Does Economic Growth Stimulate Energy Consumption? The Role of Human Capital and RD Expenditures in China

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Abstract: This study evaluates the link between human capital, energy consumption, and economic growth using data for the Chinese economy from 1971 to 2018. To test the cointegration relationship between disaggregated energy, human capital, and economic growth, a bounds testing approach is applied by taking the structural breaks into consideration. The estimated results confirm that these variables are integrated. Further, human capital accumulation has a statistically significant negative effect on all types of energy consumption. We note a positive link between energy usage and economic growth. However, a significant negative relationship is found between R&D expenditures, and energy consumption. The results also show a one-way causal effect of human capital on all forms of energy consumption. However, the association between economic growth, dirty energy usage, and clean energy usage remains interdependent, indicating a feedback effect. Further, energy consumption and R&D exhibit bidirectional causal relationship.

Keywords: Human Capital, Energy Consumption, China

I. Introduction

The driving role of energy consumption in economic growth has got much debate since the pioneering work of Kraft and Kraft (1978). Environmentally friendly and clean technologies are necessary to achieve sustainable economic growth without compromising environmental degradation mitigation. Sustainable growth can only be accomplished by internalizing the external effects through increased knowledge, technological progress, and substitutability between clean and dirty energy (Li and Lin 2016, Papageorgiou et al. 2017). Both academics and practitioners are addressing this challenge to suggest suitable strategies and policies to find solutions for clean energy, particularly in developing economies, where the contribution of human capital and productivity is not well understood (Lan and Muro 2013, Balaguer and Cantavella 2018, Sarkodie et al. 2020).

China is a rapidly growing economy that exerts a strong influence on the world energy market. Over the last few decades, energy consumption has increased rapidly. The average GDP growth rate of China remained at 8.86% from 1971 to 2018, through which its global influence as an economic participant greatly increased. This high GDP growth has changed the sectoral composition of the Chinese economy. The output value of manufacturing expanded to 4002.75 billion USD in 2018 from 625.22 billion USD in 2004, whereas the increase in net trade gap widened manyfold between 1971 and 2018 (The World Bank Group 2019). As a result, the growth rate of China's energy consumption was the highest in the world (3.7%) in 2018 (Enerdata 2018). Currently, China consumes approximately 3.13 billion tons of petroleum equivalent energy, making up 24% of the world energy use (BPSTATS 2019). According to China's Energy Outlook for 2050, China's primary energy demand will peak at approximately 3.91 billion tons of petroleum equivalent by 2035. Because the energy has a substantial influence on the economic development process, significant improvements in energy efficiency are needed to ensure sustainable development.

The United Nations' Sustainable Development Goals (SDGs) agenda has set a clear goal (i.e., SDG 7) to achieve sustainable energy through global access to clean energy, ensuring sufficient energy supply, and growing the proportion of renewable energy in overall global energy mix globally (UN 2015). As noted by Heggelund (2018), at the end of 2018, China's greenhouse gas emissions were triple those in 1990, which highlights the need for policy actions to reduce carbon emissions trends through investment in human capital and transitioning to innovative technologies (Helveston and Nahm 2019). Recently, China has announced the goal of becoming a carbon-neutral economy by 2060, and its recent focus on investing in human capital and low carbon technology development in response to climate change challenges and embracing a "green growth" strategy is a positive step to curb carbon emissions (Ma 2020). A comprehensive methodology is desired to study the impacts of recent initiatives on insightful policy analysis and its likely implications.

Human capital is a broader concept that considers whether human capabilities are internal or external, which drives higher income. Among the different kinds of human capital, health and education are considered the most important factors, which are interconnected and essential for human productivity improvement (Li and Huang 2009). Human capital influences the production of renewable energy by absorbing new knowledge and providing labor (Benhabib and Spiegel 2005). Thus, the effective management of knowledge and technology-intensive capital is particularly important for renewable energy companies. Therefore, human capital has great significance for enterprises in attaining sustainable growth (Xu and Liu 2019). In addition, it has a marginal real macroeconomic impact and it may have synergic effect on energy consumption. On the one hand, human capital investment contributes to improved productivity and economic growth; on the other, it results in positive externalities such as improved health and environment (Schultz 1961, Becker 1994, Blackman and Kildegaard 2010, Li and Ouyang 2019). A large strand of literature adopts the Mincerian approach to identify aggregate externalities of human capital (through wage earnings differentials) by focusing on the estimation of the labor supply function (Mincer 1962), which was later extended by Becker (1964) with particular emphasis on return on investment in human capital (for details see Rauch 1993, Ciccone and Peri 2006). However, endogenous growth models consider human capital as an alternative to technological progress in the production process, which is believed to be a significant contributor to economic growth (Becker 1964, Lucas 1998, Joshua 2015). However, the role of human capital in sustainable growth, particularly in the context of environmental pollution, has not yet been fully understood empirically.

While linking energy consumption with economic growth, most research has relied on either neoclassical production theory or endogenous growth models. The estimation of the neoclassical aggregate production function takes into consideration labor, capital, and energy inputs exogenously (Lee et al. 2008, Aghion and Howitt 2009). However, endogenous growth model estimation treats human capital as endogenous (Yang and Chen 2017). Few studies have focused on linking energy consumption with human capital, showing an inverse relationship between the two (Yao et al. 2019). Similarly, empirical research centered on human capital and environmental compliance relationship also shows that firms possessing higher human capital are likely to be more environmentally friendly through the adoption of innovative technologies (Dasgupta 2001, Lan and Munro 2013). However, the empirical literature that links energy consumption, human capital, and economic growth is still emerging, which requires further research.

Given that human capital is a fundamental driver of economic growth, researchers underscore its critical role in the production process. Empirical evidence shows that human capital can enrich the absorptive capacity of an economy (Haini 2019). The assessment of positive externalities of human capital (e.g. increased productivity) has been an important topic in economic theory and policy. Various approaches and estimation methods have been used to respond to policy questions (Gemmell 1997, Heckman 2000, Rudd 2000, Acemoglu and Angrist 2001). Limited research has concentrated on the connection between energy consumption and human capital when emissions are taken into account in the Chinese economy (Sarkodie et al. 2020). However, little empirical evidence exists on how human capital can be effective in mitigating environmental issues, particularly combatting emissions.

Most research on the energy-growth relationship does not consider human capital, and thus provides an incomplete picture of how the energy-growth nexus can help mitigate pollution emissions. The accumulation of human capital helps to increase public awareness about the use of energy, whereas expenditures on R&D result in the transition toward energy-efficient technologies, which may help to reduce energy consumption. The uncertainty about the net impact of human capital on energy consumption requires a more comprehensive analysis. This study augments model specification from a bivariate to multivariate balance framework considering human capital, R&D expenditures, economic growth, and imported energy to analyze the demand function. This study adds to the existing energy economics literature in several ways. First, we examine the empirical interaction between human capital, energy consumption (clean and dirty energy), R&D expenditures, and economic growth based on data for China from 1971 to 2018. Second, we employ the multiple-break sharp and smooth unit test[1]. Furthermore, we apply a single structural break ADF unit test as a robustness measure. Third, we adopt an ARDL-bounds test approach to check the existence of cointegration, while structural breaks are still present in the data. Fourth, we conduct a VECM Granger-causality test to determine relationship between the variables of economic interest, if any. The results verify the presence of cointegration. Human capital and energy consumption show an inverse relationship. Imported energy appears to reinforce the consumption of overall energy, which is stimulated by economic growth. As expected, R&D expenditures is inversely linked to energy consumption. Based on rigorous empirical analysis, it is expected that policymakers in China and developing countries will be able to formulate more effective public policies to achieve efficient and sustainable economic growth.

II. Literature Review

Human capital is a determining factor of economic growth that helps improve environmental quality through the adoption of new technologies and increased productivity (Goldar and Benerjee 2004, Lan and Munru 2013, Inglesi-Lotz 2016). Human capital is crucial in explaining fluctuations in economic growth through the absorption of improved technologies (Barro and Sala-i-Martin 1997, Barro 2001). It plays a significant role in the technological progress of any country, and researchers have shown that human capital has an affirmative and substantial effect on economic growth (Li and Liu 2011, Teixeira and Queirós 2016). Le and Bodman (2011) advocated that a skilled workforce can effectively disseminate technical knowledge, thereby contributing to the country's economic growth. Since the dynamics of production specialization are leading elements for economic growth, human capital exerts a strong constructive influence on this growth through greater innovation capacity and productivity. Consequently, human capital development is essential for improving productivity (Hulten et al. 2006, Wang and Liu 2016).

[1] For details, see Shahbaz et al. (2018).

Human capital can be measured in different ways. For example, Kanayo (2013) considered the link between the role of education and economic growth. Similarly, Ouyang and Fu (2012) and Su and Liu (2016) used the percentage share of city inhabitants enrolled in higher education to quantify this relationship. Jones et al. (2003) adopted secondary enrollment level without bearing in mind the magnitude of trained labor, and Bengoa et al. (2017) measured average years of schooling for this relation. All these measures have their reasons and limitations, but they show a positive and significant association between economic growth and human capital because they can also promote growth by helping technological innovation (Nelson and Phelps 1966). Le and Bodman (2011) and Wang and Liu, (2016) reported significant positive correlations among high life expectancy, GDP, and human capital. Oluwatobi and Ogunrinola (2011) found that government spending has a significantly positive effect on economic growth through human capital development in Nigeria.

Studies have examined various dimensions of environmental effects on human capital using different dimensions, including contamination (e.g., drinking water), toxicity (e.g., air pollution), and exposure (e.g., pollution ingestion), which ultimately affect economic development and growth (for a survey see Zivin and Zilberman 2002, Zivin and Neidell 2013). Consideration of the role of human capital in reducing the impact of climate change and environmental degradation has gained momentum in recent years (Meyer 2016, World Economic Forum 2017, Balaguer and Cantavella 2018). Studies using human capital as one of the crucial determinants show that instrumentalizing human capital not only confirms a positive impact on environmental quality but also has proven to overcome identification issues (Balaguer and Cantavella 2018). Energy consumption, economic growth, and human capital are significantly related not only to human well-being today, but also to the welfare of tomorrow. The strength of alliance prospects, contests, threats, and their consequences have attracted the attention of the international community. According to endogenous growth theory, long-term economic growth may be affected by economic factors, such as innovation mechanisms that technological progress depends on, which may involve new products, new processes, and clean energy. However, there is limited empirical literature on the role of human capital in driving energy consumption, particularly in the context of carbon emissions reduction.

Empirical evidence suggests that human capital has a favorable effect on emissions reduction using innovative technologies and conservation strategies. Researchers have shown that human capital accumulation leads to emissions reduction through enhanced productivity and improved production processes through innovative technologies (Kwon 2009, Pablo-Romero and Shanchez-Braza 2015). Improvements in work productivity rely on human capital capacity sets. The existing literature focuses on how pollution impacts human capital in view of declining health, productivity, and educational outcomes. The association between human capital and environmental pollution can be viewed through both internal and external channels. The internal source can be viewed as the absorbability of human capital endowment, which helps implement abatement technologies, whereas investment in higher education is more likely to exert pressure on regulators for stringent environmental regulations (Cole et al. 2008). Whereas, external effects of human capital are viewed through community pressure, assuming that highly educated people are more sensitive to the surrounding environment and thus evaluate those issues differently than less educated people (Dasgupta et al. 2001). Empirical evidence demonstrates that both internal and external impacts of human capital have resulted in improved environmental outcomes through better compliance within the firm's environment (Dasgupta et al. 2001, Lan and Munru 2013). Researchers link human capital to energy consumption in multiple ways (Arbex and Perobelli 2010, Li and Lin 2016, Fang and Chen, 2017). On the one hand, increased income due to improved human capital may lead to increased energy consumption. On the other hand, the promotion of R&D adoption strategies may improve the use of energy-efficient technologies, causing a reduction in energy consumption. Likewise, the accumulation of human capital through education and the promotion of energy conservation awareness could also help reduce energy consumption.

Previous studies have emphasized the importance of energy in economic development. For example, Hulten et al. (2006) found that the growth of energy production capacity has a favorable effect on productivity and economic growth. Alaali et al. (2015) noted that energy should be considered as an important production factor in neoclassical economics, along with capital and labor. Several indicators of human capital have been incorporated in research using different approaches to measuring its relationship with economic growth and energy consumption. For example, Mattalia (2012) used endogenous growth theory and applied an error correction model to test the importance of human capital. Alaali et al. (2015) used panel data from 130 countries and noted that human capital and energy consumption are key factors in promoting economic growth. Azam (2019) believed that energy consumption and capital (both physical and human) contribute to economic growth. Fang and Chang (2016) applied a multivariable framework to measure the relationship between economic growth and human capital. They also considered human capital a key variable in their cointegration analysis and found that traditional capital and energy input seem to play a secondary role with increases in human capital. Llesanmi and Tiwari (2017) employed a vector error correction model to assess the relation between human capital investment, energy consumption, and economic growth in South Africa. Their empirical results confirmed the existence of cointegration and a two-way causal relationship among these variables. Bah and Azam (2017) determined the relationship between human capital expenditures of the government (education and health) and economic performance, along with labor, capital, and energy.

Limited research has focused on linking economic growth, energy consumption, and human capital, confirming causality between the variables. For example, Ahmad and Khan (2019) determined the causality between economic growth and human capital, whereas Fang and Chang (2016) estimated a simultaneous relationship among human capital, economic growth, and energy consumption. Fang and Yu (2018) asserted that energy is an essential factor for economic growth and human capital. They noticed a positive and significant impact of energy on growth. They applied a bootstrap autoregressive-distributed lag approach and found that human capital and export diversification showed a negative relationship.

Most of the existing literature overlooks the potential role of human capital, embodied as pollution-reducing technologies in the production frontier. Generally, neoclassical models have been used to examine the link between environmental policy and economic growth, where the growth rate is determined exogenously in the long run using standard neoclassical production structures (see, for example, Forster 1973, van der Ploeg and Withagen 1991). These studies are often stimulated in part by the seminal work of Schultz (1963) and Becker (1994). Another strand of literature on the energy-growth nexus includes the literature emphasizing on the causative relationship between human capital and energy consumption (Blackman and Kildegaard 2010, Chang and Fang 2020). The empirical findings confirm that investment in higher education impacts environmental quality significantly as a result of increased commitment to the adoption of environmental policies (Salahodjaev 2018). Lan et al. (2012) used Chinese provincial data to evaluate the impact of human capital on carbon emissions reduction through FDI intermediation. They confirmed that provinces with higher human capital stocks showed a negative relationship between FDI and emissions.

Table-1 presents a survey of existing relevant studies linking various policy variables such as human capital, consumption of different types of energy, and economic growth. The evidence shows that countries or firms with larger human capital stock are more likely to increase clean energy consumption, thus reducing the consumption of dirty energy sources (Yao et al. 2019). For instance, Yao et al. (2020) find that large industrial firms with higher capital are expected to abide by external environmental legislation to adopt stringent policies aimed at pollution control. Haini (2021) used ASEAN data from 1996 to 2019 to assess the extent that ICT technologies and human capital help reduce emissions through increased absorptive capacity of the economy. Chen et al. (2021) evaluated the impact of human capital development on industrial emissions and found that investing in human capital leads to a considerable reduction in industrial emissions. Other studies that investigated human capital effects on emissions reduction have yielded the expected results (Kim and Heo 2013, Lan and Murno 2013, Fang and Chen 2017), except for a few that found human capital to show an ambiguous or opposite relationship with energy consumption (Sarkodie et al. 2020).

Table 1: Literature Survey on Human Capital, Energy Consumption and Economic Performance Nexus

Literature	Region	Period	Method	Variables	Results
Chen et al. (2021)	China	1998–2009	Difference-in-difference (DD)	CO_2 emissions, human capital, firm's characteristics	Improvement in human capital investment leads to a significant reduction in industrial waste emissions
Haini (2021)	ASEAN	1996–2019	Panel integration	GDP, human capital, ICT, energy consumption	Both human capital and ICT help reduce emissions from manufacturing and other industries.
Iorember et al. (2021)	South Africa		ARDL, VECM	Per capita GDP, human-capital, renewable energy, trade flows	Human capital, trade, and usage of renewable energy have a desirable impact on ecological footprints.
Chang and Fang (2020)	ASEAN	1965–2011	Johansen cointegration	GDP, capital (physical and human), energy-consumption	Human capital and energy-consumption exhibit a long-term relationship. Moreover, physical and human capital are substitutable.
Fang and Yu (2020)	56 countries	1970–2014	Panel Granger causality	Energy, human capital, GDP	Human capital enhances economic growth and energy efficiency.
Sarkodie et al. (2020)	China	1961–2016	ARDL simulations	Human capital index, CO2 emissions, energy	Findings confirm the Environmental Kuznets Curve (EKC) hypothesis. However, an unexpected positive relationship is observed between emissions, human

				consumption, GPD	capital, and energy consumption.
Yao et al. (2020)	OECD	1965–2014	Human capital, R&D, energy consumption,	CO_2 emissions, GDP, physical & human capital, trade, technology	Improvement in human capital tends to reduce dirty energy consumption by generating positive environmental externalities.
Azam (2019)	BRICS	1981–2015	Panel fully modified OLS	Energy, GDP environment, human & physical capital	The relationships between human capital, energy usage, investment, pollution, and growth are bidirectional and unidirectional.
Fatima et al. (2019)	Pakistan	1990–2016	Cointegration	Energy, human capital & GDP	Bilateral causal connection between energy and economic capital, human capital, and economic growth.
Li et al. (2019)	Pakistan	1990–2016	Cointegration	Human capital, energy and GDP	Feedback effect of human capital and energy in their relation to economic performance.
Xu and Liu (2019)	Listed companies	2010–2016	Ohlson model, quantile regression	Human capital, GDP, energy	Value-added human capital is prerequisite for economic growth in all three (growth, maturity, and decline) stages.
Chen and Fang (2018)	210 prefecture cities of China	2003–2012	Fully modified panel estimation	GDP, energy, human capita	Human capital positively contributes to GDP along with energy consumption.
Kahia et al. (2017)	11 MENA oil importers	1980–2012	Panel Granger causality	GDP, energy, fixed & human capital	The association between human capital, energy use, fixed capital, and GDP is long-term equilibrium.
Fnag and Chen (2017)	ASEAN	1965–2011	Single-equation estimation & cointegration	GDP, human capital, energy	When human capital increases, the influence of energy on GDP seems less important.
Fang and	16countries of	1970–2011	Augmented	GDP, energy,	There is long-term cointegration between human capital,

Chang (2016)	Asia Pacific		production function	human capital	energy, and GDP.
Alaali et al. (2015)	130 countries	1981–2009	Generalized method of moments	Energy, human capital, GDP	The impact of human capital and energy on economic performance varies considerably.
Pablo-Romero and Sánchez-Braza (2015)	38 leading countries	1995–2007	Aggregate translog production function	Energy, human & physical capital, GDP	There is a complementarity relation between energy and capital for BRIC and East European countries.
Herrerias et al. (2013)	Chinese regions	1995–2009	Panel techniques	Energy, human capital, GDP	A unidirectional causation is indicated from human capital toward economic performance and from economic performance toward energy in the long run.
Apergis and Payne (2010)	20 OECD countries	1985–2005	Panel cointegration and ECM	GDP, energy, human capital	A long-run equilibrium does exist between energy, human & fixed capital, and GDP.
Li and Huang (2009)	Chinese provincial data	1978–2005	Panel data models	GDP, human & physical capital, health investment	There is a positive impact of health and educational capital on GDP.
Hulten et al. (2006)	India	1972–1992	Solow productivity residual	Human capital, energy, GDP	Energy and human capital enhance economic growth.
Lan and Munro (2013)	China	2004	Probability model and instrumental variable approach	Environmental indicator, human capital, industry characteristics	Improved human capital helps in emissions reduction due to better environmental compliance.
Bano et al. (2018)	Pakistan	1971–2014	ARDL	CO_2 emission, GDP, human capital	Reduction in emissions are noted due to human capital improvement. Findings confirm the causality between the two variables.
Kim and Geo	72 countries	2014	2SLSL	Human capital,	A significant relationship between human capital and the

				environmental performance, physical capital	environmental performance index.
Fang and Chen (2017)	China	1995–2014	Cross-sectional dependence estimation and panel cointegration	Physical & human capital, GDP, energy	Findings are indicative of strong cross-sectional dependence and verify the e cointegration between all variables.
Lan et al. (2012)	China	1996–2006	Fixed effects and random effects error component models	Energy consumption, CO2 emissions, FDI, human capital, capital intensity, industrialization indicators	Provinces with higher levels of human capital indicate a negative association between FDI and emissions, confirming the pollution heaven hypothesis.
Salim et al. (2017)	China	1990–2010	Panel unit root analysis, cross-sectional dependence model estimation	Output, energy consumption, energy price, capital stock, human capital	Energy consumption and human capital exhibit a significantly negative relationship.

III. Empirical Modeling and Data

This study examines how economic growth and human capital affect energy consumption in China. Economic growth affects energy consumption through income and investment. The impact of economic growth on the consumption of energy is well established in the context of the environmental Kuznets curve (Andreoni and Levinson 2001, Richmond and Kauffmann 2006). Investment in human capital not only contributes to improved productivity and economic growth but also results in positive externalities, such as improved health and environment (Schultz 1961, Becker 1994, Blackman and Kildegaard 2010, Li and Ouyang 2019). Empirical evidence shows that human capital formation can increase the absorptive capacity of an economy and reduce energy consumption (Benhabib and Spiegel 2005, Salim et al. 2017, Haini 2019). Therefore, human capital has great significance in attaining sustainable growth (Xu and Liu 2019). We model the energy demands for clean and dirty energy separately, which is represented as

$$EC_t^k = f(K_t, H_t, I_t, R_t, Y_t) \quad (1)$$

where *k* represents i) the overall energy demand (O), ii) dirty energy demand (d), and iii) clean energy demand (c). All variables are converted into per capita, and the empirical strategy suggested by Shahbaz et al. (2018, 2020) is adopted in the estimation of the log-linear model. We model the aggregate energy consumption as a function of GDP, human capital, physical capital, imported energy, and R&D expenditures. The log-linear specification for the energy demand function(s) is as follows:

$$E\tilde{C}_t^o = \alpha_1 + \alpha_2 \tilde{K}_t + \alpha_3 \tilde{H}_t + \alpha_4 \tilde{I}_t + \alpha_5 \tilde{R}_t + \alpha_6 \tilde{Y}_t + \mu_i \quad (2)$$

$$E\tilde{C}_t^d = \beta_1 + \beta_2 \tilde{K}_t + \beta_3 \tilde{H}_t + \beta_4 \tilde{I}_t + \beta_5 \tilde{R}_t + \beta_6 \tilde{Y}_t + \mu_i \quad (3)$$

$$E\tilde{C}_t^c = \delta_1 + \delta_2 \tilde{K}_t + \delta_3 \tilde{H}_t + \delta_4 \tilde{I}_t + \delta_5 \tilde{R}_t + \delta_6 \tilde{Y}_t + \mu_i \quad (4)$$

where, $E\tilde{C}_t^o$, $E\tilde{C}_t^d$, $E\tilde{C}_t^c$, $\tilde{K}_t$, $\tilde{H}_t$, $\tilde{I}_t$, $\tilde{R}_t$, and $\tilde{Y}_t$ are the logarithm of the consumption of overall energy, dirty energy, clean energy, human capital, economic growth, physical capital, imported energy, and R&D expenditures, respectively. μ_i is an error term assumed to have a normal distribution.

This study utilizes Chinese data for the period–1971–2018 for energy usage (kilogram per capita oil equivalent), fossil fuels (% of energy usage), renewable energy (% of energy use), net enrollment in primary, secondary, and tertiary education, real GDP (constant local currency), gross fixed capital formation (% of GDP), net energy imports (% of energy use), and R&D expenditures (% of GDP). We divide all variables by the total population to convert them into per capita figures.

IV. Methodological Framework

SOR Unit Root Test

Following Shahbaz et al. (2018), we employ a sharp and smooth structural break unit root test (hereafter, SOR) to assess the nature of integration between variables. The SOR unit root test is unique and novel, explaining the structural breaks stemming from the series. Because of low illustrative power and vague results, conventional unit roots such as Dickey-Fuller (ADF) and Phillips-Perron (PP) fail to provide correct hypothesis testing as a consequence of Type I or Type II errors (Perron 1989). When nonlinearities and structural breaks are present in the series, the SOR test offers more justified and trustworthy empirical outcomes than the PP and ADF unit root tests. According to Leybourne et al. (1998a), the SOR unit root test requires a 2-step method to assess the integrating properties of the variables when structural breaks prevail in the data series. First, we estimate the residuals of the models presented by Equations (5-7) as follows:

$$\hat{e}_t = y_t - \hat{\delta}_1 - \hat{\delta}_2 F_t(\hat{\theta}, \hat{\tau}) \quad (5)$$

$$\hat{e}_t = y_t - \hat{\delta}_1 - \hat{\beta}_1 t - \hat{\delta}_2 F_t(\hat{\theta}, \hat{\tau}) \quad (6)$$

$$\hat{e}_t = y_t - \hat{\delta}_1 - \hat{\beta}_1 t - \hat{\delta}_2 F_t(\hat{\theta}, \hat{\tau}) - \hat{\beta}_2 F_t(\hat{\theta}, \hat{\tau}) t \quad (7)$$

Second, we follow Enders and Lee (2012) in computing the test statistic denoted as:

$$\hat{e}_t = d(t) + \varphi_1 \varepsilon_{t-1} + \nu_t \quad (8)$$

Here, with variance σ^2, the stationary disturbance is denoted as v_t and the deterministic function of *t* is denoted by $d(t)$. It should be noted here that e_t is weakly correlated with the assumption that its initial value is fixed. With known functional form of $d(t)$, it is feasible to test the null hypothesis that a unit root exists using Equation 8; however, in the absence of $d(t)$, any testing regarding ϕ_1 = 1 could be challenging and misleading. However, the methodology under consideration is capable of estimating $d(t)$ using Fourier approximation:

$$d(t) = \alpha_0 + \sum_{k=1}^{n} \alpha_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \beta_k \cos\left(\frac{2\pi kt}{T}\right), \ n \le T/2 \tag{9}$$

where the number of observations is *T*, while *k* and *n* represent the specific and cumulative frequencies enclosed for assessment. A large number of cumulative frequencies *n* is not recommended because the existence of several frequency components can lead to overfitting.

Various researchers have argued that Fourier approximation can be applied with fewer frequency components to detention vital features of an unknown functional form of a smooth break (Davies 1977, Gallant 1981). Hence, the cumulative frequencies *n* should also be smaller to accommodate the steady progress of nonlinear trends. However, restoring the series to the mean of any evolution is not practical. Thus, in this case, the testing equation is modeled as follows:

$$\begin{aligned}\Delta\hat{\varepsilon}_t = \alpha_0 + \sum_{k=1}^{n} \alpha_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \beta_k \cos\left(\frac{2\pi kt}{T}\right) + \phi_t \hat{\varepsilon}_{t-1} \\ + \sum_{i=1}^{p} \varphi_k \hat{\varepsilon}_{t-i} + v_t\end{aligned} \tag{10}$$

Generally, the lag length of the dependent variables is extended to handle the stationary dynamics of $\hat{\varepsilon}_t$ in the model. Correspondingly, the value of the EL statistic in model presented in Equation (5) is $s\tau_\delta$, which is used to construct $\hat{\varepsilon}_t$, while $s\tau_{\delta(\beta)}$ is used for Equation (6) and $s\tau_\alpha$, β for model in Equation (7). Here, for the SOR unit root test, it is important to determine whether fewer cumulative frequency components can reproduce the structural breaks that are often confronted in social science data. For such tracking, this study applies a Fourier approximation for individual frequency components, described by k, while α_k and β_k are the fullness and displacement deterministic term sinusoidal component. Thus, multiple smooth interruptions can be generated from $k = 0$ individual frequencies. We can state the hypothesis established in the model given in equations 5, 6, and 7 for unit root testing by Fourier transformation as follows:

$$H_0 : Unit\ \ Root \qquad (Linear\ \ nonstation\ ary)$$

$$H_a : Unit\ \ Root \qquad \begin{pmatrix} \text{non-linear and statoinary with} \\ \text{simultenous change in sharp and smooth trend} \end{pmatrix}$$

The ARDL Bounds Testing Approach

Various tests are available to assess the level of association between variables. However, most of these tests require integration of order one of the variables. The ARDL bounds method is highly flexible regardless of whether the integration level is I(1), I(0), or even a mixed situation. This test can provide short-run and long-run results without losing evidence regarding long-run results. The bounds testing approach is also capable of handling issues such as endogeneity and serial correlation. This is because there is a single cointegration vector (cointegration association) between variables, and ARDL bounds testing delivers consistent empirical outcomes.

For the decision regarding acceptance (cointegration exists) or rejection (no cointegration) of the null hypothesis, Pesaran et al. (2001) introduced critical bounds with lower and upper limits. Regardless of the variable integration level, this hypothesis considers only the upper and lower critical bounds. Finally, in the case of no cointegration among variables (condition of null hypothesis rejection), Pesaran and Shin's (1999) model of ARDL is used to determine the coefficients. Therefore, by taking the log of CO_2 (per capita) as a dependent variable, this study applies the unrestricted error-correction regression method for the desired analysis, as given in equation 11.

$$\Delta \ln C_t = \gamma_0 + \sum_{j=1}^{n} \gamma_1 \Delta \tilde{C}_{t-1} + \sum_{j=0}^{n} \gamma_2 \Delta \tilde{S}_{t-1} + \sum_{j=0}^{n} \gamma_3 \Delta \tilde{T}_{t-1} + \sum_{j=0}^{n} \gamma_4 \Delta \tilde{K}_{t-1}$$
$$\sum_{j=0}^{n} \gamma_5 \Delta \tilde{E}_{t-1} + \sum_{j=0}^{n} \gamma_6 \Delta \tilde{O}_{t-1} + \sum_{j=0}^{n} \gamma_7 \Delta \tilde{F}_{t-1} + \delta_1 \tilde{C}_{t-1} + \delta_2 \tilde{S}_{t-1} \quad (11)$$
$$+ \delta_3 \tilde{T}_{t-1} + \delta_4 \tilde{K}_{t-1} + \delta_5 \tilde{E}_{t-1} + \delta_6 \tilde{O}_{t-1} + \delta_7 \tilde{F}_{t-1} + \varepsilon_j$$

Here, the change in a variable is denoted by Δ, while the short-run and long-run coefficient parameters are presented in *j* (*j* = 1, …,7) of the ARDL model, and tilde (~) represents the natural log of the variables included in the model. This study uses the Akaike Information Criteria (AIC) to determine the lag order for variables because it is more helpful for choosing the delay order than the Stuart Bayesian Criteria (SBC; Shahbaz et al. 2017). According to equation 11, the null hypothesis for the non-existence of cointegration is given as follows:

$$H_0 : \delta_1 = \delta_2 = \ldots = \delta_7 = 0,$$

whereas an alternative hypothesis will be:

$$H_0 : \delta_1 \neq \delta_2 \neq \ldots \neq \delta_7 \neq 0.$$

When the computed ARDL *F*-statistic exceeds the upper threshold, the null hypothesis is rejected, and we opt for the cointegration approach. When the lower limit exceeds the calculated *F*-statistic, cointegration is not performed and its calculation within these two thresholds will be uncertain in this case. To determine the stability of the model, heteroscedasticity, model specification, and autocorrelation in the ARDL estimate, this study applies obligatory diagnostic tests such as CUSUM and CUSUMSQ.

The VECM Granger Causality Approach

We employ the VECM to investigate the determinants of energy consumption (clean, dirty). The empirical equation for VECM causality is as follows:

$$(1-L)\begin{bmatrix} \tilde{EC}_t \\ \tilde{H}_t \\ \tilde{Y}_t \\ \tilde{K}_t \\ \tilde{I}_t \\ \tilde{R}_t \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} + \sum_{i=1}^{p}(1-L)\begin{bmatrix} \psi_{11,i} & \psi_{12,i} & \psi_{13,i} & \psi_{14,i} & \psi_{15,i} & \psi_{16,i} \\ \psi_{21,i} & \psi_{22,i} & \psi_{23,i} & \psi_{24,i} & \psi_{25,i} & \psi_{26,i} \\ \psi_{31,i} & \psi_{32,i} & \psi_{33,i} & \psi_{34,i} & \psi_{35,i} & \psi_{36,i} \\ \psi_{41,i} & \psi_{42,i} & \psi_{43,i} & \psi_{44,i} & \psi_{45,i} & \psi_{46,i} \\ \psi_{51,i} & \psi_{52,i} & \psi_{53,i} & \psi_{54,i} & \psi_{55,i} & \psi_{56,i} \\ \psi_{61,i} & \psi_{62,i} & \psi_{63,i} & \psi_{64,i} & \psi_{65,i} & \psi_{66,i} \end{bmatrix} \times \begin{bmatrix} \tilde{EC}_{t-1} \\ \tilde{H}_{t-1} \\ \tilde{Y}_{t-1} \\ \tilde{K}_{t-1} \\ \tilde{I}_{t-1} \\ \tilde{R}_{t-1} \end{bmatrix} + \begin{bmatrix} \delta \\ \gamma \\ \lambda \\ \varphi \\ \phi \\ \theta \end{bmatrix} ECT_{t-1} + \begin{bmatrix} \mu_{1i} \\ \mu_{2i} \\ \mu_{3i} \\ \mu_{4i} \\ \mu_{5i} \\ \mu_{6i} \end{bmatrix} \quad (12)$$

Equation 12 shows ECT_{t-1} as an estimate of the error correction term, and $(1-L)$ is the difference operator for determining long-run equilibrium. Furthermore, random errors are shown by $\mu_{1t},\ldots,\mu_{6t}$. While the *t*-statistic determines the long-run relationship between the variables, the *F*-statistic determines the short-run causality between them.

V. Discussion

An ADF unit root test is employed to investigate the integration order, which includes structural breaks in the data series. The estimates in Table 2, show that all variables have a unit root. We identify these structural breaks in the years 2000, 2002, 1989, 1974, 1990, 1983, and 1995 for overall energy consumption, dirty energy consumption (fossil fuel consumption), clean (renewable) energy consumption, human capital, economic growth, capitalization, imported energy consumption, and R&D expenditures. All variables are stationary at the first difference.[2] We applied the SOR test and the estimates are presented in Table 2 (see lower segment). The results confirm the existence of a unit root problem when sharp and smooth structural breaks are present both at levels with intercepts as well as trends. All variables were found to be stationary

[2] We also applied ADF and PP unit root tests to check the robustness of the unit root test. The ADF and PP estimates show that all variables are stationary at the first difference.

at first difference.[3] The unique level of integrated variables allows us to employ the ARDL approach to determine the cointegration between variables.

Table 2: Unit Root Estimates

Variables	Level Structural Break: ADF			1st Difference Structural Break: ADF		
	t-statistic	*p*-value	Break-year	*t*-statistic	*p*-value	Break-year
$\ln EC_t^o$	−1.9534	0.9847	2000	−6.8445*	0.0001	2002
$\ln EC_t^d$	−3.9080	0.1904	2002	−6.6054*	0.0001	2002
$\ln EC_t^c$	−3.3371	0.4820	1989	−21.6389*	0.0001	1990
$\ln H_t$	−2.8816	0.1808	1974	−7.6276*	0.0001	2002
$\ln Y_t$	−1.4185	0.9999	1990	−5.1211**	0.0228	1976
$\ln K_t$	−2.7171	0.8239	1990	−4.7076***	0.0757	1993
$\ln I_t$	−4.4773	0.1384	1983	−20.6055*	0.0001	1983
$\ln R_t$	−2.1775	0.9565	1995	−9.0337*	0.0010	1990
SOR Unit Root Test						
	t-statistic	$\bar{\alpha}_2$	*t*-statistic	$\bar{\gamma}$	α_k	
$\ln EC_t^o$	−2.1678	1.0987	−1.2567	−0.8765	−0.2356	
$\ln EC_t^d$	−1.7865	2.8760	−0.9785	−0.2367	−0.1010	
$\ln EC_t^c$	−3.4789	0.9867	−0.6578	−0.4329	−0.2789	
$\ln H_t$	−2.5567	1.0987	−1.6789	−0.3345	−0.0986	
$\ln Y_t$	−1.9567	0.9765	−1.5589	−0.7765	−0.4597	
$\ln K_t$	−3.6538	2.0987	−1.4561	−0.8563	−0.2304	
$\ln I_t$	−2.3987	1.4567	−1.9635	−0.2044	−0.1325	
$\ln R_t$	−3.7891	2.0978	−1.5690	−0.1780	−0.2098	
Note: 1% and 5% significance levels are shown by * and **, respectively.						

We apply the ARDL bounds testing approach developed by Pesaran et al. (2001). The ARDL approach is well known for application when the variables are integrated at level, 1st difference,

[3] The results of the SOR unit root test at first-difference can be obtained upon request.

or when variables with mixed order are integrated. This approach not only provides efficient estimates but also accommodates information on structural breaks rooted in the data series. The ARDL approach is highly susceptible to the selection of variables lag-length. Lütkepohl (2006) noted that the dynamic relationship between the variables (i.e., energy consumption and its determinants) is better estimated if the lag-length is accurately chosen. We report the lag-length selection in Table 3. The estimates show that the energy demand function exceeds the upper bound at 5%, 1%, and 10%, respectively. We find four cointegrating vectors in the energy demand function, confirming the cointegration relationship between energy consumption and its determinants. The empirical results are similar for dirty (fossil fuel) and clean (renewable) energy demand functions, confirming the existence of cointegration between energy consumption and its determining factors. Overall, we conclude that when structural breaks are present in the data a long-run relationship is found for the period 1971–2018.

Table 3: The ARDL Test Results

Cointegration Bounds Tests			Diagnostics					
Models				Chi-Square Test				
	Lag-Length	*F*-Statistic	Year	*NORMAL*	*ARCH*	*RESET*	*CuSum*	*CuSum*^{2}
	Energy Consumption							
$EC_t^o = f(H_t, Y_t, K_t, I_t, R_t)$	2, 2, 1, 1, 2	8.116 **	2000	0.1301	0.2156	0.3255	Stable	Stable
$H_t = f(EC_t^o, Y_t, K_t, I_t, R_t)$	2, 2, 2, 1, 1	8.725 *	1974	0.4195	0.1305	0.7500	Stable	Stable
$Y_t = f(H_t, EC_t^o, K_t, I_t, R_t)$	2, 2, 2, 2, 1	12.082 *	1990	0.4939	1.2666	0.9448	Stable	Stable
$K_t = f(H_t, EC_t^o, Y_t, I_t, R_t)$	2, 2, 1, 2, 2	5.941 ***	1990	3.0180	0.1072	0.6992	Stable	Stable
$I_t = f(H_t, EC_t^o, Y_t, K_t, R_t)$	2, 2, 2, 2, 2	3.843	1983	0.1427	0.0675	0.6347	Unstable	Stable
$R_t = f(H_t, EC_t^o, Y_t, K_t, I_t)$	2, 2, 2, 1, 2	3.403	1995	0.1209	0.1600	0.6040	Unstable	Unstable
	Dirty Energy Consumption							
$EC_t^d = f(H_t, Y_t, K_t, I_t, R_t)$	2, 2, 1, 1, 2	9.525 *	2002	0.9335	0.0014	2.2466	Stable	Stable
$H_t = f(EC_t^d, Y_t, K_t, I_t, R_t)$	2, 2, 2, 1, 1	7.904 **	1974	0.3766	0.0004	1.2834	Stable	Stable
$Y_t = f(H_t, EC_t^d, K_t, I_t, R_t)$	2, 2, 2, 2, 1	11.809*	1990	1.1694	0.0273	0.1618	Unstable	Stable
$K_t = f(H_t, EC_t^d, Y_t, I_t, R_t)$	2, 2, 1, 2, 2	10.911 *	1990	1.0473	0.2572	0.5460	Stable	Stable

$I_t = f(H_t, EC_t^d, Y_t, K_t, R_t)$	2, 2, 2, 2, 2	1.622	1983	1.2003	0.0654	0.1415	Stable	Unstable
$R_t = f(H_t, EC_t^d, Y_t, K_t, I_t)$	2, 2, 2, 1, 2	3.321	1995	0.1090	0.1089	0.6467	Unstable	Unstable
	Clean Energy Consumption							
$EC_t^c = f(H_t, Y_t, K_t, I_t, R_t)$	2, 2, 1, 1, 2	7.905 *	1989	0.8528	1.1686	2.3688	Stable	Stable
$H_t = f(EC_t^c, Y_t, K_t, I_t, R_t)$	2, 2, 2, 1, 1	10.700 *	1974	0.5749	0.0928	1.5866	Stable	Stable
$Y_t = f(H_t, EC_t^c, K_t, I_t, R_t)$	2, 2, 2, 2, 1	6.785 ***	1990	0.3160	0.5011	0.4388	Stable	Stable
$K_t = f(H_t, EC_t^c, Y_t, I_t, R_t)$	2, 2, 1, 2, 2	7.053 **	1990	0.4566	1.8523	2.5100	Stable	Stable
$I_t = f(H_t, EC_t^c, Y_t, K_t, R_t)$	2, 2, 2, 2, 2	1.572	1983	3.7846	2.5958	2.0440	Unstable	Unstable
$R_t = f(H_t, EC_t^c, Y_t, K_t, I_t)$	2, 2, 2, 1, 2	3.031	1995	0.1009	0.1607	0.6490	Unstable	Unstable
Note: *, ** and *** indicate the level; of significance at 1%, 5%, and 10%, respectively. Further, AIC criteria is used to determine the lag-length. Critical values are taken from Narayan (2005).								

The results shown in Table 4 reveal that human capital energy consumption are linked negatively in the long run. China's economy has gradually shifted from extensive development to high-quality development, and considerable attention has been paid to the protection of resources and the environment, as well as clean and efficient utilization of energy. The status of human capital has gradually increased, and the level of human capital has greatly improved. Human capital accumulation causes a decline in energy consumption, and the results are similar to those of Pablo-Romero and Sánchez-Braza (2015), Shahbaz et al. (2019), and Fang and Yu (2020). In contrast, Chen and Fang (2018) and Azam (2019) noted a positive effect of human capital accumulation on energy consumption. Similarly, energy consumption and economic growth exhibit a significantly positive causal relationship. The results indicate that a 1% rise in economic growth explains an increase in energy consumption of 1.4172%. Capitalization impacts the energy demand negatively, on the other hand, showing that energy efficiency can considerably reduce energy demand. All else being equal, a 1% increase in capital decreases energy demand by 0.2651%. The relationship between imported energy and energy consumption was found to be positively significant. An energy consumption of 0.0603% was led by a 1% increase in energy imports. R&D expenditures have a negative effect on energy consumption, which is statistically significant. The results indicate that a 1% increase in R&D expenditures causes a reduction in energy consumption by 0.1527%.

Table 4: Long-Run Analysis

Variables	Energy Consumption		Dirty Energy Consumption		Clean Energy Consumption	
	Estimate	*t*-statistic	Estimate	*t*-statistic	Estimate	*t*-statistic
Constant	−1.0558*	−7.5185	−0.8940*	−5.5191	3.0778*	7.2207
$\ln H_t$	−1.2636*	−6.8742	−0.6906*	−3.2568	2.1856*	4.5233
$\ln Y_t$	1.4172*	13.6281	−1.3308*	−11.0941	0.9907*	3.2860
$\ln K_t$	−0.2651*	−3.7616	−0.2299*	−2.8284	0.3903**	2.0834
$\ln I_t$	0.0603*	2.6102	0.0598*	2.2425	0.0870**	2.4999
$\ln R_t$	−0.1527*	−7.4988	−0.1557*	−6.6323	0.3179*	6.2991
R^2	0.9769		0.9790		0.9734	
$Adj-R^2$	0.9663		0.9684		0.9648	
F-statistic	15.7981*		17.3562*		12.7620*	
D.W Test	2.0456		2.0378		2.1087	
Stability Analysis						
Test	*F*-statistic	*p*-Value	*F*-statistic	*p*-value	*F*-statistic	*p*-value
χ^2_{NORMAL}	1.9013	0.3684	1.1620	0.5593	1.4398	0.5644
χ^2_{SERIAL}	1.2345	0.3408	1.1324	0.3504	1.0978	0.3645
χ^2_{ARCH}	1.0987	0.4209	1.1267	0.3989	1.2308	0.2436
χ^2_{Hetero}	1.9601	0.1010	1.6648	0.1075	1.4325	0.1203
χ^2_{RESET}	1.0765	0.3609	1.2098	0.2672	0.7266	0.4715
Cumulative Sum	Stable		Stable		Stable	
Cumulative sum squared	Stable		Stable		Stable	
/Note: 1% and 5% significance levels are shown by * and ** respectively.						

In the dirty energy demand function, we find that human capital has a negative influence on dirty energy consumption. The coefficient of human capital causes in the dirty energy model remains at −0.6906%, indicating that there is a decline in energy consumption with human capital accumulation. There is also a significantly negative link between the consumption of fossil fuels and economic growth. The coefficient (i.e., 1.3308) indicates a decline in dirty energy consumption as a result of a 1% increase in economic growth. Similarly, capital and dirty energy consumption also show a significantly negative relationship. Other factors remaining equal, a 1% growth in capitalization causes a reduction in dirty energy consumption by 0.2299%. On the other hand, the estimates of imported energy show that a 1% increase in imported energy will increase the dirty energy demand by 0.0598%. The relationship between R&D expenditure and dirty energy consumption was negative. Likewise, a 0.1557% decline in dirty energy consumption results from a 1% increase in R&D expenditures. This is consistent with China's economic policy, and with the development of its economy and the improvement of the human capital level, the demand for pollution control of energy consumption is becoming increasingly urgent. The improvement of economic development level, the growth of human capital level, the increase in R&D expenditures, and the increase in imports provide conditions for reducing the consumption of dirty energy. Under the guidance and support of government policies, the reduction of dirty energy consumption has become a reality.

The estimation of the clean energy consumption model shows that human capital has a positive and significant effect on clean energy consumption. A 1% increase in human capital causes an increase in clean energy demand of 2.1856%. It is noticed that each percent increase in clean energy consumption has almost the same percentage point increase in economic growth. Similarly, capital also shows a significantly positive effect on clean energy consumption. The estimated coefficient of 0.3903% implies that each percentage point increment in capitalization causes a 0.3903% increase in clean energy consumption. The relationship between imported energy and clean energy consumption appears to be positive, which is statistically significant (i.e., 0.0870). R&D expenditures also affect the consumption of clean energy consumption positively, which is significant. The above results may be a consequence of China's strong support for the development of clean energy. The rise in human capital level and the increase in R&D expenditures provide talent, technology, and financial support for clean energy production, and imported energy provides more choices for clean energy consumption. Therefore, more economic development is linked to a greater promotion of clean energy development.

Table-5: Short Run Analysis

Variables	Energy Consumption		Dirty Energy Consumption		Clean Energy Consumption	
	Estimate	*t*-statistic	Estimate	*t*-statistic	Estimate	*t*-statistic
Constant	−0.0054*	−6.5866	−0.0070*	−6.4700	0.0118**	2.3373
$\tilde{H}_t$	3.8327*	7.5491	5.0724*	7.5414	4.1083**	2.2987
$\tilde{Y}_t$	0.2689*	2.7267	0.4082*	3.1136	−2.0675*	−3.8092
$\tilde{K}_t$	0.0672**	2.0327	0.0687	1.5636	0.2665	1.4388
$\tilde{I}_t$	−0.0167**	−2.4025	−0.0203**	−2.1976	−0.3233*	−8.1077
$\tilde{R}_t$	0.0046	0.5245	0.0066	0.5671	0.0013	0.0284

D_{2000}	0.0033*	7.7112	….	….	….	….
D_{2002}	….	….	0.0034*	6.0189	….	….
D_{1989}	….	….	….	….	−0.0005	−0.2418
ECM_{t-1}	−0.0104**	−2.3546	−0.0216**	−2.4523	−0.0226**	−2.1876
R^2	0.4051		0.3701		0.3151	
$Adj-R^2$	0.3824		0.3461		0.2873	
F-statistic	7.7801*		5.3050*		4.7260*	
DW Test	1.6630		2.4107		1.7438	
Stability Analysis						
Test	F-statistic	p-value	F-statistic	p-value	F-statistic	p-value
χ^2_{NORMAL}	1.8023	0.3704	1.2220	0.5403	1.9834	0.3604
χ^2_{SERIAL}	1.3254	0.3301	1.3124	0.3407	1.9171	0.3405
χ^2_{ARCH}	1.1917	0.4009	1.2671	0.3779	1.2030	0.2444
χ^2_{Hetero}	2.6001	0.1009	1.0648	0.1705	1.3245	0.1289
χ^2_{RESET}	1.1705	0.3700	1.2908	0.2402	1.7060	0.3905
Cumulative sum	Stable		Stable		Stable	
Cumulative sum square	Stable		Stable		Stable	
Note: 1% and 5% significance levels are shown by * and ** respectively.						

In the short-run (Table 5), human capital shows a positively significant link with the consumption of overall energy, dirty energy, and clean energy. Economic growth and capitalization also show a significantly positive effect on the overall energy consumption and consumption of dirty and clean energy. The results also show that imported energy is negatively linked to all types of energy consumption. The coefficient of R&D remains insignificant for all three types of energy consumption. The estimates for ECM_{t-1} remained negative, but statistically significant. The coefficients of overall energy consumption (−0.0104), dirty energy consumption (0.0216), and clean energy consumption (0.0226) are statistically significant at the 5% level. This confirms the long-run association between overall consumption, dirty, and clean energy consumption and its determinants. The speed of adjustment in the short run is 1.04%, 2.16%, and 2.26% for the consumption of overall energy, dirty energy, and clean energy, respectively. Finally, the diagnostic analysis confirmed that all the models were parsimonious. The Jarque-Bera and Ramsey reset tests confirm that the normal distribution of the error terms and functional forms are well specified.

Table 6 describes the results of the VECM Granger causality test. It is noted that in the long run, the overall energy demand function, human capital, causes overall energy consumption, but the reverse relationship does not hold. These results are consistent with those reported by Herrerias et al. (2013). Research and development expenditures and energy consumption show Granger causality. In this process, imported energy and R&D expenditures play a promoting role, but the increase in human capital cannot change the trend of overall energy consumption. In the short run, we note the feedback effect between human capital and energy consumption. Similarly, capitalization and energy consumption show a bidirectional relationship. R&D expenditures and energy consumption show a neutral effect.

In the dirty (fossil fuel) energy consumption function, a feedback effect is noticed between human capital and dirty energy in the long run. The estimated results also confirm a two-way causality between the consumption of dirty energy and economic growth. Likewise, capitalization causes dirty energy consumption, and vice versa. However, R&D and dirty energy consumption reveal a bidirectional relationship. This is closely related to the energy structure and government policies during this period. During the study period, although China's environmental regulations have improved, the consumption of dirty (fossil fuel) energy accounts for a larger fraction of energy consumption, and the demand for dirty (fossil fuel) energy in imported energy is also large. A two-way causality is found between dirty energy consumption and human capital in the short run. However, the results validate the neutral effect between dirty energy consumption and capitalization. The causality between dirty energy consumption and imported energy is unidirectional. R&D expenditures and dirty energy consumption also show no causal relationship.

The estimates of the clean (renewable) energy demand function show that human capital causes clean energy consumption and, as a result, consumption of clean energy affects human capital in the long run. This empirical evidence is contrary to existing evidence. The estimated results also confirmed the feedback effect of economic growth. Capitalization and clean energy consumption cause each other to increase. Imported energy is the cause of clean energy consumption, and consequently, clean energy consumption is the cause of imported energy. A bidirectional causal association is observed between R&D expenditures and energy consumption. In terms of China's national conditions, if China wants to maintain rapid and healthy development, it must vigorously develop clean energy and make continuous improvements in its energy consumption structure. With the strengthening of environmental regulations, the proportion of clean energy consumption has increased, which is the direction of China's efforts and the mainstream of future energy consumption. Human capital and clean energy consumption show a bidirectional relationship in the short run. Capitalization and the consumption of clean energy exhibit a feedback effect. However, we find no causality between R&D expenditures and the consumption of clean energy.

Table 6: Estimates of Granger Causality

Dependent Variable	Short Run							Long Run
	$\sum \Delta E\tilde{C}_t$	$\sum \Delta \tilde{H}_t$	$\sum \Delta \tilde{Y}_t$	$\sum \Delta \tilde{K}_t$	$\sum \Delta \tilde{I}_t$	$\sum \Delta \tilde{R}_t$	Break Year	ECM_{t-1}
	Energy Consumption							
$\sum \Delta E\tilde{C}_t$	…..	16.2671* [0.0000]	14.0075* [0.0000]	4.0411** [0.0192]	6.0775* [0.0028]	0.6691 [0.5135]	2000	−0.4563* [−3.2090]
$\sum \Delta \tilde{H}_t$	15.8126* [0.0000]	…..	0.2500 [0.7752]	4.5870** [0.0114]	2.6436*** [0.0739]	0.0043 [0.9573]	1974	−0.0192 [−1.3456]
$\sum \Delta \tilde{Y}_t$	10.6646* [0.0000]	0.0367 [0.9639]	…..	32.1607* [0.0000]	0.4173 [0.6594]	1.7726 [0.1729]	1990	−0.0250* [−2.6701]
$\sum \Delta \tilde{K}_t$	4.1987** [0.0165]	4.5162** [0.0112]	34.5064* [0.0000]	…..	3.6494** [0.0280]	0.3788 [0.6852]	1990	−0.0589* [−4.6487]
$\sum \Delta \tilde{I}_t$	2.2061 [0.0025]	3.0075** [0.0520]	3.0973** [0.0476]	7.0456* [0.0011]	…..	1.8987 [0.1528]	1983	−0.1046* [−4.5740]
$\sum \Delta \tilde{R}_t$	0.6511 [0.5227]	0.0803 [0.9229]	0.9295 [0.3982]	0.6044 [0.5475]	2.6892*** [0.0707]	…..	1995	−0.0624* [−3.4874]
	Dirty Energy Consumption							
	$\sum \Delta E\tilde{C}_t$	$\sum \Delta \tilde{H}_t$	$\sum \Delta \tilde{Y}_t$	$\sum \Delta \tilde{K}_t$	$\sum \Delta \tilde{I}_t$	$\sum \Delta \tilde{R}_t$	Break Year	ECM_{t-1}
$\sum \Delta E\tilde{C}_t$	…..	14.9656* [0.0000]	21.0009* [0.0000]	0.9161 [0.4019]	0.4245 [0.6548]	0.1749 [0.8396]	2002	−0.0105* [−2.7067]
$\sum \Delta \tilde{H}_t$	15.3981* [0.0000]	…..	0.1772 [0.8377]	1.5558 [0.3172]	0.4776 [0.6271]	1.8132 [0.1661]	1974	−0.0017 [−0.8707]
$\sum \Delta \tilde{Y}_t$	19.0305* [0.0000]	1.3897 [0.2518]	…..	34.6226* [0.0000]	0.4411 [0.6440]	3.7798** [0.0247]	1990	−0.0209* [−2.6142]
$\sum \Delta \tilde{K}_t$	1.2895 [0.2780]	2.8912*** [0.0581]	35.0107* [0.0000]	…..	3.2614** [0.0406]	26.2990 [0.0000]	1990	−0.0424* [−3.7601]
$\sum \Delta \tilde{I}_t$	5.7971* [0.0036]	1.1897 [0.1635]	2.5697*** [0.0794]	4.0545** [0.0190]	…..	1.8624 [0.1583]	1983	−0.1298 [1.5762]
$\sum \Delta \tilde{R}_t$	0.8076 [0.4476]	0.0657 [0.9364]	0.8186 [0.4427]	1.0009 [0.3348]	2.7096*** [0.0693]	…..	1995	−0.0843* [−4.2376]
	Clean Energy Consumption							
	$\sum \Delta E\tilde{C}_t$	$\sum \Delta \tilde{H}_t$	$\sum \Delta \tilde{Y}_t$	$\sum \Delta \tilde{K}_t$	$\sum \Delta \tilde{I}_t$	$\sum \Delta \tilde{R}_t$	Break Year	ECM_{t-1}

$\sum \Delta E\tilde{C}_t$	…..	13.7230* [0.0000]	10.6331* [0.0000]	7.5406* [0.0007]	56.0922* [0.0000]	0.0077 [0.9922]	1990	−0.0275** [−1.9553]
$\sum \Delta \tilde{H}_t$	16.3703* [0.0000]	…..	6.3170* [0.0022]	4.5673** [0.0117]	0.7312 [0.4828]	0.0742 [0.9285]	1974	−0.0068 [−0.5262]
$\sum \Delta \tilde{Y}_t$	10.2763* [0.0001]	6.0684* [0.0029]	…..	6.2478* [0.0019]	8.7960* [0.0002]	1.9174 [0.1502]	1990	−0.0163*** [−1.8917]
$\sum \Delta \tilde{K}_t$	4.8391* [0.0091]	4.1121** [0.0181]	6.1555* [0.0025]	…..	5.5621* [0.0046]	0.7566 [0.4708]	1990	−0.0571* [−4.1220]
$\sum \Delta \tilde{I}_t$	58.7081* [0.0000]	1.1341 [0.3242]	10.1264* [0.0000]	7.9860* [0.0005]	…..	0.4872 [0.6152]	1983	−0.0793* [−4.3453]
$\sum \Delta \tilde{R}_t$	0.1094 [0.8964]	0.0744 [0.9283]	1.5432 [0.2167]	0.5376 [0.5851]	1.2381 [0.2926]	…..	1995	−0.0503* [−2.6671]

Note: *t*-statistics are given in parentheses. *, ** and *** represent the level of significance at 1%, 5%, and 10%, respectively.

The long-run causality analysis for the energy consumption-human capital nexus indicates that human capital Granger causes energy consumption, but the same is not true from the opposite side. However, one-way causality from human capital to economic growth, capitalization, energy imports, and research and development expenditures is noted. There is a Granger causality between capital and energy consumption. Imported energy and energy consumption also exhibit a bidirectional causal effect. Research and development expenditures Granger-cause energy consumption and, consequently, energy consumption Granger-causes research and development expenditures. There does exist a bidirectional causality between capital and energy consumption. Imported energy causes energy consumption, but the reverse is not true. A feedback effect is also found between capital (imported energy) and human capital. Unidirectional causality exists from imported energy to R&D expenditures. Similarly, there is a feedback effect between capital and economic growth. However, imported energy and capital are interdependent.

VI. Concluding Remarks and Policy Implications

This study examined the effects of human capital, capitalization, imported energy, and economic growth on the consumption of different types of energy (e.g., dirty and clean) by estimating the augmented energy demand for China using data from 1971 to 2018. We employed bounds testing and VECM Granger causality approaches to study the nature of relationship between energy consumption and its associated variables. The empirical results indicated that variables included in the overall energy demand function, dirty energy demand, and clean energy demand function were cointegrated. We found a dismissive effect of human capital on overall energy consumption and dirty energy consumption, but a positive impact on clean energy demand.

Economic growth is positively (negatively) linked with energy consumption and clean energy consumption (dirty energy consumption). Capitalization causes a decline in the consumption of overall energy and dirty energy consumption, but it increases the consumption of clean energy. Similarly, R&D expenditures positively impact clean energy consumption, whereas an increase in R&D causes a decline in the consumption of overall energy and dirty energy. The analysis uncovers the incidence of causality from human capital to energy consumption, dirty energy consumption, and clean energy consumption. There is a two-way causality between economic growth and energy consumption (dirty energy, clean energy). Capitalization and energy consumption (dirty and clean) show a bidirectional causality. Similarly, research and development expenditures cause energy consumption, dirty energy consumption, and clean energy consumption, resulting in energy consumption, dirty energy consumption, and clean energy consumption, which cause R&D expenditures (i.e., feedback effects).

Human energy consumption is increasing daily, and coal and oil are the main energy sources. The energy consumption revolution with the priority of saving at its core drives the consumption growth rate from medium speed to low speed step by step, even decoupled from sustained economic growth, which is the general law of energy development. According to the above research, energy consumption is affected by many factors. To further promote the energy revolution and sustained economic development, China should take corresponding measures in the following respects:

First, it should enhance human capital and fully play its role in promoting the green development of energy. First, it supports the production of clean energy, optimizes the structure of energy production, and increases the supply of clean energy. Next, we optimize the energy consumption structure, increase clean energy consumption, and reduce pollution energy consumption. Finally, China should encourage the intensive and economical use of energy, improve utilization efficiency, and reduce energy consumption. Second, China should increase R&D expenditures, stimulate the technological innovation of enterprises, and improve energy efficiency and clean energy production. At present, China's clean energy development is in its initial stage, and the proportion of clean energy consumption in China's energy consumption is still relatively low. China should provide policy support and formulate preferential policies to encourage enterprises to develop a clean energy industry, which will increase clean energy consumption and reduce total energy consumption and polluting energy consumption.

Third, China's economic development needs to consume great amounts of energy, and domestic energy production cannot meet the needs of economic development. Imported energy is a useful supplement that can solve China's energy shortage. Even so, China should optimize the structure of imported energy and increase the proportion of clean energy. Taking one belt, one road construction as the key point, measures are needed to promote energy productivity cooperation, strengthen infrastructure interconnection, and build a comprehensive position and deep-level international energy cooperation pattern. Last but not least, China's economic growth has often led to an increase in total energy consumption, but high-quality economic development will support economic development with lower energy consumption. It should establish policy guidance for green energy development, improve the economic system of green and low-carbon development, build a safe and efficient energy system, and actively develop green technology, green products, and green services. The world is entering a period of economic development dominated by digital industry. Digitalization and intellectualization will continuously tap the potential of energy enterprises in cost reduction and efficient industrial collaboration, create space for marketing and value growth, and promote new platforms and modes of new changes. The deep integration of digital technology and the real economy creates conditions for the development of the modern energy industry and service systems. China should vigorously develop the digital economy, provide huge support for users to control energy consumption and independent production, and ultimately reduce costs and increase efficiency.

Reference

Aghion, P. and Howitt, P. (2009). The Economics of Growth. MIT Press: Cambridge.

Ahmad, M. and Khan, R. E. A. (2019). Does demographic transition with human capital dynamics matter for economic growth? A dynamic panel data approach to GMM. Social Indicators Research, 142, 753-772.

Akinlo, A. E. (2009). Electricity consumption and economic growth in Nigeria: Evidence from cointegration and co-feature analysis. Journal of Policy Modeling, 31(5), 681-693.

Alaali, F., Roberts, J. and Taylor, K. (2015). The effect of energy consumption and human capital on economic growth: An exploration of oil exporting and developed countries. SERPS (Sheffield Economics Research Papers Series), 015.

Andreoni, J. and Levinson, A. (2001). The simple analytics of the environmental Kuznets curve. Journal of Public Economics, 80, 269-286.

Apergis, N. and Payne, J. E. (2010). Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. Energy Policy, 38, 656-660.

Arbex, M. and Perobelli, F. S. (2010). Solow meets Leontief: Economic growth and energy consumption. Energy Economics, 32(1), 43-53.

Azam, M. (2019). Relationship between energy, investment, human capital, environment, and economic growth in four BRICS countries. Environmental Science and Pollution Research International. Environmental Science, 26(33), 34388-34400.

Bah, M. M. and Azam, M. (2017). Investigating the relationship between electricity consumption and economic growth: Evidence from South Africa. Renewable and Sustainable Energy Reviews, 80, 531-537.

Balaguer, J. and Cantavella, M. (2018). The role of education in the environmental Kuznets curve. Evidence from Australian data. Energy Economics, 70, 289-296.

Balan, F. (2016). Environmental quality and its human health effects: A causal analysis for the EU25. International Journal of Applied Economics, 13, 57-71.

Bano, S., Zhao, Y., Ahmad, A., Wang, S. and Ya, L. (2018). Identifying the impacts of human capital on carbon emissions in Pakistan. Journal of Cleaner Production, 183, 1082-1092.

Barro, R. J. (2001). Human capital and growth. The American Economic Review, 91, 12-17.

Barro, R. J. and Sala-i-Martin, X. (1997). Technological diffusion, convergence, and growth. Journal of Economic Growth, 2, 1-26.

Becker, G. (1964). Human Capital. A Theoretical and Empirical Analysis with Special Reference to Education. Columbia University Press: New York.

Bengoa, M., Román, V. M. S. and Pérez, P. (2017). Do R&D activities matter for productivity? A regional spatial approach assessing the role of human and social capital. Economic Modelling, 60, 448-461.

Benhabib, J. and Spiegel, M. M. (2005). Chapter 13 Human Capital and Technology Diffusion. In P. Aghion & S. N. Durlauf (Eds.), Handbook of Economic Growth (Vol. 1, pp. 935-966): Elsevier. Bierens, H. J. (1997). Nonparametric cointegration analysis. Journal of

Econometrics, 77, 379-404.

Bovenberg, A. L. and Smulders, S. (1995). Environmental quality and pollution-augmenting technological change in a two-sector endogenous growth model. Journal of Public Economics, 57, 369-391.

BPSTATS (2019). British Petroleum Statistical Review of World Energy Statistical Review of World. British Petroleum Statistical Review, 68th edition.

Chen, Y. and Fang, Z. (2018). Industrial electricity consumption, human capital investment and economic growth in Chinese cities. Economic Modelling, 69, 205-219.

Ciccone, A. and Peri, G. (2006). Identifying human-capital externalities: Theory with applications. Review of Economic Studies, 73, 381-412.

Cinnirella, F. and Streb, J. (2017). The role of human capital and innovation in economic development: Evidence from post-Malthusian Prussia. Journal of Economic Growth, 22, 193-227.

Cole, M. A., Elliott, R. J. R. and Wu, S. S. (2008). Industrial activity and the environment in China: An industry-level analysis. China Economic Review, 19, 393-408.

Curea, Ş. C. and Ciora, C. (2013). The impact of human capital on economic growth. Quality – Access to Success, 14, 395-399.

Davies, R. B. (1977). Hypothesis testing when a nuisance parameter is present only under the alternative. Biometrika, 64, 247-254.

Enders, W. and Lee, J. (2012). A unit root test using a Fourier series to approximate smooth breaks. Oxford Bulletin of Economics and Statistics, 74, 574-599.

Enerdata (2018). Enerdata: Global energy statistical yearbook 2018. WWW document.

Engle, R. F. and Granger, C. W. J. (1987). Cointegration and error correction representation: Estimation and testing. Econometrica, 55, 251-276.

Fang, Z. and Chang, Y. (2016). Energy, human capital and economic growth in Asia Pacific countries - Evidence from a panel cointegration and causality analysis. Energy Economics, 56, 177-184.

Fang, Z. and Chen, Y. (2017). Human capital and energy in economic growth - Evidence from Chinese provincial data. Energy Economics, 68, 340-358.

Fang, Z. and Yu, J. (2020). The role of human capital in energy-growth nexus: An international evidence. Empirical Economics, 58(3), 1225-1247.

Fang, Z. and Yu, J. (2020). The role of human capital in energy-growth nexus: An international evidence. Empirical Economics, 58, 1225-1247.

Fang, Z., Chang, Y. and Hamori, S. (2020). Human capital and energy: A driver or drag for economic growth. Singapore Economic Review, 65, 683-714.

Fatima, N., Li, Y., Ahmad, M., Jabeen, G. and Li, X. (2019). Analyzing long-term empirical interactions between renewable energy generation, energy use, human capital, and economic performance in Pakistan. Energy, Sustainability and Society, 9, 42.

Gallant, A. (1981). On the bias in flexible functional forms and an essentially unbiased form: The Fourier flexible form. Journal of Econometrics, 15, 211-245.

Gradus, R. and Smulders, S. (1993). The trade-off between environmental care and long-term growth - Pollution in three prototype growth models. Journal of Economics/Zeitschrift für Nationalökonomie, 58, 25-51.

Graff, Z. J. and Matthew, N. (2013). Environment, health, and human capital. Journal of Economic Literature, 51, 689-730.

Granger, C. W. J. (1969). Investigating causal relations by econometric models and cross-spectral methods. Econometrica, 37, 424-438.

Gregory, A. W. and Hansen, B. E. (1996). Residual-based tests for cointegration in models with regime shifts. Journal of Econometrics, 70, 99-126.

Haini, H. (2021). Examining the impact of ICT, human capital and carbon emissions: Evidence from the ASEAN economies. International Economics, 116, 116-125.

Hakooma, M. R. and Seshamani, V. (2017). The impact of human capital development on economic growth in Zambia: An Econometric Analysis. International Journal of Economics, Commerce and Management, United Kingdom, 5, 71-87.

Hakooma, M. R. and Seshamani, V. (2017). The impact of human capital development on economic growth in Zambia: An Econometric Analysis. International Journal of Economics, Commerce and Management, United Kingdom, V, 4, 71-87.

Herrerias, M. J., Joyeux, R. and Girardin, E. (2013). Short- and long-run causality between energy consumption and economic growth: Evidence across regions in China. Applied Energy, 112, 1483-1492.

Hulten, C. R., Bennathan, E. and Srinivasan, S. (2006). Infrastructure, externalities, and economic development: A study of the Indian manufacturing industry. World Bank

Economic Review, 20, 291-308.
Hussain, J. and Hassan, S. (2019). Global energy transition and the role of energy mix in creating energy crisis in Pakistan. Pakistan Journal of Humanities and Social Sciences, 7(2), 219-232.
Iorember, P. T., Jelilov, G., Usman, O., Işık, A. and Celik, B. (2021). The influence of renewable energy use, human capital, and trade on environmental quality in South Africa: Multiple structural breaks cointegration approach. Environmental Science and Pollution Research International, 28(11), 13162-13174.
Jacob, M. (1984). Human capital and economic growth. Economics of Education Review, 3, 195-205.
Johansen, S. and Juselius, K. (1990). Maximum likelihood estimation and inference on cointegration-with applications to the demand for money. Oxford Bulletin of Economics and Statistics, 52, 169-210.
Jones, D. C., Li, C. and Owen, A. L. (2003). Growth and regional inequality in China during the reform era. China Economic Review, 14, 186-200.
Joshua, J. (2015). The Accumulation of human capital as a factor of production. In: The Contribution of Human Capital Toward Economic Growth in China. Palgrave MacMillan: London. https://doi.org/10.1057/9781137529367_3.
Kahia, M. (2017). Renewable and non-renewable energy use - economic growth nexus: The case of MENA Net Oil Importing Countries. Aïssa, M.S. and ben, Lanouar, C. Renewable and Sustainable Energy Reviews, 71, 127-140.
Kanayo, O. (2013). The impact of human capital formation on economic growth in Nigeria. Journal of Economics, 4, 121-132.
Kaufman, N. A. and Geroy, G. D. (2007). An energy model for viewing embodied human capital theory. Performance Improvement Quarterly, 20, 37-48.
Keeble, B. R. (1988). The Brundtland report: Our common future. Medicine and War, 4, 17-25.
Kim, J. and Heo, E. (2013). Asymmetric substitutability between energy and capital: Evidence from the manufacturing sectors in 10 OECD countries. Energy Economics, 40, 81-89.
Kwon, D.-B. (2009). Human capital and its measurement. In: Proc. therapeutic 3rd OECD world forum on Statistics. Knowledge and Policy, 6-7.

Lan, J. and Munro, A. (2013). Environmental compliance and human capital: Evidence from Chinese industrial firms. Resource and Energy Economics, 35, 534-557.

Lan, J., Kakinaka, M. and Huang, X. (2012). Foreign direct investment, human capital and environmental pollution in China. Environmental and Resource Economics, 51, 255-275.

Le, T. and Nad Bodman, P. M. (2011). Remittances or technological diffusion: Which drives domestic gains from brain drain? Applied Economics, 43, 2277-2285.

Lee, C.-C., Chang, C.-P. and Chen, P.-F. (2008). Energy-income causality in OECD countries revisited: The key role of capital stock. Energy Economics, 30, 2359-2373.

Leybourne, S. J., Mills, T. C. and Newbold, P. (1998a). Spurious rejections by Dickey-Fuller tests in the presence of a break under the null. Journal of Econometrics, 87, 191-203.

Leybourne, S., Newbold, P. and Vougas, D. (1998b). Unit roots and smooth transitions. Journal of Time Series Analysis, 19, 83-97.

Li, H. and Huang, L. (2009). Health, education, and economic growth in China: Empirical findings and implications. China Economic Review, 20, 374-387.

Li, K. and Lin, B. (2016). Impact of energy technology patents in China: Evidence from a panel cointegration and error correction model. Energy Policy, 89, 214-223.

Li, K. W. and Liu, T. (2011). Economic and productivity growth decomposition: An application to post-reform China. Economic Modelling, 28, 366-373.

Li, P. and Ouyang, Y. (2019). The dynamic impacts of financial development and human capital on CO2 emission intensity in China: An ARDL approach. Journal of Business Economics and Management, 20, 939-957.

Li, Y., Fatima, N., Ahmad, M., Jabeen, G. and Li, X. (2019). Dynamic long-run connections among renewable energy generation, energy consumption, human capital and economic performance in Pakistan. In: 4th International Conference on Power and Renewable Energy, ICPRE 2019 2019.

Llesanmi, K. D. and Tiwari, D. D. (2017). Energy consumption, human capital investment and economic growth in South Africa: A vector error correction model analysis. OPEC Energy Review, 41, 55-70.

Lucas, R. E., Jr. (1988). On the mechanics of economic development. Journal of Monetary Economics, 22, 3-42.

Lütkepohl, H. (2006). Structural vector autoregressive analysis for cointegrated variables. AStA

Advances in Statistical Analysis, 90, 75-88.
Madariaga, N. and Poncet, S. (2007). FDI in Chinese cities: Spillovers and impact on growth. World Economy, 30, 837-862.
Mankiw, N. G., Romer, D. and Weil, D. N. (1992). A contribution to the empirics of economic growth. Quarterly Journal of Economics, 107, 407-437.
Mattalia, C. (2012). Human capital accumulation in R&D-based growth models. Economic Modelling, 29, 601-609.
McNown, R., Sam, C. Y. and Goh, S. K. (2018). Bootstrapping the autoregressive distributed lag test for cointegration. Applied Economics, 50, 1509-1521.
Meyer, A. (2016). Heterogeneity in the preferences and pro-environmental behavior of college students: The effects of years on campus, demographics, and external factors. Journal of Cleaner Production, 112, 3451-3463.
Mincer, J. (1958). Investment in human capital and personal income distribution. Journal of Political Economy, 66, 281-302.
Mincer, J. (1962). On the job training: Costs, returns, and some implications. Journal of Political Economy, 70, 550-579.
Mohamed Arabi, K. A. and Suliman Abdalla, S. Z. (2013). The impact of human capital on economic growth: Empirical evidence from Sudan. Research in World Economy, 4, 43-53.
Narayan, P. (2005). The saving and investment Nexus for China: Evidence from cointegration tests. Applied Economics, 37, 1979-1990.
Nasir, M. A., Rizvi, R. A. and Rossi, M. (2018). A treatise on oil price shocks and their implications for the UK Financial Sector: Analysis based on time-varying structural VAR model. Manchester School, 86, 586-621.
Nelson, R. and Phelps, E. (1966). Investment in humans, technology diffusion and economic growth. The American Economic Review, 56, 69-75.
Obydenkova, A. V. and Salahodjaev, R. (2017). Climate change policies: The role of democracy and social cognitive capital. Environmental Research, 157, 182-189.
Oluwatobi, S. O. and Ogunrinola, O. I. (2011). Government expenditure on human capital development: Implications for economic growth in Nigeria. Journal of Sustainable Development, 4, 72-80.
Ouyang, P. and Fu, S. (2012). Economic growth, local industrial development and inter-regional

spillovers from foreign direct investment: Evidence from China. China Economic Review, 23, 445-460.
Oyedepo, S. O. (2012). Energy and sustainable development in Nigeria: The way forward. Energy. Sustainability and Society, 2(15).
Pablo-Romero, M. del P. and Sánchez-Braza, A. (2015). Productive energy use and economic growth: Energy, physical and human capital relationships. Energy Economics, 49, 420-429.
Pablo-Romero, M. del. P. and Sanchez-Braza, A. (2015). Productive energy use and economic growth: energy, physical and human capital relationships. Energy Economics, 49, 420-429.
Perron, P. (1989). The great crash, the oil price shock, and the unit root hypothesis. Econometrica, 57, 1361-1401.
Pesaran, M. H. and Shin, Y. (1999). An autoregressive distributed lag modelling approach to cointegration analysis. In: Econometrics and Economic Theory in the 20th Century: The Ragnar Frisch Centennial Symposium. S. Strom (Ed.). Cambridge University Press.
Pesaran, M. H., Shin, Y. and Smith, R. S. (2001). Bounds testing approaches to the analysis of level relationships. Journal of Applied Econometrics, 16, 289-326.
Rauch, J. (1993). Productivity gains from geographic concentration in cities. Journal of Urban Economics, 34, 380-400.
Richmond, A. K. and Kaufmann, R. K. (2006). Is there a turning point in the relationship between income and energy use and/or carbon emissions? Ecological Economics, 56, 176-189.
Salahodjaev, R. (2018). Is there a link between cognitive abilities and environmental awareness? Cross-national evidence. Environmental Research, 166, 86-90.
Salim, R., Yao, Y. and Chen, G. S. (2017b). Does human capital matter for energy consumption in China? Energy Economics, 67, 49-59.
Sarkodie, S. A., Adams, S., Owusu, P. A., Leirvik, T. and Ozturk, I. (2020). Mitigating degradation and emissions in China: The role of environmental sustainability, human capital and renewable energy. Science of the Total Environment, 719, 137530.
Schultz, T. (1961). Investment in human capital. American Economic Review, 51, 1-17.
Sen, A. (1997). Editorial. Human capital and human capability. World Development, 25, 1959-1961.
Shahbaz, M., Gozgor, G. and Hammoudeh, S. (2019). Human capital and export diversification

as new determinants of energy demand in the United States. Energy Economics, 78, 335-349.

Shahbaz, M., Raghutla, C., Song, M., Zameer, H. and Jiao, Z. (2020a). Public–private partnerships investment in energy as new determinant of CO_2 emissions: The role of technological innovations in China. Energy Economics.

Shahbaz, M., Khraief, N. and Czudaj, R. L. (2020b). Renewable energy consumption-economic growth nexus in G7 countries: New evidence from a nonlinear ARDL approach. Economics Bulletin, 40, 2828-2843.

Shahbaz, M., Omay, T. and Roubaud, D. (2018). Sharp and smooth breaks in unit root testing of renewable energy consumption: The way forward. Journal of Energy and Development, 44, 5-39.

Šlaus, I. and Jacobs, G. (2011). Human capital and sustainability. Sustainability, 3, 97-154.

Su, Y. and Liu, Z. (2016). The impact of foreign direct investment and human capital on economic growth: Evidence from Chinese cities. China Economic Review, 37, 97-109.

Teixeira, A. A. C. and Queirós, A. S. S. (2016). Economic growth, human capital and structural change: A dynamic panel data analysis. Resources Policy, 45, 1636-1648.

The World Bank Group (2015). Beyond connections: Energy access redefined. Technical Report. World Bank, 008/15.

The World Bank Group (2019). GDP per capita (current US$). WWW Document. World Bank.

Wang, Y. and Liu, S. (2016). Education, human capital and economic growth: Empirical research on 55 countries and regions (1960-2009). Theoretical Economics Letters, 6, 347-355.

World Economic Forum (2017). The Global Human Capital Report 2017: Preparing People for the Future of Work. World Economic Forum: Geneva.

Xu, X. L. and Liu, C. K. (2019). How to keep renewable energy enterprises to reach economic sustainable performance: From the views of intellectual capital and life cycle. Energy, Sustainability and Society, 9, 7.

Zhu, X., Whalley, J. and Zhao, X. (2014). Intergenerational transfer, human capital and long-term growth in China under the one child policy. Economic Modelling, 40, 275-283.