Temperature and environmental degradation: an international evidence

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**ABSTRACT**

**Introduction:** The effects of temperature have largely been under-examined in climate change studies. This study examines both direct and indirect effects of temperature on environmental degradation using the sample of 103 middle-income countries from 1985 to 2019. Unlike previous studies in which a single equation approach is utilized, our study considers the simultaneous equations modelling to examine the energy-growth-environment nexus incorporating temperature and corruption. The difference and system generalized method of moments estimations for panel data are used.

**Outcomes:** Empirical results from this paper confirm both the direct and indirect effects (via energy consumption) of temperature on environmental degradation. We find corruption harms economic growth in middle-income countries. The continued use of fossil fuel energy in energy consumption deteriorates environmental quality. Our findings confirm the critical role of the services sector in supporting economic growth and reducing emerging consumption, leading to increased environmental quality.

**Conclusion:** Findings from our study reconfirm the vital role of renewable energy and its extended use in achieving dual objectives of supporting economic growth and improving the environmental quality in middle-income countries.

**Introduction**

The Global Climate Change of the National Aeronautics and Space Administration (NASA) in the US reveals that a global temperature has consistently and sharply increased in the last 40 years, from 0.26 Celsius degrees in 1980 to approximately 0.99 degrees in 2000 (National Aeronautics and Space Administration (NASA), 2020). Furthermore, for 140 years from 1880 to 2020, 19 of the 20 warmest years had occurred since 2001 in the last 20 years (NASA, 2020). In addition, the data indicate that human activities have raised atmospheric concentrations of CO₂ by 47% above pre-industrial levels found in 1850 over the past 170 years to date (NASA 2020). These interesting two statistics indicate that there may be a strong link between an increase in global temperature and the amount of CO₂ emissions, leading to further environmental degradation, which has caused great concern to many countries in the past 40 years.

Many studies have examined the inter-relationship between energy consumption and economic growth. However, previous studies on these issues appear to ignore the role of temperature in this nexus. An increase in temperature, particularly in winter and summer, will lead to an increase in energy demand and consumption, resulting in a deteriorating environmental quality. In addition, air pollution is always a significant concern for public health in emerging markets. We consider that the role and the extent of effect from these characteristics may affect the energy-growth nexus, particularly for the emerging markets and middle-income countries.

In addition, previous empirical studies on the energy-growth nexus appear to depend on a single-equation approach. Weaknesses from this single-equation approach have been demonstrated in various studies such as Omri (2013), Omri and Kahouli (2014), Omri et al. (2015a, 2015b) and Xia (2012). In this study, we utilize simultaneous equations modeling, which has been widely used in other areas of economics research. In this modeling approach, three different equations are simultaneously examined. The focus of this study is on the energy-environment-growth nexus. As such, the three equations examining this important inter-relationship are as follows. Using a production function, the first equation presents a link between energy consumption and economic growth. The second equation focuses on the energy function. The last equation is the environmental Kuznets curve (EKC) equation or the pollution function.

This study is different in comparison to previous studies. In this paper, two factors incorporated into the model are worth mentioning. The first factor is corruption which is incorporated in the production function representing economic growth. This factor is proxied by the institutional quality of the nation, which is well
documented to affect economic growth (Arminen et al., 2019; Sekrafi and Sghaier 2018b; Fredriksson, Vollebergh, and Dijkstra 2004). The second factor is the average temperature in winter and summer. This factor is significant in considering the growth-energy-environment nexus because the temperature is expected to affect both energy consumption and air pollution. In our paper, these two factors are used as external instruments, so it is appropriate to use the system estimation methods in simultaneous equations modeling.

The contributions of this study to the existing literature are threefold. First, previous empirical studies focus exclusively on the direct effects of temperature or energy consumption on the quality of the environment. Our study examines both the direct and indirect effects of temperature on environmental quality (air pollution) via energy consumption. Second, this study uses simultaneous equation modeling to examine the inter-relationship between energy consumption – economic growth – air pollution. Third, our study focuses exclusively on the middle-income countries which have to balance the benefits from economic growth and the costs of the deteriorated quality of the environment arising from economic growth.

Key highlights of the paper can be summarized as follows. First, there appears to have a link between temperature and CO₂ emissions based on NASA’s 150 years of observations and data. Second, temperature has been largely ignored in previous studies on the growth-energy-environment inter-relationship. Third, unlike previous studies, simultaneous equations modeling is used on a sample of 103 high-income and upper-middle-income countries. Fourth, this study confirms the presence of both direct and indirect effects (via energy consumption) of temperature to environmental degradation.

Following this introduction, the remainder of the paper is structured as follows. A literature review is discussed in section 2. The discussions of the simultaneous equation model are in section 3. Data and the methodological framework are presented in section 4 and section 5, respectively. Finally, empirical results are presented in section 6, followed by the conclusions and policy implications in section 7 of the paper.

Literature review

Many scholars have examined the inter-relationship among various aspects in the energy-environment-growth nexus. Our literature review indicates extensive interest in the relationship between economic growth, energy consumption and environmental degradation. In what follows, the following relationship is considered in this study, including (i) economic growth and energy consumption; (ii) energy consumption and air pollution (or CO₂ emissions); and (iii) air pollution and economic growth. Each of these important relationships is discussed in turn below.

Economic growth and energy consumption

The first strand of academic studies on this area is the energy-growth nexus. Kraft and Kraft (1978) paper is generally considered a pioneering study in this area of research. Following this paper, the energy-growth nexus has been investigated using different econometric methods and/or for different groups of countries. Four specific hypotheses are used to explain the cause-effect relationship between economic growth and energy consumption (Payne, 2010a, Payne, 2010b). First, the growth hypothesis on the relationship between energy consumption and economic growth. This hypothesis is confirmed as long as a unidirectional relationship running from energy consumption to economic growth is found. Second, the conservation hypothesis is that any reduction in energy consumption will be associated with a reduction in economic growth. Again, as long as there is a unidirectional relationship between energy consumption and economic growth, this hypothesis is validated. Third, the feedback hypothesis on the existence of a bidirectional causal relationship between these two variables. In particular, energy consumption has a positive effect on economic growth and economic growth, increasing energy consumption. This process continues in the short term and even in the long term. Fourth, the neutrality hypothesis on the presence of no cause-effect relationship between energy consumption and economic growth nexus.

Findings from other empirical studies have confirmed a bidirectional causality in the long run between these two variables (Abdouli and Hammami 2017; Adewuyi and Awodumi 2017; Darvishi and Varedi 2018; Omri 2013; Omri et al., 2015b; Saidi and Hammami 2016; Sekrafi and Sghaier, 2018; Xia 2012).

In their analysis, Dong, Dong, and Jiang (2019) examine the effect of renewable energy consumption on carbon dioxide emissions with different income levels for a global panel of 120 countries and four income-based subpanels. Findings from their paper indicate that renewable energy consumption harms CO₂ emissions. However, the effect is not significant. The authors consider that the mitigation effect may be obscured by higher economic growth and increasing nonrenewable energy consumption.

As for the aggregate energy consumption, empirical studies regarding the energy-growth-environment nexus have generally been carried out in the developed world and the OECD sample. For example, Topcu, Altinöz, and Aslan (2020) analyze the impact of natural resources and gross capital and energy consumption on economic growth with a global sample of 124 countries.
over the period 1980–2018 using the Panel Vector Autoregressive (PVAR) approach. The empirical results reveal that energy consumption increases economic growth, a similar positive relationship is confirmed for low, middle and high-income groups, and the growth hypothesis is supported across all four panels. Furthermore, in an analysis of OECD members, Ozcan, Tzeremes, and Tzeremes (2020) find a feedback effect between economic growth and CO₂ emissions using the sample of 35 countries during the period 2000–2014.

**Energy consumption and air pollution**

Concerning the energy-environment relationship, Soytas, Sari, and Ewing (2007) consider that energy consumption has a positive impact on air pollution (or CO₂ emission) in the long run. Recent studies from Abdouli and Hammami (2018), Bhattacharya, Churchill, and Paramati (2017) and Sinha (2016) also confirm unilateral causality from energy consumption to air pollution. The consumption of fossil energy and renewable energy has a relationship with CO₂ emissions in the long run. On the other hand, Abdouli and Hammami (2017), Darvishi and Varedi (2018), Sekrafi and Sghaier (2018), and Tiba et al. (2018) conclude the unilateral causality from air pollution to energy consumption. Meanwhile, other studies such as Adewuyi and Awodumi (2017) Säidi and Hammami (2016) confirm the presence of the bidirectional relationship between energy consumption and pollution in their analyses.

Zhao et al. (2020) examine whether environmental regulation improves the greenhouse gas benefits of natural gas use in China. Their analysis investigates the causal relationships among CO₂ emissions, natural gas consumption, and environmental regulation in China, based on panel data of China’s 30 provinces. Key findings from their analysis confirm that China’s environmental Kuznets curve (EKC) hypothesis for CO₂ emissions is valid. Furthermore, the authors consider that environmental regulation directly affects CO₂ emissions and indirectly affects CO₂ emissions by influencing energy consumption. Their findings consider that environmental regulation cannot significantly improve the greenhouse gas benefits of natural gas use. However, environmental regulation in China can indirectly reduce CO₂ emissions by decreasing coal consumption rather than increasing natural gas consumption.

**Air pollution and economic growth**

The environmental Kuznets curve (EKC) hypothesis states that the relationship between growth and air pollution (or CO₂ emissions) follows an inverted U-shaped curve. It means that economic growth increases the pollution level until a threshold is reached. When the economy grows after this threshold, the pollution level decreases. The EKC hypothesis has been widely investigated. Previous studies confirm the existence of this relationship in some countries, while in other countries, there is no clear relationship between economic growth and CO₂ emissions. Various studies such as Grossman and Krueger (1991) along with Shafik (1994), Dinda and Coondoo (2006), Heil and Selden (2001), Friedl and Getzner (2003) have been conducted, and the empirical findings from these studies are mixed. Therefore, an inverted U-shaped relationship cannot be robustly confirmed. In addition, findings from empirical studies indicate that the relationship between economic growth and CO₂ emissions can be either bidirectional (Abdouli and Hammami 2018; Adewuyi and Awodumi 2017; Liu 2005;9; Omri 2013; Omri et al., 2015a) or it can be unilateral from economic growth to CO₂ emissions (Bhattacharya, Churchill, and Paramati 2017).

In OECD countries, economic growth is proved to be affected by both nonrenewable and renewable energy consumption (Gozgor, Lau, and Lu 2018; Wang and Wang 2020). Conversely, economic development is a determinant of renewable energy consumption, but it does not reduce the dependence on nonrenewable energy (Alvarado et al. 2021). Aydin (2019) explores the Granger causality link between renewable and nonrenewable electricity consumption and economic growth on the sample of 26 OECD countries. The author utilizes two Granger causality tests, both the Dumitrescu-Hurlin panel causality and the frequency domain panel causality. The former test highlights a bidirectional causality between economic growth and nonrenewable electricity consumption in the short run. However, the latter strengthens the two-way effect in short, intermediate and long runs. Additionally, the frequency domain panel causality shows a bidirectional causality between economic growth and renewable electricity consumption in such three-time domains. Furthermore, environmental concern is a crucial driver to the adoption of renewable energy not only in OECD members (Säidi and Omri 2020) but also on a global scale (Omri and Nguyen 2014). To conclude, an implication is that an empirical relationship among these three variables in the OECD members should be cautious with timeframes and the surveyed countries.

In a very recent analysis, Wang, Dong, and Dong (2021) explore how renewable energy reduces carbon dioxide emissions by decomposing the impacts of renewable energy consumption on CO₂ emissions. A key conclusion from their paper is that the growth in renewable energy scale is the critical driving force responsible for promoting CO₂ emissions.
The research methodology – the simultaneous equations modeling and data

Brief discussions on the simultaneous equations modeling

In this paper, simultaneous equations modeling is adopted. By definition, a simultaneous equation model (SEM) is a model in the form of a set of linear simultaneous equations. Maddala (1992) considers that there are two ways to estimate a set of regression equations: (i) single-equation (or limited information methods) and (ii) system-equation (or complete information methods). If an equation is precisely identified, all the single-equation methods should be equivalent, and the results are the same. By contrast, in the case of over-identification, they will provide different estimates depending on how they treat endogeneity. System-equation methods such as the 3-stage least square (3SLS) and the full information maximum likelihood (FIML) are appropriate to estimate over-identification equations. Under many circumstances, the GMM estimator is analogous, even better, than the 3SLS and the FIML estimators in estimating simultaneous equations. As long as full distributional assumptions are not required, the GMM is preferred to other estimations.

Compared with other common estimators, the GMM provides a better unifying framework (Pagan and Wickens 1989). Least squares, instrumental variables, and maximum likelihood are considered special cases of the GMM (Hall 1993; Zohar 2010; Greene 2018, pp. 328–362). Hall (1993) confirms that the GMM can fit well the sequential estimators by estimating all the coefficients simultaneously. Arellano and Bond (1991) find that the GMM estimators provide smaller variances and insignificant sample biases associated with instrumental variable (IV) methods.

Another reason to use GMM is to correct the endogeneity problem. In simultaneous equation modeling, endogeneity refers to a situation in which an explanatory variable in one model is determined by a predetermined variable(s) in another model. As a result, the endogeneity problem will lead to inconsistent estimates and, thus, misleading interpretations. Ullah, Akhtar, and Zaeefarian (2018) consider that the GMM model, together with the use of lagged values of the dependent variable as the instruments, can control the dynamic endogeneity problem. Abdallah, Goergen, and O’Sullivan (2015) conclude that the system GMM is a valid methodology to correct the endogeneity problem in the panel data.

Moreover, the data sample in this paper has a very short time series (T = 7 periods of time) against a large number of observations (N = 529 observations). Concerning a sample with few periods (T) and many individuals (N), Han and Phillips (2010) consider that the GMM estimator provides better estimates in dynamic panel data models.

Roodman (2009) considers that the GMM method is appropriate in the case of small T and large N. The general model is as follows:

\[ y_{it} = ay_{i,t-1} + x'_{it} \beta + \epsilon_{it} \]

where the error term \( \epsilon_{it} \) includes two components: fixed effects \( \mu_i \) and individual effects \( u_{it} \).

\[ \epsilon_{it} = \mu_i + u_{it} \]

In this study, subscript \( i \) stands for panel variable (surveyed countries), and subscript \( t \) denotes time variable (periods). This process requires idiosyncratic disturbances that are uncorrelated across individuals. As such:

\[ E(\mu_i) = E(u_{it}) = E(\mu_i u_{it}) = 0 \]

Nickell (1981) concludes that with the correlation between \( y_{i,t-1} \) and fixed effects in general, the bias problem does exist. As such, the data transformation is considered a solution to eliminating the dynamic panel bias. Applying the first-difference transformation to the general model, we have:

\[ \Delta y_{it} = a \Delta y_{i,t-1} + \Delta x'_{it} \beta + \Delta u_{it} \]

Nevertheless, the first-difference transformation is inefficient in the case of unbalanced panels. Arellano and Bover (1995) developed a different transformation to correct this inefficiency called forward orthogonal deviations.

System GMM is considered the expanded estimator of the difference GMM because it involves the moment conditions from the levels of the residuals. As such, the system GMM assumes the fixed effects are not correlated with the changes in the idiosyncratic terms:

\[ E(\mu_i \Delta u_{it}) = 0 \]

Roodman (2009) considers that the difference and system GMM are designed for panel data without requiring external instruments. The lags of the instrument variables are taken into account as “internal instruments.”

The interlink between temperature, energy consumption, economic growth and air pollution in the middle-income countries

This paper adopts the simultaneous equations modeling to examine the energy-growth-environment nexus for middle-income countries. Corruption is consistently found to affect economic growth in empirical analyses (Chong and Calderon 2000; Fredriksson, Vollebergh, and Dijkgraaf 2004). Temperature is associated with energy consumption. A freezing winter is linked with an increase in energy demand. Energy demand increases during the very hot summer days. As such, temperature affects energy consumption, leading to a deterioration of environmental quality (Arminen and Menegaki 2019). On these bases, we consider that incorporating both corruption and
temperature into the examination of the inter-relationship between energy consumption, economic growth, and environmental degradation is appropriate. These two factors have largely been ignored in previous empirical studies, except for Arminen and Menegaki (2019). Their study, albeit outdated, examine the nexus for high-income countries for the 1985–2011 period. In addition, our study also considers the important role of urbanization in the energy-growth-environment inter-relationship. The vital role of urbanization is partially recognized in previous studies (Destek and Ozsoy 2015; Kasman and Duman 2015; Pata 2018). This study considers that urbanization has both direct and indirect effects (via energy consumption) on environmental degradation. As such, unlike previous studies, we incorporate three important variables, including corruption, temperature and urbanization, into our examination of the energy-growth-environment nexus. Each of these three equations is briefly discussed in turn below.

**The production function**

Following Mankiw (2008), a general form of the production function is as follows:

\[ Y = A f(K, L, H, N) \]

where \( Y \) denotes the aggregate output, \( A \) reflects the available production technology or technology, and the function \( f() \) shows how the inputs are combined to produce the output. These inputs include physical capital (\( K \)), labor (\( L \)), human capital (\( H \)) and natural resources (\( N \)). Arminen and Menegaki (2019) consider that labor and human capital contribute similar shares in output. Therefore, energy consumption is considered a natural resources factor. CO\(_2\) emission is also included (Omri 2013) in considering the electricity generation process. As such, the augmented production function can be rewritten as follows:

\[ Y = AK^{\alpha_1}(LH)^{\alpha_2}E^{\alpha_3}C^{\alpha_4} \]

where \( E \) denotes total energy consumption, and \( C \) represents CO\(_2\) emissions, which is proxied for air pollution. Assuming that the production function has constant returns to scale, then \( \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1 \). Dividing both sides by the labor factor, the preceding equation can be rewritten as follows:

\[ \frac{Y}{L} = A \left( \frac{K}{L} \right)^{\alpha_1} \left( \frac{H}{L} \right)^{\alpha_2} \left( \frac{E}{L} \right)^{\alpha_3} \left( \frac{C}{L} \right)^{\alpha_4} \]

The natural logarithmic transformation function for country \( i \) at time \( t \) is as follows:

\[ gdp_{it} = a_{it} + a_1k_{it} + a_2h_{it} + a_3e_{it} + a_4c_{it} \]

where \( gdp_{it} \) stands for the aggregate production per capita or country’s productivity; \( k_{it}, h_{it}, e_{it}, \) and \( c_{it} \) represent physical capital per capita, human capital, energy consumption per capita and CO\(_2\) emissions per capita, respectively.

The first component of the above equation, \( a_{it} \), is generally known as the total factor productivity (TFP). Isaksson (2007) concludes policies support TFP growth through accumulating capitals directly or as a by-product. Bloom, Canning, and Sevilla (2004) utilize the quality of a political institution as a proxy for its steady-state level of TFP. In this paper, corruption is used to proxy the institutional quality, which is associated with the TFP (Chong and Calderón, 2000):

\[ gdp_{it} = a \alpha_0 + a_1k_{it} + a_2h_{it} + a_3e_{it} + a_4c_{it} + a_5corr_{it} + \epsilon_{gdp_{it}} \]

(1)

**The energy consumption function**

Samuel, Manu, and Wereko (2013) show an inconsistent impact of growth measured by GDP per capita on energy consumption. However, due to the endogeneity problem, economic growth should be considered part of energy consumption’s determinant. In the context of sustainable development, Zaharia et al. (2019) find that greenhouse gas emissions have a substantial and significant impact on primary energy consumption. In addition, industrial growth and air temperature are identified as significant determinants (Samuel, Manu, and Wereko 2013). Countries with extreme climates (winters or summers) generally use more energy (Dawson and Spannagle 2009). The average temperature in the winter and summer seasons is used to examine the effect of temperature on energy consumption. The energy consumption function is augmented with the level of corruption is written as follows:

\[ e_{it} = \beta_0 + \beta_1gdp_{it} + \beta_2ind_{it} + \beta_3corr_{it} + \beta_4stem_{it} + \epsilon_{e_{it}} \]

(2)

All variables above are in natural logarithms form, including energy consumption per capita \( (e_{it}) \), GDP per capita \( (gdp_{it}) \), industrialization \( (ind_{it}) \), corruption \( (corr_{it}) \), the average temperature in summers \( (stem_{it}) \) and the average temperature in winters \( (wtem_{it}) \).

**The air pollution function**

The environmental Kuznets curve (EKC) offers a useful operational framework for examining the relationship between the environment and economic growth (Chowdhury and Moran 2012). Countries at lower income levels appear to focus on quantity rather than quality, leading to environmental deterioration as income levels grow. However, once a threshold of a higher income level is achieved, the countries then
shift their focus on the high-quality environment, resulting in a gradual decrease in environmental degradation. Sarkodie and Strezov (2019) employ meta-analysis and validate this inverted U-shaped relationship. Sarkodie and Strezov also consider that the most frequently environmental indicators which are utilized in these studies are based on atmospheric indicators. As such, CO₂ emission is considered a good proxy for pollution level or environmental degradation.

Dawson and Spannagle (2009) consider that economic structure and primary energy supply can determine the emissions intensity. Economic activities that rely heavily on energy consumption such as heavy industry, manufacturing and agriculture generate more greenhouse gas per unit of GDP than activities from the services-based sectors. In addition, different sources of energy that a country uses also have a relationship with emissions intensity. For example, energy sourced from fossil resources generates more greenhouse gas emissions than those from renewable energy sources and nuclear power. Moreover, Sarkodie and Strezov (2019) argue that the urban population is indirect for atmospheric indicators. Due to the impact of weather variations on energy consumption, we argue that weather should be included in the pollution function, which can be expressed as follows:

$$c_{it} = \gamma_0 + \gamma_1 GDP_{it} + \gamma_2 GDP_{it}^2 + \gamma_3 FE_{it} + \gamma_4 UR_{it} + \gamma_5 STEM_{it} + \gamma_6 WT_{it} + \gamma_7 CORR_{it} + \epsilon_{c, it}$$

(3)

Except for the two variables representing the variations of weather (STEM{it} and WT{it}), the remaining variables are in natural logarithms. \(c_{it}\) stands for the amount of CO₂ emissions per capita, GDP_{it} and GDP_{it}^2 stand for GDP per capita and the square of GDP per capita, FE_{it} denotes the proportion of fossil fuel energy consumption, UR_{it} denotes the urbanization, STEM_{it} and WT_{it} denote the average temperature in the three summer and winter months.

**Data**

The time period of this study starts in 1985 because it is the first year when data for corruption becomes available. Data are averaged for every three years to avoid measurement errors and short-run fluctuations such as shocks to money supply or fiscal policy (Arminen and Menegaki 2019). Countries in this study are classified using the income level reported in the World Development Indicators developed by the World Bank.

Three endogenous variables are collected from the World Bank indicators, including (i) GDP per capita in purchasing power parity (current international $), (ii) CO₂ emissions per capita (kt) and (iii) electricity power consumption (kWh per capita).

The exogenous variables, from the World Bank Indicators, include (i) fossil fuel energy consumption per capita (per cent of total consumption and total population); (ii) urbanization (per cent of the total population); and (iii) industrialization (per cent of total GDP). Temperature variables are from the data portal of the World Bank on climate. These temperature variables are the average temperatures over three months in summer (Celsius degree) and the average temperatures over three months in winter (Celsius degree). The human capital index and capital stock per capita (million US$) are from the Penn World Table. Feenstra, Inklaar, and Timmer (2015) consider that capital stock and human capital should be used simultaneously to measure the total factor productivity.

The corruption perception index is collected from Transparency International. Transparency International draws on many surveys and experts’ assessments to measure the corruption level in different countries and territories worldwide. They then score each country from 0 to 100 (extremely corrupt). They also rank surveyed countries based on their corrupt score every year. Even though the corruption perception index is not perfect, Hamilton and Hammer (2017) conclude that the corruption perception index is one of the most appropriate indicators for representing a corruption level.

GDP sector composition is an external instrument variable. Data is collected from the United Nations Conference on Trade and Development. Data is then coded from 0 to 2, which represents the main sector composition of a nation, including (i) agriculture, (ii) industry and (iii) service, respectively. Countries that rely heavily on agricultural or industrial activities are expected to consume more energy and emit more harmful gases causing air pollution.

**Empirical results on the interlink between temperature, energy consumption, economic growth and air pollution**

We use both difference GMM and system GMM estimations in this paper. The models estimated using the difference GMM method are labeled with the odd numbers (1; 3; 5; 7, and 9). In addition, the models using the system GMM method are labeled with even numbers (2; 4; 6; 8 and 10). Findings from this paper using three simultaneous equations modeling are summarized as follows.

We focus on discussing key findings from the production function (equation 1) in which economic growth, which is proxied by GDP per capita, is used as the dependent variable. Results are presented in Table 1. Each of the three key findings from our analysis is discussed in turn below. First, empirical findings from this paper indicate that corruption and economic growth are negatively correlated. This finding implies that controlling corruption is
an effective mechanism to support economic growth in middle-income countries. Corruption erodes trust from businesses, causing significant distortion of resources allocation into the production process. Second, we find a significant and positive contribution from physical capital to economic growth in middle-income countries. It appears that countries in our research sample require capital to continue supporting their economic growth. Our findings indicate that attracting foreign direct investment appears to play an essential role in providing physical capital for economic growth in these countries. Third, our empirical findings confirm the vital role of the

| Table 2. Results from the energy consumption function. |
|-----------------------------------------------|
| Dependent variable: Energy consumption per capita |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| Energy consumption per capita, lagged | 0.424* | 0.410* | 0.425* | 0.451* | 0.384* | 0.392* | 0.450* | 0.414* | 0.442* | 0.453* |
| (0.09) | (0.08) | (0.09) | (0.07) | (0.09) | (0.07) | (0.09) | (0.07) | (0.07) | (0.07) | (0.07) |
| GDP per capita | 0.403 | 0.475* | 0.400 | 0.546* | 0.443 | 0.503* | 0.413 | 0.484* | 0.411 | 0.546 |
| (0.12) | (0.10) | (0.12) | (0.12) | (0.12) | (0.11) | (0.10) | (0.11) | (0.10) | (0.11) | (0.11) |
| Industrialization | 0.058 | 0.085* | 0.057 | 0.074* | 0.073 | 0.093* | 0.051 | 0.109* | 0.057* | 0.086* |
| (0.11) | (0.10) | (0.11) | (0.11) | (0.12) | (0.09) | (0.11) | (0.08) | (0.10) | (0.09) | (0.09) |
| Average temperature, summer | 0.011*** | 0.010*** | 0.011*** | 0.008*** | n/a | n/a | 0.005*** | 0.005** | 0.004*** | 0.003*** |
| (0.01) | (0.01) | (0.01) | (0.01) | (0.01) | (0.01) | (0.01) | (0.01) | (0.01) | (0.01) | (0.01) |
| Average temperature, winter | 0.013*** | 0.008*** | 0.013*** | 0.009*** | n/a | n/a | 0.014*** | 0.006*** | 0.014*** | 0.009*** |
| (0.01) | (0.00) | (0.01) | (0.00) | (0.01) | (0.00) | (0.01) | (0.00) | (0.01) | (0.01) | (0.00) |
| Sector, services | -0.003** | -0.068*** | n/a | -0.066** | -0.068*** | -0.066** | -0.065*** | n/a | n/a | n/a |
| (0.03) | (0.01) | (0.01) | (0.03) | (0.01) | (0.03) | (0.01) | (0.01) | (0.01) | (0.01) | (0.01) |
| Constant | -0.004 | -0.004 | -0.004 | -0.006 | -0.006 | -0.004 | -0.004 | -0.004 | -0.004 | -0.004 |
| (0.02) | (0.02) | (0.02) | (0.02) | (0.02) | (0.02) | (0.02) | (0.02) | (0.02) | (0.02) | (0.02) |
| Observations | 325 | 426 | 325 | 426 | 325 | 426 | 325 | 426 | 325 | 426 |
| Number of groups | 99 | 101 | 99 | 101 | 99 | 101 | 99 | 101 | 99 | 101 |
| Number of instruments | 23 | 28 | 22 | 27 | 21 | 26 | 19 | 23 | 18 | 22 |

| p < .1, ** p < .05, *** p < .01 |
| Notes: Models (1; 3; 5; 7) are estimated using the difference GMM whereas the system GMM is used in the other models (2; 4; 6; 8).
| n/a means the variable is not included in the regression model. |
service sector in these middle-income countries. The middle-income countries in our sample should reconsider the composition of various sectors contributing to economic growth. For example, the important role of the agriculture sector may have been diminished. The manufacturing sector may harm the environment. As such, the services sector appears to be a soon-to-be key pillar supporting economic growth in middle-income countries.

We now shift our attention to the key findings from the energy consumption function (equation 2) in which energy consumption is used as the dependent variable. Empirical findings from this analysis are presented in **Table 2**. Our results indicate that energy consumption per capita is significantly and positively affected by the previous period’s energy consumption per capita. This finding sheds light on the important role of energy policies targeting electricity users’ behavior to switch to more environment-friendly products to save energy. We also find that an increase in GDP per capita and industrialization is generally linked to increased energy consumption. Industrialization supports economic growth. Both industrialization and economic growth increase energy consumption. This finding implies that industrialization has both a direct effect and indirect effect (via economic growth) on energy consumption. As such, economic policies targeting industrialization should consider the effects of increased energy consumption, leading to further deterioration of the environment. We also find that the services sector significantly reduces the demand for energy consumption. This finding appears to play an important role of the service sector in the economy to achieve economic growth and reduce a negative impact on the environmental quality.

Interestingly, the temperature over the three-month periods in summer and winter significantly and positively affect energy consumption in middle-income countries. These findings are consistent across various models and different econometric techniques. These results imply that temperature plays an important role in energy consumption. Our findings support the view that extreme weather may increase demand for energy consumption for heating (in the winter) and cooling (in the summer) in middle-income countries. These findings indicate that middle-income countries in the extreme weather zones – too cold in the winter and too hot in the summer – may need to reconsider their energy consumption structure toward renewable energy in order to reduce the negative impacts of energy consumption from fossil fuel sources into renewable energy sources such as wind, solar and water.

Our final group of key findings results from the pollution function (equation 3) where CO₂ emissions per capita are the dependent variable. The results are presented in **Table 3. First**, findings from this paper confirm that economic growth, which is proxied by

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**Table 3. Results from the air pollution function.**

| Dependent variable: CO₂ emissions per capita | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| CO₂ emissions per capita, lagged            | 0.055*   | 0.149*   | 0.065*   | 0.151*   | 0.080* | 0.155* | 0.074* | 0.146* | 0.090* | 0.168* |
| GDP per capita                              | 0.057 (0.09) | 0.107 (0.09) | 0.097 (0.09) | 0.105 (0.10) | 0.070 (0.09) | 0.112 (0.09) | 0.082 (0.09) | 0.107 (0.09) | 0.097 (0.09) | 0.168* |
| GDP per capita, squared                      | 0.039* (0.05) | 0.028* (0.05) | 0.065* (0.05) | 0.031* (0.05) | 0.030* (0.05) | 0.039* (0.05) | 0.042* (0.05) | 0.033* (0.05) | 0.063* (0.05) | 0.043* (0.05) |
| Fossil fuel consumption                      | 0.569*** (1.15) | 0.515*** (1.15) | 0.560*** (1.15) | 0.533*** (1.15) | 0.486*** (1.15) | 0.483*** (1.15) | 0.521*** (1.15) | 0.528*** (1.15) | 0.452** (1.15) | 0.479*** (1.15) |
| per capita                                   | 0.020 (0.02) | 0.011 (0.02) | 0.019 (0.02) | 0.015 (0.02) | 0.022 (0.02) | 0.014 (0.02) | 0.020 (0.02) | 0.015 (0.02) | 0.018 (0.02) | 0.013 (0.02) |
| Urbanization                                | 1.571 (1.76) | 0.934 (0.73) | 1.887 (1.23) | 0.965 (1.23) | 1.028 (1.23) | 0.961 (1.23) | 1.028 (1.23) | 1.385 (1.23) | 0.896 (1.23) | 0.892 (1.23) |
| Corruption                                   | −0.110 (0.16) | 0.100 (0.17) | −0.103 (0.16) | 0.120 (0.16) | n/a (0.16) | n/a (0.16) | n/a (0.16) | n/a (0.16) | n/a (0.16) | n/a (0.16) |
| Average temperature, summer                  | 0.003 (0.01) | 0.005*** (0.01) | 0.004*** (0.01) | 0.004*** (0.01) | 0.003*** (0.01) | 0.004*** (0.01) | 0.001*** (0.01) | 0.004*** (0.01) | n/a (0.01) | n/a (0.01) |
| Average temperature, winter                  | 0.010** (0.00) | 0.010** (0.00) | 0.013** (0.00) | 0.013** (0.00) | 0.013** (0.00) | 0.013** (0.00) | 0.013** (0.00) | 0.013** (0.00) | n/a (0.00) | n/a (0.00) |
| Sector, services                             | −0.035** (0.05) | −0.031** (0.02) | n/a (0.02) | −0.028** (0.05) | −0.038** (0.03) | n/a (0.03) | −0.012** (0.05) | −0.035** (0.03) | n/a (0.03) | n/a (0.03) |
| Constant                                     | 0.000     | -0.207     | 0.008     | -0.207     | 0.008     | -0.207     | 0.008     | -0.207     | 0.008     | -0.207     |
| Observations                                 | 325       | 426       | 325       | 426       | 325       | 426       | 325       | 426       | 325       | 426       |
| Number of groups                             | 99        | 101       | 99        | 101       | 99        | 101       | 99        | 101       | 99        | 101       |
| Number of instruments                        | 31        | 38        | 30        | 37        | 27        | 33        | 26        | 32        | 25        | 31        |

* p < 1, ** p < 0.05, *** p < 0.01

Notes: Models (1; 3; 5; 7; 9) are estimated using the difference GMM whereas the system GMM is used in the other models (2; 4; 6; 8; 10).

d/a means the variable is not included in the regression model.
GDP per capita, does harm the quality of the environment in the middle-income countries during the research period. These findings are important for the governments of these countries as policies only targeting economic growth may negatively affect the environment in the long run. Second, we note that the estimated coefficients of fossil fuel consumption are positive and significant on the environmental quality, which is proxied by CO₂ emissions per capita. Empirical results indicate that fossil fuel consumption plays a significant role in deteriorating the environment. These two key findings support the view that balancing the benefits from economic growth and the cost from the environmental quality plays an essential role in implementing policies from middle-income countries. Third, the services sector does lead to a moderating effect of deteriorating the quality of the environment because this sector reduces CO₂ emissions. Once again, the vital role of the service sector is confirmed in supporting economic growth and limiting the deterioration of the environment in middle-income countries.

Our empirical results also indicate that the average temperature of the three-month periods during winter and summer affects the level of CO₂ emissions across various models and regression techniques. Together with previous results from the energy consumption function, these findings confirm that a higher temperature over the three-month periods during the winter and summer leads to an increase in the demand for energy consumption. An increase in energy consumption is then associated with higher CO₂ emissions, leading to a further deterioration of the environment in middle-income countries during the research period.

**Conclusions and policy implications**

Global warming as a direct effect of climate change and environmental degradation is a vital issue for current generations to consider. The complicated nexus between economic growth – energy consumption and the quality of the environment has attracted significant attention from policymakers, academics and practitioners in several decades. Moreover, the issue appears to be a continuing dominant issue in policy agenda for all countries around the globe for many decades to come.

The growth-energy-environment nexus has been widely examined in previous empirical studies. However, temperature appears to have been largely ignored in current literature. Corruption and urbanization – the two main factors in empirical analyses on economic growth – are also incorporated into our analysis. In addition, unlike previous analyses, simultaneous equation modeling with a GMM estimator is used in this paper. As such, this study examines the energy-growth-environment relationship with the presence of temperature, corruption and urbanization. Our analysis is theoretically and empirically based on the Cobb-Douglas production function for economic growth consideration and the environmental Kuznets curve hypothesis for energy consumption and environmental degradation functions. The sample of 103 middle-income countries across the globe for the 1985–2019 period is used. Key findings from our analysis can be summarized as follows.

The first key finding is the unidirectional relationship between economic growth and energy consumption without a feedback effect. We find economic growth increases energy consumption, but the reverse does not hold. This finding is consistent with the neo-classical assumption about the neutral role of energy consumption in economic growth. Our results show that economic growth is a significant and positive determinant for energy consumption. In the opposite effect, energy consumption does not significantly impact economic growth even though energy is considered input of the production process.

The second key finding is the counter effect to the quality of the environment from the services sector and the use of fossil fuel energy in the national energy mix. Empirical results from our paper confirm a significant and negative effect from the services sector on environmental degradation. In addition, we find a negative effect of fossil fuel energy consumption on environmental degradation. These findings imply that supporting the service sector may achieve a dual objective of enhanced economic growth and reduced environmental degradation in middle-income countries.

The third key finding from our paper, the focus of our interests, is on the crucial role of the temperature in examining the energy-growth-environment nexus. Our findings indicate that temperature, which is proxied by the average temperature over the three-month periods in winter and summer, provides both direct and indirect effects on environmental degradation. For the indirect effect, temperature is associated with increased energy consumption leading to further environmental degradation. For a direct effect, temperature increases the CO₂ emissions leading to a further deterioration of the quality of the environment.

Policy implications have emerged based on the findings from this study. First, countries that source a large proportion of their energy supply from fossil energy resources should consider switching over clean and renewable energy such as hydropower, wind, solar and geothermal. In addition to seeking other energy sources for fossil fuel alternatives, these countries should also focus on investing and improving technologies that they have used to meet the energy demand. Another important implication based on the findings from this paper is that the
governments should support the services sector because economic activities in this sector generate less CO₂ emissions than other sectors, leading to an improvement of the environmental quality.

Findings from this paper confirm both direct and indirect effects of temperature on the quality of the environment. Furthermore, we find both direct and indirect effects of temperature on environmental degradation. As such, policymakers should carefully consider the impact of climate change on implementing energy policies and the sustainable development goals in their economic policies. We argue that keeping track of extreme weather events is necessary because it provides crucial information concerning energy consumption and CO₂ emissions emitted to the economy. Limiting these negative effects on the environment reconfirms the importance of renewable energy in the national energy policy for achieving sustainable economic growth and reducing environmental degradation for future generations.

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Authors’ contributions
Conceptualization: Duc Hong Vo; Methodology: Duc Hong Vo; Formal analysis and investigation: Duc Hong Vo; Writing - original draft preparation: Duc Hong Vo; Writing - review and editing: Duc Hong Vo; Funding acquisition: Duc Hong Vo; Resources: Duc Hong Vo; Supervision: Duc Hong Vo.

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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