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Institutional quality and its spatial spillover effects on energy efficiency

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ABSTRACT

Several studies have studied the determinants of energy efficiency. However, the influence of government institutions was mostly ignored as only few studies have provided evidence on the role of institutions in enhancing domestic energy efficiency. In this paper, we extend the previous literature by asking whether neighboring country's institutions could also have an impact on domestic energy efficiency. Thus, with the stochastic frontier approach and spatial econometric model, we investigate the spatial effect of institutional quality on energy efficiency in a panel of 99 countries (economies) for the period 1995–2016. Our results, first confirm the presence of spatial correlations in energy efficiency across countries. Secondly, we discover that the direct positive effect of institutional quality on energy efficiency is such that it overcomes the insignificant indirect negative effect, which suggests a total positive and significant effect. Our results, therefore, indicate that institutional quality matters in energy efficiency improvement and being close to countries with good institutional framework has a positive effect on domestic energy efficiency. Finally, the energy efficiency estimates demonstrate that global energy issue can only be addressed with long-term policies that increases technological progress.

1. Introduction

The neoclassic economies once considered capital and labor as the engine of economic growth. But, in recent times, energy has become one of the fundamental building blocks of economic growth. Thus, a country's economic growth somehow depends on growth in its energy inputs [1]. But, the use of energy and the emission of greenhouse gases (GHG) are often two terms that are interlinked [2–5]. According to a report by the International Energy Agency, around 67% of total CO_2 emissions are generated in energy sector, suggesting that mitigating energy pollution will contribute enormously in meeting the global climate target. Thus, in attempt to reduce emissions from energy use, several studies have advocated for the adoption of renewable energy technology [6–9]. However, efficient use of energy is considered the best and cost effective means of mitigating pollution from energy consumption [10]. For instance Ref. [11], claim that fostering energy efficiency in the industrial sector offers the best tool in terms of cost efficiency for reducing GHG emissions from energy sources. Therefore, energy efficiency is viewed as one of the major GHG emission reduction policy strategies and it is often considered as "low-hanging fruit" for climate mitigation [12].

In the view of the above, many governments have strategically included in their national agenda several cost-effective energy-efficiency policies [13], for instance, policy to commercialize use of energy technologies [14], policies to drive the diffusion of renewable energy [15,16], policies to respond to high-energy intensities [17–19] and policies to drive energy transition [20,21]. But, effective implementation of such policies depends on the institutions mandated to enforce them. According to Ref. [22], energy policies effectively enforced by government institutions to encourage energy efficiency can later affect citizens' energy consumption behavior. This shows that promoting energy efficiency is an institutional problem. Recent empirical and theoretical studies on this subject highlighted the importance of having good institutions [23–30]. This strand of literature argues that the quality of institutions for example, control of corruption, respect for democratic principles, promoting freedom international trade and respect for the laws and the legislative authority are all important in environmental and energy efficiency improvements. Indeed, it is interesting to note that the results of these studies, examining the effects of institutional quality on energy efficiency, are mostly mixed. The lack of consensus in the existing literature may have emanated from the differences in the institutional proxy used or the small set of institutional variables selected. Though, previous studies have provided evidence on the effects

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of institutional quality on energy efficiency, they have mainly focused on limited number of basic institutional factors such as judiciary independence, government size democracy, and corruption on energy intensity. Besides, in most cases, the energy efficiency used in the previous studies is the conventional energy efficiency measures such as energy intensity which regard energy as the single input that produces GDP and neglect other key inputs like capital and labor.

In an effort to contribute to the existing knowledge: First, we consider new set of satisfactory institutional measures. Therefore, we consider a larger set of institutional variables which include political and economic institutional variables such as corruption, law and order, democracy, the legal system, property rights, sound money, freedom to trade internationally, regulation of credit, labor, and business, government stability and size.

Second, instead of using the conventional energy efficiency measures such as energy intensity (as done in the previous studies) which regard energy as the single input that produces GDP and neglect other key inputs like capital and labor, we adopt a multi-factor energy efficiency assessment model, because it provides better estimates than the traditional partial energy intensity measure [31]. In most cases, the energy intensity indicator is frequently assumed to be synonymous to energy efficiency. But, there are many disadvantages to the use of the energy intensity measure to calculate energy efficiency. First, according to the Ref. [32], the use of energy intensity indicators as energy efficiency measures may not be entirely accurate, as it requires strong assumptions about factors related to efficiency. For example, if the level of technology, economic structure, demographics, lifestyles, and weather conditions differ between countries, the energy intensity would not adequately capture such variations between countries in its measurement [33]. Since efficiency is affected by variations and factors that are not connected to energy, the application of energy intensity as calculation of energy efficiency may be misleading because it does not eliminate or even take into account all the behavioral and structural factors required for actual energy efficiency measurement. Second, the energy intensity measure does not reveal precisely what is inefficient. It may implicitly point to an industry or an economy's general state of affairs, but it provides no basis for concrete recommendations on improving energy efficiency [34]. Third, energy intensity provides no estimates of to what degree the energy efficiency of a given technology or product can be enhanced [35]. Due to these limitations, policy and decision-makers are liable to have an incorrect estimate of the true energy efficiency which will result in poor policy decisions.

Third, we extend the nexus between institutional quality and energy efficiency by examining the spatial effects of institutional quality on energy efficiency. In other words, we are interested in finding out if the geography of institutions matters in understanding cross-country energy efficiency differences. The idea of spatial relationships is not new in environmental or energy economics [36–48]. As governments and citizens learn from each other, institutions and policies can spread across countries in a number of ways. For example, in the quest for regional markets, multinational companies may engage in policy reforms in order to bring local laws into conformity with common principles. Governments, in the hope to take advantage of external opportunities, such as the opportunity to supply to the foreign markets and attract foreign investments, may adopt policies of other countries [49]. Imperialist nations impose their institutions and policies on neighboring nations, be it by peaceful or violent means [49,50]. Countries may imitate each other's institutions because of their proven attractiveness, as showed by Ref. [51] for sub-Saharan African countries.

Ref. [50] empirically observe such institutional spillover effects across neighboring countries. Ref. [39] finds evidence of spatial spillover of explanatory variables in environmental Kuznets curves models for series of anthropogenic greenhouse gas emissions and mentions that it is unclear whether spatial spillover occurs because governments are mimicking each other's environmental policy or whether these are purely incidental effects caused by the geographic diffusion of technology and lifestyles. Ref. [52] finds that because of cross-border copying of environmental policy or institutions, countries are able to influence positively the environmental policies of their neighbors. In other words, the environmental policies in neighboring countries are important for a country's environmental efficiency. Ref. [53] argues that environmental quality of countries spreads spatially to their neighbors through the spillover of the institutional quality of countries in recent decades. Ref. [54] finds that a policy change to increase foreign investment in one country, increases the polices favoring foreign investment in another country.

To achieve the above objectives, we asked the following questions. We ask, whether differences in energy efficiency performance depend on the institutional differences across countries. Does improved institutional arrangement help in improving energy efficiency? Does spatial spillover effect of institutional quality exist? In other words, do institutions of country *i* matter for the energy efficiency performance of country *j*? If they do, how much can they explain differences energy efficiency level across countries? How efficient are countries in energy use? What are the sources of efficiency in energy use?

By providing answers to these questions, the main subjects of this study are as follows:

(1) The energy efficiency performance of countries is first of all established by means of stochastic frontier analysis (SFA).
(2) Next, along with other environmental factors, we investigate the spillover effects of neighboring country's institution on one's domestic energy efficiency. In other words, we account for spatial dependence between energy efficiency and institutional quality.

2. Literature review

2.1. Energy efficiency - institutions nexus

In an attempt to tackle the increasing dangers of climate change, scholars are trying to identify ways to reduce greenhouse gas emissions. Two mitigation methods are often mentioned in the literature, i.e.: (i) use of renewable energy; and (ii) efficient use of energy resources. Nevertheless, other researchers are emphasizing the role of governments in reducing CO_2 emissions and maintaine that improvement in the energy consumption behavior of countries depends on energy policies successfully implemented by governmental institutions [22]. Also, the fact that the energy sector requires strong management, direction and infrastructure, makes the public sector an important player [55]. In this context, neglecting the influence of institutional variables such as corruption, law and order, democracy, the legal system, property rights, sound money, freedom to trade internationally, regulation of credit, labor, and business, government stability and size will result in an incomplete understanding of energy efficiency improvement strategies. The promotion of energy efficient technology or renewable energy consumption is mainly a political decision. On the other hand, the establishment of a strong business ethics by governmental institutions can increase the importance that people attach to the use of energy saving technology and consumption of renewable energy. Furthermore, because increasing energy efficiency is the most cost-effective way to reduce greenhouse gas emissions, strategic actions to promote the use of energy saving technology or renewables may require a strong institutional framework [56,57].

Institutions can indeed matter for energy efficiency, and for the same reasons different streams of literature have shown increased interest in the institutional perspective on energy intensity and environmental strategies. Ref. [58] defines institutions as the "rules of the game", i.e., structures and constraints that shape and influence social conduct or behavior. Institutions, therefore, consist of both informal restrictions (like taboos, traditions, fines, codes of conduct, and customs) and formal rules (like constitutional laws and regulations, the legal system, and property rights) that shapes economic, politics, and ultimately how people think and interact with each other [59]. According to Ref. [60], institutions are considered to have strong constitutional, legislative, and political power, which make them more resourceful in implementing effective policies. More particularly, government institutions are known to provide incentives as well as mount pressures on economic agents which result in a surge environmental and energy efficiency virtuous behavior [27]. These pressures are claimed to be channeled through strict energy and environmental regulations which over time change the energy consumption pattern and behavior of citizens [22]. Therefore, in this context, government institutions are known to be effective in promoting energy policies.

However, outcomes of the institutions-energy efficiency nexus remain contradictory, mixed, and unsatisfactory. Using various proxies, some studies have supported the arguments that institutions have a positive impact on energy efficiency. For instance Ref. [26] observed that greater independence of the judiciary system, better bureaucracy quality, and stricter corruption controls seem to reduce energy intensity emissions. Ref. [61] examined governments role in saving energy in the Chinese iron and steel industry and found it to be effective. In sub-Saharan Africa (SSA), Ref. [62] observed that the quality of institutions significantly promotes good environmental outcomes. Ref. [25] observed that improving institutional quality improves the productivity of the countries and also contributes to the energy efficiency improvements in China. Ref. [22] explored the impact of government efficiency on energy efficiency and found a connection between government efficiency and energy efficiency. Ref. [63] finds judiciary independence important in the implementation of energy policy in Gulf Cooperation Council (GCC) countries. Ref. [24] explore the effect of democracy on carbon emissions and energy efficiency and their finding suggests an improvement of energy-efficient outcomes from the enhancement of democratic institutions.

However, some have concluded that institutions do not present a positive effect on environmental and energy efficiency improvement. For example, Ref. [23] investigate institutional quality (proxy as corruption) and the energy-environment-growth nexus and their findings suggest that trying to reduce corruption may be a relatively inefficient way of increasing energy efficiency and reducing emissions. Ref. [64] explore whether political institutions can moderate the energy-saving effects of bank performance and their results demonstrate that a democratic environment marked by a strong interest group can undermine the energy-saving position of improved banking performance. Ref. [65] and Ref. [20] suggest that, as a result of broken institutions, poor infrastructure, poor regulatory systems, and entrenched corruption, it is difficult for Cameroon and Nigeria to escape an energy-inefficient state. Ref. [28] disclosed that clean energy consumption is hindered by rent-seeking and corruption. Ref. [29] studied the influence of democratic institutions on energy intensity of well-being and observed that democracy does not appear to improve energy intensity. Ref. [66] found that non-democratic government tend to provide access to public goods, like energy infrastructural at levels far below the democratic institutions. Sharing the same view, Ref. [67] observed that democratic institutions perform better comparatively than autocratic government when it comes to energy and environmental policies. However, some studies are more skeptical of these results [68].

This lack of consensus in the above studies may be the consequence of the differences in the institutional proxy used or the small set of institutional variables selected. Though the previous studies have made a major contribution to the understanding of institutional determinants for improving energy efficiency, they have mainly focused on limited number of basic institutional factors such as judiciary independence, government size democracy, and corruption on energy intensity. Also, in most cases, the energy efficiency used in the above studies is the conventional energy efficiency measures such as energy intensity which regard energy as the single input that produces GDP and neglect other key inputs like capital and labor. Thus, unlike the previous studies we measure institution using the World Economic Freedom (EFW) Index which covers both political and economic institutions. These include government size, legal system and property rights, sound money, freedom to trade internationally, and regulation of credit, labor, and business. With this in view, our study intends to ask the following questions: Does the difference in institutions across countries have any implications for the energy efficiency improvement? Does improved institutional arrangement help in reducing energy intensity?

2.2. *Energy efficiency - institutions diffusion nexus*

It is evident from the above literature that institutions have a significant influence on energy and environmental efficiency of a country, but they can also affect institutions of their neighbors simultaneously. This mechanism, which can be called the spatial institutional spillover effect, links the energy efficiency performance of countries together.

Countries are not independent of each other because technological transfers, diffusions of knowledge, labor migrations and contagious economic crises are daily occurrences. Thus, countries interact with each other and are in fact spatially dependent. It could therefore be argued, of course, that institutionally similar countries might have a higher tendency to engage with one another, and finally achieve comparable environmental and energy efficiency and greater interaction. For example, solid guidelines from institutions in a country can compel companies in a country and neighboring countries to control their energy consumption and CO_2 emissions. Institutional quality may therefore be seen as an input in support of sound legislation that reduces global environmental and energy inefficiency.

The institutional quality of a country may impact the institutional quality of a neighboring country, which subsequently affects their implemented energy regulations. Institutional spillovers across countries may occur for a variety of reasons. When governments compete for foreign direct investments or external opportunities, they may change their policies to entice foreign companies into their economy resulting in institutional change [49]. Similarly, multinational companies may engage in policy reforms in order to bring domestic laws into conformity with common principles leading to neighboring countries where these multinational firms reside passing similar policies and having similar institutions. Also, international coordination of standards, such as those members within the European Union, may also spur harmonizing institutional quality across neighboring countries. Finally, imperialist nations can endeavor to impose their institutions or policies on neighboring nations, be it by peaceful or violent means [50]. Refs. [50,51] empirically identify such institutional spillover effects across neighboring countries.

Ref. [53] estimate an empirical model of spatial institutional spillover effects on carbon dioxide (CO_2) emissions. They hypothesize that institutional quality of a country may impact the quality of institutions of neighbors and their resulting environmental quality. Using a panel data of CO_2 emissions from 129 countries from 1980 to 2007, they conclude that institutional spillovers represent a major factor in determining neighboring pollution intensity. Ref. [47] examine the impacts of own and neighboring institutional quality as well on environmental regulation stringency in own country. Using the Spatial Panel Durbin model, they find no evidence that strategic environmental regulations implemented by a neighbor have significant impact on environmental regulations implemented in the own country.

Similarly, in the context of energy efficiency, one of the objectives of this paper is to empirically examine whether improved institutional arrangement in neighboring countries impact the quality of a country's own institutions, thereby improving energy efficiency. With this objective, we ask the following questions. First, we ask, does spatial spillover effect of institutional quality exist? If they do, how much can they explain the energy efficiency level of a country?

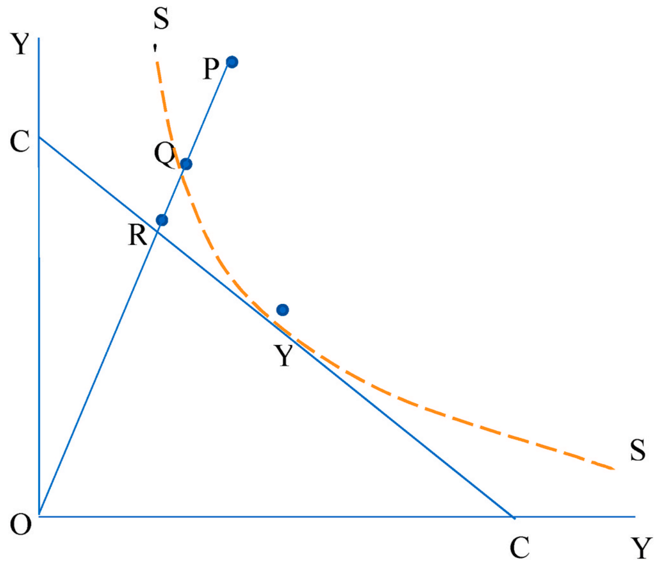

Fig. 1. An illustration of technical and allocative efficiencies, based on Farrell (1957).

3. Theoretical framework, methodology and variable definition

3.1. Theory and methods of energy efficiency estimation

The ***standard economic theory*** posits a production function that assumes that economic agents such as individuals, households, and firms are rational enough to produce output efficiently, that maximize output given existing technology and inputs in place or combine inputs in an ideal manner with regards to available prices and technology to minimize the cost of production or finally to maximize the profit given the current technology as well as the input and output prices. Even though these are reasonable assumptions, the notion of optimization for various reasons might not always be achieved thus the ***efficiency theory*** attempts to extend the traditional economic theory and suggests that economic agents may be technically or allocatively inefficient or both, in production decisions. Technical inefficiency shows how much inputs can be saved for a given level of output. The allocative inefficiency indicates how efficient inputs are put together to minimize cost and maximize profit.

The theory of efficiency goes back at least to Ref. [69] who initially challenges the viewpoint of optimization within the standard economic theory. But, it was Ref. [70] groundbreaking research on estimation of a frontier production function that brought the frontier analysis to the fore. Ref. [70] being the first to empirically estimate productive efficiency, describes efficiency in an input-orientation framework. Motivated by the works of Refs. [70–72] introduced cost efficiency measures, decomposing them into two. i.e. technical and allocative. Ref. [70] suggested that to increase efficiency, firms can either optimally increase their output given the level of inputs without absorbing additional resources (technically efficient) or optimally combine input in terms of prices and marginal productivities (allocative efficiency).

To illustrate the above, Ref. [70] introduced the *'efficient isoquant'* method of productive efficiency measurement by assuming a production technology with constant returns to scale (CRS). This idea of efficiency was demonstrated in the form of a simple case involving a firm that uses two inputs (x_1 and x_2) to produce one output (Y). Therefore, as shown in Fig. 1, the curve SS' symbolizes the unit isoquant of an efficient firm to enable the estimation of technical efficiency. The isoquant line is therefore the minimum input or cost required to produce a unit of output.

In Fig. 1, when the firm combines certain quantity of inputs to generate a volume of output above the isoquant line at point P, the firm is said to suffer from technical or allocative inefficiency. Thus, technical efficiency is generated when the input combination occurs along the isoquant line. Ref. [70] defined technical efficiency as the ratio of the distance from origin O to technical efficient combination of input Q and the distance from the origin O to the combination of input P. In other words, technical efficiency defined as $\frac{OQ}{OP}$. A firm can reduce the quantity of input while producing at the same level of output by decreasing the inputs used from P to Q.

In the case of allocative efficiency, it involves the appropriate input choices with respect to prices of input and output level. Therefore, the isocost CC line measures the minimum cost needed to produce a level of output associated with the isoquant. Therefore, the input combination that reduces costs is defined at point Y where the line of isocost is tangential to the isoquant line. Again, Ref. [70] defined allocative efficiency of a firm as the ratio of distance from origin O to allocative efficient combination of input R and the distance from origin O to technical efficient combination of input Q. In other words, allocative efficiency is defined as $\frac{OR}{OQ}$. By switching from Q to R, an allocative efficient firm will produce the same amount of output at a lower cost.

In summary, technical efficiency indicates the comparing actual to maximum output, whereas allocative efficiency compares the minimum cost to actual input cost. They work together to define the possibility to reduce the cost of generating a certain level of output. Thus, total or cost efficiency is the product of allocative and technical efficiency and that gives the ratio of the distance from the origin O to the combination of input R and the distance from the origin O to combination of input P. In other words, total or cost efficiency is defined as $\frac{OQ}{OP} \times \frac{OR}{OQ} = \frac{OR}{OP}$. All three measures are bounded by the value of zero and one. A value of one suggests that the firm is fully efficient.

Since the seminal work of [70], the estimation of frontier production function is quite a complicated task as it involves different broad methods. Among all the approaches for measuring efficiency, two main approaches stand out. The first is the non-parametric Data Envelopment Analysis (DEA) which was originally presented by Ref. [73] and the second is the parametric Stochastic Frontier Analysis (SFA) and independently suggested by Refs. [74,75]. The parametric SFA approach concentrates on economic optimization, while non-parametric DEA techniques focus on technical optimization. Each approach has its advantages and drawbacks, and therefore the decision to use any of them requires a tradeoff.

In the case of SFA, it enables the residual to be decomposed in two terms: statistical noise and the effect of inefficiency. Therefore, the main advantage of the SFA is the ability to measure efficiency, while simultaneously controlling for the presence of statistical noise. However, as a shortcoming, it needs a certain functional form a priori that defines the shape of the efficient frontier, and a probability distribution for efficiency levels. The function form selected presents inductive bias in the stochastic process and, where the shapes are not compatible with the data, may cause significant degradation of the results. The DEA on the other hand avoids such misspecification errors because it is not based on assumptions about the shape of the efficient frontier nor distribution of probability. The DEA, therefore, does not account for random errors in estimation, such that any deviation is deemed inefficiencies. For this reason, the DEA performs a deterministic frontiers analysis that appears to suggest that there are no statistical foundations. In all, neither approach seems to be better than the other and the decision to select one strategy at the cost of the other is a challenging task. The parametric SFA approach is however employed in this research because the SFA approach is more appealing to study energy efficiency when modeling unobserved heterogeneity in the production of energy service [31].

3.2. Methodology and data definition

Here, we first explain how the dependent variable, energy efficiency is calculated using the stochastic frontier analysis (SFA). Next, we provide the econometric model for spatial analysis.

Using the productivity measure model, we constructed the stochastic panel data model using inputs of capital stock (Cap), labor (Lab) and energy use (Ene) and Gross Domestic Product (GDP) as output. The model is as follows:

$$\ln GDP_{ct} = \beta_o + \beta_1 \ln Cap_{ct} + \beta_2 \ln Lab_{ct} + \beta_3 \ln Ene_{ct} + \mu_c + \varepsilon_{ct} \tag{1}$$

where $\ln GDP_{ct}$ is the natural log of real GDP figures at current Purchasing Power Parities (PPPs) (i.e. in US$ as at 2011) of country **c** (c = 1,2, 3 …. ,N) at time, *t* (t = 1,2,3, …,*T*), $\ln Cap_{ct}$ is the capital stock input converted into a natural logarithm at current PPPs (in US$ as at 2011), $\ln Lab_{ct}$ is the labor force calculated in the natural logarithm of number of persons working in a country in a given year, $\ln Ene_{ct}$ is energy consumption converted into natural logarithm. All data was extracted from Penn World Tables (PWT), except for energy consumption which is obtained from Energy Information Administration (EIA). μ_c is country c's error-term throughout all the time periods and ε_{ct} is the error component of country c at time *t*.

Using the two error terms, Ref. [76] differentiated between persistent and transient inefficiency. To this end, they began by splitting the fixed error-term μ_c into two, one part accounting for exogenous events affecting a country's energy use v_{oc} and the other denoting the inefficient part attributable to energy consumption u_{oc}.

$$\mu_c = v_{oc} + u_{oc} \tag{2}$$

Per definition, v_{oc} is the fixed country effect that captures time-invariant country's heterogeneity which should be controlled for. While, u_{oc} denotes the persistent inefficiency, of country c, which is fixed over time.

Also, the variable error-term ε_{ct} is divided into two, i.e. a random part which accounts for exogenous events affecting production is denoted as v_{ct} and an inefficient part to be attributed to errors in during the country's production is represented by u_{ct}.

$$\varepsilon_{ct} = v_{ct} + u_{ct} \tag{3}$$

So, per definition, $\mathbf{u_{ct}}$ changes over time and it is temporary. It therefore represents transient inefficiency of country **c**. Putting all together, the production function becomes:

$$\ln GDP_{ct} = \beta_o + \beta_1 \ln Cap_{ct} + \beta_2 \ln Lab_{ct} + \beta_3 \ln Ene_{ct} + v_{oc} + u_{oc} + v_{ct} + u_{ct} \tag{4}$$

There are now four different components in the error term. The first part of v_{oc} records the latent heterogeneity of energy use, which over time is constant. The second part u_{oc} captures the persistent time-invariant inefficiency of country c's energy use. The third part v_{ct} contains random shocks affecting the production in country c at each time t. The fourth component u_{ct} records time-varying inefficiency.

In the estimation, the first step is to calculate the value of $\boldsymbol{\mu_c}$ and $\boldsymbol{\varepsilon_{ct}}$ in equation (1). In the next stage, we use the predicted value $\boldsymbol{\varepsilon_{ct}}$ obtained in equation (1) to calculate the transient energy inefficiency $\mathbf{u_{ct}}$ in equation (3). Here, we assume that $\mathbf{v_{ct}}$ is a random noise i. i.d $N(0, \sigma_v^2)$ and $\mathbf{u_{ct}}$ is $N^+(0, \sigma_u^2)$. We estimate $\mathbf{u_{ct}}$ with a standard stochastic-frontier method. To this end, we attain the country's transient energy inefficiency $\mathbf{u_{ct}}$ using the stochastic-frontier method procedure. The transient energy efficiency (TEE) is calculated as in Ref. [77]; $TEE = \exp(\mathbf{u_{ct}} | \boldsymbol{\varepsilon_{ct}})$.

In the third step, we retrieve the country's persistent energy inefficiency. For this, we split the country fixed-effect $\boldsymbol{\mu_c}$ as in equation (2) in two parts, the country's latent heterogeneity $\mathbf{v_{oc}}$ and the country-specific persistent energy inefficiency $\mathbf{u_{oc}}$. Again, we assume that $\mathbf{v_{oc}}$ is a random noise i. i.d $N(0, \sigma_v^2)$ and $\mathbf{u_{oc}}$ is $N^+(0, \sigma_u^2)$. Following stochastic-frontier method, we predicted the country's persistent energy inefficiency $\mathbf{u_{oc}}$. The persistent energy efficiency (PEE) is also calculated as in Ref. [77]; $PEE = \exp(\mathbf{u_{oc}})$.

Lastly, the total energy efficiency (TOEE) is extracted as the product of the persistent energy efficiency and transient energy efficiency, that is $TOEE = PEE \times TEE$. Where total energy efficiency index is equal to one if the country is on the frontier and therefore considers to be energy efficient while an index less than one is below the frontier and is energy inefficient.

3.3. Spatial econometric model

Next, using the total energy efficiency index estimated above for each country, we assume that a country's energy efficiency is not just influenced by its own environmental factors, but also by the countries surrounding it. As governments and citizens learn from each other, a country's institution and policies may diffuse from one country to another. Thus, instead of relying on the results of the traditional panel econometric model, we adopt a spatial econometric model to explore the spatial spillover effects of institutional quality on energy efficiency.

In general, three spatial econometric models exist. These are spatial lag model (SLM), spatial error model (SEM) and spatial Durbin model (SDM). Since the SDM is able to capture spatial correlations between the dependent variable and the spillover effects of the explanatory variables [78], we went ahead to adopt the SDM to assess the effect of institutional quality on energy efficiency. Besides, with this model, the total effect of the independent variables can be broken down into direct and indirect effects [79], which is important in this study.[1] To be specific, the SDM consists of a spatial lag both of the dependent variable and the explanatory variables. The dependent variable's spatial lag is introduced in order to capture energy efficiency dependence between countries, while the spatial lag of the independent variables is incorporated to measure the impact on other countries' environmental factors (such as institutional quality) on neighboring country's energy efficiency. The panel SDM specification is therefore specified as follows:

$$TOEE_{ct} = \rho \sum_{j=1}^{N} W_{cj} TOEE_{jt} + X\beta + \sum_{j=1}^{N} W_{cj} X_{jt} \gamma + \mu_c + \varepsilon_{ct} \tag{5}$$

where $TOEE_{ct}$ is the total energy efficiency index for the $\mathbf{c_{th}}$ country (c = 1 … N) at time t (t = 1 … T), $WTEI = \sum_{j=1}^{N} W_{cj} TOEE_{jt}$ denotes the effects of the dependent variables' $TOEE_{ct}$ endogenous interaction with other dependent variables, $TOEE_{jt}$ in neighboring countries. $WX = \sum_{j=1}^{N} W_{cj} X_{jt}$ stands for the independent variable spatial lag terms, which allows us to assess the independent variables' spillover effect. $\boldsymbol{\rho}$ symbolizes the spatial autocorrelation coefficient, **W** represents the spatial weight matrix element, which is built from the inverse square distance between country **c** and **j**, which is normalized to have a row that sum to one,[2] **X** represents the independent variables, $\boldsymbol{\beta}$ are yet to be estimated unknown parameters and $\boldsymbol{\gamma}$ is the vector of the independent variables spatial autocorrelation coefficient. $\boldsymbol{\mu_c}$ stands for the country effect; and $\boldsymbol{\varepsilon_{ct}}$ represents the error component of country **c** and at time **t**.

As shown in equation (3), the coefficient of the independent variables and spatial lag of variables are in the model. However, as pointed out by Ref. [80]; in the regression model, the coefficients of the independent variables cannot reflect the marginal effect precisely. It is therefore misleading that the coefficients should be interpreted as the partial derivatives of the dependent variable with regards to the independent variables, since the coefficients also have spatial interaction effects. The correct analysis of the marginal effect is therefore rewriting the SDM with respect to each cross-section.

[1] According to Refs. [79,116]; in testing the hypothesis of whether spatial spillover exist or not, the decision should be based on the computed indirect effects of the independent variables instead of results from the corresponding regression results of the spatial lagged dependent and explanatory variables.

[2] We also consider other spatial weight matrix to test for robustness of our results.

$$E(Y)_t = (I_n - \rho W)^{-1}\mu + (I_n - \rho W)^{-1} + (X_t\beta + WX_t\gamma), \tag{6}$$

where I_n is an (n × n) identity matrix and the spatial multiplier matrix $(I_n - \rho W)^{-1}$ is equal to: $(I_n - \rho W)^{-1} = I_n + \rho W + \rho^2 W^2 + \rho^3 W^3 + \rho^4 W^4 + \ldots$. Thus, at a specific time in t, with regard to the explanatory variable kth, the matrix of partial derivatives of the dependent variable in the various units is:

$$\left[\frac{\partial E(Y)}{\partial x_{1k}} \cdots \frac{\partial E(Y)}{\partial x_{Nk}}\right]_t = \begin{bmatrix} \frac{\partial E(y_1)}{\partial x_{1k}} & \cdots & \frac{\partial E(y_1)}{\partial x_{Nk}} \\ \vdots & \ddots & \vdots \\ \frac{\partial E(y_N)}{\partial x_{1k}} & \cdots & \frac{\partial E(y_N)}{\partial x_{Nk}} \end{bmatrix}_t$$

$$= (I_n - \rho W)^{-1} \begin{bmatrix} \beta_k & W_{12}\gamma_k & \ldots & W_{1n}\gamma_k \\ W_{21}\gamma_k & \beta_k & & W_{2n}\gamma_k \\ \vdots & \vdots & \ddots & \vdots \\ W_{n1}\gamma_k & W_{n2}\gamma_k & \cdots & \beta_k \end{bmatrix}$$

The matrix above can be symbolized by. $S = \frac{\partial E(Y)}{\partial x_{1k}} = (I_n - \rho W)^{-1}C$.

Therefore, the mean direct effect on Y of a unit change in x_k could be attained as the mean of the diagonal elements of matrix S. Mathematically, it can be denoted as:

$$\overline{M}(k)\text{direct} = \frac{1}{n}\sum_{i,j}^{n} \frac{\partial E(y_i)}{\partial x_{ki}} = \frac{1}{n}\ \text{trace}\left[(I_n - \rho W)^{-1} l_n \beta\right] \tag{7}$$

The mean total effects can be computed by averaging over all countries the addition of the rows or columns of matrix S. Mathematically, it can be denoted as:

$$\overline{M}(k)\text{total} = \frac{1}{n}\sum_{i,j}^{n} \frac{\partial E(y_i)}{\partial x_{ki}} = \frac{1}{n} l_n\left[(I_n - \rho W)^{-1} C\right] l_n \tag{8}$$

The average indirect impacts are also estimated as a difference between the total and direct impacts. Mathematically, it can be denoted as:

$$\overline{M}(k)\text{indirect effect} = \overline{M}(k)\ \text{total effect} - \overline{M}(k)\ \text{direct effect} \tag{9}$$

3.4. Variable definition

As mentioned earlier, the dependent variable is total energy efficiency, which is estimated using the SFA model for 99 countries during the period of 1995–2016. The accessibility of reliable data on different proxies was the reason for considering 99 countries. In terms of the determinants of energy efficiency, our main explanatory variable, institutional quality along with four other control variables were considered in this paper. The reason and source of this selection are explained below:

3.4.1. Institutional quality

As a proxy for our main explanatory variable, institutional quality, we extracted data from the World Economic Freedom (EFW) Index. These sorts of data are commonly used for assessing institutional efficiency (e.g. Refs. [81–83]). It is cooperatively published by Fraser and the Cato institutes. It is a very comprehensive measure for evaluating a country's institutional and its levels of economic freedom and policies, which began in the 1970s to date. We put together five different groups or sub-groups to evaluate the quality of institutions. These are government size, legal system and property rights, sound money, freedom to trade internationally, and regulation of credit, labor, and business. In those five sectors, there are 24 components with various sub-components, which give rise to a total index of 42 variables. For a full index for all countries, the Fraser institute uses a scale of 0–10 per category to calculate the average of these five indices: 0 is the lowest institutional quality and 10 is the highest institutional quality. There are data for every five years between 1970 and 1995. However, there are yearly data for each country from 2000 to 2016. As our sample data began in 1995, we computed the missing data for 1996–1999 using real values for 1995 and 2000.

Table 1
Summary statistics of variables.

Variable	Mean	Std. Dev.	Min	Max
Ln (EEI)	−0.732	0.484	−2.382	−0.132
Ln (GDP)	25.839	1.744	22.464	30.532
Ln (Insti)	1.900	0.164	1.076	2.222
Ln (Serv)	3.960	0.237	2.691	4.520
Ln (Urb)	3.904	0.271	2.476	4.520
Ln (Indus)	3.316	0.369	1.904	4.349
Ln (Pop)	16.46	1.638	12.497	21.062

3.4.2. Economic growth

A country's economic growth determines its energy consumption pattern. Thus, energy consumption has been linked to economic growth. However, over the years, researchers have had diverse views on the role of economic growth and development in energy efficiency enhancement. Thus, as one of our control variables, we assume that it is likely for economic growth to influence energy efficiency either positively or negatively [3]. We obtain this variable from the Penn World Tables (PWT).

3.4.3. Service sector

To report for the influence of economic structure on energy efficiency, we assume that changing the production structure to that which promotes less energy consumption reduces energy demand, thereby improving energy efficiency [84]. To capture this effect, we include the service sector (proxy as the measured by value added from the services sector as a percentage of GDP). As such, we assume that countries with larger proportion of its economy in the services sector tend to consume less energy than countries dominated by the industrial sector. Thus, we anticipate a positive relationship between the service sector and energy efficiency. The data for this variable is obtained from the World Development Indicators (WDI).

3.4.4. Industrial sector

Unlike the service sector, the industrial sector is one of the major factors, which determines the energy intensity level of a country [85, 86]. However, energy intensity can be reduced without an adverse impact on economic growth, provided the structure of the industry is adjusted appropriately [86]. Industrial structure is measured by the value added by the industrial sector (including construction) as a percentage of GDP and it is extracted from WDI. In contrast to the service sector, we expect the industrial structure to exhibit a negative effect on energy efficiency.

3.4.5. Urbanization and population growth

Next, we include urbanization and population into the model. In the literature, the effect of urban development on energy efficiency is mixed [87] meaning that the predicted impact of urbanization on energy efficiency is not clear, because the relationship can be positive [88] or negative [89,90]. The same story can be said of the predicted impact of population growth on energy efficiency, some found a positive relationship, e.g. Refs. [91,92] for low-income countries, while others found a negative relationship, e.g. Refs. [93,94] for middle-income countries. However, in this study, we anticipate a negative relationship for both variables, because increasing population coupled with rapid urbanization in most cases lead to a rise in energy consumption globally. Production of sufficient goods and services to meet the increasing demands of additional people in a country, calls for the expansion of present or creating new facilities. All these require huge energy consumption, which may ultimately lead to an increase in energy intensity. Table 1 presents descriptive statistics and their symbols for these variables.

Table 2
Average estimates of persistent, transient and overall energy efficiency.

Countries (economies)	Transient	Persistent	Total
United States	0.944	0.908	0.858
Saudi Arabia	0.935	0.904	0.847
Turkey	0.942	0.877	0.829
Egypt	0.944	0.874	0.826
Germany	0.944	0.865	0.817
Italy	0.941	0.866	0.816
France	0.943	0.858	0.809
Norway	0.941	0.856	0.806
Japan	0.945	0.852	0.806
United Kingdom	0.944	0.846	0.799
United Arab Emirates	0.944	0.835	0.789
Spain	0.943	0.830	0.783
Iran	0.941	0.825	0.778
Switzerland	0.945	0.818	0.773
Mexico	0.942	0.820	0.773
Algeria	0.944	0.799	0.755
Qatar	0.937	0.802	0.753
Brazil	0.940	0.798	0.752
Australia	0.944	0.789	0.745
Ireland	0.944	0.785	0.741
Netherlands	0.943	0.763	0.720
Poland	0.939	0.754	0.708
Canada	0.944	0.745	0.703
Pakistan	0.945	0.737	0.697
Hong Kong	0.943	0.730	0.688
Denmark	0.945	0.720	0.681
Austria	0.942	0.711	0.670
Korea, Rep.	0.942	0.708	0.668
Chile	0.944	0.699	0.660
India	0.944	0.698	0.660
Belgium	0.943	0.699	0.659
Russia	0.933	0.693	0.646
Singapore	0.945	0.683	0.646
Nigeria	0.945	0.682	0.645
Argentina	0.943	0.681	0.643
Colombia	0.944	0.680	0.643
Venezuela	0.934	0.681	0.638
Brunei Darussalam	0.931	0.672	0.627
Sweden	0.943	0.662	0.625
Malaysia	0.944	0.661	0.624
Gabon	0.899	0.690	0.623
Sri Lanka	0.946	0.650	0.615
South Africa	0.943	0.647	0.611
China	0.937	0.636	0.596
Jordan	0.944	0.621	0.587
Israel	0.945	0.609	0.575
Romania	0.941	0.610	0.574
Greece	0.939	0.607	0.570
Portugal	0.942	0.592	0.558
Philippines	0.943	0.584	0.550
Hungary	0.943	0.579	0.546
New Zealand	0.943	0.572	0.540
Panama	0.945	0.572	0.540
Finland	0.943	0.571	0.539
Morocco	0.943	0.558	0.526
Peru	0.943	0.550	0.520
Tunisia	0.943	0.543	0.512
Dominican Republic	0.945	0.529	0.500
Thailand	0.945	0.524	0.495
Bangladesh	0.945	0.521	0.492
Costa Rica	0.945	0.497	0.469
Guatemala	0.939	0.495	0.465
Ecuador	0.945	0.488	0.461
Uruguay	0.945	0.482	0.455
Botswana	0.941	0.466	0.441
Bulgaria	0.944	0.462	0.437
Congo, Rep.	0.932	0.455	0.424
Cyprus	0.944	0.440	0.415
Namibia	0.941	0.438	0.412
Angola	0.938	0.431	0.404
El Salvador	0.941	0.415	0.391
Mauritius	0.942	0.415	0.391
Bahrain	0.933	0.417	0.389
Vietnam	0.946	0.411	0.389
Malta	0.946	0.402	0.380
Bolivia	0.944	0.386	0.364
Trinidad and Tobago	0.935	0.376	0.354
Albania	0.939	0.374	0.351
Luxembourg	0.945	0.355	0.335
Paraguay	0.947	0.345	0.327
Kenya	0.945	0.335	0.316
Senegal	0.944	0.331	0.312
Ghana	0.942	0.309	0.291
Cameroon	0.945	0.307	0.290
Honduras	0.944	0.299	0.282
Jamaica	0.930	0.295	0.274
Mongolia	0.943	0.279	0.263
Nicaragua	0.946	0.268	0.254
Tanzania	0.945	0.262	0.247
Iceland	0.943	0.259	0.244
Zambia	0.935	0.251	0.235
Nepal	0.945	0.223	0.211
Benin	0.945	0.198	0.187
Haiti	0.932	0.187	0.174
Ethiopia	0.938	0.170	0.159
Mozambique	0.937	0.146	0.137
Congo, Dem. Rep.	0.941	0.139	0.130
Togo	0.941	0.134	0.126
Zimbabwe	0.926	0.120	0.111
Average	0.942	0.563	0.530

4. Empirical Analysis and discussion of results

4.1. Discussion of results for energy efficiency

The 1995–2016 annual average persistent, transient and total energy efficiency index for all 99 countries are summarized in Table 2. For total energy efficiency, as can be seen, there is a significant difference in the level of energy efficiency across countries. The average total energy efficiency score is 53%, which varies from 11% to 86%. Of the 99 countries understudied, 53 of them lie above the mean score while 46 are below. Countries like the United States, Saudi Arabia, Turkey, Egypt, Germany, Italy, France, Norway, Japan, the United Kingdom and United Arab Emirates (UAE) lie extremely above the overall efficiency average. Several of these countries are high-income and developed countries. For instance, countries like the United States, Germany, Italy, France, Norway, Japan and the United Kingdom are characterized by better technology, high economic development and high education level. Also, such countries as Saudi Arabia, Egypt and UAE are among the leading oil-producing countries with an abundance of oil resources, with a high per capita income. Furthermore, in these areas, oil quality is much better.

In contrast, from Table 2, countries like Nicaragua, Mongolia, Ghana, Cameroon, Honduras, Senegal, Iceland, Tanzania Benin, Nepal, Haiti, Zambia, Ethiopia, Mozambique, Congo, Rep., Togo and Zimbabwe with a comparatively low economic growth level, lie extremely below the overall efficiency average. This shows that in these countries, demand is much more than the required energy input for production activities indicating high inefficiency. Ref. [95] explained, however, that with rapid economic growth and developments in energy technology, these countries have greater potential for energy conservation.

Regarding the estimates for persistent and transient energy efficiency, as anticipated, the estimates for persistent efficiency, on average is 56%, which is far lower than the 94% average estimate for transient energy efficiency [96]. A low average persistent efficiency of 56% means the use of inefficient technology is more prevalent globally, except for countries like the United States, Saudi Arabia, Turkey, Egypt, Germany, Italy, France, Norway, Japan, United Kingdom, United Arab Emirates, Spain, etc. For the other countries, especially those whose efficiency index lies extremely below the average index, they will have their energy efficiency to be relatively low over time unless governments modify

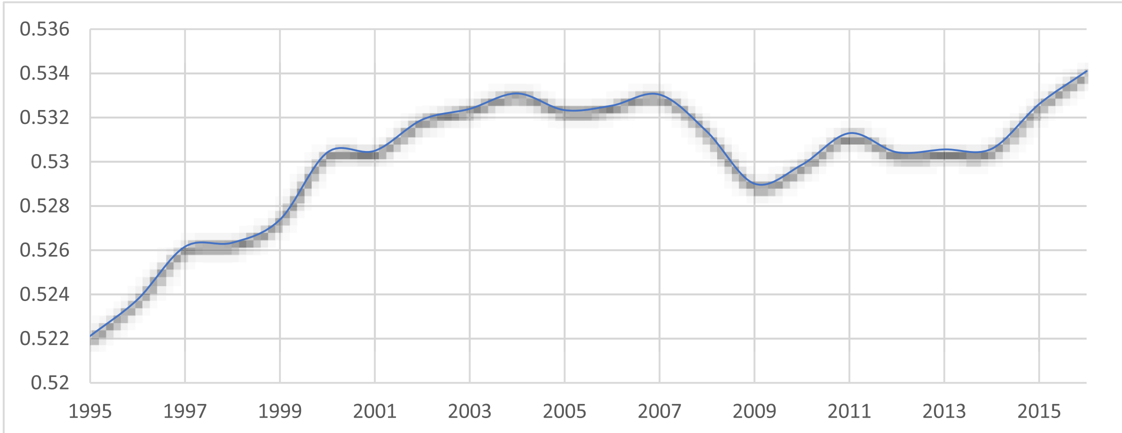

Fig. 2. Time trend in total average energy efficiency.

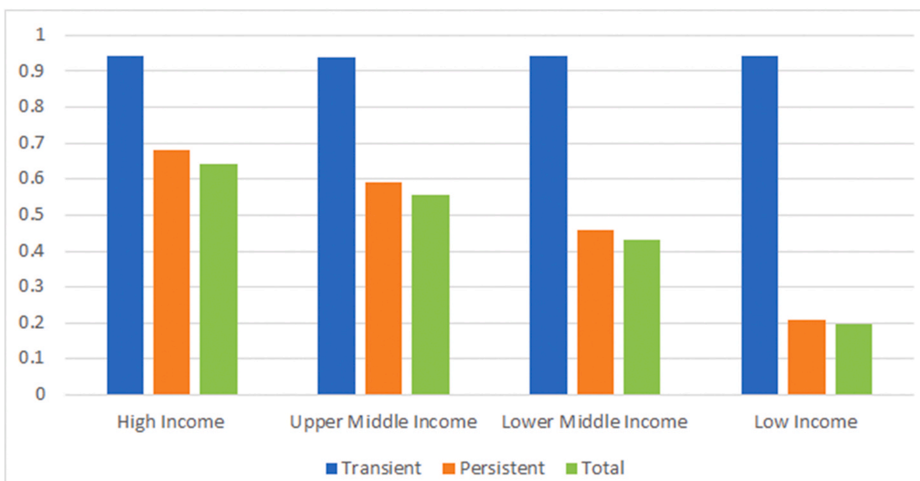

Fig. 3. Energy efficiency performance by income levels.

their energy or environmental policies. That is, energy security and carbon emissions reduction in these economies' can only be addressed by long-term policies rather than from short-term policies. The level of persistent efficiency here (i.e. from a global perspective) is higher than those estimated by Ref. [84] for African countries (16%). Unlike persistent energy efficiency, a high transient efficiency score of 94% suggests that globally countries on average, gradually progresses toward the benchmark technology in the short term.

In terms of time, globally the trend has been increasing from 1995 to 2007, decreased from 2007 to 2009, and slowly increasing thereafter (Fig. 2). The increase in efficiency between 1995 and 2007 may be influenced by emphasis played on climate change mitigation policies all around the world. The decrease, on other hand, between 2007 and 2009 would have been influenced largely by the 2007/08 global economic crunch, due to the weakening of economies across the globe with excessive use of inputs for the production of specific level of output. However, the increase after 2009 may be due to the recovering of some economies.

To examine the energy efficiency index further and following the world bank income classification, we group the 99 countries into four income groups, that is high, upper middle, lower middle and low income. As can be seen in Fig. 3, the results for high income group are the highest, followed by the upper middle income and the least being the low-income group. This is highly anticipated because the high-income countries have highly developed economies with cutting-edge technology and industries.

In contrast to the high-income countries, the other income groups are characterized by lower economic growth and poor infrastructure. However, with the rapid growth of their economy and development of energy technology, the upper middle, lower middle, low income groups have a greater potential for energy conservation than the high-income group [95]. Thus, from Fig. 4, the upper-middle income, lower-middle income, and low-income groups seem to have an efficiency index rising faster than the high-income group.

Again, following the world bank regional classification, we group these countries into seven regions (i.e. Latin America and the Caribbean, Middle East and North Africa, North America, South Asia, Sub-Saharan Africa, East Asia and Pacific and Europe and Central Asia) to examine energy efficiency performance from regional perspective. As seen in Fig. 5, as expected, Europe and Central Asia, which comprises of high income countries leads the chart, followed by North America and the least being Sub-Saharan African.

4.2. Spatial analysis

Before we proceed with the spatial analysis, we did some preliminary tests on the variables, for example, unit root test, cross sectional dependence test and co-integration test to ensure that the above models were properly specified. See appendix for details.

4.2.1. Global spatial autocorrelation test

In carrying out spatial analysis, we first examined if energy efficiency

Fig. 4. Time trend in total energy efficiency performance by income levels.

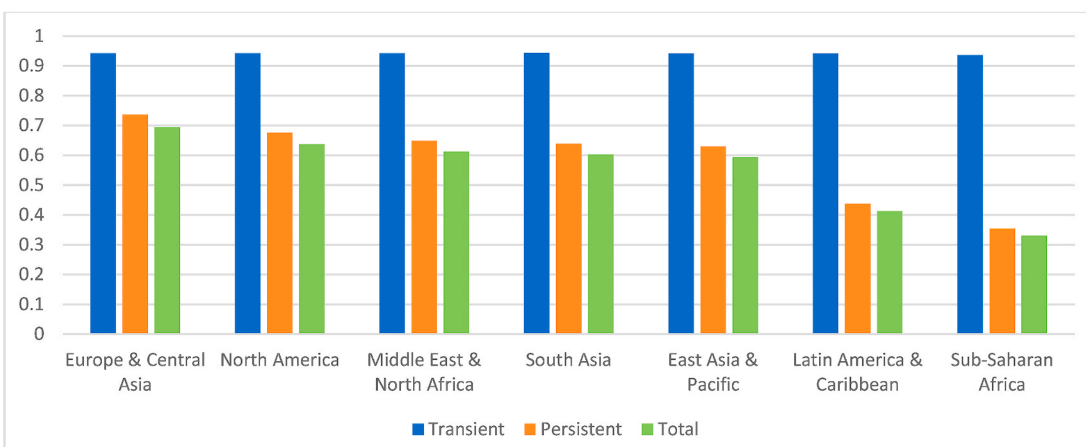

Fig. 5. Energy efficiency performance from regional levels.

Table 3
Value of Moran's I global spatial autocorrelation.

Years	Morans I	p-value*	Years	Morans I	p-value*
1995	0.328	0.000	2006	0.324	0.000
1996	0.325	0.000	2007	0.328	0.000
1997	0.326	0.000	2008	0.327	0.000
1998	0.329	0.000	2009	0.328	0.000
1999	0.331	0.000	2010	0.328	0.000
2000	0.329	0.000	2011	0.328	0.000
2001	0.327	0.000	2012	0.326	0.000
2002	0.325	0.000	2013	0.327	0.000
2003	0.324	0.000	2014	0.328	0.000
2004	0.325	0.000	2015	0.326	0.000
2005	0.327	0.000	2016	0.325	0.000

in the sample countries is spatially auto-correlated using the Moran I test. We used the Moran's I to study the depth of spatial autocorrelation. A Moran's I of a significant positive figure points to spatial clustering while a significant negative figure denotes spatial dispersion in the countries. Using the estimated energy efficiency index for the 99 countries, for each year between 1995 and 2016, we computed the Moran I index figure. From the results in Table 3, the value of the Moran's index is greater than zero, so we can conclude that the global energy efficiency exhibits positive spatial auto-correlation. The value of the Moran's I is always positive and at 1% significant level. This result means high energy efficiency countries are surrounded by countries with high energy efficiency, and low energy efficiency areas are surrounded by countries with low energy efficiency. Furthermore, the indices range from 0.324 to 0.329 as a result of the changing trend in Moran's I index. This insignificant change in the Moran's I indices makes us conclude that the

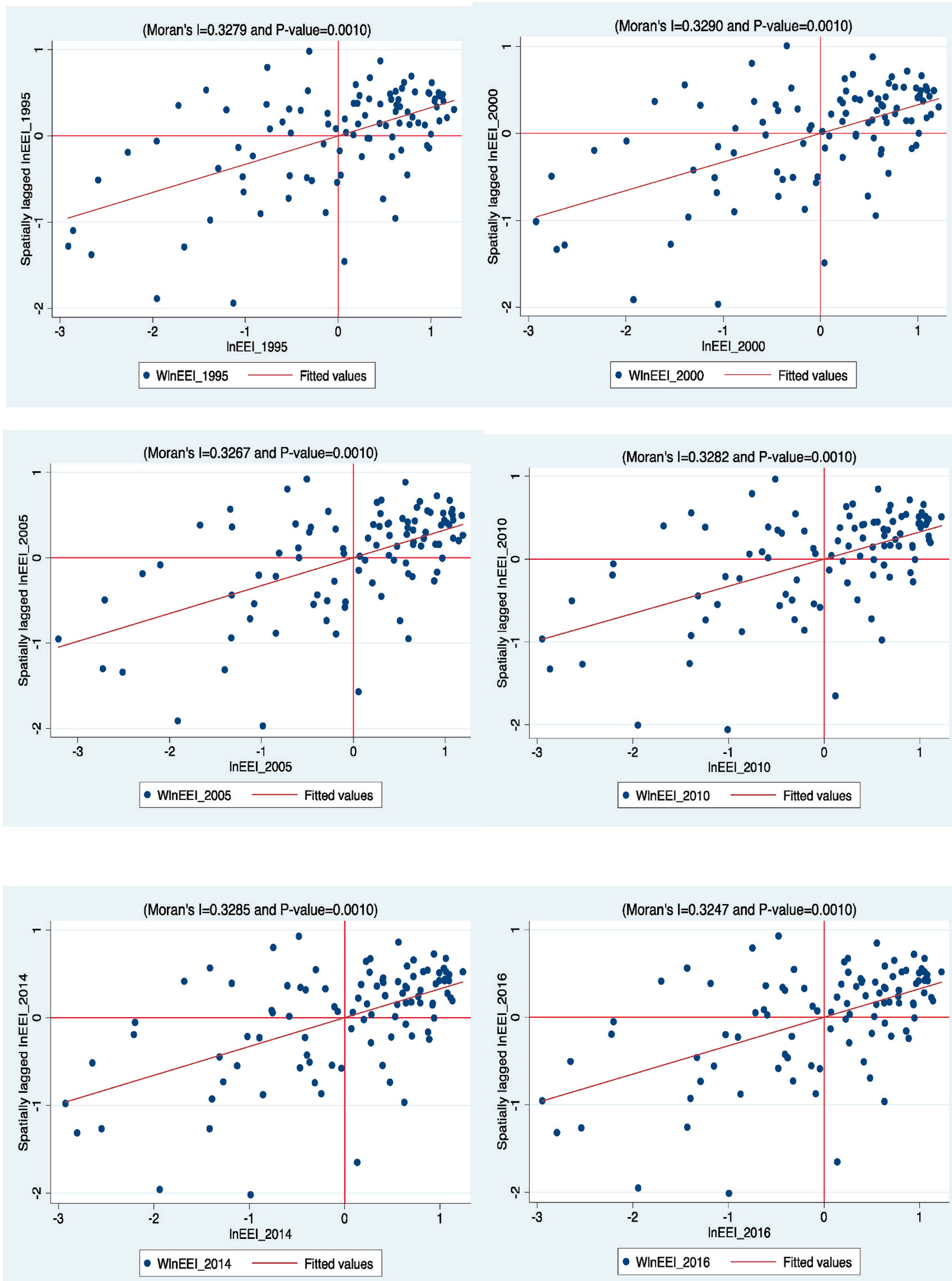

Fig. 6. Moran I scatter plot of energy efficiency.

global spatial agglomeration impact has been stable in energy efficiency.

In as much as Moran I test can show that there are spatial correlations, it also has certain limitations. The Moran I test, for example, can only provide the total average correlation. But when a positive spatial autocorrelation is found in certain countries and in other countries a negative spatial autocorrelation, the effects can be mutually annulled [47]. The Moran I Index becomes zero in this case and exhibits no spatial autocorrelation. On this note, we adopt a Moran's I scatterplot analysis to further test for spatial dependency. For brevity, we use data for the year 1995, 2000, 2005, 2010, 2014 and 2016 to show the Moran's I scatter plots of energy efficiency index and this is reported in Fig. 6. Each dot in the figure denotes a country's energy efficiency performance. The red diagonal line in the figure is Moran's I global test regression line and its slope constitutes the test statistics.

The Moran's I scatter plots shows the spatial clustering characteristics via four main quadrants. The 1st quadrant on the upper right shows the region where high-value countries are close to other countries with high-value (i.e. High-High values). The 2nd quadrant on the upper left

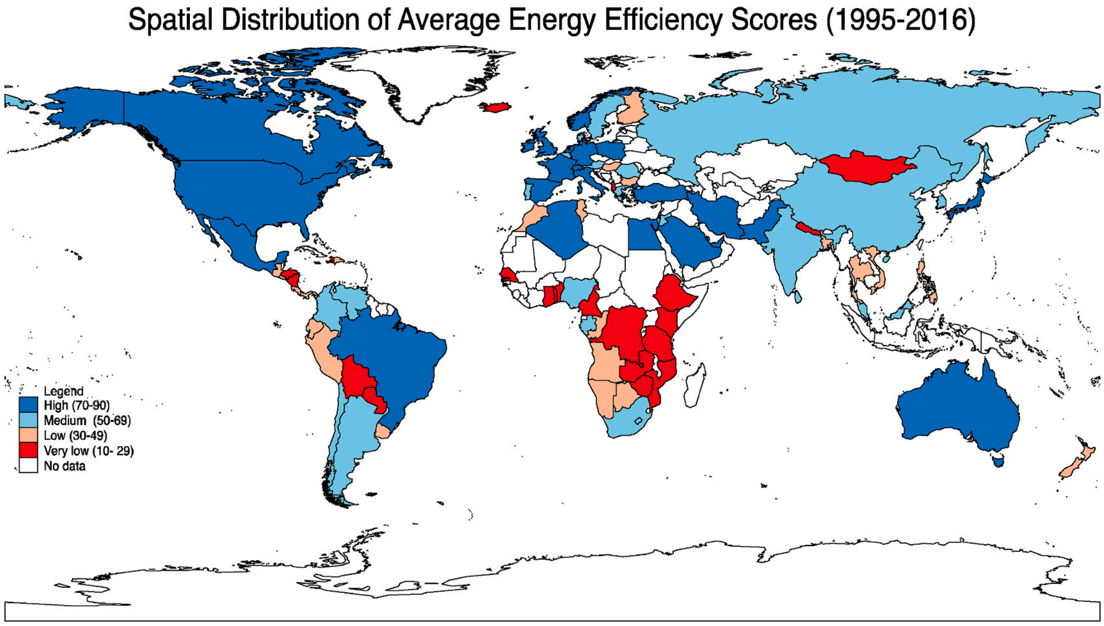

Fig. 7. Spatial distribution of energy efficiency. Notes: the natural log of the arithmetic mean of the energy efficiency is employed here.

displays the region where a low-value country is interacting with high-value countries (i.e. Low-High values). The 3rd quadrant on the lower left shows the territory where a low-value country is close to other low-value countries (i.e. Low-Low values). The 4th quadrant on the lower right shows the region where a high-value country is interacting with low-value countries (i.e. Low-High values).

In the 1st and 3rd quadrants, the observations of the Moran's I scatter plot have spatial cluster characteristics, meaning countries with similar features are located with each other. However, observations in the 2nd and 4th quadrants, have spatial heterogeneity, suggesting that their characteristics are different from those of their surroundings.

From Fig. 6, the countries are located mainly in the first and third quadrants, with relatively some countries in the 2nd and 4th quadrants. Therefore, these findings show that global energy efficiency is characterized by spatial heterogeneity as well as spatial clustering, with the dominant feature being the spatial clustering. That is to say, the energy efficiency of the world differs not only in its efficiency but also in relation to the efficiency correlation between the countries adjacent to it. Furthermore, countries with like energy efficiency levels tend to form a cluster, with neighboring countries with the same efficiency level. In conjunction with the spatial energy efficiency distribution in Fig. 7, we can conclude, in the interim, that countries with the same energy efficiency levels tend to cluster, particularly those with like values. As a result, we went ahead to examine spatial econometrics models and select the suitable model for the analysis.

4.2.2. Spillover effects results

Here we present empirical estimates of the spillover effect of institutional quality on energy efficiency by estimating the specifications of Equation (5). We started with the spatial Durbin Model (SDM).[3] But to use the SDM, first, we select the most appropriate model by estimating both the random effect (in model 1) and fixed effect (in model 2) of the SDM in order to establish a robust conclusion. To do so, we adopted the Hausman test to choose between the two models. While, the results, in terms of signs and values, are quite similar for both the fixed and the random effect models, the Hausman test results reject the random effect model with a significant level of 1%. Since it is possible to simplify the SDM model to either the spatial lag or the error model, we test this hypothesis by using the Wald test. Therefore, the hypothesis of simplifying the SDM model to the lag model is rejected with a test statistic of 330.68 and a p-value = 0.0000. For the error model, it is rejected with a test statistic of 193.18 and a p-value = 0.0000. The rejection of both the spatial error and the lag models, suggests that we should use the SDM model. So, we went ahead to adopt the SDM. In model 3, we also check whether the model regression results are robust considering the time lag effect.

As indicated in Table 4, the coefficient of the spatial effect of energy efficiency is positive and significant, which means there is spatial dependence in energy efficiency, where a percentage rise in energy efficiency of the adjoining regions will contribute to a 0.22% energy efficiency improvement in own country. This implies that breaking down the world's targets for reducing energy intensity into smaller targets for individual countries can help to increase global energy efficiency. With regards to the main explanatory variable-institutional quality, we note that the direct effect is significantly positive, which shows that a country's institutions has a significant positive effect on its energy efficiency performance. This is in line with the results of [22,82] who also found that institutions play a key role in enhancing energy efficiency.

Also, essential is an examination of other factors which influence energy efficiency. For example, the coefficients of industrialization are significantly negative at 1% significant level, thereby revealing a negative relationship with energy efficiency. This indicates that increasing industrial activity would reduce energy efficiency. These results are largely consistent with our forecast, since increasing industrialization in most cases increases excessive use of energy. Increasing industrialization will therefore requires more energy in order to support industrial activities. The direct negative effect of industrial activities on energy efficiency is established by some other studies (e.g. Refs. [92–94]). However, the services sector exhibits a positive relationship with energy efficiency, thus a 1%-point growth in the share of the services sector will reduce energy intensity by 0.0146%. Generally, the service sector consumes less energy. In consequence, a transition in economic structure to the service sector cuts overall energy needed for a country to carry out economic activities. This result is generally consistent with previous studies (e.g. Refs. [97,98]), given that, in contrast to the industrial sector, the service sector is more associated with less energy use [99].

[3] [79,116] advice to start with SDM and test for alternative models.

Table 4
Results from the Spatial Durbin models.

Variables	Model 1	Model 2	Model 3
	Spatial Random Effects Model	Spatial Fixed Effects Model	Space-and-time lag-fixed effects
W*Ln (EEI)	0.256***	0.222***	0.0934**
	(0.0341)	(0.0347)	(0.0452)
L.W*Ln (EEI)			0.280***
			(0.0586)
Ln (Insti)	0.0905***	0.0909***	0.0891***
	(0.00673)	(0.00659)	(0.00694)
Ln (Serv)	0.0141***	0.0146***	0.0137***
	(0.00491)	(0.00480)	(0.00486)
Ln (Indus)	−0.0178***	−0.0176***	−0.0187***
	(0.00393)	(0.00385)	(0.00395)
Ln (GDP)	0.115***	0.113***	0.111***
	(0.00380)	(0.00372)	(0.00388)
Ln (Pop)	−0.0565***	−0.0607***	−0.0589***
	(0.00717)	(0.00725)	(0.00733)
Ln (Urb)	−0.0481***	−0.0492***	−0.0480***
	(0.00931)	(0.00914)	(0.00940)
W*ln (Insti)	−0.0436***	−0.0379***	−0.0560***
	(0.0139)	(0.0136)	(0.0148)
W*ln (Serv)	0.0270***	0.0261***	0.0184**
	(0.00925)	(0.00905)	(0.00910)
W*ln (Indus)	0.0430***	0.0412***	0.0423***
	(0.00893)	(0.00874)	(0.00890)
W*ln (GDP)	−0.0409***	−0.0391***	−0.0507***
	(0.00728)	(0.00717)	(0.00798)
W*ln (Pop)	−0.0346***	−0.0304***	−0.0127
	(0.0115)	(0.0115)	(0.0120)
W*ln (Urb)	−0.0706***	−0.0720***	−0.0536***
	(0.0187)	(0.0183)	(0.0195)
lgt_theta	−4.535***		
	(0.0750)		
sigma2_e	0.000306***	0.000293***	0.000284***
	(9.53e-06)	(8.91e-06)	(8.41e-06)
R-Squared	0.725	0.732	0.767
Log-like	6776.41	6776.41	5585.36
Obs.	2178	2178	2079

Note: 1%, 5% and 10% significant level are indicated by * * *, * * and * respectively.

At 1% significant level, the GDP coefficient is positive. All else unchanged, a rise in economic growth by 1% increases energy efficiency by 0.113%, pointing to the fact that global economic growth may stimulate efficient use of energy, which is consistent with previous studies (e.g. Refs. [100–103]). As for the effects of urbanization on energy efficiency, the results show that a 1% increase in the urban population will cause a 0.049% reduction in total energy efficiency. Similarly, for the population coefficient, a rise in the world's population will cause a 0.0607% decrease in energy efficiency. This indicates that an increase in both urban population and actual population increase the costs of facilities to deliver energy service. This result is therefore similar to those of Ref. [104] and Ref. [105] who found a negative relationship between population density and energy efficiency. Ref. [106] also showed that urbanization increases residential energy consumption, while Ref. [107] found that urbanization increases production energy consumption during production.

As stated in Ref. [80], the SDM coefficients do not actually reveal the marginal effect of the explanatory variable on the dependent variables, we therefore reported the direct, indirect and total effect of the respective independent variable on energy efficiency. Here, the direct effect refers to the impact on energy efficiency in a particular country as a result of changes in the explanatory variables. The indirect effect on the other hand represents the impact, as a result of changes in neighboring countries' explanatory variables on their own energy efficiency. The addition of the direct and indirect effect is simply the total effect.

Table 5
Results for the direct and indirect effects.

Variables	Direct Effect	Indirect Effect	Total Effect
Ln(Insti)	0.0905***	−0.0226	0.0678***
	(0.00671)	(0.0165)	(0.0175)
Ln(Serv)	0.0154***	0.0362***	0.0516***
	(0.00465)	(0.0102)	(0.0115)
Ln(Indus)	−0.0160***	0.0470***	0.0309***
	(0.00371)	(0.0102)	(0.0113)
Ln(GDP)	0.113***	−0.0172**	0.0955***
	(0.00362)	(0.00736)	(0.00738)
Ln(Pop)	−0.0621***	−0.0554***	−0.118***
	(0.00694)	(0.0117)	(0.00976)
Ln(Urb)	−0.0518***	−0.103***	−0.155***
	(0.00893)	(0.0205)	(0.0206)

Note: 1%, 5% and 10% significant level are indicated by * * *, * * and * respectively.

Table 5 presents the direct, indirect and total effects of the respective explanatory variables on energy efficiency. The direct effects results are similar to the corresponding regression results in Table 4, but there is some variation in terms of their coefficient estimates. This is because of the feedback that occurs due to the effects passing through the neighbors and back to the observation itself. While part of these feedback effects is from the spatial lagged dependent variable coefficient, some are from the coefficient of the spatially lagged explanatory variables.

Beginning with our main independent variable-institutional quality, like in the corresponding regression, the direct effect results show a positive statistically significant effect. A 1% rise in institutional quality will directly cause a 0.0905% increase in energy efficiency because of the spatial aggregation. But, for the indirect effects, the coefficient is negative (−0.0226) but turns out to be statistically insignificant. This indicates that institutional quality has an insignificant spatial spillover effect in neighboring countries. However, from the perspective of the total effect, it is worth noting that the positive impact of institutional quality on energy efficiency effect surpass the negative and insignificant indirect effect, resulting in a total positive and highly significant effect. On a general note, this result indicates that being close to countries with better institutions has a positive outcome on energy efficiency of own country. It is worth noting in this sense that the quality of government institutions play an important role in reducing global energy intensity. A good institutional framework in the neighboring countries can therefore provide a favorable environment for adopting cooperative environmental policies that in turn will help improve energy efficiency while fostering economic growth.

Now turning to the control variables, for the service sector, a 1% growth will increase energy efficiency by 0.0154% directly while indirectly improving energy efficiency by 0.0362%, with an increase of 0.0516% in net effect. This result also suggests that being close to countries dominated by service sector positively impacts energy efficiency in their own country. This suggests that increasing economic activities in the service sector is one of the main drivers of energy efficiency. As for the industrial sector, 1% growth of the sector's share will increase the energy intensity directly by 0.016% while reducing it indirectly by more (0.047%) with an increase in the net effect by a 0.0309%. Therefore, optimization of the structure of industry is vital in promoting energy efficiency; promoting modern industrialization and service industry will significantly contribute to energy reduction [86]. For GDP, its impact on energy efficiency is positive with a negative spillover effect that amounts to 0.0172. As a result, 1% GDP growth will increase energy efficiency by 0.113% directly and lower energy efficiency by 0.0172% indirectly, with a total net effect growth of 0.0955%.

Table 6
Results the Direct and Indirect Effects using other spatial matrix.

Variables	K-4 nearest Distance			K-6 nearest Distance			K-8 nearest Distance		
	Direct Effect	Indirect Effect	Total Effect	Direct Effect	Indirect Effect	Total Effect	Direct Effect	Indirect Effect	Total Effect
lnInsti	0.0858***	−0.0532***	0.0325***	0.0843***	0.0418***	0.0425***	0.0854***	−0.0333**	0.0521***
	(0.00678)	(0.0111)	(0.0126)	(0.00678)	(0.0140)	(0.0150)	(0.00679)	(0.0169)	(0.0176)
lnServ	0.0240***	0.0548***	0.0788***	0.0202***	0.0692***	0.0894***	0.0210***	0.0769***	0.0978***
	(0.00470)	(0.00884)	(0.00975)	(0.00469)	(0.0120)	(0.0129)	(0.00470)	(0.0146)	(0.0158)
lnIndus	−0.00969***	0.0556***	0.0459***	−0.0147***	0.0763***	0.0616***	−0.0127***	0.0822***	0.0695***
	(0.00371)	(0.00717)	(0.00794)	(0.00369)	(0.00914)	(0.00975)	(0.00371)	(0.0109)	(0.0118)
lnGDP	0.107***	0.00385	0.110***	0.115***	−0.0246***	0.0909***	0.114***	−0.0100	0.104***
	(0.00370)	(0.00558)	(0.00558)	(0.00369)	(0.00631)	(0.00634)	(0.00371)	(0.00750)	(0.00742)
lnPop	−0.0659***	−0.0733***	−0.139***	−0.0720***	−0.0608***	−0.133***	−0.0665***	−0.0875***	−0.154***
	(0.00624)	(0.00809)	(0.00693)	(0.00617)	(0.00953)	(0.00829)	(0.00609)	(0.0115)	(0.0100)
lnUrb	−0.0497***	−0.118***	−0.167***	−0.0481***	−0.0558***	−0.104***	−0.0458***	−0.0878***	−0.134***
	(0.00864)	(0.0159)	(0.0170)	(0.00855)	(0.0215)	(0.0224)	(0.00858)	(0.0235)	(0.0246)

Note: 1%, 5% and 10% significant level are indicated by * * *, * * and * respectively.

In contrast, a 1% increase in global population will reduce energy efficiency by 0.0621% directly and also decrease it by 0.0554% indirectly; the net effect is a 0.118% reduction in energy efficiency. Similarly, a 1% rise in the urban population will directly reduce energy efficiency by 0.0518% and indirectly reduce energy efficiency by 0.103%, for a total decline in energy efficiency of 0.155%. Thus, growth in overall population as well as in urban population increases energy intensity.

4.2.3. Robustness checks

Since the choice of spatial weight matrix may affect our estimated results, we re-computed the SDM model with the following spatial weight matrices so as to ensure the robustness of the results according to spatial weight matrix specifications. With the K- nearest neighbor, we set the three matrices using the K-4, K-6 and K-8 distance, by so we assume that countries share 4, 6 and 8 neighbors respectively. Table 6 shows the estimated results of various matrices of spatial weights. The results from these other spatial matrices are almost the same as those from the previously reported distance matrix. The results indicate that using different matrices of spatial weight typically offer fairly similar direct, indirect and total estimates.

5. Conclusions, policy implications and limitations

There have been studies on the effect of institutional quality on energy efficiency, but, the understanding of the relationship between government institutions and energy efficiency is still limited especially in this era of rapid globalization, where countries interact more frequently with each other. To offer more insight on the effects of institutional quality on energy efficiency, we examine its spillover effects on energy efficiency, using both SFA and spatial panel model.

In general, the empirical results indicate that energy efficiency has spatial correlations in the countries under study. More importantly, the study finds empirical support for institutions-efficiency spatial dependence. Specifically, in the study we discover the direct effect of institutions on energy efficiency to be positive and statistically significant, which prevails over the insignificant negative indirect effect to produce a highly significant and positive total effect. Therefore, the level of energy efficiency of a country depends not only on own-country institutions and policies but also on the quality of its neighboring countries. This demonstrates that being surrounded by countries with good institutional framework improves energy efficiency performance.

On the basis of the results of this study, we can draw some significant policy implications: first of all, energy efficiency improvement is not only stimulated by improved own-country institutions but also by better institutions in neighboring countries or regions. Thus, government and policymakers should focus on enhancing the function and efficiency of domestic institutions to achieve sustainable global energy efficiency performance. This is only possible when institutions are empowered enough to take some important legislative and administrative decisions that foster energy saving and efficiency. Secondly, as the industrial sector is shown to be energy intensive, efforts to invest in less energy-intensive industrial technology should be a priority globally. This can be done by setting up research & development funds (unless already done) in some countries and provide low-interest loans for entrepreneurs investing in energy research & development projects. In addition, like in Slovenia, countries should take a deliberate step to stop operations of some energy intensive industries. Finally, our energy efficiency result also discloses that the global energy efficiency issue is structural in nature. This means long-term policies rather than short term policies will be more helpful in addressing energy security, carbon emission and energy intensity issues. Thus, low and middle income countries, need to increase energy technology to significantly reduce persistent inefficiency. More investments should go into energy related infrastructure to increase technological progress.

This work is not without limitations. The weakness has to do with two-step approach adopted in the paper, that is when energy efficiency index is first estimated using the SFA approach and then regressed on the vector of exogenous variables. Though this approach has been criticized in the literature [108], but like in other studies [36,90,109], the results are still valid. Moreover, given how this paper estimates total energy efficiency, to the best of our knowledge no method exists in the literature on how the energy efficiency variable can be endogenized in the spatial stochastic frontier model.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seps.2021.101023.

Appendix

Preliminary tests on variables

We perform some preliminary tests on the variables, to ensure that the models used in this paper were properly specified. For the start, we check for non-stationarity of the variables and then for a co-integration relationship in the specifications. When the error term is stationary then all variables are cointegrated. Therefore, long term regression analyses are not spurious and panel data models can be carried out. Of the 99 countries considered in this study, two economies (Singapore and Hong Kong) are not incorporated into panel unit root testing, the cointegration test as well the cross-sectional dependence test. This is because there is no within variation for Hong Kong and Singapore for the urbanization variable. So, for consistency, we used data of 97 countries for these tests.

Cross-sectional dependence (CD) tests

Starting with the CD test, we assess whether there is spatial dependence across countries.[4] From the results, for all variables, the null hypothesis is rejected that the variables are cross-sectionally independent, which emphasizes the importance in this context of considering spatial dependence in each country. Table 1A shows the results.

Table 1A
The Cross-Section Dependence Test.

Variables	CD Test	Variables	CD Test
Ln (EEI)	33.23 ***	lnUrb	215.16 ***
Ln (GDP)	290.26***	lnInsti	85.25***
Ln (Indus)	28.97***	lnPop	231.80***
LnService	74.96***		

The statistical test follows the standard normal distribution N (0, 1). *** means significant 1% level.

Panel unit root tests

For the root unit panel testing, we adopted four methods. These are Levin-Lin-Chu (LLC) [110], Breitung [111], Im–Pesaran–Shin (IPS) [112] and CIPS [113] approach. While, LLC, IPS and Breitung methods are a unit root test of first generation, the CIPS approach is the unit root test of the second generation that assumes cross-sectional panels dependence. Due to the fact that the CIPS approach provides better results when the variables are cross-sectionally dependent [47], our conclusion is based on the second-generation unit root test rather than the first-generation test. Table 2A shows the results of all tests. The results demonstrate that most of our variables are stationary at 1% significant level after the first difference. Tests for panel cointegration are therefore necessary.

Table 2A
Results for Panel Unit Root Tests

Variable		L-L-C	Breitung	IPS	CIPS
LnEEI	Level	−10.882 (0.000)	6.606 (0.988)	−1.904 (0.028)	−1.756
	1st Difference	−11.247 (0.000)	−7.451 (0.000)	−12.909 (0.000)	−4.031***
Ln (GDP)	Level	−1.565 (0.059)	26.616 (0.979)	9.627 (0.0.988)	−1.622
	1st Difference	−12.871 (0.000)	−10.429 (0.000)	−13.003 (0.000)	−2.893***
Ln (Insti)	Level	−11.267 (0.000)	4.903 (0.999)	−6.5191 (0.000)	−2.000***
	1st Difference	−15.449 (0.000)	−11.597 (0.000)	−15.156 (0.000)	−4.016***
Ln (Serv)	Level	−4.731 (0.000)	5.396 (0.997)	0.1067 (0.542)	−1.803***
	1st Difference	−17.653 (0.000)	−11.426 (0.000)	−18.803 (0.000)	−3.978***
Ln (Indus)	Level	−1.586 (0.000)	4.235 (0.988)	2.653 (0.998)	−2.372***
	1st Difference	−14.213 (0.000)	−11.275 (0.000)	−16.870 (0.000)	−4.157***
LnUrb	Level	−6.071 (0.000)	31.153 (0.401)	4.029 (0.924)	−1.472
	1st Difference	−1.6017 (0.000)	2.549 (0.937)	4.029 (0.000)	−2.105**

Note: 1%, 5% and 10% significant level are indicated by * * *, * * and * respectively.

Co-integration tests

Finally, we carry out panel co-integration tests employing the Pedroni cointegration test [114,115]. Evidence suggests that the null of cointegration cannot be rejected by most of the statistics. See results in Table 3A. Therefore, in the next stage, we explore the long-term relationship.

Table 3A
Panel Co-integration Test.

Test statistic	Result	Group Test statistic	Result
panel v	−3.405	group rho	12.24
panel rho	8.81	group pp	−10.95

(*continued on next page*)

[4] The specification of a spatial weighing matrix is not required for this test.

Table 3A (*continued*)

Test statistic	Result	Group Test statistic	Result
panel pp	−10.23	group ADF	9.962
panel ADF	7.17		

Note: All test statistics are distributed N(0,1), under a null of no cointegration.

List of countries (economies)

Albania, Algeria, Angola, Argentina, Australia, Austria, Bahrain, Bangladesh, Belgium, Benin, Bolivia, Botswana, Brazil, Brunei, Darussalam, Bulgaria, Cameroon, Canada, Chile, China, Colombia, Congo, Dem. Rep., Congo, Rep., Costa Rica, Cyprus, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Ethiopia, Finland, France, Gabon, Germany, Ghana, Greece, Guatemala, Haiti, Honduras, Hong Kong, Hungary, Iceland, India, Iran, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kenya, Korea, Rep., Luxembourg, Malaysia, Malta, Mauritius, Mexico, Mongolia, Morocco, Mozambique, Namibia, Nepal, the Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Pakistan, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Qatar, Romania, Russia, Saudi Arabia, Senegal, Singapore, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Tanzania, Thailand, Togo, Trinidad and Tobago, Tunisia, Turkey, United Arab Emirates, the United Kingdom, United States, Uruguay, Venezuela, Vietnam, Zambia and Zimbabwe.

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