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ORIGINAL RESEARCH ARTICLE

The heterogeneous impact of oil price shocks on traditional and modern renewable energy in developed and developing countries

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ABSTRACT

The prevalence of renewable energy helps solve environmental problems and strengthens energy security with less dependence on nonrenewable energy, mainly fossil fuels. One important aspect is that renewable energy consists of two components: traditional and modern renewable energy. This paper examines the effects of an oil price shock on these two different types of renewable energy consumption by applying a local projection method to panel data from 147 countries during the period from 1993 to 2015. Our results show that the effects of an oil price shock depend on the development level and the dependence on nonrenewable energy. In highly nonrenewable energy-dependent countries, traditional renewable energy is sensitive to oil price changes, irrespective of their development levels. However, both traditional and modern renewable energy are insensitive to oil price changes in less nonrenewable energy-dependent countries, regardless of their development levels. Meanwhile, an oil price shock positively affects modern renewable energy in developed countries with high dependence on nonrenewable energy, but not in developing countries. These results provide important policy implications for policymakers and investors to foster modern renewable energy and call for balancing macroeconomic development with environmental benefits and costs.

Keywords: traditional; modern renewable energy; fossil fuels; oil price shock; local projection

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1. Introduction

Renewable energy is one of the keys to addressing global warming, mitigating air pollution, and enhancing energy independence and security. Its development has gained traction worldwide through initiatives such as the United Nations' Sustainable Development Goals, the Kyoto Protocol, and the Paris Agreement. Renewable energy is derived from various sources, including hydro, solid biofuels, wind, solar, liquid biofuels, biogas, geothermal, marine, and waste[1]. These sources can be categorized into two primary forms: traditional and modern renewable energy[2,3]. However, certain traditional renewables, such as solid biofuel, wood, and charcoal combustion, are not deemed sustainable[3]. To advance clean energy, it is crucial to promote sustainable renewable energy consumption, which is primarily generated from modern renewable energy sources[3,4].

The use of renewable energy is influenced by several factors, such as oil prices, human capital, output, pollutant emissions, and energy consumption[5–7]. Among these factors, the price of oil plays a pivotal role in shaping people's behavior to transition between renewable and nonrenewable energy. Additionally, the demand and supply of nonrenewable energy are vulnerable to price fluctuations; therefore, it is essential to promote energy sources with sustainable pricing. Given this critical aspect, numerous studies have explored the relationship between oil prices and renewable energy consumption for specific countries or different groups of countries, but their findings have not yet reached a clear consensus[8–14]. Previous studies have generally relied on data for total renewable energy sources without distinguishing between the components of renewable energy. One possible explanation may be that these past empirical studies do not account for the distinct characteristics of traditional and modern renewable energy. Unlike previous research, this study aims to examine the relationship between oil prices and the two components of renewable energy (traditional and modern), offering a novel contribution to empirical studies in the energy field at the macro level and providing new insights for sustainable energy policy. The relationship between oil prices and these two components warrants further investigation to inform energy policy effectively. Notably, renewable energy could serve as a crucial alternative to fossil fuels or complement energy demand. It is also important to recognize that the two components of renewable energy vary across countries, suggesting that energy policies could be adopted differently.

In addition, the dependence on nonrenewable energy is another crucial issue for climate change and sustainable energy security[15,16]. Several countries gradually use renewable energy to complement or substitute for nonrenewable energy consumption. Concerning the environment and cost, renewable energy sources could play an important role in substituting fossil fuels[8]. The patterns of renewable energy use depend on the development stage that a country faces[7,8,13]. The rationale behind this dependence is that renewable energy development varies across countries due to the country's income stage and ability to accelerate renewable energy consumption. Hence, these two states of a country—the dependence of nonrenewable energy and the development level—can alter the relationship between oil prices and renewable energy sources. Moreover, this study also discusses the roles of the two states in relation to the effects of oil price changes on traditional and modern renewable energy, which is also a novel contribution to understanding the effects of oil price changes on renewable energy and its two components. Although previous studies focused on the link between oil prices and renewable energy, this study goes further into the types of renewable energy sources to make it more comprehensive and capture more renewable energy policy as well as sustainable energy policy. The comprehensive study of renewable energy sources and their determinants is vital for developing the roadmap for sustainable energy policy. Sustainable energy policy also requires an appropriate roadmap of renewable energy technology from developed and developing countries, such as technology transfer or investment given a timeline in the near future. Therefore, it is very useful to diagnose the effect of oil price changes on the components of renewable energy sources.

To assess the impact of oil price fluctuations on the two categories of renewable energy consumption, we estimate the impulse responses of overall renewable energy consumption (overall REC), traditional renewable energy consumption (traditional REC), and modern renewable energy consumption (modern REC) to an oil price shock. We employ the local projection (LP) method of Jordà[17] using panel data from 147 countries spanning the period from 1993 to 2015. Additionally, since the LP method can readily be extended to estimate state-dependent impulse responses, we also evaluate the nonlinear effects of oil price changes, taking into account two states: the level of development and the dependence on nonrenewable energy. The data from 147 countries are segmented into a full sample, developed countries, and developing countries, following the World Bank's classification, to facilitate a nuanced comparison and deeper understanding of the context at different levels of national development. It is crucial to interpret the results distinctly for developed and developing countries so that the implications can provide insightful contributions to energy policy.

The results of the LP method indicate a positive effect of an oil price shock on the share of overall REC in total energy consumption but reveal insignificant effects on the shares of traditional and modern REC. However, when the two states are integrated into the LP model, it becomes evident that the effects of an oil price shock are contingent upon the level of development and the dependence on nonrenewable energy. First, in countries highly dependent on nonrenewable energy, traditional REC is sensitive to oil price changes, irrespective of their development levels. Consequently, it serves as a substitute for nonrenewable energy consumption in these nations. Second, in countries with lower dependence on nonrenewable energy, both traditional REC and modern REC are insensitive to oil price changes, regardless of their development levels. This is intuitive, as reduced dependence on nonrenewable energy renders these countries unaffected by oil price fluctuations. However, the effects of the oil price on modern REC are dependent on the development level in countries with high nonrenewable energy dependence. Specifically, an oil price shock positively influences modern REC in developed countries but not in developing countries. Therefore, modern REC can act as a substitute for nonrenewable energy consumption in developed countries with high nonrenewable energy dependence. Conversely, developed countries possess advanced green technology and heightened environmental concerns, enabling them to transition between modern renewable energy and nonrenewable energy in response to oil price changes.

Given that oil prices often exhibit large fluctuations in the international market and that fostering the development of modern REC rather than traditional REC is crucial to mitigating environmental degradation, our findings provide several important implications for policymakers, particularly in developed countries with high dependence on nonrenewable energy. A positive oil price shock causes people to encourage the use of environmentally friendly modern REC, but with an increase in production costs. In contrast, a negative oil price shock discourages them from promoting modern REC, but there are economic benefits associated with the decline in production costs. Thus, balancing macroeconomic and environmental benefits and costs should be crucial for economic growth in a sustainable environment. However, there is a big obstacle for developing countries to develop those modern renewable energy sources, which is technology transfer. The majority of developing countries only rely on investment from developed countries, but they cannot produce or create by themselves. In addition, the technology transfer from developed countries to developing countries is still limited by patent issues and copyrights, which are still problems for developing countries to develop modern renewable energy sources. These results provide new evidence toward the contribution to energy policy at the national and international level, which also calls for promoting modern renewable energy sources to sustain future energy and tackle environmental issues. Further, it is important that international communities break the barriers of these obstacles for developing countries to develop modern renewable energy sources following the agenda of sustainable energy.

The remainder of the paper is structured as follows: Section 2 provides literature reviews on the relationship between renewable energy and oil prices. Section 3 explains the empirical method, the identification of oil price shocks, and the data description. Section 4 presents the estimated results and their related implications. Finally, Section 5 provides the conclusion.

2. Literature review

Numerous empirical studies have discussed the effects of oil prices on renewable energy use or consumption using different model specifications and country-specific and cross-country samples. Some studies find a positive relationship between the two indicators. Apergis and Payne[8] use the fully modified ordinary least squares (FMOLS) estimator to explore the determinants of renewable energy consumption for Central Americans from 1980 to 2010. They find a positive impact of an oil price change on renewable energy consumption, so renewable energy and fossil fuel energy are substitutes. Apergis and Payne[9] also find positive effects for 25 OECD countries using the FMOLS estimator. Apergis and Payne[10] employ panel cointegration techniques in 11 South American nations from 1980 to 2010 and confirm the positive long-run relationship between oil prices and renewable energy consumption. Sadorsky[18] estimates the renewable energy consumption model in G7 economies by applying the panel cointegration method from 1980 to 2005. In the long run, an increase in oil prices has a positive effect on renewable energy consumption in France, Germany, and Italy but a negative effect in Canada, Japan, the United Kingdom, and the United States. Azad et al.[19] find the positive effect of oil prices on renewable energy consumption by applying the generalized method of moments to the case of Australia during the period from 1990 to 2011.

Recent studies also find that the price of oil has a positive relationship with renewable energy. Nguyen and Kakinaka[11] investigate the relationship between renewable energy consumption and real oil prices for 107 countries from 1990 to 2013 by applying a panel cointegration analysis. Their results confirm a positive long-run relationship between renewable energy consumption and oil prices for high- and low-income countries. Murshed and Tanha[20] model the nonlinear association between renewable energy consumption and crude oil prices over South Asian countries from 1990 to 2018 and confirm the nonlinear U-shaped relationship, suggesting that an increase in oil price does not accelerate renewable energy consumption until reaching a threshold of 135 US dollars per barrel. Finally, Shah et al.[13] find a positive effect of an oil price shock on renewable energy investment for Norway and the United States, but less clear results for the United Kingdom. They conclude that the impacts of an oil price shock on renewable energy development vary substantially across countries.

In contrast, some studies find a negative relationship between renewable energy consumption and oil prices. Omri and Nguyen[7] use the generalized method of moment to estimate the elasticity of renewable energy consumption with respect to changes in real oil prices in 64 countries from 1990 to 2011. They show a negative relationship for all samples and middle-income countries but less significant results in low-income and high-income economies. Aguirre and Ibikunle[21] apply forecast error variance decomposition (FEVD) and panel-corrected standard errors (PCSE) estimators for China, Russia, Brazil, India, and South Africa during 1990–2010 and confirm a negative effect of oil prices on renewable energy growth. Using the quantile-based analysis, Troster et al.[14] find a negative shock in the oil price to decrease renewable energy consumption in the United States; however, the increase in oil prices does not affect renewable energy consumption. In addition, a few studies find a less clear relationship between the price of oil and renewable energy. Payne[22] examines the dynamics between renewable energy consumption and real oil prices in the United States from 1949 to 2009 using long-causality tests, showing that the real oil price does not impact renewable energy consumption. Damette and Marques[23] apply the FMOLS and dynamic ordinary least squares (DOLS) estimators for the case of European Union nations and reveal that there are no substitution effects of oil prices on renewable energy sources.

Hence, the relationship between real oil prices and renewable energy varies across economies depending on the country's characteristics, such as economic development stage, environmental issues, and demand for energy. Besides, among the previous studies, there is no study on the effect of oil prices on a subcomponent of renewable energy, which could be very crucial to discussing environmental degradation and economic conditions.

3. Empirical methodology and data

This study applies the local projection (LP) method of Jordà[17] to estimate the response of renewable energy to an oil price shock and its relevance to countries' development stages and dependence on nonrenewable energy. The LP method requires us to obtain the exogenous shock of oil prices as a prerequisite for estimation. Following the work of Kilian[24], we estimate a structural vector autoregression (SVAR) model to derive the shock of the real oil price:

$$A_0 z_t = \alpha + \sum_{i=1}^{l} A_i z_{t-i} + e_t.$$

This SVAR model consists of the order of three endogenous variables z_t = (ΔWOP, GEA, ROP), where ΔWOP is the log difference (growth rate) of world oil production, ROP is the log of global real oil price, and GEA is the global real economic activity index proposed in Kilian[24]. Kilian[24] constructed this index using an equal-weighted index of the percent growth rates obtained from global bulk dry cargo ocean shipping rates. This index is a proxy for the global business-cycle index. A_0 represents the 3 × 3 matrix that summarizes the contemporaneous relationship among the variables of the model. A_i represents the 3 × 3 autoregressive coefficient matrices, and e_t is a vector of error term "structural shocks". This specification also includes time trends as an exogenous variable in the model. The lag length is set based on Akaike information criterion[1]. The world crude oil supply and crude oil price data are obtained from the U.S. Energy Information Administration, and the global economic activity index is obtained from the Federal Reserve Bank of Dallas.

Once we obtain a series of real oil price shocks from the estimates of the SVAR model, we apply the LP method in a panel setting to analyze the dynamic effects of an oil price shock on renewable energy consumption and its two components (traditional and modern). The LP method is a flexible one to be adapted to estimating a state-dependent or nonlinear model, which allows us to study how the dynamic impulse responses of renewable energy to an exogenous shock of real oil price differ depending on the state of the economy, i.e., the status of the dependence level of nonrenewable energy consumption in the economy[2].

The model specification is as follows:

$$Y_{i,t+h} - Y_{i,t-1} = \alpha_i + \beta^h Shock_t + \theta^h X_{i,t} + \varepsilon_{i,t} \tag{1}$$

where $Y_{i,t}$ represent the measure of renewable energy consumption in country i and period t; $Shock_t$ is the identified oil price shock obtained from the SVAR model; $X_{i,t}$ is the set of control variables, including two lags of the dependent variables, the oil price shocks, and other control variables that are expected to relate to renewable energy consumption; α_i is the country-specific fixed effects; and $\varepsilon_{i,t}$ is the disturbance term with zero mean and constant variance[3].

For the measure of renewable energy consumption, this study uses three dependent variables: (i) the share of overall renewable energy consumption in total energy consumption (overall REC), (ii) the share of modern renewable energy consumption (modern REC), and (iii) the share of traditional renewable energy consumption (traditional REC). Our modern and traditional classification of renewable energy sources follows the International Energy Agency (IEA)[2] and UNCTAD[3]. Modern sources are solar photovoltaics, solar thermal, tide, wave, ocean, geothermal, wind, hydro, bio-gas, bio-gasoline, bio-diesel, and bio-jet-kerosene. Traditional sources are composed of solid biofuel and charcoal. Traditional renewable energy is less clean for the environment and less sustainable, while modern renewable energy is generally developed using green technology and is environmentally friendly. The overall renewable energy share in developing countries is much higher than in developed countries[2]. The modern renewable energy share is relatively high in developed countries, while the traditional one is relatively high in developing countries.

Regarding other control variables, the LP models incorporate the log of real GDP per capita, the log difference of GDP deflator, and the log of CO_2 per capita to countries' income level, inflation rate, and environmental pollution, respectively. We estimate Equation (1) for each time horizon $h = 0, 1, \ldots, 4$, following the common practice of using the medium-term five-year horizon of which $h = 0$ is the year when the shock

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[1] To check the robustness, we also change the optimal 1 lag in the SVAR to 2 lags. Kilian[24] introduces the GEA index in the SVAR model to get the oil price shock, which the GEA can measure the real global activity. Thus, to additionally check robustness, we also replace the variable GEA with the log of real US GDP since the US plays the important role of a global economy affecting many countries over the globe[25].

[2] This LP method was also supported by several research[26–28]. The LP method does not restrict the shape of the impulse response function, i.e., no requirement of specification and estimation of the underlying dynamic system. It is less sensitive to the SVAR model misspecification. The LP method is robust against model misspecification and produces stable and precise estimates.

[3] In the local projection, we also check the robustness by changing the optimal 2 lags of the model to 1 lag.

occurs. Impulse response functions are computed using a sequence of the estimated coefficients β^h and the confidence bands associated with the estimated impulse-response functions are obtained using the estimated standard errors of the coefficients β^h.

Our objective is to examine how the development level and the dependence of nonrenewable energy relate to the effect of an oil price shock on overall REC, modern REC, and traditional REC. To do so, we first examine the countries' development levels by dividing all sample countries into two subsamples of developed and developing countries, based on the World Bank's income classification. We then estimate the LP models in Equation (1) for each of the two country groups. Such subsample analyses enable us to evaluate possible differences in the effects of oil prices between developed and developing countries. After examining the differences between the two country groups, we further extend the analysis to evaluate the countries' dependence level on nonrenewable energy by incorporating it into the models of developed and developing countries. Thus, we estimate the following extended regime-switching model with the state capturing countries' dependence level on nonrenewable energy for each country group:

$$Y_{i,t+h} - Y_{i,t-1} = \alpha_i + \beta_H^h I_{i,t} Shock_t + \beta_L^h (1 - I_{i,t}) Shock_t + \theta^h X_{i,t} + \varepsilon_{i,t} \tag{2}$$

where $I_{i,t}$ is a dummy state variable that takes one if a country has a high dependence on nonrenewable energy and zero otherwise. We use the share of fossil fuel energy consumption to total energy consumption. Countries whose share is above (below) its average value is classified as highly (less) nonrenewable energy-dependent countries. The estimated coefficients, β_H^h and β_L^h, represent impulse response functions for highly (less) nonrenewable energy-dependent countries. **Table 1** presents the data and shocks derived from SVAR model.

Table 1. Data and shock derived from SVAR.

Year	D. Log of world oil production	Global real economic activity	Log real oil price	Shock from SVAR
1990	0.012	–4.659	3.788	0.141
1991	–0.006	9.931	3.580	–0.290
1992	0.000	–19.470	3.516	–0.037
1993	0.001	–4.875	3.374	–0.209
1994	0.016	–1.294	3.299	–0.134
1995	0.020	28.394	3.379	–0.087
1996	0.022	–13.567	3.533	0.174
1997	0.031	–11.688	3.406	–0.137
1998	0.019	–45.890	2.963	–0.371
1999	–0.016	–35.224	3.295	0.235
2000	0.038	5.928	3.735	0.344
2001	–0.006	–25.176	3.478	–0.232
2002	–0.012	–29.666	3.533	0.041
2003	0.032	48.879	3.675	–0.076
2004	0.044	107.020	3.899	–0.083
2005	0.017	74.773	4.178	0.138
2006	–0.003	68.610	4.333	0.013
2007	–0.004	146.148	4.434	–0.282
2008	0.013	108.984	4.714	0.153
2009	–0.016	44.351	4.277	–0.408
2010	0.024	55.711	4.508	0.157
2011	0.001	–2.754	4.777	0.382
2012	0.020	–54.645	4.743	0.248
2013	0.000	–31.599	4.698	0.055
2014	0.024	–35.823	4.591	0.072
2015	0.030	–78.556	3.935	–0.357
2016	0.001	–87.081	3.737	–0.040
2017	0.003	–29.637	3.958	0.169
2018	0.022	–12.575	4.149	0.201
2019	–0.006	–19.915	4.078	–0.039

Table 2. Description of variables.

Variables	Full name of variables	Unit	Data sources
Y/REC	Share of renewable energy consumption	Percentage of total energy consumption	World Development Indicators
Fossil fuel consumption	Share of fossil fuel consumption	Percentage of total energy consumption	World Development Indicators
CO_2 per capita	Amount of CO_2 per capita	Metric tons per capita	World Development Indicators
GDP per capita	Real gross domestic product per capita	Million US dollar per capita constant 2010	World Development Indicators
GDP deflator	Gross domestic product deflator	Index	World Development Indicators
ROP	Global real crude oil price	Price in USD deflated by CPI (monthly average)	U.S. Energy Information Administration (EIA)
WOP	World crude oil supply	Million barrels per day (monthly average)	U.S. Energy Information Administration (EIA)
GEA	Global economic activity	Kilian index (monthly average)	Federal Reserve Bank of Dallas
Shock	Real oil price shock	Percentage change	Authors' calculation
Total renewable energy	Total renewable energy consumption	TJ (thousand terajoules)	World Development Indicators
Traditional renewable energy	Solid biofuel and charcoal	Percentage of total energy source	International Energy Agency
Modern renewable energy	Solar-photovoltaics, solar-thermal, wind, hydro, tide, wave, ocean, geothermal bio-gases, bio-gasoline, bio-diesel, and bio-jet-kerosene	Percentage of total energy source	International Energy Agency

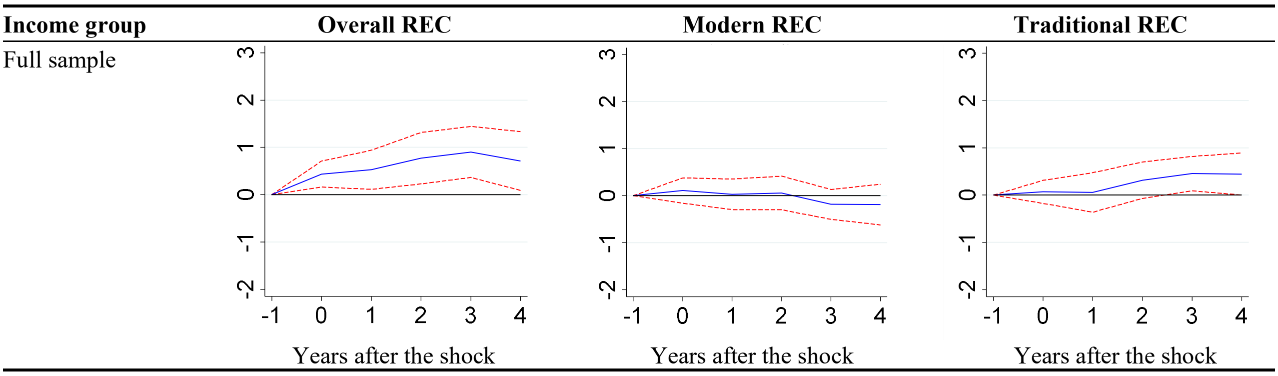
Table 3. Data descriptive statistics.

Variables (1993–2015)	Obs	Mean	Std. Dev.	Min	Max
Share of renewable energy consumption	3504	31.98	30.66	0.00	98.34
Share of fossil fuel consumption	2417	65.32	30.39	0.00	100.00
CO_2 per capita	3606	4.60	5.55	0.02	40.48
Real Gross domestic product per capita	3458	13,534.92	19,163.86	178.80	141,200.40
Gross domestic product deflator	3517	98.88	182.55	0.00	5068.10
World real oil price	3772	60.29	32.76	19.36	118.77
World crude oil supply	3772	70,542.61	5555.14	60,178.65	80,723.31
Global economic activity	3772	13.83	57.32	–78.56	146.15
Oil price shock	3772	–0.02	0.22	–0.41	0.38

This study employs panel data covering 147 countries during the period from 1993 to 2015. We take the data of renewable energy consumption and its components from the International Energy Agency (IEA) and other data of macroeconomic and environmental conditions from the World Bank's World Development Indicators (WDI). **Tables 2 and 3** show the descriptions and summary statistics of the variables used in this study.

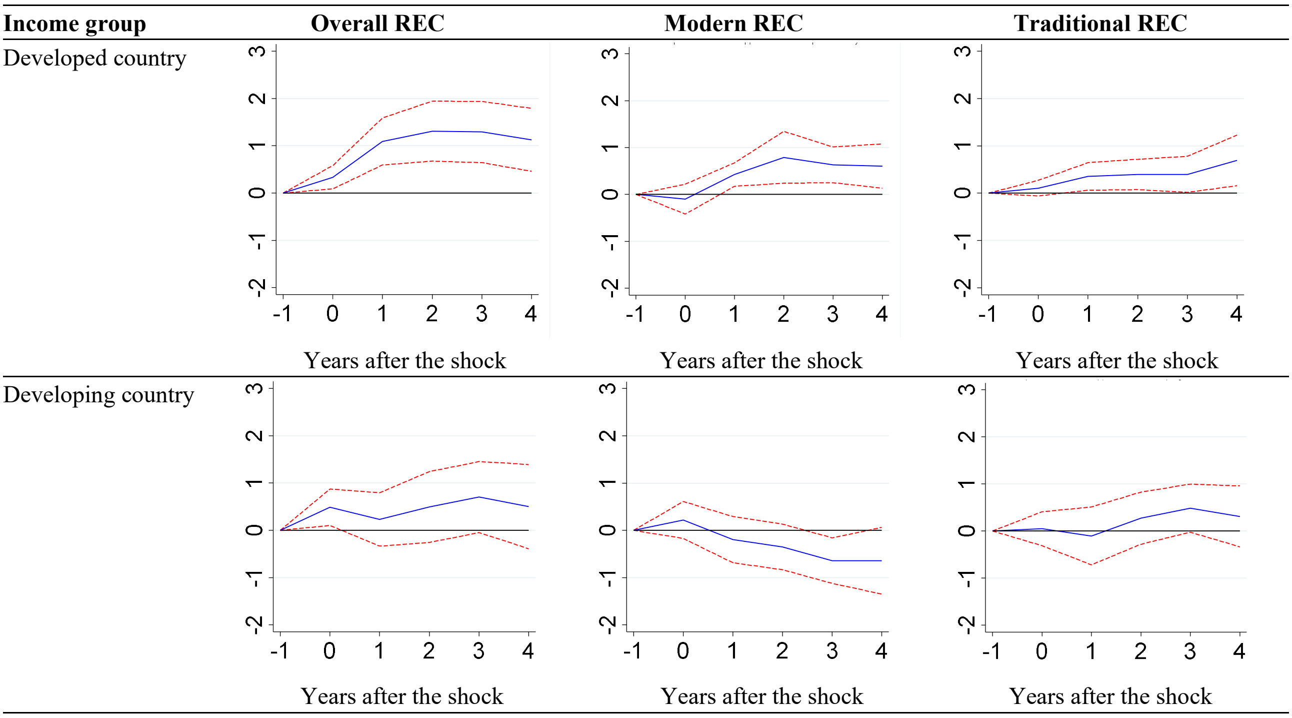
4. Results

We estimate Equation (1) to impulse the responses of the share of overall renewable energy consumption, the share of modern renewable energy consumption, and the share of traditional renewable energy to the oil price shock by using the LP method. The effect of oil prices in this model reflects the short-run effect. **Figure 1** represents the cumulative impulse responses obtained from Equation (1), where the horizontal axes measure years after the shock. **Figure 1** shows that oil prices have a positive effect on overall REC for all samples, which implies that a 1% positive shock on oil prices increases overall REC by 0.43% in year 0 and 0.71% in year 4. This positive effect of oil prices on renewable energy consumption aligns with previous studies[8–11,18], which found that oil prices have a positive association with renewable energy. When oil prices increase, people tend to use renewable energy, which could be costless compared to higher oil prices. Nevertheless, the responses of modern and traditional renewable energy sources are not significant for all samples. In **Figure 2**, in developed countries, both modern and traditional REC responses are positive and statistically significant. For developing countries, the responses of traditional REC are statistically insignificant, and the responses of modern REC are relatively insignificant. **Tables A1** and **A2** display the detailed results of the regression analysis for Equation (1), corresponding to **Figures 1** and **2**.



Note: $t = 0$ is the year of the shock. Solid lines present the responses (in percent) to shock. Dashed lines denote 90%, confidence bands.

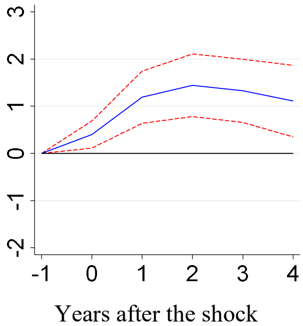
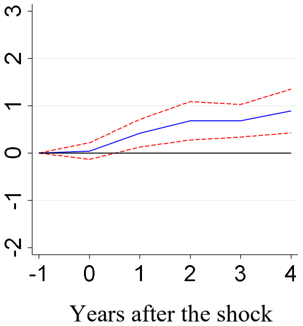
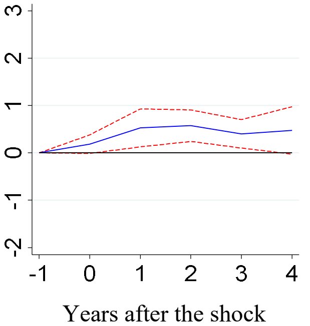
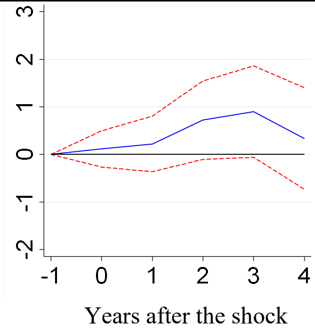
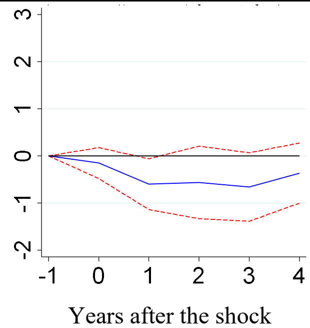
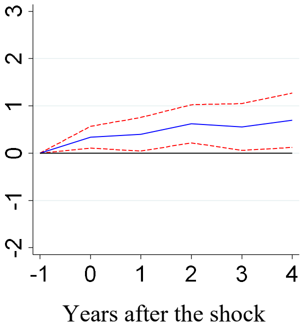
Figure 1. Equation (1): the response of each dependence variable to the shock.



Note: $t = 0$ is the year of the shock. Solid lines present the responses (in percent) to shock. Dashed lines denote 90%, confidence bands.

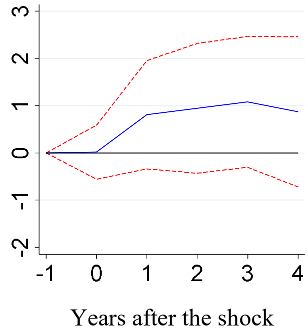
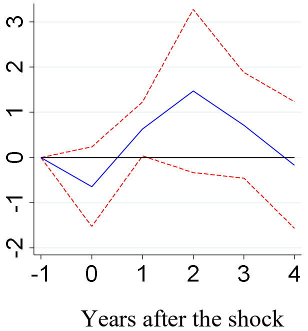
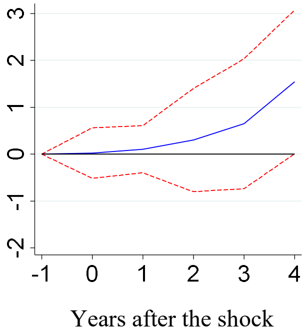
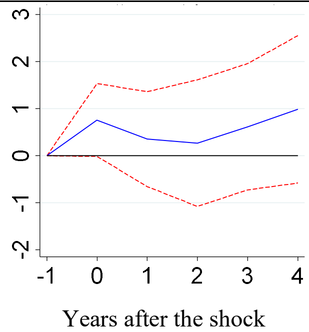
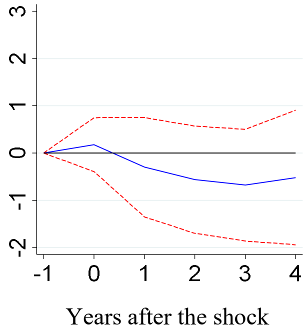
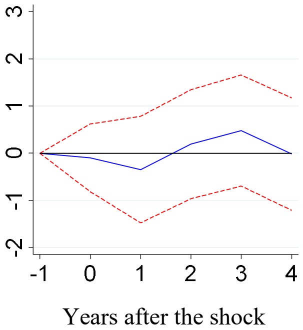
Figure 2. Equation (1): the response of each dependence variable to the shock.

Next, we examine the state-dependent nature of nonrenewable energy by estimating Equation (2) in developed and developing countries. **Figures 3 and 4** report the effects of the oil price shock in developed and developing countries that are state-dependent on nonrenewable energy, respectively. In **Figure 3**, for developed countries with high dependence on nonrenewable energy, a 1% positive shock on the oil price is associated with increasing the overall REC, modern REC, and traditional REC from year 0 to year 4. For developing counties with high dependence on nonrenewable energy, the overall REC and modern REC effects are insignificant, but the responses of traditional REC are positive and statistically significant. In **Figure 4**, for

High dependence of nonrenewable energy	**Overall REC**	**Modern REC**	**Traditional REC**
Developed countries			
Developing countries			

Note: $t = 0$ is the year of the shock. Solid lines present the responses (in percent) to shock. Dashed lines denote 90%, confidence bands.

Figure 3. Equation (2): high dependence of nonrenewable energy (developed and developing countries).

Low dependence of nonrenewable energy	**Overall REC**	**Modern REC**	**Traditional REC**
Developed countries			
Developing countries			

Note: $t = 0$ is the year of the shock. Solid lines present the responses (in percent) to shock. Dashed lines denote 90%, confidence bands.

Figure 4. Equation (2): low dependence on nonrenewable energy (developed and developing countries).

developed countries with low dependence on nonrenewable energy, an oil price shock positively affects modern REC in year 1 after the shock, while overall REC and traditional REC responses are insignificant. Also, the responses of overall REC, modern REC, and traditional REC are statistically insignificant in developing countries with low dependence on nonrenewable energy. For less nonrenewable energy-dependent countries, both traditional REC and modern REC are insensitive to oil price changes, which can imply that less dependence on nonrenewable energy makes the countries unaffected by oil price changes can imply that less dependence on nonrenewable energy makes the countries unaffected by oil price changes. Energy-dependent countries, both traditional REC and modern REC, are insensitive to oil price changes, which can imply that less dependence on nonrenewable energy makes the countries unaffected by oil price changes. **Table A3** presents the detailed results of Equation (2), corresponding to **Figures 3** and **4**.

These findings are relatively consistent with our expectations. Furthermore, these results suggest that traditional REC is sensitive to oil price changes, irrespective of their development levels.

At the same time, the modern REC is sensitive to oil price changes only in developed countries with high dependence on nonrenewable energy. Overall, this is intuitive because developed countries have better advantages in accessing renewable energy sources due to technology and innovation. In contrast, people in developing countries have many challenges in accessing renewable energy consumption[3]. These results show that developing countries use high-quality traditional renewable energy sources compared to modern renewable energy, while traditional energy is not sustainable and not clean. Therefore, the results suggest that developing countries should promote modern renewable energy sources, such as modern biomass, which could be transformed from traditional biomass. In addition, developing countries can help develop low-cost modern renewable energy technologies to facilitate the development of modern renewable sources in developing countries where renewable energy technologies are still insufficient.

5. Robustness checks

This section checks the empirical validity of our baseline findings by performing a sensitivity analysis. Although the local projection method is robust to misspecification[17], our studies also do a robustness check to see whether our results hold for the chosen dependent variable. First, we check whether our results hold for changing the lag of the local projection estimation from lag 2 to lag 1 in Equation (2). Second, we use the log of USA GDP to replace the Kilian index in the SVAR model. Finally, we change the lag of the SVAR from 1 to 2. The robustness results are reported in the appendix. The estimated results generally confirm our findings (**Tables A4–A6**).

6. Conclusion and policy implications

Sustainable energy is very crucial for energy policy toward sustainable development. Renewable energy sources are important for sustainable energy; however, some renewable energy sources are not considered as clean and sustainable, such as traditional biomass. Moreover, the price of oil is the main determinant of nonrenewable energy sources, which is related to all energy sources' demand and supply. Thereby, the change in oil price could alter the demand and supply of renewable energy sources, which include modern and traditional renewable energy sources. Considering the local projection method of Jordà[17], this study analyzed the effect of the oil price shock on renewable energy, traditional renewable, and modern renewable energy sources for developed and developing countries.

The results of this study show the positive response of overall renewable energy, modern renewable energy, and traditional renewable energy to an oil price shock. Furthermore, our results show that the impact of the oil price shock on overall, modern, and traditional renewable energy depends on countries' development levels and their dependence on nonrenewable energy. Concerning highly nonrenewable energy-dependent countries, people in developed countries tend to shift to modern renewable energy. In contrast, traditional renewable energy is sensitive to oil price changes, irrespective of countries' development levels. In contrast, people in developed and developing countries remain passive to the positive oil price shock for their low dependence on nonrenewable countries because they might have higher renewable energy development. This implies that it is important for energy policy to develop a renewable energy technology roadmap toward sustainable energy and a clean environment.

It is vital to promote renewable energy, especially renewable energy sources from wind, solar, and sustainable biomass. Furthermore, it is essential that developed countries, which have technological innovations in renewable energy development, could produce low-priced renewable energy products such as solar systems to reduce the challenges in developing countries. Therefore, this study suggests that developing countries consider increasing their use of modern renewable energy sources rather than traditional renewable energy. Emerging countries among developing countries may have high-potential technologies to adopt and produce renewable energy sources compared to low-income countries. It is important that those emerging countries join hands with developed countries to produce low-cost technology products to supply and produce modern renewable energy sources such as modern biomass, solar power, and wind turbines. Lastly, this study called for synergy in renewable energy policy within the public and private sectors internationally to support the energy transition in developing countries, which is a very urgent need for sustainable energy and environmental issues. Although other studies call for promoting overall renewable energy policy, these studies call for only promoting modern renewable energy, which could be sustainable sources for future energy use. The future energy policy should specifically mention modern and sustainable energy.

Although this study supports the positive response of modern and traditional renewable energy to oil price shocks, it does not capture the long-run effect of oil prices and renewable energy consumption. For future research, other studies should incorporate aspects of long-term relationships or effects and the determinants of traditional and modern renewable energy sources. Moreover, other studies, which aim to promote modern renewable energy development, may consider more components of renewable energy for better energy policy at different countries' development levels.

Conflict of interest

No potential conflict of interest was reported by the author.

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Appendix

Table A1. Equation (1): the cumulative responses of renewable energy to the oil price shock.

Variable	**Years after shock**	**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	Oil price shock	0.4376***	0.5274**	0.7730**	0.9045***	0.7138*
		(0.0097)	(0.0379)	(0.0211)	(0.0068)	(0.0614)
	Observations	2331	2229	2124	2020	2124
Modern REC	Oil price shock	0.1105	0.0293	0.0590	–0.1839	–0.1886
		(0.5012)	(0.8821)	(0.7865)	(0.3435)	(0.4741)
	Observations	2463	2461	2459	2356	2459
Traditional REC	Oil price shock	0.0682	0.0561	0.3150	0.4546**	0.4457
		(0.6463)	(0.8258)	(0.1810)	(0.0421)	(0.1027)
	Observations	2470	2470	2470	2367	2470

Note: Robust p-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A2. Equation (1): the cumulative responses of renewable energy to the oil price shock (development level).

Developed country	**Years after shock**	**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	Oil price shock	0.3363**	1.0929***	1.3098***	1.2914***	1.1265***
		(0.0270)	(0.0005)	(0.0010)	(0.0014)	(0.0063)
	Observation	2331	2229	2124	2020	2124
Modern REC	Oil price shock	–0.1010	0.4241***	0.7908**	0.6322***	0.6043**
		(0.6029)	(0.0063)	(0.0204)	(0.0075)	(0.0374)
	Observation	2463	2461	2459	2356	2459
Traditional REC	Oil price shock	0.1050	0.3534**	0.3951**	0.3983*	0.6928**
		(0.2972)	(0.0488)	(0.0450)	(0.0885)	(0.0355)
	Observation	2470	2470	2470	2367	2470

Note: Robust p-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Developing country	**Years after shock**	**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	Oil price shock	0.4883**	0.2307	0.4922	0.7032	0.5016
		(0.0398)	(0.5028)	(0.2823)	(0.1266)	(0.3562)
	Observation	2331	2229	2124	2020	2124
Modern REC	Oil price shock	0.2202	–0.1958	–0.3500	–0.6394**	–0.6424
		(0.3551)	(0.5116)	(0.2349)	(0.0311)	(0.1373)
	Observations	2463	2461	2459	2356	2459
Traditional REC	Oil price shock	0.0488	–0.1043	0.2729	0.4862	0.3115
		(0.8239)	(0.7804)	(0.4193)	(0.1211)	(0.4300)
	Observations	2470	2470	2470	2367	2470

Note: Robust p-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0$.

Table A3. Equation (2): State-dependence of nonrenewable energy.

High dependence of nonrenewable energy	**Years after shock**	**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	Developed countries	0.4008**	1.1904***	1.4445***	1.3256***	1.1079**
		(0.0245)	(0.0006)	(0.0005)	(0.0015)	(0.0182)
	Developing countries	0.1145	0.2207	0.7207	0.9000	0.3352
		(0.6228)	(0.5361)	(0.1536)	(0.1268)	(0.6068)
	Observations	2173	2146	2050	1949	2050
Modern REC	Developed countries	0.0421	0.4198**	0.6822***	0.6824***	0.8891***
		(0.6937)	(0.0203)	(0.0068)	(0.0015)	(0.0020)
	Developing countries	–0.1524	–0.5998*	–0.5638	–0.6612	–0.3655
		(0.4470)	(0.0707)	(0.2314)	(0.1374)	(0.3496)
	Observations	2174	2172	2170	2169	2170
Traditional REC	Developed countries	0.1834	0.5270**	0.5734***	0.4008**	0.4729
		(0.1264)	(0.0328)	(0.0055)	(0.0300)	(0.1226)
	Developing countries	0.3371**	0.3996*	0.6212**	0.5538*	0.6964**
		(0.0177)	(0.0674)	(0.0128)	(0.0685)	(0.0490)
	Observations	2180	2180	2180	2180	2180

Note: Robust p-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Low dependence of nonrenewable energy	**Years after shock**	**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	Developed countries	0.0156	0.8087	0.9439	1.0822	0.8703
		(0.9645)	(0.2490)	(0.2612)	(0.2019)	(0.3707)
	Developing countries	0.7580	0.3514	0.2671	0.6150	0.9846
		(0.1108)	(0.5677)	(0.7446)	(0.4529)	(0.3032)
	Observations	2173	2146	2050	1949	2050
Modern REC	Developed countries	–0.6475	0.6302*	1.4720	0.7098	–0.1697
		(0.2289)	(0.0853)	(0.1830)	(0.3202)	(0.8423)
	Developing countries	0.1774	–0.3004	–0.5650	–0.6794	–0.5179
		(0.6103)	(0.6393)	(0.4147)	(0.3466)	(0.5509)
	Observations	2174	2172	2170	2169	2170
Traditional REC	Developed countries	0.0208	0.1061	0.2993	0.6478	1.5422
		(0.9494)	(0.7290)	(0.6556)	(0.4436)	(0.1010)
	Developing countries	–0.0977	–0.3485	0.1909	0.4789	–0.0192
		(0.8233)	(0.6127)	(0.7861)	(0.5044)	(0.9789)
	Observations	2180	2180	2180	2180	2180

Note: Robust p-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A4. Robustness check 1. Using different lags of the local projection model: The cumulative responses to the oil price shock[4].

Developed country/Horizontal		**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	State: High fossil fuel	0.2380	0.7784**	1.0146***	0.9985***	0.7752**
		(0.1928)	(0.0192)	(0.0045)	(0.0050)	(0.0494)
	State: Low fossil fuel	–0.1119	0.4634	0.4212	0.3561	0.3643
		(0.7526)	(0.5520)	(0.6251)	(0.6673)	(0.6594)
	Observations	2286	2258	2162	2060	2162
Modern REC	State: High fossil fuel	–0.0355	0.2518	0.5226**	0.5205***	0.4807***
		(0.7710)	(0.1097)	(0.0136)	(0.0041)	(0.0074)
	State: Low fossil fuel	–0.9402	0.4062	1.3334	0.3835	–0.3330
		(0.1774)	(0.1514)	(0.2137)	(0.5455)	(0.5811)
	Observations	2290	2288	2286	2285	2286
Traditional REC	State: High fossil fuel	0.1169	0.4262	0.4390**	0.2662**	0.3139*
		(0.2828)	(0.1009)	(0.0349)	(0.0489)	(0.0728)
	State: Low fossil fuel	–0.0716	–0.0609	–0.1136	0.1770	0.5237
		(0.7994)	(0.8537)	(0.8476)	(0.8141)	(0.5167)
	Observations	2295	2295	2295	2295	2295

Note: Robust *p*-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Developing country/Horizontal		**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	State: High fossil fuel	–0.0028	–0.0618	0.4384	0.8339	0.3030
		(0.9906)	(0.8739)	(0.3366)	(0.1587)	(0.5522)
	State: Low fossil fuel	0.6037	0.1753	0.2369	0.4126	–0.0176
		(0.2542)	(0.7959)	(0.7642)	(0.5823)	(0.9801)
	Observations	2286	2258	2162	2060	2162
Modern REC	State: High fossil fuel	–0.1340	–0.4549	–0.4357	–0.6327	–0.4133
		(0.5488)	(0.2190)	(0.3996)	(0.2095)	(0.3408)
	State: Low fossil fuel	0.1801	–0.2773	–0.5783	–0.6869	–0.4528
		(0.5699)	(0.6318)	(0.3181)	(0.2678)	(0.5139)
	Observations	2290	2288	2286	2285	2286
Traditional REC	State: High fossil fuel	0.2870**	0.3419*	0.4906**	0.4584	0.5791*
		(0.0109)	(0.0648)	(0.0173)	(0.1140)	(0.0734)
	State: Low fossil fuel	–0.2023	–0.4634	0.0819	0.3356	–0.2065
		(0.6535)	(0.5188)	(0.9052)	(0.5928)	(0.7622)
	Observations	2295	2295	2295	2295	2295

Note: Robust *p*-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

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[4] We change the local projection estimation from 2 lags to 1 lag to check the robustness.

Table A5. Robustness check 2. Using a log of USA GDP instead of Kilian index in the VAR model: the cumulative responses to the oil price shock.

Developed country/Horizontal		**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	State: High fossil fuel	0.5008***	1.7120***	2.5452***	3.0505***	3.6707***
		(0.0017)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
	State: Low fossil fuel	0.2812	1.6781**	2.5249***	3.3877***	4.9887***
		(0.5550)	(0.0301)	(0.0059)	(0.0024)	(0.0000)
	Observations	2181	2154	2058	1957	2058
Modern REC	State: High fossil fuel	0.1044	0.4998***	0.7799***	0.9211***	1.0753***
		(0.1852)	(0.0005)	(0.0003)	(0.0001)	(0.0003)
	State: Low fossil fuel	–0.7784	0.1725	1.0818***	1.0315**	0.4026
		(0.3586)	(0.8331)	(0.0005)	(0.0148)	(0.7278)
	Observations	2182	2180	2178	2177	2178
Traditional REC	State: High fossil fuel	0.2669***	0.6468***	0.9126***	0.8939***	0.9992***
		(0.0062)	(0.0027)	(0.0006)	(0.0008)	(0.0016)
	State: Low fossil fuel	0.1615	0.3749	0.7798	1.2166	1.6676
		(0.7366)	(0.3215)	(0.3776)	(0.2899)	(0.2115)
	Observations	2188	2188	2188	2188	2188

Note: Robust *p*-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Developing country/Horizontal		**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	State: High fossil fuel	–0.0348	–0.1453	0.3048	0.5932	0.6059
		(0.8926)	(0.7470)	(0.6288)	(0.4013)	(0.4557)
	State: Low fossil fuel	0.8939*	0.6276	0.2216	0.2490	–0.4054
		(0.0523)	(0.4424)	(0.7983)	(0.7906)	(0.7348)
	Observations	2181	2154	2058	1957	2058
Modern REC	State: High fossil fuel	–0.0965	–0.5026	–0.4779	–0.5876	–0.6412
		(0.6406)	(0.2908)	(0.4825)	(0.3504)	(0.2501)
	State: Low fossil fuel	0.3698	–0.1128	–0.3467	–0.4867	–0.4658
		(0.2063)	(0.8166)	(0.4304)	(0.3294)	(0.4599)
	Observations	2182	2180	2178	2177	2178
Traditional REC	State: High fossil fuel	0.5215**	0.5628**	0.7037*	0.7089	0.8846
		(0.0156)	(0.0437)	(0.0760)	(0.1675)	(0.1212)
	State: Low fossil fuel	0.3288	0.2476	0.7605	0.6298	–0.2380
		(0.4481)	(0.7019)	(0.3231)	(0.4247)	(0.7786)
	Observations	2188	2188	2188	2188	2188

Note: Robust *p*-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A6. Robustness check 3. Using different lags in the VAR model: the cumulative responses to the oil price shock[5].

Developed country/Horizontal		**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	State: High fossil fuel	0.3676**	1.1360***	1.3576***	1.2148***	0.8210*
		(0.0471)	(0.0012)	(0.0009)	(0.0034)	(0.0723)
	State: Low fossil fuel	–0.0696	0.6208	0.7723	0.9157	0.1895
		(0.8317)	(0.3665)	(0.4007)	(0.3009)	(0.8436)
	Observations	2181	2154	2058	1957	2058
Modern REC	Oil price shock: High fossil fuel	0.0026	0.3472**	0.6216**	0.6262***	0.5659***
		(0.9813)	(0.0475)	(0.0132)	(0.0028)	(0.0094)
	Oil price shock: Low fossil fuel	–0.6711	0.7069*	1.5913	0.7123	–0.2757
		(0.1945)	(0.0515)	(0.1615)	(0.3491)	(0.6093)
	Observations	2182	2180	2178	2177	2178
Traditional	Oil price shock: High fossil fuel	0.1859	0.5089**	0.5394**	0.3729**	0.3784*
		(0.1341)	(0.0476)	(0.0111)	(0.0253)	(0.0651)
	Oil price shock: Low fossil fuel	0.0237	0.0176	0.0675	0.4666	0.8280
		(0.9367)	(0.9571)	(0.9199)	(0.5635)	(0.3417)
	Observations	2188	2188	2188	2188	2188

Note: Robust *p*-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Developing country/Horizontal		**(1) Year 0**	**(2) Year 1**	**(3) Year 2**	**(4) Year 3**	**(5) Year 4**
Overall REC	State: High fossil fuel	0.0986	0.1796	0.7439	0.9837	0.3995
		(0.6920)	(0.6589)	(0.1774)	(0.1511)	(0.6042)
	State: Low fossil fuel	0.7510	0.3228	0.1366	0.6457	1.0878
		(0.1399)	(0.5908)	(0.8619)	(0.4158)	(0.2583)
	Observations	2181	2154	2058	1957	2058
Modern REC	Oil price shock: High fossil fuel	–0.1613	–0.5951*	–0.5617	–0.7117	–0.5100
		(0.4499)	(0.0924)	(0.2473)	(0.1508)	(0.2272)
	Oil price shock: Low fossil fuel	0.1482	–0.2750	–0.5717	–0.5999	–0.4293
		(0.6124)	(0.6112)	(0.3450)	(0.3273)	(0.5528)
	Observations	2182	2180	2178	2177	2178
Traditional REC	Oil price shock: High fossil fuel	0.3717**	0.4444*	0.6468**	0.5892	0.6985
		(0.0128)	(0.0622)	(0.0256)	(0.1229)	(0.1024)
	Oil price shock: Low fossil fuel	0.0123	–0.3061	0.1259	0.4996	0.1010
		(0.9795)	(0.6484)	(0.8501)	(0.4808)	(0.8895)
	Observations	2188	2188	2188	2188	2188

Note: Robust *p*-value in parentheses below coefficient as *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

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[5] We change the SVAR estimation from 1 lag, which suggested by AIC, to 2 lags to check the robustness.