2020), who revealed that policy uncertainty unfavorably affects environment quality in both the short and the long run as well as that there is bidirectional causality between energy consumption and CO₂ emission in resource-rich countries. Wang et al. (2020) discovered that an increase in EPU leads to more CO₂ emissions in the USA in the long run, which implicitly means that it leads to more energy consumption. However, Adedoyin and Zakari (2020) covered the case of the UK and found that higher EPU reduces CO₂ emissions in the short run, but they failed to detect a recognizable relationship in the long run. The diminishing effect of

EPU over time seems to be the result of learning and adjustment processes, i.e., increasing knowledge and experience of all economic actors and the formulation of more effective strategies to deal with EPU. Indeed, learning and adjustment are integrally interconnected. Learning about policy-induced uncertainty during adjustment is a continuous process through which economic actors strive to find a balance and restore stability in their environment, as well as achieve the goals set.

Economic institutions, proxied by the economic freedom index, statistically significantly influence energy consumption in both the long and the short run. Unlike EPU, its effect becomes stronger over time. Institutions structure incentives not only in political and economic relations, but also in social ones, helping to ensure at least basic energy needs and services for all citizens. This finding is consistent with Assi et al. (2020), who provided evidence that more economic freedom is associated with an increase in gasoline consumption in *free* countries. Implicitly, it is also in line with Cadoret and Padovano (2016), who showed that institutions, measured by the level of corruption, positively affected renewable energy deployment in 26 European Union countries during 2004–2011. Fredriksson et al. (2004) also discovered that poor governance (proxied by the level of corruption) reduced the effect of energy policy and indirectly decreased energy efficiency in 14 OECD countries during 1982–1997. Bhattacharya et al. (2017) showed that sound institutions along with renewable energy development reduced CO₂ emissions in selected developed and developing countries in the period 1991–2012. In contrast, Aminem and Menegaki (2019) failed to find a significant relationship between institutions, measured by control of corruption, and energy consumption for 67 high- and upper-middle income countries during 1985–2011.

The strengthening of the impact over time is also observed in real GDP per capita. Interestingly, an increase in real GDP per capita boosts energy consumption in the short run. However, this effect reverses into the opposite. In the long run, an increase in GDP per capita reduces energy consumption, suggesting that G7 countries still failed to decouple energy consumption from income. Liu et al. (2019) reported that only the UK has a fully decoupled relation between these variables in the G7. In the short run, economic development requires energy for its materialization, but in the

long run, it appears that a sustainable energy framework is set up and sustained with less energy. This finding thus continues on the finding obtained by Menegaki and Tugcu (2017), who revealed bidirectional causality between energy consumption and sustainable economic welfare. It is also consistent with Adams et al. (2020), who concluded that the square of real GDP adversely affects environmental quality in the short run, but enhances it in the long run. Boosting GDP per capita changes the type of energy and the way it is used, directing it towards renewable energy and more efficient and economical manner of its use. In the long run, this leads to a reduction in energy consumption, as the present paper shows.

Public RD&D expenditure on energy does not have a statistically significant impact in the short run; however, its impact becomes significant in the long run. Here, an increase in the RD&D budget reduces energy consumption in the long run. Energy public RD&D expenditure is closely related to energy innovation, which results in new or improved energy technologies that use energy in a more effective, efficient, and environmentally friendly manner. Additionally, it improves the quality of energy services and reduces the cost of their usage. Previous literature also detected the importance of energy innovation in reducing energy consumption in general (Popp, 2001), or for OECD (Alvarez-Herranz et al., 2017) and G7 countries in particular (Inglesi-Lotz, 2017; Khan et al., 2020). Obviously, developed countries mainly consume more energy, but at the same time, they are able to invest more in RD&D activities and enhance energy efficiency as well as accelerate the transition to a low-carbon future.

To deepen our understanding of the results and perform robustness analysis, the EPU variable is replaced by the WUI variable. As shown in Table 3, the sign and significance of income, energy innovations, and economic institutions are largely the same. However, WUI does not affect energy consumption in the short run, in contrast to the long run, where an increase in WUI causes a significant response in energy consumption. This is not unexpected given that WUI is broader in scope since it counts the number of times the word “uncertain” (or its variant) is mentioned regardless of its cause. Comparing the effects of EPU and WUI on energy consumption, it seems that economic policies in G7 countries successfully find a way to reduce

the effect of uncertainty they cause in the long run. This cannot be said for other causes whose influence becomes dominant over time. Implicitly, model specification with WUI indicates that if energy policy cannot properly manage uncertainty it causes, it will be difficult for businesses and households to go forward with new energy efficient projects. Consequently, energy consumption will increase and strategic energy targets will not be met.

Conclusions and policy implications

The paper estimated the asymmetric effect of EPU together with economic institutions, energy innovation, and economic development on energy consumption in G7 countries over the period 1997–2019. A panel nonlinear ARDL method applied to that end indicates that both a decrease and an increase in EPU considerably influence energy consumption only in the short run, with the response appearing to be stronger in terms of the latter. In contrast, there is a significant impact of economic institutions and real GDP per capita in the short and the long run. Unlike economic institutions, whose improvement increases energy consumption, a boost to economic activity initially increases energy consumption and then reduces it over time. The beneficial effect of RD&D on energy consumption only comes to the fore in the long run. Relying on these findings, three interrelated energy policy challenges and implications can be derived with respect to policy-induced uncertainty, economic institutions and energy innovation.

First, although the effect of EPU weakens over time in statistical terms, its asymmetric effects should not be ignored. Economic policy, together with energy policy, contributes to uncertainty, which increases considerably, especially in times of economic turbulence. Energy policy is under constant pressure to create, support, and promote an energy efficient and environmentally friendly general and business environment while maintaining economic stability. Whether it succeeds in doing so is closely related to its ability to understand the determinants of energy consumption and the dynamics of its impacts over time, as well as to minimize the uncertainty that arises. If energy policy fails to manage uncertainty, it may grow and result in reduced

interest in investing in innovative, more energy-saving and efficient business processes, products and services. Consequently, energy consumption may considerably increase in the long run, as implicitly suggested by model specification with WUI.

The paper did not consider the contribution of energy policy uncertainty to economic policy uncertainty or the channels through which energy policy influences EPU, such as energy prices. However, the results suggest that they are important and should be addressed in further research. Acknowledging both the level of energy policy uncertainty, which is unavoidable to some extent, and the asymmetries in the adjustment process to the long-run equilibrium, energy policy authorities can properly manage policy measures by at least keeping them clear and transparent when economic stability cannot be fully maintained. This points to the importance of strategic planning and implementation of policy measures, which must be consistent, announced in advance and adequately communicated to the public.

Second, improving economic institutions is associated with more transparent, stable, fair, i.e., better economic and social interactions, as well as an increasing demand for energy regardless of the time frame. The paper shows that energy policy faces the major challenge of how to translate improvements in economic institutions and greater economic freedom into reductions in energy consumption, while maintaining at least the existing levels of quality of life or the environment. Sound institutions ensure, inter alia, a conducive investment environment and greater readiness to implement new solutions to energy innovation. Their quality should therefore be continuously upgraded. Additionally, individual freedoms and the readiness of the private sector to innovate in the energy sector are important and should not be burdened by unnecessary regulation. However, more economic freedom leads to an increase in demand for more energy-consuming products, sometimes without regard to harmful emissions and environmental protection in general. It is clear that energy policy must strike an optimal balance between economic freedom and government interventions in the energy sector.

It seems that an important key to this challenge lies in the creation of various energy policies and

programs with clear goals and incentives that ensure affordable energy at competitive prices and environmentally friendly energy options and that encourage the use of more efficient, modern energy, and energy/environmentally friendly services. This requires more government funding for basic research and development of the cutting-edge energy technologies and solutions that the private sector is not interested in. Eliminating cronyism is certainly a necessary precondition therefor.

Third, the paper clearly shows that the accumulation of energy innovations over time reduces energy consumption. Certainly, it is understandable that it takes time for innovations to produce positive effects and tangible results in terms of energy consumption. But, to ensure the full impact of innovations and the achievement of strategic energy and environmental goals, it is necessary to ensure the continuity of RD&D expenditure inflows, prioritize RD&D, rationalize and increase public RD&D, strengthen private RD&D, and develop collaboration networks. Energy policy authorities have already created various types of energy efficiency policies and programs aimed at implementing energy innovation outcomes. However, the paper shows their outcomes should be more explicit. New and properly communicated policies, programs, and measures are needed to capitalize more on energy innovation in businesses, transportation, and homes and provide positive feedback on energy use, even in the short run. This is important along with the promotion of clean energy sources and sustainable energy practices, as an increase in per capita income increases energy consumption in the short run, which is not the case in the long run.

The paper focuses on G7 countries, which are the largest energy consumers, the richest countries in the world and countries with well-developed institutions. In addition to the suggestions for further research that have already been mentioned, it would be interesting to investigate the effects of energy policy-driven uncertainty in countries that are opposite to them in terms of their economic, social and institutional systems. Moreover, further research should explore possible interaction effects between the variables of interest, particularly EPU and economic institutions within the context of energy consumption.

Appendix

Table 4 Pearson's correlation matrix.

	<i>lnEC</i>	<i>lnEPU</i>	<i>lnEPU</i>	<i>lnEPU</i> ⁺	<i>lnEPU</i> ⁺	<i>lnGDP</i>	<i>RD_D</i>
<i>lnEC</i>	1						
<i>lnEPU</i>	0.0496	1					
<i>lnEPU</i> ⁻	-0.0228	-0.2245*	1				
<i>lnEPU</i> ⁺	0.031	0.4034*	-0.9822*	1			
<i>lnEFI</i>	0.5150*	0.1749*	0.0096	0.0247	1		
<i>lnGDP</i>	-0.1975*	0.2740*	-0.0318	0.0826	0.4666*	1	
<i>RD_D</i>	0.4314*	-0.1415	-0.0509	0.0206	0.1151	-0.1104	1

* significant at the 5% significance level

Table 5 VIF statistics

Variable	VIF	1/VIF
<i>lnEPU</i>	1.37	0.731
<i>lnEFI</i>	1.29	0.777
<i>lnGDP</i>	1.14	0.874
<i>RD_D</i>	1.07	0.934

Table 6 Results of the CIPS Pesaran test

	Level		First difference	
	Constant	Con-stant + trend	Constant	Con-stant + trend
<i>lnEC</i>	-2.920*	-3.369*		
<i>lnGDP</i>	-1.905	-2.899	-3.366*	-3.770*
<i>lnEPU</i>	-2.769*	-3.098*		
<i>lnEFI</i>	-2.218	-2.145	-4.479*	-4.679*
<i>RD_D</i>	-3.145*	-4.036*		

Note: * significant at the 1% significance level

Table 7 Westerlund panel cointegration test results

Statistic	Value	Z-value	p-value	Robust p-value
Gt	-1.353	3.027	0.999	0.63
Ga	-0.297	4.371	1	0.81
Pt	-1.549	3.817	1	0.06
Pa	-0.307	3.14	0.999	0.09

Author contribution Conceptualization: DB; methodology: DB, BB; writing — original draft preparation: DB; writing — review and editing: DB, BB; software: BB; funding acquisition: DB; supervision: DB.

Funding This work has been supported by Croatian Science Foundation under the project IP-2020-02-1018.

Data availability The data that support the findings of this study is openly available.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

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