Does energy intensity matter in the nexus between energy consumption and economic growth regarding capital-energy substitution?

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Abstract
This article investigates how the non-linear connection between energy consumption and economic development is influenced by energy intensity level in the context of energy-capital substitution. We firstly analyze the substitutability/complementarity between energy and capital by estimating VES production function within the standard Solow growth model framework for 58 countries over the period of 1975–2017. The selected countries are classified into four groups according to their relative energy intensity levels and their accessibility to energy. The estimation findings reveal that energy and capital are complements in the final output for each country group. Hence, in this paper, as further analysis, the study examines whether or not energy consumption always fosters economic growth. We investigate the non-linear link between energy consumption and economic development by constructing a panel smooth transition regression (PSTR) model for each country group and looking at the impact of energy intensity in this relationship. The empirical results provide that for each country group, there is a threshold level for energy intensity. Regardless of whether a country is a net energy exporter or net energy importer, it needs to use energy efficiently and not exceed the ideal energy intensity level in both production and consumption to maintain long-term economic growth.

Keywords Substitution elasticity · Energy consumption · Energy intensity · VES production function · Economic growth · PSTR

Introduction

The substitutability of energy and capital has been a constant issue of debate and inquiry. Energy substitution with alternative production inputs is critical for minimizing the consequences of energy crises and meeting fossil fuel reduction goals while maintaining economic development. Substitutability refers to the adoption of energy-saving technology through capital purchases, which can be seen as a critical way to reduce greenhouse gas emissions and fossil-fuel exhaustion. Additionally, energy-saving technologies help to reduce an economy’s vulnerability to energy price changes while also boosting overall production efficiency (Cleveland et al. 2000). Thus, in the framework of producer theory, the adoption of energy-saving technology can be regarded as a capital-energy substitution.

There are many significant concerns about energy and capital substitutability, but two are significant. Primarily, substitutability between energy and capital is essential in the real economy and industrial sector. If capital and energy
are substitutes, capital purchases can lower energy demand. In other words, if capital investment substitutes for energy demand, energy consumption can be lowered by capital purchases while the amount of total output is sustained. However, in the case of complementary capital and energy, higher-priced energy can reduce the demand for energy and capital investment (Berndt and Wood 1975; Kim and Heo 2013).

As a second concern, the elasticity of energy and capital substitution is significant in the context of economic growth. Between two countries commencing from the same initial baseline point, the one with the greater elasticity of substitution (EoS) between production inputs has a higher per capita GDP and higher long-term growth rates (Klump and De La Grandville 2000; Klump & Preißler 2000). Furthermore, regardless of the absence of exogenous technological progress and non-renewable inputs, unbounded endogenous growth occurs when the EoS between factors is greater than 1 (Palivos and Karagiannis 2004; Karagiannis et al. 2005). Lazkano and Pham (2016) stated that countries with high-income levels have higher EoS between energy and capital, and reversely higher EoS between capital and energy fosters economic growth. The study also shows that an increment in EoS between energy and capital leads to higher economic growth.

The empirical literature on energy substitution elasticity often hinges to reveal whether energy and capital are substitutes or complements (Denny et al. 1981; Burney and Al-Matrouk 1996; Arnb erg and Björner 2007; Smyth et al. 2011; Shen and Whalley 2013; Kim and Heo 2013; Adetutu 2014; Altunc and Yildirim 2020; Razzaq et al. 2021). Rare papers have attempted to analyze the effect of EoS between energy and other factors on economic growth (Ozatalay et al. 1979; Zheng and Liu 2004; Lazkano and Pham 2016; Esen and Bayrak 2017; Lin and Abudu 2019; Wesseh and Lin 2020; Zhou et al. 2022). However, studies analyzing the effect of energy-capital substitution elasticity on economic growth have only focused on the substitutability between energy and capital. To examine only the relationship between substitution of energy and economic performance would prove futile. Since, in case of energy and capital are not substitutes but complements in the final output, more energy consumption is required for capital accumulation and sustainable economic growth. In this sense, whether the continuous increase in energy consumption affects economic growth always positively or not becomes a crucial subject that needs to be analyzed thoroughly. For example, the empirical study of Lazkano and Pham (2016) reveals that energy and capital are complements for the upper middle income, lower middle income, and low-income countries and also for the countries that have very low environmental performance index. These countries need to consume more energy to accelerate capital accumulation and sustain the long-run economic growth. However, whether energy consumption always fosters economic growth becomes a critical question and has not been answered yet.

This paper takes the literature a step further by examining the influence of continuous energy consumption on economic performance for the countries in which capital and energy are complementary. So, we firstly analyze the substitutability/complementarity between energy and capital for selected country groups. Secondly, in the case of energy and capital complements, we analyze the effect of energy consumption on long-run economic growth. In the second analysis, we employ the energy intensity levels of the country groups as a threshold variable. Therefore, we construct conjunction between two analyses. For the first analysis, the countries are divided by their energy intensity levels to observe how different energy intensity levels affect the substitutability/complementarity between energy and capital. For the second analysis, energy consumption is set to be the independent variable, and energy intensity levels are set to be the threshold variable to observe the optimal energy intensity level to sustain the economic growth for the country groups that have a complementary relationship between energy and capital. Along this line, it would be suggested to use the capital/energy ratio as an independent variable in our second analysis, instead of energy consumption. The reason is that the variable elasticity of substitution (VES) production function involves the relationship between capital/energy substitution and economic growth. However, in this case, the capital/energy ratio may remain unchanged although capital and energy consumption increase. Therefore, the second analysis may not give the proper results. Since we consider sustainable economic growth under the optimal energy intensity level, we determine the energy consumption as an independent variable.

The studies on the analysis of the effect of energy consumption on economic development are mostly based on the assumption that the relationship between two variables is linear. In other words, most papers claim that the relationship between the use of energy and economic performance is symmetric and that the absolute effect of energy consumption remains the same on long-term economic growth over time. As a result of employing a linear model, the presupposition that the variables exhibit the same type of movements independent of economic structure is accepted as mandatory.

Lazkano and Pham (2016) adopted the country classification according to the World Bank database for income classification and to Yale University’s Environmental Performance Index (EPI) for environmental classification.
The empirical results of the linear model support whether an increment in energy consumption consistently leads to a rise in economic growth (Stern 2000; Aqeel and Butt 2001; Apergis and Payne 2010; Munir et al. 2020) or energy consumption has a constant negative impact on economic performance (Narayan and Popp 2012; Ocal and Aslan 2013; Komal and Abbas 2015; Yıldırım et al. 2019; Cevik et al. 2021; Aydin et al. 2022). In real life, however, the variables might have non-linear or asymmetric properties, both individually and in relation to one another. Thus, this type of asymmetry is not compatible with linear models, and non-linear models need to be employed.

The literature review on energy and growth gives relatively little information regarding whether energy use has a non-linear influence on GDP, or whether there is a threshold level in this relationship. Most of the studies focusing on the non-linearity employed parametric functional forms (e.g., quadratic, cubic polynomials, logarithmic forms of cubic functions) of the regression model (Lee and Chang 2007; Huang et al. 2008; Omay et al. 2014). However, implementing such functional forms restrict the true shape of the link between energy and growth. Some studies have employed non-linear methods with threshold effects that do not set prior relationships between variables to address this issue (Aydin and Esen 2017, 2018). In these studies, the dynamic panel threshold regression (DPTR) model was employed to analyze the effect of energy intensity on the link between energy consumption and GDP. The DPTR model suggests that the transition from one regime to another regime is sharp and sudden. However, from the point of economics, such an axiom might not be valid in every case. For instance, when the relationship between energy consumption and economic growth is to be examined, it is admitted that change in energy consumption swiftly changes economic growth as well. However, economic growth or recession does not occur abruptly but over a period of time. Therefore, estimated parameters do not change suddenly but rather smoothly. In this paper, we employ the PSTR model which was developed by Teräsvirta et al. (1994) and González et al. (2005). PSTR model is an approach that allows parameters to change smoothly when moving from one regime to another.

To conclude, we primarily estimate the EoS between energy and capital. EoS between production factors can be estimated by the help of production functions. It is important to know which production function is utilized in this estimation. In this paper, the nested VES (variable elasticity of substitution) production function is examined within the standard Solow-Swan Growth model for 58 countries over the period 1975–2017. VES production function is a non-linear function and was developed by Revenkar in 1971 (Revenkar 1971). The distinction of the VES function from others is that EoS between factor changes pursuant to the relative share of factors and overtime in this function. So, the VES production function provides more flexibility in the parameters. Therefore, estimated EoS coefficients via the VES production function are closer to reality than other production functions. After estimating the EoS between energy and capital, in case of energy and capital are complementary, we further examine the non-linear connection between energy consumption and economic development by estimating PSTR model.

Hence, this research is expected to contribute three significant aspects to the literature: (i) previous studies examining the EoS between capital and energy by estimating VES production function generally have selected or have classified the sample countries according to their income levels. However, the main emphasis is needed to be given to energy. So, this paper is the first in classifying selected countries primarily according to their relative energy intensity levels and then according to whether the country is a net energy importer or net energy exporter based on the selected year. The second classification aims to differentiate the countries based on their accessibility to energy. By doing so, our paper represents the differences among these country groups regarding the effect of the EoS between energy and capital on economic growth. (ii) Studies analyzing the EoS between energy and capital have focused on only the substitutability or complementarity between two variables. However, in case of complementarity between energy and capital, whether energy consumption always fosters economic growth is a very significant scope to be researched. So, our paper is the first in gathering two analyses (VES and PSTR). First, we examine the variable EoS between energy and capital, and then in the case of complementarity, we analyze the non-linear effect of energy consumption on long-run economic growth; (iii) previous studies have generally employed the parametric functional form of regression models or threshold regression models in which transition from one regime to another regime is sharply and sudden. In this paper, we estimate the PSTR model, which is an innovative approach that allows parameters to change gradually when moving from one regime to another. In the second analysis, our main aim is to understand whether there is a threshold value for energy intensity that is above and below this level; energy consumption affects economic growth in a different way.

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2 Energy intensity is used to monitor and compare the energy efficiency of countries, sector, and businesses. Energy intensity level is determined by calculating the consumed energy amount in order to produce one unit of product. Thus, increase in energy intensity value is an indicator of less energy efficiency. Quantitatively, it can be showed as energy efficiency (Fisher-Vanden et al. 2004). Therefore, between the two countries that produce the same output during the same time interval, the one that consumes more energy would have the higher energy intensity. In addition to less energy consumption, the low energy intensity also shows the more efficient usage of energy resources during the production process (Aydin and Onay, 2020).
To that end, in this paper, “Model and estimation method” presents the models and econometric methods. “Data” gives the data, and “Empirical findings” represents the empirical findings by estimating EoS between capital and energy and estimating the PSTR model for four country groups. “Conclusion” concludes the study by appraising empirical findings regarding analyses.

**Model and estimation method**

Standard VES production function examines the EoS between capital and labor. In this paper, the main interest is EoS between capital and energy. We follow the way of the studies of Lazkano and Pham (2016) and Yıldırım (2018). To that end, a nested (two level) VES production function is constituted and examined. For the nested VES function, preliminary functions are evaluated as follows:

\[
\begin{align*}
    Y &= f(P, L) = AP^{\alpha_1}(L + b_1\alpha_1 P)^{(1-\alpha_1)\nu_1} \\
P &= q(K, E) = K^{\alpha_2}(E + b_2\alpha_2 K)^{(1-\alpha_2)\nu_2}
\end{align*}
\]  

(1)

(2)

In Eq. (1), \( P \) shows the physical inputs and is the function of capital stock and energy as stated in Eq. (2) (for simplicity, total factor productivity \( A \) did not account twice). \( \alpha_1 \) indicates the role of physical input in the function (1), and \( \alpha_2 \) indicates the share of capital stock to energy in the function (2). \( \nu_1 \) and \( \nu_2 \) are the returns to the scale for both Eq. (1) and (2). While \( b_1 \) stands for variable elasticity of substitution parameter between physical inputs and labor, \( b_2 \) stands for variable elasticity of substitution parameter between capital stock and energy. Thereby, the general nested VES function can be obtained as follows:

\[
\begin{align*}
    Y &= A(K^{\alpha_2}(E + b_2\alpha_2 K)^{(1-\alpha_2)\nu_2})^{\nu_1} \\
    (L + b_1\alpha_1 K^{\alpha_2}(E + b_2\alpha_2 K)^{(1-\alpha_2)\nu_2})^{(1-\alpha_1)\nu_1}
\end{align*}
\]  

(3)

\[
\begin{align*}
    MP_K &= AL^{1-\alpha_2}\alpha_2(E + b_2\alpha_2 K)K^{\alpha_2}(E + b_2\alpha_2 K)^{(1-\alpha_2)\nu_2}]^{\nu_1} \\
    K(E + b_2\alpha_2 K)
\end{align*}
\]  

(4)

\[
\begin{align*}
    MP_E &= AL^{1-\alpha_2}\alpha_2(1 - \alpha_2)(E + b_2\alpha_2 K)^{(1-\alpha_2)\nu_2} \\
    E + b_2\alpha_2 K
\end{align*}
\]  

(5)

The elasticity of substitution between energy and capital in nested VES production function is described as follows by using Eqs. (4) and (5) which show the marginal physical products of capital and energy, respectively:

\[
\sigma(E, K) = \frac{\partial \ln(E/K)}{\partial \ln(MP_K/MP_E)} = 1 + b_2 \left( \frac{E}{K} \right)
\]  

(6)

In Eq. (6), expression \( b_2 \) indicates that EoS \( (\sigma) \) changes with regard to the energy-capital ratio \( (E/K) \). When \( b_2 \) is smaller than zero, energy and capital are complements. Adversely, when \( b_2 \) is greater than zero, energy and capital are substitutes. VES production function is the extended form of the constant elasticity of substitution (CES) production function. So, in Eq. (3), the values of \( b_1 \) and \( b_2 \) are important to identify function (3) if it is a CES or VES function. In the case of \( b_1 \) equals 0 (zero), the EoS between physical input and labor will be constant over time. Similarly, the condition \( b_2 = 0 \) leads the EoS between capital and energy to the constant elasticity. Thus, \( b_1 = b_2 = 0 \) implies the Cobb–Douglas production function, which is the special form of the CES function. Additionally, the VES function (3) can also be reduced to other well-known output functions by restricting the parameters \( b_{1,2}, \alpha_{1,2}, \) and \( \nu_{1,2} \).

In this study, we examine the implications of EoS between capital and energy on long-run economic growth by using the Solow-Swan growth model. Standard Solow growth model contains capital and labor as production inputs. In our paper, the standard Solow growth model is enhanced with two new elements. Initially, we consider the energy besides labor and capital as a production factor in the production process. Secondly, the nested VES production function is estimated as a production function in the Solow growth model. We build a framework of the Solow model without population growth, technological progress, and depreciation for analytical simplicity. Our framework begins with the analysis of energy accumulation. Aggregate energy stock at the period \( t \) can be evaluated as follows:

\[
\theta_{t+1} = \theta_t(1 + q_t^\theta) - E_t
\]  

(7)

\( q_t^\theta \) denotes exogenous augmentation in energy resources. \( \theta_t \) grows as a result of the regeneration of energy and the emergence of new energy reserves. Adversely, \( \theta_t \) decreases through the consumption of energy by the rate of \( E_t \). Energy accumulation is exogenous and unaffected by the EoS between capital and energy \( (b_2) \).

Let \( K_t \) denote physical capital stock at the period \( t \) without depreciation and constant exogenous fraction. Moreover, in line with no population growth and no technological progress, we suppose that final output \( (Y_t) \) is accumulated only through physical capital stock accumulation (i.e., \( Y_t = K_{t+1} - K_t \)). Hence, aggregate capital stock can be derived using the nested VES production function in Eq. (8). In Eq. (8), returns to scale are constant \( (\nu_1 = \nu_2 = 1) \), and \( b_1 \) is taken 0 which is the EoS between labor, and physical input is constant. So, capital accumulation only depends on the ease with which capital and energy are substituted \( (b_2) \):
\[ K_{t+1} - K_t = sA K_t^{a_1}(E_t + b_2 \alpha_2 K_t)^{a_2} L_t^{1-a_1} \]  

(8)

As energy and capital are substituted \((b_2 > 0)\), a rise in energy efficiency contributes to a faster accumulation of capital and long-run economic growth. Otherwise, when \(b_2 < 0\), capital and energy are complements, and higher capital accumulation needs more capital stock and more energy together. So, in case of supply of energy is reduced compared to capital for production, for example during energy crisis, energy-capital complementarity will decrease the long-run economic growth. As a consequence, we indicated in the theoretical framework of nested VES production function within the Solow model that substitutability between energy and capital \((b_2)\) has an impact on capital accumulation and long-run economic growth.

While analyzing the substitutability, we construct two main hypotheses: (1) the EoS between capital and energy is variable and changes according to the energy-capital ratio \((b_2 \neq 0)\); (2) in the production process, energy is an important production input \((a_2 \neq 1)\). For testing the hypotheses, the log-linearizing form of the Eq. (3) is produced as a baseline estimating equation as follows:

\[
\log Y_{it} = \log A_i + a_1 \log K_{it} + (1-a_2) a_2 \log (E_{it} + b_2 \alpha_2 K_{it}) + \log (L_{it} + b_1 \alpha_1 K_{it}^{a_1} (E_{it} + b_2 \alpha_2 K_{it})^{1-a_1}) + \varepsilon_{it} 
\]  

(9)

In the Eq. (9), \(i, t, \) and \(\varepsilon\) represent the country index, year index, and error term, respectively. \(a_1\) indicates the shares of physical input (capital and energy) and labor, while \(a_2\) indicates the shares of capital and energy. In case of \(a_1 = 1\), labor plays a very small role in the production process and Eq. (9) turns into VES production with two inputs (capital and energy). Additionally, if \(a_2 = 1\), energy plays a very small role in the production process, and Eq. (9) evolves into VES production function with two inputs (capital and labor).

We use both raw labor and human-adjusted labor separately in place of labor input as a production factor. The importance for creating human adjusted labor series comes from the studies Romer (1986), Lucas (1988), Tallman and Wang (1994), Duffy and Papageorgiou (2000), Lazcano and Pham (2016), and Yıldırım (2018). We follow the way of the studies Lazcano and Pham (2016) and Yıldırım (2018) to create human-adjusted labor series. Firstly, we denote \(H_i\) as human capital index where \(i\) indicates each of the country at time \(t\). \(H_i\) (human capital index) is evaluated based on years of schooling and return to education by Penn World Table. So, we obtain the data from Penn World Table for each 58 countries over the period 1975–2017. Later on, we generate the human capital adjusted labor \((HL)\) as \(HL_{it} = H_{it} \times L_{it}\).

As a nonlinear function, the nested VES production function remains non-linear after taking the logarithm of Eq. (3). Hence, the baseline Eq. (9) is estimated by non-linear least square (NLLS) regression method. Nonlinear least square regression method needs initial values to estimate our baseline Eq. (9). For the initial values of the variables, we benefit from the estimation of an OLS (ordinary least square) regression.

We use PSTR model to understand how the non-linear connection between energy consumption and economic progress is influenced by energy intensity level for country groups with the period 1975–2017. PSTR model is an approach that allows parameters to change smoothly when moving from one regime to another.

While estimating the model, we construct the main hypothesis: there is a non-linear relationship between energy consumption and economic growth and at least one threshold point regarding energy intensity. The estimated model is evaluated on the basis of PSTR model with two extreme regimes with reference to the models implemented by González et al. (2005), Yuxiang and Chen (2010), and Aydin and Onay (2020). Equation (10) represents the PSTR model with two extreme regimes including the parameters GDP per capita and energy consumption per capita.

\[
LnperGDP_{it} = \mu_i + \beta_1 LnperET_{it} + \beta_2 LnperET_{it} \ast g(q_{it}; \gamma, \theta) + u_{it} 
\]  

(10)

In Eq. (10), \(LnperGDP\) is a dependent variable and stands for the log form of real GDP per capita; \(LnperET\) is an independent variable and indicates the log-form of energy consumption per capita; \(i\) \((i=1, 2, \ldots, T)\) is time periods; \(i\) \((i=1, 2, \ldots, N)\) represents countries; \(u\) is the error term, and \(\mu\) represents unit-specific fixed effects. \(g(q_{it}; \gamma, \theta)\) employs as a transition function; \(q_{it}\) gives transition parameter, \(\theta\) represents threshold parameter, and \(\gamma\) is smoothing parameter. The transition function \(g(q_{it}; \gamma, \theta)\) is defined as a logistic form:

\[
g(q_{it}; \gamma, \theta) = \left[ 1 + \exp(-\gamma (q_{it} - \theta)) \right]^{-1}, \gamma > 0
\]  

(11)

PSTR model can have more than two regimes. In that case, PSTR model is evaluated as follows:

\[
LnperGDP_{it} = \mu_i + \beta_1 LnperET_{it} + \sum_{j=1}^{J} \beta_j LnperET_{it} \ast g_j(q_{it}; \gamma_j, \theta_j) + u_{it}
\]  

(12)

In PSTR model with more than two regimes, the transition function \(g(q_{it}; \gamma, \theta)\) is stated as follows:

\[
g(q_{it}; \gamma, \theta) = \left( 1 + \exp \left( -\gamma \prod_{j=1}^{m} (q_{it} - \theta_j) \right) \right)^{-1}, \quad \gamma > 0, \quad \theta_1 \leq \theta_2 \leq \ldots \leq \theta_m
\]  

(13)
In case of \( q \neq \ln\text{perET}_i \), that is, transition variable \( (q) \) differs from the explanatory variable \( (\ln\text{perET}) \) in Eq. (12), the estimation of the flexibility value is stated as follows:

\[
e_{it} = \frac{\partial \ln\text{perGDP}_it}{\partial \ln\text{perET}_it} = \beta_0 + \sum_{j=1}^{r} \beta_j * g_j(q_{it}^{(j)}, \gamma_j, \theta_j)
\] (14)

If \( q = \ln\text{perET}_i \), which is transition variable \( (q) \) equals one of the explanatory variables \( (\ln\text{perET}_i) \) in Eq. (12), the estimation of the flexibility value is stated in the equation:

\[
e_{it} = \frac{\partial \ln\text{perGDP}_it}{\partial \ln\text{perET}_it} = \beta_0 + \sum_{j=1}^{r} \beta_j * g_j(q_{it}^{(j)}, \gamma_j, \theta_j)
\] (15)

\( \theta \) parameter is proportional to \( \gamma \). Therefore, the constraint \( (\theta_i = 0) \) is to be applied in order to test the axioms that the null hypothesis is linear model and the alternative hypothesis is PSTR model. This is tested by \( F \)-statistic. According to \( LM_r \) statistic, the rejection of null hypothesis requires the estimation of PSTR model. After the rejection of linear model hypothesis, the regime number is determined. At this stage, the null hypothesis that the model includes one transition function \( (r = r^* = 1) \) is tested against \( r = r^* + 1 \) (model includes two transition functions) alternative hypothesis. If the null hypothesis is admitted, then the process finalizes.

In case of rejection of the null hypothesis, the null hypothesis \( (r^* + 1) \) will be tested against \( r = r^* + 2 \) alternative hypothesis. This stage of determination of the number of regime goes on until the admittance of null hypothesis for the first time (Fouquau et al. 2008). At the final stage, the model is estimated by NLLS (non-linear least square) regression.

## Data

The dataset is obtained from two sources: the Penn World Table (Feenstra et al. 2015) and BP Energy Statistical Review of World Energy (BP Statistics 2020). Penn World Table (PWT) is a large-scale dataset measuring the economic activity of a nation over time. PWT covers data on GDP, productivity, employment, population, and capital stock of currently 167 countries with the period 1950–2017. BP Statistical Review of World Energy 2020 includes data of 110 countries with the period 1965–2019. However, our dataset covers 58 countries with years from 1975 to 2017 (43 years). The variables are chosen based on the Eq. (3) — general nested VES production function. Equation (3) needs data on variables such as labor force \( (L) \), physical capital stock \( (K) \), energy \( (E) \), total output \( (Y) \), and total factor productivity \( (A) \). Table 1 summarizes the variables, unit of measurement, and sources of data.

The sample countries are divided into four groups. First, classification is adopted according to their relative energy intensity levels. We firstly compute energy intensity levels of 58 countries. For calculation, we use primary energy consumption data and real GDP data both in the year 2013. After determining the energy intensity levels of the countries, we order the countries by ascending sort according to their energy intensity levels. Then, we take the median value where values that are higher than the median value are grouped as “high-intensity” countries and values that are lower than the median value are grouped as “low-intensity” countries.

### Table 1 Variables and source of data (VES)

| Variable                        | Unit of measurement                                      | Source of data                                      |
|---------------------------------|---------------------------------------------------------|-----------------------------------------------------|
| Real GDP                        | Expenditure-side real GDP at chained PPPs (in millions 2011US$) | Penn World Table (version 9.1)                      |
| Real total factor productivity  | Total factor productivity at constant national prices (2011 = 1) | Penn World Table (version 9.1)                      |
| Real capital stock              | Capital stock at constant national prices (in millions 2011US$) | Penn World Table (version 9.1)                      |
| Population*                     | Millions of people                                       | Penn World Table (version 9.1)                      |
| Human capital index             | Greater than 1                                           | Penn World Table (version 9.1)                      |
| Primary energy consumption      | Million tons of oil equivalent                           | BP Energy Statistical Review of World Energy 2020    |

PPP indicates purchasing power parity

*Population stands for the labor input \( (L) \) in VES production function. While the estimation of the model is more accurate with data on labor force for each country, this is impractical considering the vast scale of our research, which covers 58 countries with the time period 1975–2017. Thus, we employ population dataset. However, in order to obtain more appropriate estimation, we also use human capital index besides data on population (unadjusted labor force). The human capital index is measured using average years of schooling approach (Barro and Lee 2013) and the return to education rate from Mincer equation (Psacharopoulos 1994) for each country by PWT version 9 (Inklaar and Timmer 2013)
As for the second classification, we group the countries according to their energy import values based on the year 2013. The data on energy import is obtained from World Bank Open Data (World Bank 2021). In the dataset, which presents the energy import values, “net energy importer” countries are indicated with negative values, while “net energy exporter” countries are indicated with positive values. Due to availability of most comprehensive data, 2013 has been designated as the base year for computing energy intensity levels and determining energy import values. The reason for the second classification is, for net energy exporter countries, accessing energy is easier than for net energy importer countries. Hence, even though the countries belong to the same upper group (“low energy intensity” or “high energy intensity” group), in case of energy crisis, net energy exporter countries can be effected differently than net energy importer countries.

Thus, we have four groups, namely, (1) “low energy intensity and net energy exporter” countries, (2) “low energy intensity and net energy importer” countries, (3) “high energy intensity and net energy exporter” countries, and (4) “high energy intensity and net energy importer” countries. Appendix Table gives the country groups in detail.

An alternative way for the classifications is taking the mean value of each variable for the years from 1975 to 2017 for each country. For instance, after determining the energy intensity levels for a country for the years from 1975 to 2017, we can take the mean value of energy intensity levels for that country. Then, we can order the countries by ascending sort according to their mean value of energy intensity levels. Hence, we can take the median value where values that are higher than the median value are grouped as high intensity, and values that are lower than the median value are grouped as low intensity. Additionally, this calculation can be repeated for the second classification. However, our selected period is considerably long (43 years). In this period, countries’ energy consumption amounts and real GDP values vary considerably. Taking into account the whole time period for the calculations may not reflect the countries’ current situations. So, the empirical findings of the analyses may not give accurate results.

The variables of PSTR model are chosen from the first analysis. Thus, the dataset is obtained from Penn World Table (Feenstra et al. 2015) and BP Energy Statistical review of World Energy (BP 2020) including 58 countries with years from 1975 to 2017. Additionally, country classification remains the same that we have four subgroups. Table 2 summarizes the variables, unit of measure, and source of data.

In Table 2, LnperGDP indicates the log form of total output per capita and LnperET stands for log form of energy consumption per capita. In the second analysis, we analyze the effect of energy intensity level on the relationship between energy consumption and economic growth. Hence, our third parameter is energy intensity. However, energy intensity is not placed in Table 2, because for the calculation of energy intensity, we use the data on energy consumption and real GDP, which are represented in Table 1.

Descriptive statistics (mean, maximum, and minimum values of variables and number of observations etc.) are represented in Appendix Table and Appendix Table for each group with the period 1975–2017.

### Empirical findings

Results of empirical analyses are presented in this subsection. In VES function analysis, our main estimation builds on the baseline Eq. (9) that includes both physical input-labor elasticity ($b_1$) and capital-energy elasticity ($b_2$). We mainly test two hypotheses: (1) in the production process, energy is an important production input ($a_1 \neq 1$), and (2) the EoS between capital and labor is not constant ($b_2 \neq 0$) and changes according to the energy-capital ratio. The empirical findings of the nonlinear regression estimates of the model are represented by Table 3. In the first two lines of Table 3, the country classifications are given. Additionally, Table 3 is divided into two subsections. The first subsection gives the values of the parameters estimated for unadjusted labor (raw labor $L$). The second subsection reports the values of the parameters computed for adjusted labor (human adjusted labor $HL$).

Table 3 reports that parameters $a_1$ and $a_2$ are not equal to 1 ($a_1 \neq a_2 \neq 1$) and the elasticity parameters $b_1$ and $b_2$ are not constant ($b_1 \neq b_2 \neq 0$) for all groups. Additionally, all parameters are statistically significant with different significance levels. So, the results support our hypothesis for variable EoS between capital and energy ($b_2$). The constant EoS can be rejected in favor of variable EoS for all country groups. Moreover, Table 3 provides evidence for our second hypothesis that energy is an important production input in

### Table 2 Variables and source of data (PSTR)

| Variable | Unit of measurement | Source of data |
|----------|----------------------|----------------|
| LnperGDP | Expenditure-side real GDP at chained PPPs per capita (in mil. 2011 US$) | Penn World Table (version 9.1) |
| LnperET  | Primary energy consumption per capita (million tons of oil equivalent) | BP Energy Statistical Review of World Energy 2020 |

GDP and PPP indicate gross domestic products and purchasing power parity, respectively.
Table 3 Nonlinear regression estimation (country classification)

| Parameters  | Low energy intensity | High energy intensity |
|-------------|----------------------|-----------------------|
|             | (1) Net energy exporter countries | (2) Net energy importer countries | (3) Net energy exporter countries | (4) Net energy importer countries |
| Unadjusted labor (L) | | | | |
| $\alpha_1$ | 0.9598*** (0.0209) | 0.9387*** (0.0123) | 0.5470*** (0.0055) | 0.9356*** (0.0118) |
| $\alpha_2$ | 0.8960*** (0.0185) | 0.9206*** (0.0129) | 0.7233*** (0.0018) | 0.9424*** (0.0132) |
| $b_1$ | $-0.0000111^* (6.55e-06)$ | $-7.55e-06** (3.84e-06)$ | $-0.0000336** (1.54e-05)$ | $-5.56e-06*** (9.76e-07)$ |
| $b_2$ | $-6.44e-06*** (1.26e-06)$ | $-6.19e-06* (3.31e-06)$ | $-0.0000254*** (2.96e-06)$ | $-0.0000142*** (1.91e-07)$ |
| Adjusted labor (HL) | | | | |
| $\alpha_1$ | 0.9357*** (0.0279) | 0.9083*** (0.0110) | 0.8330*** (0.0079) | 0.9007*** (0.0144) |
| $\alpha_2$ | 0.9142*** (0.236) | 0.9470*** (0.0113) | 0.7134*** (0.0053) | 0.0733*** (0.0155) |
| $b_1$ | $-0.000033* (0.000189)$ | $-0.0000234***$ | $-0.00011*** (2.02e-05)$ | $-0.0000136*** (2.71e-06)$ |
| $b_2$ | $-6.32e-06** (1.52e-07)$ | $-6.85e-06** (3.32e-06)$ | $-0.0000252*** (1.70e-06)$ | $-0.0000137*** (2.46e-07)$ |
| $R^2$ (L) | 0.9992 | 0.9996 | 0.9986 | 0.9990 |
| $R^2$ (HL) | 0.9992 | 0.9997 | 0.9507 | 0.9991 |
| N | 344 | 946 | 430 | 774 |

The terms in parentheses are standard errors. $N$ is the number of observations.

**Significance level at 1%; *** significance level at 5%; * significance level at 10%.

the production process. Even though our main focus is on the estimations of $b_2$ and $\alpha_2$, the results of $b_1$ and $\alpha_1$ are also taken into consideration.

The estimation of the elasticity parameter between capital and energy ($b_2$) is negative for all country groups in case of both raw labor (L) and adjusted labor (HL). The negative value of $b_2$ indicates the complementary relationship between capital and energy. Additionally, since the value of $b_2$ is negative, the EoS for all country groups is smaller than one. Elasticity of substitution by country groups is given in Appendix Table.

For low intensity and net energy exporter countries, $b_2$ takes a negative value both in case of unadjusted labor ($-6.44e-06$) and adjusted labor ($-6.32e-06$). The negative value means that a one-unit increment in the capital-energy-ratio reduces the EoS between capital and energy by approximately $-6.4e-06$ units in this country group. There is a similar conclusion for low intensity and net energy importer country group that $b_2$ is negative. For high intensity and net energy exporter country group, one-unit increment in the capital-energy-ratio reduces the EoS between energy and capital by $2.5e-05$ units approximately. “High energy intensity and net energy importer countries” have also negative $b_2$ value when both raw labor and adjusted labor are considered. Eventually, for all country groups, the results reject constant EoS between capital-energy and prove that energy and capital are complements in the final output.

Since energy and capital are complements in the final output for all country groups, we analyze the role of energy intensity in the non-linear relationship between energy consumption and economic growth for all country groups. However, before estimating PSTR model, cross-section dependence test and unit-root test are applied to our panel dataset. Table 4 gives the cross-section dependence test results for each country group.

For the cross-sectional dependence test, our null hypothesis is that “there is no cross-sectional dependence.” According to the statistics, null hypothesis is rejected with 1% significance level for each parameter and each group. The empirical findings suggest that in the series and in the model, there is a cross-sectional dependence. After cross-sectional dependence test, the stationary of the series is researched. Moon and Perron’s (2004) unit root test, which is a second-generation panel unit root test and takes into consideration cross-sectional dependence, is employed for stationary of the series. The null hypothesis of the unit root test is that “the series have a unit root test.” Table 5 represents the test results for each parameter and each group. The statistics gives that the null hypothesis is rejected strongly for each parameter and each group. Hence, the series are stationary at level (I(0)).

After cross-section dependence tests and unit root test, we estimate PSTR model. The first stage of PSTR is to test the non-linearity model against the linearity model. In this
Our null hypothesis is that “the model is linear.” In case of rejection of the null hypothesis, the second stage would cover the analysis of the proper number of transition functions (number of regimes). Table 6 gives the test results of Wald tests (\(\text{LM}^a\)), Fisher tests (\(\text{LMF}^b\)), and LRT tests (\(\text{LRT}^c\)) for linearity.

The terms in parentheses are standard errors

| \(\text{CD}_{BP}\) | \(\text{CD}_{LM}\) | \(\text{CD}\) | \(\text{LM}_{adj}\) |
|-----------------|-----------------|--------|-----------------|
| Low energy intensity and net energy exporter | 794.6929*** | 102.4536*** | 27.7761*** | 102.3584*** |
| LnperGDP | 639.4069*** | 81.7027*** | 23.4926*** | 81.6074*** |
| LnperET | 8680.963*** | 393.1279*** | 93.0659*** | 392.8660*** |
| High energy intensity and net energy exporter | 897.5177*** | 89.8633*** | 28.3864*** | 89.7442*** |
| LnperGDP | 804.9967*** | 80.1107*** | 26.6886*** | 79.9916*** |
| LnperET | 5795.0670*** | 159.0584*** | 18.5971*** | 158.8441*** |

Statistics given in Table 5 indicate that the null hypothesis is rejected for each country group with 1% significance level. So, the alternative hypothesis is accepted: the model includes at least one non-linear threshold effect. Thus, there is a nonlinear relationship between energy consumption and economic growth and at least one threshold point for energy intensity. The next step is to evaluate the proper regime numbers. The tests are repeated to find the certain regime numbers. For the remaining analysis, the null hypothesis is that “the model includes only one threshold effect.” So, the

| \(\bar{r}\) | \(t\)\(^a\) | \(t\)\(^b\) | \(\bar{p}\)\(^c\)\(_{pool}\) |
|-------|---|---|-------|
| Low energy intensity and net energy exporter | -2.2241** | -1.6471** | 0.9620 |
| LnperGDP | -271.4525*** | -20.9982*** | -2.9573 |
| LnperET | -12.5410*** | -6.0289*** | 0.8898 |
| Low energy intensity and net energy importer | -4.9054** | 0.9270 |
| LnperGDP | -3.9409*** | -2.4053*** | 0.9482 |
| LnperET | -3.1856*** | -2.8884*** | 0.9474 |
| High energy intensity and net energy importer | -14.9068*** | -6.3546* | 0.8629 |
| LnperGDP | -14.9068*** | -6.3546* | 0.8629 |
| LnperET | -15.3265*** | -7.2223** | 0.8661 |

\(\bar{r}\) is the estimated number of common factors. \(t\)\(^a\) and \(t\)\(^b\) are the unit root test statistics based on de-factored panel data. \(\bar{p}\)\(^c\)\(_{pool}\) is the corrected pooled estimates of the autoregressive parameter. The terms in parentheses are standard errors

*** Level of significance at 1%; ** level of significance at 5%
alternative hypothesis is designated as “there are at least two threshold effects in the model.” The test results are presented in Table 7.

According to Table 7, the null hypothesis cannot be rejected for each country group which means the model has only one threshold effect and can be estimated using PSTR with two extreme regimes. The final step is to estimate the model, and the results are given in Table 8.

As it is observed from Table 8, slope parameter \( \gamma \) is highest (201.613) in the low intensity and net exporter countries. For other country groups, estimated slope parameters are relatively low and extend from 10.025 to 22.816. This means that in the low energy intensity and net energy exporter country group, the transition from one regime to another is sharper than the other country groups.

The statistics in Table 8 indicates that for low energy intensity and net energy exporter countries, the estimated coefficient \( \beta_0 \) of energy consumption per capita in the first regime is positive (2.152) and statistically significant. This positive value states that energy consumption affects economic growth in a positive way in the first regime. For the second regime, we consider the sum of the estimated coefficients \( \beta_0 + \beta_1 \) and interpret the sign of the sum. The sum (2.152 + (−4.609)) has a negative magnitude. The negative value indicates that in the second regime, increase in energy consumption leads to decrease in economic growth. Threshold level for energy intensity is about 24% (\( \theta = 0.236 \)) for low intensity and net energy exporter countries.

For the low energy intensity and net energy importer countries, the estimated coefficient \( \beta_0 \) of energy consumption per capita in the first regime is positive (1.710) and statistically significant at 1% level. However, in the second regime, the sum of the estimated coefficients \( \beta_0 + \beta_1 \) has a negative sign (1.710 + (−2.038)). The threshold level for energy intensity (\( \theta = 0.140 \)) is 14%. Hence, the relationship between energy consumption and economic growth is negative in the second regime.

The estimated coefficient \( \beta_0 \) of energy consumption per capita in the first regime is positive (2.810) and statistically significant for high energy intensity and net energy exporter countries. Thus, the relationship between energy consumption and economic growth is positive in that rise in energy consumption increases economic growth in the first regime. For the second regime, the sign remains positive

Table 7 Tests for the remaining non-linearity of the PSTR model

| Threshold variables (Intensity) | Low intensity | High intensity |
|--------------------------------|--------------|---------------|
| \( H_0 : r = 1 \) vs Net energy exporter | Net energy importer | Net energy importer |
| \( H_1 : \text{at least } r = 2 \) | | |
| \( LM \) | 3.441 (0.179) | 0.048 (0.827) | 0.096 (0.757) | 0.000 (0.988) |
| \( LM_F \) | 1.677 (0.188) | 0.046 (0.829) | 0.093 (0.760) | 0.000 (0.988) |
| \( LR_F \) | 3.459 (0.177) | 0.048 (0.827) | 0.096 (0.757) | 0.000 (0.988) |

Under \( H_0 \), the \( LM \) and \( LR \) statistics have an asymptotic \( \chi^2(\mu K) \) distribution, whereas \( LM_F \) has an asymptotic \( \Theta(\mu K, TN - N\mu(K + 1)) \) distribution. Moreover, \( r \) is the number of transition functions. \( P \)-values are in parentheses.

Table 8 Estimated results of the PSTR model

| Threshold variables (energy intensity) | Low intensity | High intensity |
|---------------------------------------|--------------|---------------|
| | Net energy exporter | Net energy importer | Net energy exporter | Net energy importer |
| \( LuperET_1 \) | 2.152*** (0.092) | 1.710*** (0.037) | 2.810*** (0.154) | 1.313*** (0.031) |
| \( LuperET_2 \) | −4.609*** (0.316) | −2.038*** (0.062) | −2.312*** (0.133) | −0.765*** (0.024) |
| Location parameters, \( \theta \) | 0.236 | 0.140 | 0.040 | 0.206 |
| Slope parameters, \( \gamma \) | 201.613 | 18.396 | 10.025 | 22.816 |

Dependent variable is per capita real GDP in natural logarithm. Standard errors are corrected for heteroskedasticity in parentheses

***Significance at 1% level
(2.810 + (−2.312)). Additionally, we observe from Table 8 that the threshold level for energy intensity is 4% ($\theta = 0.040$) for high energy intensity and net energy exporter countries.

For high energy intensity and net energy importer countries, the estimated coefficient ($\beta_0$) of energy consumption per capita in the first regime is positive (1.313) and statistically significant at 1% significance level. For the second regime, the sum of the estimated parameters ($\beta_0 + \beta_1$) is again positive (1.313 + (−0.765)). Table 8 represents that the energy intensity threshold level is approximately 21% ($\theta = 0.206$). Hence, rise in energy consumption raises economic growth in both two regimes.

**Conclusion**

Policies aimed at decreasing energy consumption play an essential role in both reducing greenhouse gas emissions and lowering energy intensity while meeting energy demand to sustain economic growth. The success of such strategies is mainly determined by the energy substitution with alternative production inputs (Nijkamp et al. 2005). This paper examines substitutability between energy and capital through estimating VES production within the standard Solow growth model framework. By integrating the VES production function into the Solow growth model, the EoS between energy and capital directly determines the capital accumulation in our model.

We employed global aggregate data for 58 countries with the period 1975–2017. To understand the role of energy intensity, we classify the selected countries primarily according to their relative energy intensity levels and then according to whether the country is a net energy importer or net energy exporter based on the selected year.

The estimation of the VES production function reports significant empirical results; firstly, energy has a significant role in the final output, and the EoS between capital and energy is not constant for all country groups. Secondly, for each group, energy is not substituted by capital that capital and energy are complements in the final production output. The magnitudes of EoS parameter in high energy–intensity countries (both net energy exporter and net energy importer countries) are smaller than the magnitudes in low energy–intensity countries (both net energy exporter and net energy importer countries). Although the differences are very low, the smaller magnitudes show that high energy intensity countries have a stronger complementary relationship between capital and energy than low energy intensity countries have. High energy intensity level is an indicator of inefficient usage of energy. So, our results support the work of Lazkano and Pham (2016) which revealed that energy and capital are complements for the countries having very low environmental performance.

A complementary relationship indicates the following: a conjunct increase of capital stock and energy consumption is necessary in order to achieve capital accumulation and sustainable long-run economic growth. Hence, in this paper, as further analysis, we investigate whether or not energy consumption always fosters economic growth. So, we estimate PSTR model for analyzing the non-linear relationship between energy consumption and economic growth by examining the role of energy intensity in this relationship.

The estimation of the PSTR model also presents important findings; firstly, for each country group, there is one threshold level for energy intensity that is above and below this level, and energy consumption affects economic growth divergently. Secondly, the effect of energy consumption on economic growth remains positive above threshold level for both two low energy intensity country groups (net energy exporter and net energy importer countries). However, for the low energy intensity and net energy exporter countries, the negative effect of energy consumption on economic growth goes into reverse above threshold level for both two low energy intensity country groups (net energy exporter and net energy importer countries).

Energy intensity threshold level is higher for low energy intensity and net energy exporter countries (23.6%) than the energy intensity threshold level for low energy intensity and net energy importer countries (14%). High energy intensity and net energy exporter country group has the lowest threshold level for energy intensity (4%). Additionally, high energy intensity and net energy importer countries should not exceed the 21% energy intensity level to keep the strong positive effect.

Our findings contribute a new approach to the policy discussion about minimizing energy use while sustaining economic development. Our estimates reveal that capital is not a substitute for energy and that more energy consumption is required to accelerate capital accumulation and sustain economic growth. However, more energy consumption does not always foster economic growth. Regardless of whether a country is a net energy exporter or net energy importer, it needs to use energy efficiently and not exceed the ideal energy intensity level in both production and consumption to maintain long-term economic growth. Additionally, the ideal level of energy intensity gives policymakers more flexibility while implementing cost-effective energy consumption policies for economic growth and reaching environmental policy goals.
## Appendix

### Table 9 Country classification

| Low energy intensity | High energy intensity |
|----------------------|-----------------------|
| **Net energy exporter countries** | **Net energy importer countries** | **Net energy exporter countries** | **Net energy importer countries** |
| Colombia | Austria | Australia | Argentina |
| Ecuador | Brazil | Canada | Belgium |
| Egypt | Chile | Iran | Bulgaria |
| Indonesia | China, Hong Kong SAR | Kuwait | China |
| Iraq | Denmark | Malaysia | Cyprus |
| Mexico | France | Qatar | Finland |
| Norway | Germany | Saudi Arabia | Greece |
| Peru | Hungary | South Africa | Iceland |
| India | Trinidad and Tobago | Venezuela | Luxembourg |
| Ireland | | | Netherlands |
| Israel | | | New Zealand |
| Italy | | | Poland |
| Japan | | | Singapore |
| Morocco | | | South Korea |
| Philippines | | | Sweden |
| Portugal | | | Taiwan |
| Romania | | | Thailand |
| Spain | | | Unites States of America |
| Sri Lanka | | | |
| Switzerland | | | |
| Turkey | | | |
| United Kingdom | | | |
Table 10 Descriptive statistics of variables (VES)

| Variables          | Unit of measurement         | Statistics | Low energy intensity | High energy intensity |
|--------------------|-----------------------------|------------|----------------------|-----------------------|
|                    |                             |            | (1) Net energy exporter | (2) Net energy importer |                        |
| Real GDP           | Millions of 2011 US dollar  | Mean       | 43,927.54739         | 892,048.7617          | 395,983.8             | 1,256,206             |
|                    |                             | Max        | 2,862,116.75         | 8,412,113             | 1,629,508             | 18,396,068            |
|                    |                             | Min        | 28,422,50781         | 30,710,5781           | 8814,254              | 2996,073              |
|                    |                             | Std. Dev   | 541,793,5296         | 1,176,367,139         | 394,260,5            | 3,229,540             |
| Real TFP           | Constant 2011 National Prices | Mean     | 1.1077                | 0.9607                | 1.1817                | 0.9114                |
|                    |                             | Max        | 3.1233                | 1.3164                | 5.2521                | 1.3853                |
|                    |                             | Min        | 0.5843                | 0.5648                | 0.5724                | 0.4384                |
|                    |                             | Std. Dev   | 0.2953                | 0.1159                | 0.5554                | 0.1464                |
| Real Capital Stock | Millions of 2011 US Dollar | Mean       | 1,864,804.656         | 4,270,330.839         | 1,694,198,562         | 4,484,390             |
|                    |                             | Max        | 15,846,835            | 29,931,072            | 6,748,094.5           | 94,903,728            |
|                    |                             | Min        | 90,796,2188           | 110,732,7344          | 42,174,3515           | 17,434,7             |
|                    |                             | Std. Dev   | 2,636,729,213         | 5,258,859.39          | 1,498,613,715         | 11,606,617            |
| Population         | Millions of People          | Mean       | 57.4918               | 83.4246               | 21.7307               | 96.9164               |
|                    |                             | Max        | 263.9914              | 1339.1802             | 81.1628               | 1409.517              |
|                    |                             | Min        | 4.00803               | 3.1841                | 0.1644                | 0.2181                |
|                    |                             | Std. Dev   | 62.9127               | 205.4996              | 19.0147               | 278.9511              |
| Primary Energy Consumption | Million tons of oil equivalent | Mean | 46.4561                | 106.1902              | 86.4118               | 227.469               |
|                    |                             | Max        | 188.5770              | 748.4129              | 336.9992              | 3124.862              |
|                    |                             | Min        | 1.8354                | 1.0806                | 1.2950                | 0.7335                |
|                    |                             | Std. Dev   | 46.2825               | 135.1136              | 84.9547               | 569.2807              |
| Human Capital Index| Greater Than 1               | Mean       | 2.2538                | 2.6896                | 2.4090                | 2.7891                |
|                    |                             | Max        | 3.6431                | 3.8071                | 3.70629               | 3.9742                |
|                    |                             | Min        | 1.1461                | 1.1224                | 1.1584                | 1.4957                |
|                    |                             | Std. Dev   | 0.5524                | 0.6266                | 0.6356                | 0.4796                |
| Human Capital Adjusted Labor* |               | Mean | 123.7230              | 180.7671              | 51.8072               | 233.1321              |
|                    |                             | Max        | 611.4409              | 2844.1777             | 196.7272              | 3617.424              |
|                    |                             | Min        | 11.5756               | 7.9549                | 0.2699                | 0.5023                |
|                    |                             | Std. Dev   | 140.2180              | 372.7156              | 44.0920              | 615.0471              |
| Number of Observations |                   |            | 344                   | 946                   | 430                   | 774                   |
| Number of          |                             |            |                        |                       |                       |                       |

GDP indicates gross domestic product. TFP indicates total factor productivity. Std. Dev. is the abbreviation of standard deviation. Max. is the maximum value. Min. is the minimum value. Obs. means the number of observation.
Table 11 Descriptive statistics of variables (PSTR)

| Low energy intensity and net energy exporter | Mean | Std. Dev | Max  | Min  | Obs |
|---------------------------------------------|------|----------|------|------|-----|
| LnperGDP                                    | 8.9191 | 0.8332 | 11.0630 | 7.1017 | 344 |
| LnperET                                     | −0.0780 | 0.9754 | 2.3614 | −2.2591 | 344 |
| Intensity                                   | 0.0940 | 0.0398 | 0.3815 | 0.0365 | 344 |

| Low energy intensity and net energy importer | Mean | Std. Dev | Max  | Min  | Obs |
|---------------------------------------------|------|----------|------|------|-----|
| LnperGDP                                    | 9.6202 | 0.9059 | 11.2023 | 6.9294 | 946 |
| LnperET                                     | 0.5160 | 1.0081 | 1.5678 | −2.5606 | 946 |
| Intensity                                   | 0.1048 | 0.0391 | 0.2924 | 0.0241 | 946 |

| High energy intensity and net energy exporter | Mean | Std. Dev | Max  | Min  | Obs |
|-----------------------------------------------|------|----------|------|------|-----|
| LnperGDP                                    | 9.8767 | 0.8167 | 11.9412 | 7.8116 | 430 |
| LnperET                                     | 1.5296 | 0.8423 | 3.3060 | −0.9057 | 430 |
| Intensity                                   | 0.1857 | 0.0958 | 0.5030 | 0.0342 | 430 |

| High energy intensity and net energy importer | Mean | Std. Dev | Max  | Min  | Obs |
|-----------------------------------------------|------|----------|------|------|-----|
| LnperGDP                                    | 9.8695 | 0.8090 | 11.5077 | 7.3331 | 774 |
| LnperET                                     | 1.2538 | 0.8005 | 2.7623 | −1.5032 | 774 |
| Intensity                                   | 0.1896 | 0.0715 | 0.5070 | 0.0687 | 774 |

GDP indicates gross domestic product. Std. Dev. is the abbreviation of standard deviation. Max. is the maximum value. Min. is the minimum value. Obs. means the number of observation.

Table 12 Elasticity of substitution by country groups (1975–2017)

| Low intensity | High intensity |
|---------------|----------------|
| (1) Net energy exporter | (2) Net energy importer | (3) Net energy exporter | (4) Net energy importer |
| Raw labor (L) | Mean 0.7445 (0.1634) | 0.7053 (0.1241) | 0.4871 (0.2194) | 0.6238 (0.2010) |
|               | Max 0.9466 | 0.9589 | 0.8707 | 0.9673 |
|               | Min −0.1131 | 0.1629 | −0.3836 | −0.0645 |
| Adjusted labor (HL) | Mean 0.7493 (0.1604) | 0.6739 (0.1374) | 0.4911 (0.2176) | 0.6370 (0.1939) |
|               | Max 0.9476 | 0.9545 | 0.8718 | 0.9684 |
|               | Min −0.0924 | 0.0737 | −0.3727 | −0.0270 |
| N              | 344 | 946 | 430 | 774 |

The terms in parentheses are standard errors. N is the number of observations. Max. is the maximum value. Min. is the minimum value.
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Author contribution Reyhan Demir Onay and Celil Aydin performed the analyses with constructive discussions. Reyhan Demir Onay and Ismail Sahin wrote the manuscript. All the authors read and approved the final manuscript.

Data availability The datasets supporting the results of this article are included within the article and its additional files.

Declarations

Ethics approval and consent to participate Not applicable.

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