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The Impact of Technological Innovation on Energy Consumption in OECD Economies: The Role of Outward Foreign Direct Investment and International Trade Openness

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ABSTRACT

Over the last few years, empirical evidence has revealed that technological innovation plays a significant impact in reducing energy consumption and mitigation of carbon emission. But to achieve technological progress toward energy consumption sustainability, depend on several other factors. To this end, this study examines the role of outward foreign direct investment and international trade openness in innovation-energy nexus for 24 OECD countries for the period 1996-2015. To address econometric issues such as cross-sectional dependence, endogeneity, heterogeneity in the panel estimation process, this study employs the cross-sectionally augmented autoregressive distributed lags (CS-ARDL), augmented mean group estimator (AMG), and the System Generalized Methods of Moments (SYS-GMM) techniques. Finding reveals that the moderating effects of outward FDI and trade openness in the indirect relationship between technological innovation and energy demand exhibits an inverted U-shape curve. Specifically, this study finds that the impact of technological innovation on energy consumption via reverse technology spillover effect from outward FDI reinforces OECD countries toward energy-saving environmental sustainability both in the short-run and long-run. Furthermore, the joint impact of technological innovation and trade openness on energy demand is negative and statistically significant in the short and long run. This strengthens the efficiency of technologically innovative capabilities of OECD countries to effectively reduce energy consumption. These results are robust to different specifications and consistent across the various estimators, with sets of policy implication discussed.

Keywords: Energy Consumption, Outward FDI, Trade Openness, CS-ARDL, Technology Innovation, OECD
JEL Classifications: F18, F23, O32, Q43

1. INTRODUCTION

Studies have showed that energy consumption remain an integral part of economic development (Belke et al., 2011; Apergis and Payne, 2010) and follows the growth hypothesis which suggests that an increase in energy consumption causes an increase in real GDP and vice versa (Apergis and Tan, 2013). But the continuous increase in both domestic and industrial energy demand, have become worrisome to policymakers, practitioners and academic scholars. This has led to numerous scientific publications with several energy policy recommendations. Report shows that approximately 84% of global energy consumption comes from fossil fuels (Ritchie and Roser, 2020), and the production and consumption of fossil fuels releases large amounts of carbon dioxide (CO_2) which has severe adverse environmental effects such as global warming, increased health risks, air pollution, etc. Energy consumption in residential buildings account for 23% of global final energy demand (IEA, 2007) and 17% of world's carbon dioxide (CO_2) emissions (OECD/IEA, 2015). Specifically, lighting, cooking, appliances, water heating, and space heating in residential sector account for 5%, 5%, 21%, 16%, and 53% respectively (IEA, 2008). High energy consumption give rise to the emissions of greenhouse gas (GHG), which in-turn affect climate change and global warming (Murad et al., 2019). Thus, there is a great need to reduce the overall energy consumption and CO_2 emission for environmental sustainability as well as for the survival of mankind (Sayigh, 2013).

Recently, scholars have turned attention to technological innovation as a way to solve problems related to global fossil fuels production and energy consumption. Environmental related technologies and innovation are seen as one major driver of energy generation, energy transformation and efficient energy usage that reduces CO_2 emission toward environmental sustainability and economic growth. Technological innovation can affect energy demand leading to greener growth and a cleaner environment (Ulucak, 2020). The rising awareness and gains of the impact of technological innovation toward energy consumption and carbon reduction has encouraged various countries' governments and policymakers to increase investment for greener awareness programs and environmental protection, especially in terms of energy efficiency and energy transformation (Paramati et al., 2021; Ulucak, 2020; Lin and Du, 2013). According to Khazzoom (1987), Brookes (1992), the impact of technology on energy efficiency may reduce energy consumption in the short run, but the advent of new, green and advanced technology are likely to enhanced energy efficiency toward achieving minimum energy consumption in the long run. Technological innovation has shown to facilitates economic growth which in turn increases energy demand and promotes carbon emission in the long term, a phenomenon explained as a rebound effect (González, 2011). Thus, technological innovation which drives economic growth strategies have become a suitable approach to reduce energy intensity and mitigate CO_2 emission in many countries particularly developed countries.

However technological progress toward sustainability in consumption is contingent not only on R&D input, but also need the synergy of other crucial determinants such as human capital, outward FDI, trade openness, etc., in order to make tremendous impact in achieving clean environment with less energy consumption. Hence, Liu et al. (2022) paper put it succinctly, "a country can not only realize technological progress through independent innovation, but also through technology spillover of foreign trade and global investment". Considering the global rapid economic growth and development with the expected increase in energy demand, numerous studies have sought to examine the relationship between technological innovation and energy demand (Liu et al., 2021; Zhu et al., 2021; Li et al., 2021; Zeraibi et al., 2020; Zhang et al., 2020; Murad et al., 2019; Grushevenko et al., 2018; Dudin et al., 2017; Zhang and Lu, 2015; Chou, 2015). But to our knowledge, most of these studies examine the direct impact of technological innovation on energy consumption, and the analysis are often in country-specific framework (Li and Solaymani, 2021; Zhang et al., 2020; Grushevenko et al., 2018; Chou et al., 2015). Nevertheless, few studies have examined how and whether other economic determinants drive the impact of technological innovation on energy consumption (Uddin et al., 2022 - financial development; Lin and Chen, 2020 - non-ferrous metal). This implies that technology innovation dependency of other economic determinant in examining energy consumption are often ignored in previous literature, therefore, the influencing mechanism between these two variables (technological innovation and energy demand) are often not known. To this end, this study examines the role of outward FDI and trade openness in the impact of technological innovation on energy consumption for 24 OECD countries for the period 1996-2015.

Foreign direct investment (FDI) plays a significant role in transferring advanced technology from home countries to host or its affiliate abroad leading to higher productivity and economic growth through high quality labor mobility, transfer of advanced technology to domestic firms, and the introduction of advanced managerial experience (Cole et al., 2008; Blalock and Gertler, 2008). Thus, multinational corporation (MNCs) increases technology absorption and promote intellectual capital investment of enterprises. These activities help integrate domestic economy into the global economy. However, one of the major sources of technology transfer is via firm's outward FDI internationalization activities which bring about reverse technology spillover effects to the home country. Such spillover may be put in three groups, namely, energy-saving technologies, efficiency of production, and an economic structure shift. Reverse technology spillover effect from outward FDI improves domestic technology innovation and enhances energy efficiency through increasing energy-saving technologies and products which reduces energy consumption (Zhou et al., 2021). But on the dark side, some economic scholars view that the reverse technology spillover may stimulate economic growth, increase household consumption, and raises industrial production which give rise to increase in energy demand and increases carbon emission (Bu et al., 2019; Hübler and Keller, 2009). But whether outward FDI flow bring about technology improvement and increase energy demand which in-turn increases the amount of carbon emission for home country remain controversial (Pan et al., 2020). Thus, examining the technique effect of outward FDI in innovation-energy nexus for OECD countries will be of great significance.

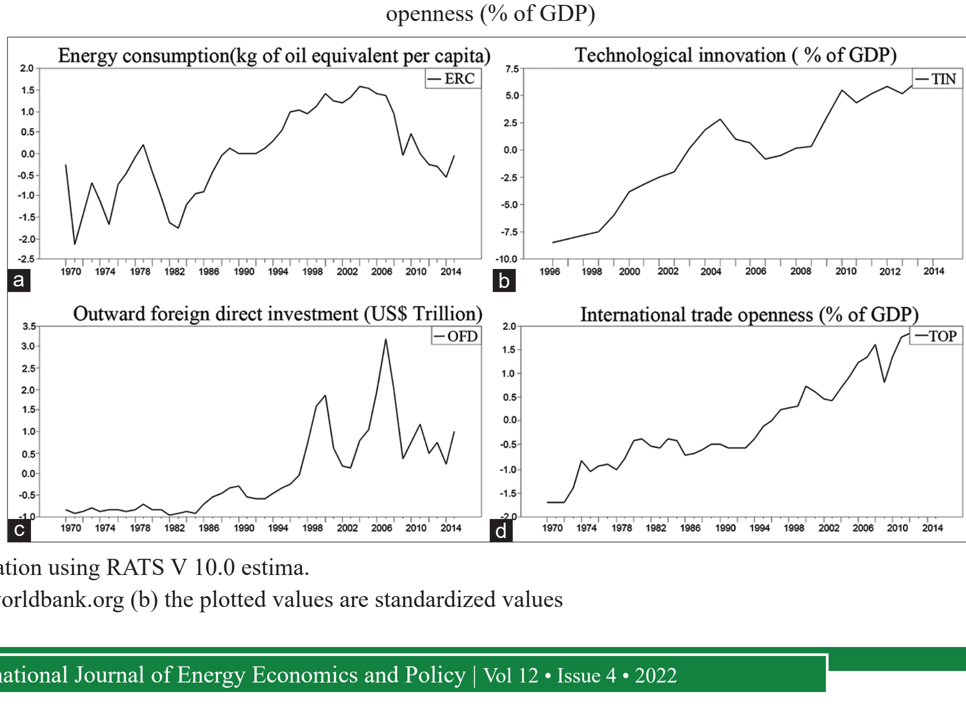
Trade openness is another crucial determinant that also influences energy consumption through trade policies. Trade openness among OECD countries enables member country to transfer and receive foreign advanced technologies for economic growth and development, and simultaneously promote environmental sustainability. With technological progress, higher level of trade openness may bring about structural transformation that reduces energy demand (Gozgor, 2017). Thus, trade openness can lead to a reduction in energy consumption, particularly in developed countries, such as OECD countries. Effects of trade openness on energy demand maybe positive or negative, and these effects can be scale, technique and composite effect. The increase in domestic production which increases energy consumption via trade openness, is known as scale effect (Shahbaz et al., 2014) and the use of new and advance technologies in lowering energy demand is known as technique effect (Shahbaz et al., 2014; Arrow, 1962). However, the shift in the use of technology for energy intensive production from agricultural sector to industrial sector is known as composite effect. Positive impact of trade openness on energy demand suggests more energy conservations policies should be adopted to counterbalance the trade liberalization policies formulated to stimulate economic activity (Koengkan, 2018). However, negative effect suggests that trade openness abet energy consumption reduction. This study examines the direct and indirect impact of technological innovation on energy consumption via trade openness.

Figure 1 displays more than four decades time series trend of energy consumption, technological innovation, outward FDI and trade openness for OECD countries. Plot (a) reveals that energy consumption in OECD countries in the last two decades have been reduced considerably, given the continuing rising trend of technological innovation (see Plot b) in OECD respective countries. This suggests that OECD government investments in green technology is yielding desirable results. However, outward FDI flow in OECD countries showed an upward trend and appears to have gained momentum in early 1990s (see Plot c) and seems to have been impacted by the early 2000s recession and the 2007-2009 global financial crisis (GFC). Plot (d) shows that trade openness in OECD countries has been in upward trend before 1970s and appears to have also been affected by the 2007-2009 global crisis. The upward fluctuation of trade in OECD countries indicates that member countries have continued to open it borders for international trade and cooperation. OECD countries are high-income and economically developed countries with advanced technological infrastructure. The positive link between energy demand and economic growth clearly suggests that OECD countries may have expended huge capital investment on environmental-friendly technologies in an effort to reduce energy demand and abate carbon emission. However, outward FDI spillover effects and trade openness among OECD countries may improve the economy, reduce energy demand and mitigate carbon emission via the scale and technique effect or bring about more carbon if spillover of high energy consuming technologies and products enters OECD market due to poor Trade policies. Thus, outward FDI and trade openness are crucial determinants in lowering energy demand and abating carbon emission.

The contributions of this study to literature are as follows: Firstly, unlike previous studies which examines only the direct impact of home country innovation on energy consumption, this study examines both the direct and indirect (intermediary effects) effect of technological innovation on energy consumption in improving the efficiency of energy-using systems and products to reduce energy demand and enhance environmental sustainability. The indirect impact mediated via outward FDI spillover effects and trade openness reveals some crucial findings both in the short-run and long-run. Finding reveals that the inclusion of outward FDI to innovation-energy demand nexus in OECD countries, give rise to negative effect both in the short-run and long run. This indicates that outward FDI spillover effect stimulates domestic innovation to enhance eco-friendly technologies toward energy efficiency and energy saving economies. Secondly, this study finds that trade openness in OECD countries boost domestic innovation capabilities and system to improve energy efficiency through the technique effects. Thirdly, the moderating effect of outward FDI spillovers appears to be more efficient in lowering energy demand than the joint impact of innovation and trade openness, both in the long run and in the short run. Finally, the indirect models appear to support an inverted U-shape curve. Based on these contributions, this study provides policy reference for energy-saving toward sustainability.

The rest of the paper is organized as follows. Section 2 discuss briefly related literatures on the relationship between energy consumption and technology innovation. Section 3 introduces the empirical model and data as well as explains the econometric methodology. Section 4 reports the empirical findings. Section 5 concludes the paper by discussing the findings and the policy implications.

Figure 1: Plots showing energy consumption, technological innovation, outward FDI and international trade. (a) Energy consumption (kg of oil equivalent per capita). (b) Technological innovation (% of GDP). (c) Outward foreign direct investment (US$ Trillion). (d) International trade openness (% of GDP)



Source: Authors evaluation using RATS V 10.0 estima.

Data: (a) https://data.worldbank.org (b) the plotted values are standardized values

2. REVIEW OF RELATED LITERATURE

2.1. Technological Innovation and Energy Consumption Nexus

Prior to discussing the linkages between energy consumption and technological innovation, this study addresses the different proxy previous literature have used to measure technological innovation. Wurlod and Noailly (2018); Noailly and Shestalova (2017); Popp (2005) studies describe some characteristic of patents and patent data and applied it as proxy for technological change. They argued that number of patents are not only used as an indicator that measure technological innovation, but it can also be applied at development level of the technological innovation activities (Popp, 2005). However, total factor productivity (TFP) which refers to the joint impact of industrial structure adjustment, institutional innovation, technological innovation, and resource allocation optimization, including capital and labor have also been used as a measure of technological innovation (Jin et al., 2018; Ladu and Meleddu, 2014; Solow, 1956). Nevertheless, the use of total factor productivity as measure of technological innovation seems complex due to its high computation, and the associated parameters may influence results (Jin et al., 2018). Another strand of study applied research and development (R&D) as measure of technological innovation (Bloom et al., 2013; Irandoust, 2016). They argued that R&D improved technology that provides competitive advantage at different level; at the business, industry, or national level (Almeida and Kogut, 1997; Casper and vanWaarden, 2005; Cohen and Klepper, 1992; Casper and vanWaarden, 2005). In view of the foregoing, this study applies R&D as proxy to measure technological innovation in examining the changes in OECD energy consumption.

This study objective is to examine the moderating role of outward FDI and trade openness in the impact of technological innovation on energy demand, thus, we examine two strands of literatures for technological innovation and energy demand nexus. The first strand discusses the direct impact of technological innovation on energy demand, and most of the literature are country-specific using the China data. Pan et al. (2019) applied structural vector autoregression (SVAR) approach to the relationship between technological innovation, energy efficiency, and environmental regulation, in 30 Chinese provinces. Their results reveal that technological innovation improves energy efficiency in the short run and long run, and further suggests that energy efficiency can be achieve in high energy consumption are when command control environmental regulation is applied. Study of 284 Chinese cities shows that energy efficiency is positive and significantly affect technological progress at the country level (Wang and Wang, 2020). They found that technological innovation is suitable in western, eastern, and northeast regions compare to the central region where progress on energy efficiency is hindered. However, in Malaysia industry, reduction of energy consumption as well as abating carbon emissions are effective using technological innovation that enhances energy efficiency (Li and Solaymani, 2021). Their empirical results also showed that in the agricultural sector, export was found to be the second largest contributor to energy demand. In a comparative analysis, Chou et al. (2015) study examined the different automobiles that improve their energy consumption using technological innovation. Their results suggest energy consumption in automobile such as the Ford turbo petrol/diesel engine, the EcoBoost/TDCi were improved using innovative engines.

The second strand of literatures that examines the impact of the indirect relationship between technology innovation and energy demand, through the moderation of other variables are scanty. For instance, Uddin et al. (2022) explores the role of financial development in technological innovation-energy consumption nexus using the threshold regression model applied to 23 European union (EU) countries, and their results shows that the effects of stock market development, banking sector development, and overall financial development on energy demand in the 23 European countries depend on the levels of technological innovation. Wen et al. (2022) study investigate energy efficiency and renewable energy on technological innovation using panel data from 1995 to 2017. Their results reveal that renewable energy and energy efficiency supports technological innovation performance both at disaggregate and aggregate levels. Based on an interaction model, Gu et al. (2019) investigate the relationship between energy technological progress and energy consumption on carbon emissions in China's 30 provinces for the period 2005-2016. They found an inverted U-shaped relationship between technological progress and carbon emissions which suggests that at the initially time, the interaction increases carbon emissions, and then reduce them. Fei and Rasiah (2014) applied ARDL and VECM methodology on annual data for Canada, Ecuador, Norway and South Africa from 1974-2011 to examine the short-term and long-term relationship between technological innovation, electricity consumption, energy prices, and economic growth. Whilst technological innovation does not influence fossil fuel powered electricity in the long run, its impact economic growth for all the countries examined.

Literatures on the impact of technological innovation on energy consumption have also been grouped into positive and negative effects, which examines whether technological innovation reduces or increases energy consumption. In China, between 1978 and 1995, technical change within sectors accounted for most of the decrease in energy output ratio, and imports of energy products also contribute to the fall in energy consumption (Garbaccio et al., 2019). However, Chen et al. (2021); Wang and Wang (2020) found that technology innovation positively affects energy efficiency, which implies that energy demand increases as technological innovation increases. Yin et al. (2018) study found negative results. Furthermore, some of the studies that have attempted to examine technological innovation and energy consumption nexus in the context of OECD countries include Paramati et al. (2022), Sun et al. (2021), Wong et al. (2013); Awaworyi et al. (2021); Alvarez-Herranz et al. (2017); Alam and Murad (2020); etc. These studies examined the direct impact of technological innovation and energy consumption nexus, but our study seek to deepen the understanding between this nexus by examining both the direct effects and the indirect impact of technological innovation on energy consumption. For the indirect analysis, this study explores the outward and trade openness as the moderating variables.

2.2. Technological Innovation and Outward FDI

Although there are several literatures that have examined the reverse spillovers effect from outward FDI, most of them focused on the induced improvement of outward FDI and firm's innovation on the domestic economy. However, literature on technological innovation and firm internationalization is still at the infancy stage, and the few available literatures have different findings from different perspective. For instance, empirical evidence shows that firms that are highly productive are more likely to engage in outward FDI and at the same time pursue the advantages in R&D (Dong et al., 2021; Keller and Yeaple, 2009). More so, Lang et al. (2012) paper revealed that due to the technological innovation impact, the Vietnamese firms' activities would lead to technological progress in developing outward FDI and improve efficiency demand. More so, outward FDI can improve the technological innovation level as well as the investment in high-income countries, than in low-income countries due to the technologically innovative capabilities of enterprise (Wang et al., 2021). Zhou et al. (2019) study reveals that the Chinese firm innovation performance is positively linked with outward FDI in developed economies, but negatively impact outward FDI in emerging economies.

Similarly, Bagheri et al. (2019) examines the mediating role of technological innovation between firm's internationalization orientation and international performance of small and medium-sized enterprises (SMEs). Their empirical analysis found an inverted U-shaped relationship between technological innovation and internationalization of firm performance among SMEs. Besides, technological innovation was revealed to positively mediates the effect of internationalization orientation on international firm performance. Montresor and Vezzani (2015) examines the hypotheses of the capacity of entering and remaining among top R&D circles of the European Industrial Research and Innovation. Their study found that increase in outward FDI projects in R&D makes entrance in the circles more likely, but with non-R&D outward FDI entrance is found to be more unlikely. While the number of non-R&D-FDI increases the probability of exiting from the circles, the numbers of R&D reduce it. Furthermore, Li et al. (2016) study confirmed that the Chinese outward FDI has a significant effect on domestic innovation. Extant literatures examine either the impact of technological innovation on outward FDI or the impact of outward FDI on innovation. Our study partly develops new strand of literature on technological innovation and outward FDI nexus by examining the interaction of both variables on the impact of energy consumption.

2.3. Technological Innovation and Trade Nexus

Several existing strands of literature on international trade openness restrict their analysis to economic growth (Kong et al., 2021; Majumder et al., 2020; Pradhan et al., 2017), carbon emission (Wang et al., 2021; Mutascu, 2018; Shahbaz et al., 2017; Ertugrul et al., 2016), energy consumption (Zeren and Akkuş, 2020; Koengkan, 2018; Wang and Wang, 2020), income (Tiba and Frikha, 2018); etc. Our review suggests that the study examining domestic technological innovation and international trade openness are scanty and has not been explored. Some of the few available literature finds that trade liberalization increases productivity through the inducement of production factor allocation or the acquisition of more advanced technologies (Bustos, 2011). According to De Loecker (2007), trade liberalization integrates local markets to international competition, enable them to adopt new and advanced technology and innovation, so that they can be more competitive. He opined that trade openness may increase innovation, facilitates the dominance of more efficient products and improve resources. But Yanikkaya (2003) argued that trade openness supports technology diffusion which promotes energy efficiency and reduces energy consumption needed to produce certain level of economic output. Findings shows that international trade remains a viable channel for technological diffusion due to trade of tangible commodities leading to an intangible trade giving rise to exchange of ideas (Eaton and Kortum 2002). Evidence suggests that the total factor productivity (TFP) for countries with greater openness in import of machinery and equipment may be enhanced, due to advantage of external knowledge (Caselli and Wilson, 2004). Nevertheless, Gonçalves et al. (2021) study examines 58 countries trade openness, and its technology transfer channels for a period of 45 years using the system generalized method of moments (System GMM). They found that productivity growth is not affected by trade transfer, but openness level affects productivity positively in high-and middle-income countries.

3. METHODOLOGY AND DATA

3.1. Data Description

The aim of this study is to examine the role of outward FDI and trade openness in the impact of technology innovation on energy consumption. The selected variables are shown in Table 1 with sources data from https://data.worldbank.org for 24 OECD member states over the period 1996-2015. The list of these countries are as follows, Austria, Belgium, Canada, Switzerland, Chile, Denmark, Spain, Finland, France, United Kingdom, Greece, Hungary, Ireland, Italy, Luxembourg, Mexico, Japan, Netherlands, Norway, New Zealand, Portugal, Sweden, Turkey, and the United States. The period of the analysis and country chosen are based on the availability of dataset. In our empirical analysis, energy consumption variable is regressed on technological innovation (TIN), outward FDI flow, trade openness (TOP), economic growth (GDP), gross capital formation (GCF), and financial development (FDV).

3.2. Econometric Model Techniques and Model Specifications

In this study, we specify a conventional energy demand function augmented with energy consumption (ERC), followed by an independent variable as technology innovation (TIN), outward FDI (OFD), trade openness (TOP), gross domestic product (GDP), gross capital formation (GCF) and financial development (FDV).

$$Energy\ consumption\ (ERC)=f(TIN,OFD,TOP,GDP,GCF,FDV) \quad (1)$$

We begin by estimating a panel regression model specification given as,

$$ERC_{it}=\beta_0+\beta_1(TIN_{it})+\beta_2(OFD_{it})+\beta_3(TOP_{it})+\beta_4(GDP_{it})+\beta_5(GCF_{it})+\beta_6(FDV_{it})+\varepsilon_t \quad (2)$$

Table 1: Definitions of variables and data sources

Code	Variables	Description	Sources
ERC	Energy consumption	Energy use (kg of oil equivalent per capita) in natural logarithm	World Bank (2020)
TIN	Technology and Innovation	Research and development expenditure (% of GDP) expressed in natural logarithm	World Bank (2020)
OFD	Outward FDI flow	The natural logarithm of Foreign Direct Investment net outflows as a % of GDP	World Bank (2020)
TOP	Trade Openness	Trade openness of each country, calculated as (EXP+IMP)/GDP expressed in natural logarithm.	World Bank (2020)
GDP	Economic growth	Per capita real GDP (constant 2010 US$)	World Bank (2020)
GCF	Gross capital formation	Also called investment, is defined as the acquisition of produced assets based on constant local in natural logarithm.	World Bank (2020)
FDV	Financial Development	The natural logarithm of total values of stocks traded as a percentage of GDP	World Bank (2020)

Source: https://data.worldbank.org. Note: Author's compilation

where subscripts $i = 1, 2$ N and $t = 1, 2\ldots$ T denote OECD countries and year respectively, β_0 to β_7 are the unknown parameters to be estimated while is an error term. All the variables are expressed in natural logarithm.

In this study, we hypothesize that outward FDI moderates technological innovation (TIN) - energy consumption (ERC) nexus. Therefore, equation (2) is extended to include the interaction term ($TIN_{it} \times OFD_{it}$) to measure the indirect impact of technological innovation (TIN) on energy consumption (ERC) through the channel of outward FDI (OFD).

$$ERC_{it}=\beta_0+\beta_1\ (TIN_{it})+\beta_2\ (OFD_{it})+\beta_3\ (TOP_{it})+\beta_4\ (GDP_{it})+\beta_5\ (GCF_{it})+\beta_6\ (FDV_{it})+\beta_7\ (TIN_{it}\times OFD_{it})+\varepsilon_t\} \quad (3)$$

Similarly, we hypothesize that the trade openness (TOP) in OECD countries moderates technological innovation (TIN) - energy consumption (ERC) nexus. Therefore, we construct equation (4) by adding the interaction term ($TIN_{it}\times TOP_{it}$) to gauge the indirect impact of technological innovation (TIN) on energy consumption (ERC) through home country trade openness.

$$ERC_{it}=\beta_0+\beta_1\ (TIN_{it})+\beta_2\ (OFD_{it})+\ \beta_3\ (TOP_{it})+\beta_4\ (GDP_{it})+\beta_5\ (GCF_{it})+\beta_6\ (FDV_{it})+\beta_7\ (TIN_{it}\times TOP_{it})+\varepsilon_t \quad (4)$$

The joint impact of outward FDI spillover and trade openness in OECD countries is also examined to determine its significant in the energy consumption (ERC)-technological innovation (TIN) nexus. This relationship is shown in equation (5), thus,

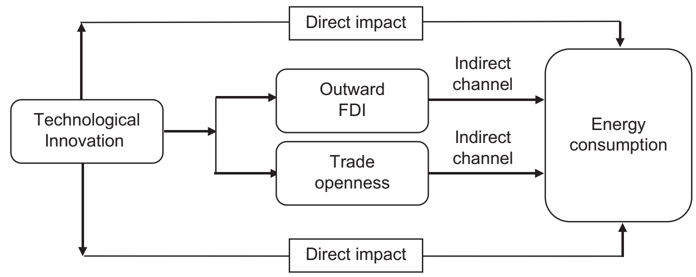
$$ERC_{it}=\beta_0+\beta_1\ (TIN_{it})+\beta_2\ (OFD_{it})+\beta_3\ (TOP_{it})+\beta_4\ (GDP_{it})+\beta_5\ (GCF_{it})+\beta_6\ (FDV_{it})+\beta_7\ (OFD_{it}\times TOP_{it})+\varepsilon_t \quad (5)$$

This study examined the dynamic linkage between energy consumption (ERC), technological innovation (TIN), outward FDI (OFD) and trade openness (TOP) in 24 OECD countries from 1996 to 2015. In addition to the clarity in the estimation approach shown equations (1)-(5), Figure 2 illustrates the mechanism of the study via the direct and indirect channels. The outward FDI and trade openness function as a mediating factor in the relationship between technological innovation and energy consumption.

3.3. Estimation Strategy

In this section, we applied numerous econometric techniques to examine the role of outward FDI and trade openness in the impact of technological innovation on energy consumption. These estimations are crucial in order to address econometric issues such as cross-sectional dependence, endogeneity, heterogeneity, heteroscedasticity in the panel estimation process, and these techniques are discussed as follows.

Figure 2: The mechanism of technological innovation on Energy consumption via outward FDI and trade openness



3.3.1. Cross-sectional dependence (CSD) test

Cross-sectional dependence (CSD) in panel analysis is considered the most critical test which may arise due to unobserved shocks, leading to bias estimates and inconsistence results (Phillips and Sul, 2003). Thus, the presence of the CSD assumption in panel analysis is not appropriate for empirical investigation. Therefore, to address the issue of CSD in panel analysis between variables, this study applied the cross-sectional dependency test (CD test) introduced by Pesaran (2004) under the null hypothesis of no cross-sectional dependence, and the statistic is asymptotically distributed. The CSD test also help determine whether to apply the first- or second-generation panel unit root tests (Yameogo et al., 2021). To this end, four CDS tests are performed: The breusch-pagan lagrange multiplier (LM), the Pesaran Scaled Lagrange multiplier (LM), bias-corrected (LM) and the pesaran cross-sectional dependence (CD), and the test is given as follows:

$$CD=\sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \quad (6)$$

Where T indicates the period, N represents the cross-section in the panel, and $\hat{\rho}_{ij}$ indicates the pair-wise correlation residual sample estimates

3.3.2. Second-generation panel unit-root test

To examine weather thevariables are stationary at level I (0) or first difference I (1), this study used the Pesaran (2007) second-generation panel unit root test of cross-sectional augmented dickey-fuller (CADF) and cross-sectional ım-pesaran-shin (CIPS) tests. These unit root tests are most suitable for panel heterogeneous data and shows consistency and better performance compared to the first-generation unit root test. The CADF tests which is an extended version of augmented dickey-fuller (ADF) test, is given as

$$\Delta CA_{i,t} = \varphi_i + \varphi_i z_{i,t-1} + \varphi_i \overline{CA}_{t-1} + \sum_{I=0}^{p} \varphi_{i,t} \Delta \overline{CA}_{t-1} + \sum_{I=0}^{P} \varphi_{i,t} \Delta CA_{i,t-1} + u_{i,t} \quad (7)$$

Where $CA_{i,t}$ indicates the variable to be analyzed, φ_i is the individual intercepts, $u_{i,t}$ represents the white noise error term, Δ indicates the difference, $CA_{i,t-1}$ $CA_{i,t-1}$ and $\overline{CA}_{t-1}$ are the cross-sectional averages. The optimal lag lengths selected are based on the akaike information criterion (AIC). However, the cross-sectional ım-pesaran-shin (CIPS) tests test statistic as be written as,

$$\widehat{CIPS} = \frac{1}{N} \sum_{i=1}^{N} CDF_i \quad (8)$$

3.3.3. Westerlund (2007) panel cointegration test

This study applies the Westerlund's (2007) dynamic panel cointegration test approach to examine the cross-sectional dependence and heterogeneity in selected variables. The cointegrating relationship between dependent and independent variables are explored to determine the long-run relationship. The test produces reliable and robust results even in short time series, with the null hypothesis of no cointegration exists in the error-correction term (ECT). For instance, to examine the cointegrating relationship between the dependent variable $y_{i,t}$ and the independent variables $x_{i,t}$, the error-correction model is estimated.

$$\Delta y_{i,t} = \delta_i' d_t + \alpha_i \left(y_{i,t-1} - \beta_i' x_{i,t-1} \right) + \sum_{j=1}^{P_i} \alpha_{i,j} \Delta y_{i,t-1} + \sum_{j=0}^{P_i} \gamma_{i,j} \Delta x_{i,t-1} + \varepsilon_{i,t} \quad (9)$$

Where d_t indicates the deterministic element, α measures the degree of velocity of adjustment, cointegration is expressed by $y_{i,t-1} - \beta_i' x_{i,t-1} = 0$, assured by $a_i < 0$ whereas $\alpha_i = 0$ falsifies the presence of cointegration, and is the error correction coefficient.

The Westerlund's (2007) test statistics are separated in two - group statistics (G^{α}, G^{τ}) and panel statistics (P^{α}, P^{τ}). The group statistic does not require the information of error-correction compared to the panel statistics that pools information along the cross-sectional dimension of the panel of error-correction. Empirically, the test can be demonstrated as:

$$G_{\tau} = \frac{1}{N} \sum_{i=1}^{N} \frac{\hat{\alpha}_i}{SE(\hat{\alpha}_i)} \quad (9.1)$$

$$G_{\alpha} = \frac{1}{N} \sum_{i=1}^{N} \frac{T\hat{\alpha}_i}{\hat{\alpha}_i(1)} \quad (9.2)$$

where SE($\hat{\alpha}_i$) is the conventional standard error of $\hat{\alpha}_i$

$$\hat{\alpha}_i \quad (9.3)$$

$$P_{\alpha} = T_{\hat{\alpha}} \quad (9.4)$$

Where, $\hat{\alpha}_i$ is the standardized speed of correction. The null hypothesis to be investigated is that there is no cointegration for at least one cross section for the G_{τ} and all cross-section for P_{τ}.

3.3.4. Short-run and long-run analysis

The use of the first generation cointegration estimators, such as fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS) may give rise to bias and inconsistence results in the presence of cross-sectional dependence and heterogeneity in panel data (Ahmad et al., 2021). Given the level of interrelationship among the OECD countries, there are chances of occurrence of cross-sectional dependence, which if ignored could lead to estimation bias. To this end, Chudik and Pesaran (2015) proposed the CS-ARDL model, which is robust to cross-sectional dependency, heterogeneity, endogeneity etc. Therefore, this study examines the short and long-runs relationship between energy consumption, technological innovations, outward FDI and trade openness in OECD countries by using the CS-ARDL approach. The equation is given as,

$$ERC_{i,t} = \alpha_i + \sum_{j=1}^{py} \delta_{i,t} ERC_{i,t-j} + \sum_{j=0}^{px} \varphi_{i,t} x_{i,t-j} + \sum_{j=0}^{p} \lambda_{i,t} \bar{Z}_{i,t-j} + \varepsilon_{i,t} \quad (10)$$

Where

$\bar{Z}_{i-j}$ is the lagged cross-sectional average,

$Z_{i-j} = ERC_{i,t-j}, x_{i,t-j}$

$x_{i,t-j}$ denotes a vector of the regressors, py and px are the optimal lag lengths of $ERC_{i,t-j}$ and each variable in $x_{i,t-j}$.

$\hat{\theta}_{cs-ADRL,\,i} = \frac{\sum_{j=0}^{px} \hat{\varphi}_{i,t}}{1 - \sum_{j=1}^{py} \hat{\delta}_{i,t}}$, the CS-ARDL specification style of error correction model is given by:

$$\Delta ERC_{i,t} = \psi_i \left[ERC_{i,t-1} - \hat{\theta}_i x_{i,t} \right] - \alpha_i + \sum_{j=1}^{py-1} \delta_{i,t} \Delta ERC_{i,t} + \sum_{j=0}^{px-1} \varphi_{i,t} \Delta x_{i,t} + \sum_{j=0}^{p} \lambda_{i,t} \Delta \bar{Z}_{i,t-j} + \varepsilon_{i,t} \quad (11)$$

3.3.5. Generalised method of moments test

This study also applies the System Generalised Method of Moments (SYS-GMM) technique to examine the impact of outward FDI and trade openness in energy consumption-technological innovation nexus in OECD countries. Arellano and Bover (1995) and Blundell and Bond (1998) developed the SYS-GMM model in order to address the problem of weak instruments associated with Arellano and Bond (1991) Differenced Generalised Method of Moments (DGMM). Besides, its usefulness in correcting for endogeneity and heterogeneity, the SYS-GMM estimation techniques is also useful for short panel datasets, robust and efficient in the presence of heteroskedasticity of unknown form (Baiashvili and Gattini, 2020)**.** The regression specification is tested using the Sargan test for instrument validity with the null hypothesis that the instruments are exogenous, and the serial correlation test for the second order serial correlation with the null hypothesis of no autocorrelation. The higher the p-value of the Sargan test, the better the model. Therefore, our ERC model equation is given as,

$$ERC_{it} = \beta_0 + \beta_1(ERC_{i,t-1}) + \beta_2(TIN_{i,t}) + \beta_3(OFD_{i,t}) + \beta_4(TOP_{i,t}) + \beta_5(GDP_{i,t}) + \beta_6(GCF_{i,t}) + \beta_7(FDV_{i,t}) + \varepsilon_t \quad (12)$$

Where $\varepsilon_t = \xi_t + \eta_i$

i indicates the countries in OECD, t represents the time, $\varepsilon_{i,t}$ denotes the error term, ξ_t and η_i are the unobserved heterogeneity country-specific effects and time specific effects in the model. The $\beta_0, \beta_1, \beta_2, \ldots, \beta_7$ indicates the parameters to be estimated.

4. RESULTS AND DISCUSSION

Table 2 presents summary statistics including the correlation matrix for the selected variables in 24 OECD countries during the period 1996-2015. The mean value of energy consumption (ERC) is 3.65 with standard deviation of 0.186, whilst technological innovation has average value of 0.185 with a deviation of 0.241. It is observed that outward FDI and financial development have the highest standard deviation compared to other variables with a mean of 0.495 and 1.466 respectively. This indicates that FDI outflow activities and financial development (financial markets in traded stocks) are relatively high in OECD countries. In addition, trade openness (TOP) has a mean of 0.220 and standard deviation of 1.895, and the GCF has the least deviation of 0.071. The correlation matrix explains the strength of relationship among the variables, and it is observed that apart from TIN, all other variables such as outward FDI, TOP, GDP, GCF, and FDV positively correlate with the dependent variable (ERC), See column (1), Table 2., an indication of near absence of multicollinearity.

Table 3 reports the raw average annual growth rate of the variables for each country. Energy consumption (ERC) is positive for all cross-sections, but the magnitude varies significantly across countries. Belgium, Canada, Finland, Norway, Sweden, and United States are countries that uses more than 5000 kg of oil equivalent (kgoe) annually. From our report, Chile, Luxembourg, Mexico, and Turkey are some of the countries with low energy demand. Low energy might depend on the size of country's economy. Countries which support domestic research and development activities with between 2.0 and 3.5 % of GDP are Austria, Switzerland, Denmark, Finland, France, Japan, Sweden, and United States. However, for the period under review, outward FDI flow was low in Greece, Luxemburg, Mexico, and Turkey. New Zealand oversea investment flow shows negative which indicates that the repatriated direct investment from external economies was more than the direct investment made by domestic investors to external economies. Results from Table 3 shows that the economic openness in OECD countries is almost the same, but countries such as Belgium, Switzerland, Hungary, Ireland, Luxemburg and Netherland appear to have more trade liberalization policies than some other countries in OECD.

Table 4 presents the results of cross-sectional dependence test calculated by estimating equation (6). The null hypothesis (Ho) of no cross-sectional dependence in the variable is rejected by the four CDS tests which include Breusch and Pagan (1980) LM, Pesaran (2004) scaled LM, Baltagi et al. (2012) bias-corrected scaled LM, and Pesaran (2004). This implies that there is high cross-sectional dependence among the 24 OECD countries and suggests that respective members may apply common policies to confront high energy consumption. Cross-sectional dependence, like serial correlation in time series, may leads to efficiency loss for least squares estimation and invalidates conventional F-tests and t-tests which relies of standard variance-covariance estimators, and in some cases, it may result in inconsistent estimators (Andrews, 2005; Lee, 2002,). Besides, the issue of CDS test, the assumption of slope homogeneity on panel data models can lead to inconsistent and misleading statistical inference if assumption is not true; see, Hsiao (2003, Ch, 6); Baltagi et al. (2008), hence we employ the Pesaran and Yamagata (2008) tests to examine the models' slope homogeneity. Table 5 report the outcome of the Pesaran and Yamagata (2008) tests where the delta and adjusted delta values are significant at 1%, and the null hypothesis of homogeneous slope is rejected. This indicates that all four models have significant heterogeneous slopes in cross-sectional panels.

In the presence of cross-sectional dependence and significant heterogeneous slopes, this study explores the second-generation panel unit root tests of cross-sectional augmented dickey-fuller

Table 2: Descriptive statistics and correlation matrix of OECD countries (1996-2015)

Variables		Descriptive statistics					Correlation matrix						
		Obs.	Mean	St. D	Min.	Max.	1	2	3	4	5	6	7
1	ERC	480	3.602	0.186	3.160	3.974	1						
2	TIN	480	0.185	0.241	−0.601	0.610	−0.691	1					
3	OFD	480	0.495	0.569	−1.678	2.141	0.368	0.287	1				
4	FDV	480	1.466	0.608	−0.796	2.506	0.153	0.350	0.018	1			
5	GDP	480	0.328	0.348	−1.593	1.401	0.099	0.080	0.149	0.025	1		
6	GCF	480	1.354	0.071	1.075	1.595	0.046	0.031	0.023	0.161	0.313	1	
7	TOP	480	1.895	0.220	1.347	2.545	0.137	0.096	0.547	0.480	0.049	0.043	1

Source of data: Source: https://data.worldbank.org. Author's calculation

Table 3: Average annual growth rate of each variable: 1996–2015 (percent)

Countries	ERC	TIN	OFD	TOP	GDP	GCF	FDV
Austria	3838.49	2.34	4.47	91.92	3.39×10^{11}	8.30×10^{11}	10.20
Belgium	5351.91	1.99	15.17	143.42	4.00×10^{11}	8.80×10^{11}	21.96
Canada	8042.58	1.83	3.80	69.37	1.20×10^{12}	2.90×10^{12}	74.10
Switzerland	3423.22	2.85	8.78	103.71	5.80×10^{11}	1.50×10^{12}	138.14
Chile	1773.78	0.89	3.54	65.41	1.70×10^{11}	3.60×10^{11}	12.99
Denmark	3482.15	2.42	3.44	89.38	2.70×10^{11}	5.50×10^{11}	28.14
Spain	2870.00	1.09	4.38	56.00	1.00×10^{12}	2.40×10^{12}	99.90
Finland	6502.32	3.22	4.52	73.70	2.10×10^{11}	4.80×10^{11}	71.36
France	4059.83	2.14	3.98	54.39	2.10×10^{12}	4.80×10^{12}	56.55
United Kingdom	3445.19	1.60	5.25	54.29	2.50×10^{12}	4.10×10^{12}	85.28
Greece	2484.06	0.51	0.49	53.12	2.10×10^{11}	4.30×10^{11}	26.02
Hungary	2520.23	0.98	6.48	137.55	1.01×10^{11}	2.80×10^{11}	13.45
Ireland	3272.43	1.29	15.55	168.26	1.90×10^{11}	4.20×10^{11}	11.64
Italy	2917.54	1.12	1.40	50.30	1.80×10^{12}	3.70×10^{12}	51.79
Luxembourg	1001.15	1.23	0.49	278.03	2.10×10^{11}	2.30×10^{11}	12.84
Mexico	1576.85	0.38	0.60	56.05	3.50×10^{11}	2.10×10^{12}	07.99
Japan	3891.97	3.23	1.87	23.08	4.20×10^{12}	1.19×10^{12}	87.12
Netherlands	4792.10	1.80	26.54	127.41	6.80×10^{11}	1.30×10^{12}	86.85
Norway	5915.71	1.37	4.48	70.39	3.30×10^{11}	8.60×10^{11}	38.13
New Zealand	4246.54	1.28	-0.27	59.04	2.30×10^{11}	3.00×10^{11}	7.768
Portugal	2271.30	1.00	2.86	67.98	1.90×10^{11}	4.10×10^{11}	23.76
Sweden	5471.59	2.67	6.24	80.94	4.10×10^{11}	9.20×10^{11}	74.34
Turkey	1329.26	0.62	0.27	48.39	5.40×10^{11}	3.10×10^{11}	36.89
United States	7519.23	2.62	2.05	26.15	7.50×10^{13}	4.00×10^{13}	204.57

1. Author's calculation

2. Source of data: Source: https://data.worldbank.org

Table 4: Cross sectional dependence test for OECD countries (1996-2015)

Variables	Breusch-Pagan LM		Pesaran Scaled LM		Bias-corrected LM		Pesaran CD test	
	Test stat.	Prob	Test stat.	Prob.	Test stat.	Prob.	Tests stat.	Prob.
ERC	274.83**	0.046	64.03**	0.038	63.47***	0.000	9.54**	0.042
TIN	381.45**	0.045	45.28*	0.082	45.03**	0.028	13.20**	0.036
OFD	396.01***	0.000	87.74***	0.000	87.56**	0.044	11.32***	0.000
TOP	243.11**	0.019	68.73**	0.035	68.01***	0.000	7.83*	0.068
GDP	269.70***	0.000	58.62***	0.000	58.37***	0.000	21.36***	0.000
GCF	101.54***	0.000	99.20***	0.000	99.00***	0.000	6.74***	0.000
FDV	213.65**	0.032	73.19*	0.056	73.01*	0.073	8.19**	0.042

Significance: * P<0.1; ** P<0.05; ***P<0.01. Author's calculation

Table 5: Pesaran-Yamagata homogeneity test

Tests	1		2		3		4	
	Test	Prob.	Test	Prob.	Test	Prob.	Test	Prob.
Delta	10.45***	0.006	4.068***	0.001	7.763***	0.000	9.955***	0.000
Delta_Adj	13.82***	0.000	9.279***	0.000	16.88***	0.004	12.85***	0.000

Significance: * P<0.1; ** P<0.05; ***P<0.01. Author's calculation. H_0: Slope coefficients are homogenous

(CADF) and cross-sectional ım-pesaran-shin (CIPS) tests to examine the stationary properties of variables, and whether they are cross-sectionally correlated. The basic estimating principle of unit root is that if the tests (CADF and CIPS) do not reject the null hypothesis (H0) at level, but rejects it in first difference, it means variable is integrated of order 1 or non-stationary. However, when the null hypothesis is rejected both at the level and first difference, it means the variable is integrated of order 0, and suggests stationary. Table 6 summaries the results for both CADF and CIPS tests performed both at level and first difference. Apart from ERC and GCF variables that appears to be integrated to order zero I(0), all other variables are integrated to order one I(1). This implies that most of the selected variables have unit roots at the level and at first difference.

Next, we examine the possibility of any cointegrating relationship using the Westerlund (2007) cointegration test. The estimation results of equations (9.1)-(9.4) presented in Table 7 shows that both the panel statistics (Pt, Pa) and group statistics (Gt, Ga) rejects the null hypothesis of no cointegration. This implies the presence of cointegrating relationship between energy consumption (ERC), technological innovation (TIN), outward FDI, financial development (FDV), gross domestic capital (GDP), gross capital formation (GCF), and trade openness (TOP). Thus, confirms the existence of a long-run relationship among the selected variables. The Westerlund test produces a more consistent and robust panel cointegration result for dependent and independent variables. The group statistic (Gt and Ga) examines the alternative hypothesis that at least one unit is cointegrated, whilst the panel statistic (Pt and Pa) explores the alternative hypothesis that the entire panel is cointegrated (Heiko et al., 2016). To this end, this study considers a long-run elasticity model, and employ the CS-ADRL model to examines the short-run and long-run relationship.

4.1. Individual/Direct Impacts and Discussion

This section discusses the individual and direct impact of all explanatory variables on the dependent variables. Table 8 shows the result of CS-ADRL model and confirm that a short-run relationship exists due to the negative and statistically significant error correction term (ECM (−1)) coefficients reported in panel A, column (1)-(4), suggesting that the whole system (the energy consumption model) can converge back to long run equilibrium quickly after short term shock at the speed of 69.6%, 71.8%, 60.3% and 58.4% respectively. This implies that the short-run disturbance will be corrected in about 1.43 years, 1.39 years, 1.65 years, and 1.71 years respectively to get back to equilibrium level or achieve the long-run equilibrium level.The results shows

Table 6: Second-generation panel unit root test outcomes.

Variables	Unit root tests	At level		At first difference	
		Constant	Const. and Trend	Constant	Const. and Trend
ERC	CADF	−10.19*	−23.83	−21.59***	−16.61*
	CIPS	2.46	5.68*	−13.042*	−10.94***
TIN	CADF	−7.46	−9.911	−1.84*	−5.97**
	CIPS	−5.03	−8.45	0.94***	−1.94
OFD	CADF	−3.73	−3.63*	−11.24*	−8.71
	CIPS	−2.40	3.96	−5.73***	−11.37*
TOP	CADF	−59.05	−8.472	−0.972**	−0.23**
	CIPS	−0.48	−−11.61	−7.632***	−9.97*
GDP	CADF	−13.58	−4.043	−1.422*	−3.21***
	CIPS	−1.88	3.741	−9.94***	−10.84*
GCF	CADF	−9.05*	−13.33	−19.53**	−23.89***
	CIPS	−13.47	−9.69	−13.23***	−20.24***
FDV	CADF	34.60*	42.573	17.34	23.04**
	CIPS	15.84	19.180*	−14.07*	−7.42

Significance: * P<0.1; ** P<0.05; ***P<0.01. Author's calculation. CADF indicates cross-sectional augmented dickey-fuller. CIPS indicates cross-sectional im-pesaran-shin test

Table 7: Westerlund (2007) panel cointegration tests

Statistic	1		2		3		4	
	Value	*Z*-value	Value	*Z*-value	Value	*Z*-value	Value	*Z*-value
Panel: OECD countries								
G_t	−6.71**	−1.97	8.71**	2.17	9.83***	1.12	7.44***	2.05
G_a	−13.45**	−2.97	2.04***	0.56	4.76**	0.34	5.95**	1.86
P_t	7.82***	3.62	9.27**	3.22	6.88**	3.56	3.49**	0.95
P_a	5.71*	0.45	3.38***	1.75	1.94***	078	2.78***	1.13

Author's calculation. Note: Significance: * P<0.1; ** P<0.05; ***P<0.01

Table 8: The CS-ARDL estimation outcome of OECD countries (1996-2015)

Variables	(1)	(2)	(3)	(4)
Panel A: Short-run estimates				
ΔTIN	-0.027** (0.012)	-0.019** (0.008)	-0.043*** (0.012)	-0.005** (0.002)
ΔOFD	-0.002** (0.0009)	-0.003*** (0.0013)	-0.005* (0.0028)	-0.017* (0.009)
ΔTOP	-0.025** (0.011)	-0.014** (0.006)	-0.021** (0.011)	-0.004* (0.003)
ΔGDP	0.302*** (0.032)	0.311** (0.156)	0.219** (0.055)	0.142 (0.400)
ΔGCF	0.219* (0.146)	0.122*** (0.021)	0.118 (0.295)	0.093 (0.190)
ΔFDV	0.095*** (0.029)	0.034** (0.019)	0.084** (0.045)	0.032*** (0.011)
Δ (TIN×OFD)	-0.006*** (0.003)			-0.005* (0.0029)
Δ (TIN×TOP)		-0.008** (0.004)		-0.012** (0.005)
Δ (OFD×TOP)			-0.009* (0.005)	-0.013*** (0.004)
ECM(-1)	-0.696*** (0.005)	-0.712** (0.002)	-0.603** (0.301)	-0.584** (0.020)
Panel B: Long-run estimates				
TIN	-0.031** (0.015)	-0.043 (0.056)	-0.019** (0.009)	-0.056* (0.032)
OFD	-0.018** (0.008)	-0.006** (0.003)	-0.014*** (0.004)	-0.025** (0.013)
TOP	-0.023* (0.013)	-0.016* (0.009)	-0.010** (0.005)	-0.007 (0.006)
GDP	0.104*** (0.054)	0.153*** (0.007)	0.118** (0.050)	0.136** (0.068)
GCF	0.033* (0.018)	0.082*** (0.027)	0.040** (0.020)	0.057** (0.031)
FDV	0.012** (0.006)	0.010** (0.004)	0.026** (0.013)	0.013** (0.007)
TIN×OFD	-0.009** (0.004)			-0.007*** (0.002)
TIN×TOP		-0.014*** (0.005)		-0.013** (0.006)
OFD×TOP			-0.023*** (0.006)	-0.031** (0.015)

1. Author's calculations, 2. Values in the parentheses are the standard errors, 3. Significance: * P<0.1; ** P<0.05; ***p<0.01

that the disequilibrium from these shocks can only be adjusted in the next period after 1 year but <2 years (Table 8). The study finds that the direct impact of technological innovation on energy consumption is negative and significant both in the short and long. This implies that, a 1% increase in technological innovation in OECD countries reduces energy consumption by −2.70%, −1.90%, −4.30% and −0.5% in the short run as shown in Table 8, panel A column (1)-(4) respectively. In the long run, 1% increase in home country research and innovation sector reduces energy consumption by −3.1%, −4.3%, −1.9% and −5.6%. This suggest that technological innovation owing to investment in R&D activities in OECD countries promotes the reduction of energy consumption through the use of energy efficient technologies and products which supports energy efficiency in OECD countries. This result corroborates with Cheng et al. (2021) and Sharma et al. (2021) studies using OECD and BRICS data respectively, finds negative results and suggests that technological innovation plays a significant impact toward the reduction of energy consumption.

Similarly, the direct impact of overseas investment flow (OFD) on energy consumption in OECD countries is negative and statistically significant both in the short run and long run (Table 8, Panel A and B). This indicates that 1% increase in reverse technology spillover effects from outward FDI, decreases energy consumption in the short run by −0.2%, −0.3%, −0.5% and −1.7%, and in the long run by −1.8%, −0.6%, −1.4% and −2.5% respectively (column Table 8, (1)-(4)). This follows that the spillover effects from outward FDI appears to decrease energy consumption in OECD countries. The implication of this is that the reverse technological spillover effects from horizontal and vertical linkages via outward FDI flow contains new, and advance technology which improves energy efficient, and reduces energy consumption. The spillover effect may increase the size of the market of OECD economies, stimulates domestic firms, leading to higher productivities but with lower energy efficiency. This finding confirms the results of many scholars that found negative impact of outward FDI technology spillover effects on energy consumption (Ren et al., 2022, Zhou et al., 2021, Muhammad and Khan, 2019). Narayan and Narayan (2010) paper estimates the coefficient of the short run and the long-run elasticities of income and confirm the presence of EKC hypothesis which validates an inverted U-shape relationship if the coefficient of the short run elasticity is higher than the long-run elasticities. Therefore, the impact of outward FDI on energy demand confirm the existence of inverted U-shape curve. Thus, energy demand may initially increase with outward FDI flow, reach some turning point, and then decreases.

Table 8 also reports the results of the direct impact of trade openness (TOP) on energy consumption in OECD countries. The finding is negative and statistically significant in the short and long run elasticity (shown in column (1)-(4)). Its indicates that trade openness supports energy consumption in the short run with coefficients of 2.5%, −1.4%, −2.1%, and −0.4% respectively. Similarly, the coefficients of the impact of trade openness in energy consumption is negative and statistically significant in the long run with coefficients −2.3%, −1.6%, −1.0%, and −0.7%. This suggest that an increase in trade openness, reduces energy consumption in short and in the long-run term. These findings imply that trade policies in OECD countries favor energy consumption sustainability, and this may be due to the importation of new and advance technologies and products from member countries which lower energy intensity in home country. This result further shows that developed countries gain from international trade openness. This finding is supported by previous results of Alam and Murad (2020); Nasreen and Anwar (2014); Afonso et al. (2021); Gozgor (2017) studies. Thus, trade-openness in OECD countries is a crucial determinant that drives energy efficiency in OECD countries.

The report from Table 8 suggests that the impact of GDP on energy consumption is positive both in the short run and long run. Positive impact indicates economic growth due to scale effect increases energy demand. This finding follows the growth hypothesis which suggest that an economy is energy dependent, that is, an increase in energy consumption leads to an increase in GDP. Our findings corroborate the positive view of Gozgor et al. (2018); Naseri, et al. (2016); Wang and Wang (2020) that OECD economies uses higher energy demand due to booming economic activities. Similarly, the gross capital formation (GCF) of OECD economies which is measure for total "investment" is positive and significantly impact energy consumption both in the short-run and long-run. Thus, investment increase in OECD economies increases economic development which may lead to a higher energy demand. However, the impact of the values of traded stocks in OECD economies proxied as financial development (FDV) is also positive and statistically significant in the short run and long run estimates. This suggests that OECD financial environment creates easy access to loans and other financial grants which increases consumption in households, and production potential in industries, which in-turn increases energy consumption both in short and long run. Studies such as Shobande and Ogbeifun (2022) contradict this finding and suggests that home country may use FDV as a medium for investment opportunities and funding of technologies projects which help to lower energy intensity. Empirical findings and views of financial development and energy demand nexus among scholars remain inconclusive.

4.2. Interactive/Indirect Impacts and Discussion

Regarding the interaction terms, we found that the interaction of outward FDI with domestic technological innovation (TIN) indicated as TIN×OFD is negative and statistically significant at 5% and 1% significant level both in the short-run and long run respectively (column (1), Table 8, Panel A and B). This implies that 1% increase in the joint impact of outward FDI and TIN reduces energy consumption by −0.6% and −0.9% in the short and long run respectively toward achieving sustainable development in OECD countries. The mutual impact of TIN and outward FDI (TIN×OFD) give rise to new and advanced reverse technology spillover effect that enhances OECD counties technological innovation and reinforce efficient energy consumption sustainability strategy. The linkage between home country's research and development sector and outward FDI flow acts as a vehicle of integration of new ideas and technologies that reduces energy demand as foreign technologies and knowledge are transferred/exchanged among member countries. This implies that the backward FDI vertical integration spillover effects from oversea investment flows stimulates home countries' R&D activities toward achieving technological advancement with innovation capacity that improves energy efficiency and reduce energy demand, and at the same time increasing home country level of economic activity. Therefore, OECD countries' technological innovation capacity supported by home country reverse technology spillover facilitates efficient energy consumption among member countries. In line with Narayan and Narayan (2010) paper, the joint impact of outward FDI and TIN on energy use supports an inverted U-shape curve.

Furthermore, the joint effect of technological innovation (TIN) and trade openness (TOP) on energy consumption is also evaluated using the interaction term (TIN×TOP) shown in column (2), Panel A and B. The combine effect is negative and statistically significant at 5% and 1% significance level in the short-run and long run respectively. This implies that TIN is strengthened by TOP toward improving energy efficiency and lowering energy consumption by −0.8% and −1.4% in the short and long run respectively. That is, a 1% increase in TIN×TOP reduces energy demand by −0.8% in the short-run, and −1.4% in the long run. This indicates that trade openness policies among OECD countries facilitate the importation and exportation of technological research products that advances energy research toward the improvement of energy saving technologies as well as the mitigation of carbon emission. Hence, trade openness strengthens OECD countries' technological innovation in achieving sustainability. This results also supports the U-shape curve where energy consumption become more efficient in the long run compares to the short run. Beside been a tool for the reduction of energy demand in OECD countries, the TIN×TOP linkage also enables developing countries receive advanced eco-friendly technologies from OECD member countries. Thus, substantial capital is received which may further be used in the purchase of environmentally friendly technologies or expand domestic production of energy saving products. Given that the short and long effects for TIN×OFD are −0.6% and −0.9% respectively, and the impact of TIN×TOP is −0.8%, and −1.4% respectively for short and long run term, this implies that the interactions of domestic technological innovation with outward FDI spillovers appears to be more efficient in lowering energy demand than the joint impact of innovation and trade openness both in the short run and long run (Table 8, Panel A and B).

In addition, the interaction of trade openness (TOP) and outward FDI spillover proxied as OFD×TOP seems to support the energy efficiency goal strategies of OECD countries toward achieving the sustainable development goals (SDGs) vision 2030. The coefficients are negatives and statistically significant in short run and long run, an indication that trade openness synergize with outward FDI to enable oversea investment flow as well as the spillover of foreign technologies which reduces energy consumption. The Negative coefficient of OFD×TOP may also be attributed to the stringent environmental regulatory and trade policies in OECD countries which help to decouple in-bound trade and FDI from non-eco-friendly products and technologies. Thus, standard environmental regulations and trade policies in OECD countries enhance economic growth, but controls energy consumption and carbon emission via restriction of pollutants technologies and products.

4.3. Robustness Check Estimates

Table 9 discusses the robustness of the long run estimates using the Augmented Mean Group estimator (AMG) developed by Eberhardt (2012). The estimated results in column (1)-(4) shows that the direct impact of technological innovation (TIN), outward FDI (OFD), and trade openness (TOP) reduces energy demand in OECD countries, but gross domestic product (GDP) per capital, gross capital formation (GCF), and financial development (FDV) have positive and significant impact on energy consumption (ERC). These results are statistically not different from the estimation of CS-ARDL technique presented in Table 8, this confirms the long-run results. The estimation of the interaction terms such as TIN×OFD, TIN×TOP and OFD×TOP is also examined. The technological innovation interactions with outward FDI and trade openness are negatively significant at 1% and 5% significance level. This result also aligns with the CS-ARDL long run estimations. Nevertheless, the joint impact of outward FDI and TOP is positively significant and do not conform to the long run estimates presented in Table 8.

Table 10 presents the results of the re-estimation of the energy consumption model (ERC) using the System Generalised Methods of Moments (SYS-GMM) technique. The SYS-GMM estimator proposed by Arellano and Bover (1995) and fully developed Blundell and Bond (1998) is highly robust to numerous econometric issues such as endogeneity, heterogeneity, omitted variable bias, simultaneity bias, reverse causality, as well as heteroskedasticity of unknown form. The results reveal that the lagged ERC (ERC_{t-1}) in all specifications (Table 10, column (1)-(4)) are positive and statistically significant, and the values are less than one. This indicates that changes in explanatory variables such as TIN, OFD, TOP, GDP, GCF and FDV, would influence energy consumption at a specific point in time after the current period. The direct impact of technological innovation, outward FDI, and trade openness negatively affects energy consumption in OECD countries, which implies that energy demand may become low if domestic technological innovation, outward FDI and trade openness increases. However, the joint impact of TIN×OFD and TIN×TOP enhances energy efficiency which reduces energy demand in OECD countries. Similarly, the estimation of OFD×TOP is negatively significant, and implies that OECD trade policies facilitate direct investment abroad as well as backward FDI spillover flow. Thus, the estimated results reported in Table 10 confirms the results of CS-ARDL long run estimate. The values of AR (2) tests statistic which examines the null hypothesis of absence of second order serial correlation in the residual is insignificant. This suggests that the estimations of energy consumption model shown in equation (12) are not second order serially correlated. The Hansen's (1982) J test which examines the overall instruments validity in the panel regression model, do not reject the null hypothesis that the over identifying restrictions are valid, indicating that the sets of instruments applied in the energy model are exogenous. The values of the instrument ratio reported in Table 10 column (1)-(4) are not less than 1 (≥ 1) and within the acceptable range (Roodman, 2009, Osabuohien-Irabor and Drapkin, 2022). This indicates absence of instrument proliferation which weaken both autocorrelation and Hansen tests.

Table 9: The results of Augmented Mean Group estimator (AMG) for OECD countries (1996-2015)

Variables	(1)	(2)	(3)	(4)
TIN	-0.007** l(0.003)	-0.020** l(0.008)	-0.031*** (0.001)	-0.045*** (0.006)
OFD	-0.002** l(0.001)	-0.006** (0.003)	-0.024** (0.012)	-0.007* (0.004)
TOP	-0.042** l(0.019)	-0.004* l(0.003)	-0.008** (0.0036)	-0.014*** (0.003)
GDP	0.124* l(0.073)	0.393*** l(0.098)	0.156** (0.075)	0.276** (0.134)
GCF	0.217* l(0.126)	0.167*** (0.021)	0.293* (0.169)	0.213 (0.190)
FDV	0.006** l(0.003)	0.020** (0.011)	0.011** (0.005)	0.013** (0.006)
TIN×OFD	-0.009*** l(0.003)			-0.016*** (0.005)
TIN×TOP		-0.010** 0.005)		-0.019** (0.009)
OFD×TOP			0.019*** (0.006)	0.023** (0.011)
Constant	1.463*** l(0.005)	3.631** (0.012)	-2.503* (1.390)	-5.380** (2.693)

1. Author's calculations, 2. Values in the parentheses are the standard errors, 3. Significance: * *P*<0.1; ** *P*<0.05; ***p<0.01

Table 10: System Generalized Method of Moments (SYS-GMM) results of OECD countries (1996-2015)

Variables	(1)	(2)	(3)	(4)
ERC_{t-1}	0.643*** (0.214)	0.352** (0.176)	0.552*** (0.184)	0.425*** (0.141)
TIN	-0.032** (0.016)	-0.027*** (0.008)	-0.029** (0.861)	-0.002* (0.0011)
OFD	-0.005**** (0.001)	-0.014* (0.008)	-0.029**** (0.008)	-0.045* (0.025)
TOP	-0.004** (0.002)	-0.093** (0.043)	-0.037 (0.650)	-0.016** (0.008)
GDP	0.211* (0.124)	0.016*** (0.005)	0.238* (0.133)	0.213 (0.190)
GCF	0.264** (0.132)	0.302** (0.151)	0.292* (0.161)	0.313 (0.476)
FDV	0.062* (0.033)	0.017 (0.042)	0.006* (0.0033)	0.003** (0.0015)
TIN×OFD	-0.003** (0.0015)			-0.006*** (0.002)
TIN×TOP		-0.011*** (0.003)		-0.021*** (0.004)
OFD×TOP			-0.016** (0.007)	0.032* (0.018)
Constant	2.183*** (0.727)	7.310*** (0.362)	5.421*** (1.003)	6.314* (3.714)
Numbers of Obs.	472	472	472	472
Number of Group	24.00	24.00	24.00	24.00
Numbers of Instr.	17.00	15.00	16.00	21.00
Instrument Ratio	1.410	1.600	1.500	1.140
A-B. (1) P value	0.000	0.000	0.001	0.002
A-B. (2) P value	0.749	0.218	0.628	0.503
Hansen P value	0.611	0.516	0.417	0.629

1. Author's calculations, 2. Values in the parentheses are the standard errors, 3. Significance: * P<0.1; ** P<0.05; ***p<0.01

5. CONCLUSIONS AND IMPLICATIONS

In this study, we examined the dynamic interactions between energy consumption, technological innovation, outward FDI, and trade openness in OECD economies. We controlled for other variables such as gross domestic capital, gross capital formation and financial development.

Specifically, this study explored the domestic technological innovation dependency of outward FDI and trade openness on energy demand in 24 OECD economies for the period 1996-2015. To this end, we applied battery of econometric and statistics techniques to examine the direct relationship, and explore the indirect relationship moderated by outward FDI and trade openness. Findings supports the existence of an inverted U-shape curve between technological innovation and energy demand, moderated by outward FDI and trade openness. Thus, energy demand may increase at the initial level due to the joint impact of moderation factors and technological innovation, but reach some turning point, and then decline. However, the impact of technological innovation on energy consumption via trade openness reduces energy demand in OECD countries. The technique effect of trade openness stimulates factors of production which increases economic activities and at the same time facilitates the components and products of advanced energy saving technologies which help in reducing energy consumption. Thus, increasing trade openness reinforces the impact of domestic technological innovation on energy consumption among OECD countries. OECD countries' technological innovations indirectly affect energy demand through negative moderation of outward FDI to boost the energy-saving strategy toward achieving the sustainable development goals (SDGs) vision 2030. Eco-friendly reverse technology spillover effect from outward FDI enables foreign technologies (from other OECD countries) to combine with home country technological innovation to improve energy efficiency, lower energy consumption and reduces carbon emission. This follows that the oversea investment flow from OECD countries drives the technology integration among OECD countries to strengthen the domestic technology innovative capabilities toward energy consumption and environmental sustainability. More so, trade policies in OECD countries synergize with domestic enterprise to facilitates oversea investment flow as well as other eco-friendly products and technologies which reduces energy consumption. Similar effects are observed both in the short run and long run, which demonstrates that the spillover from outward FDI and trade policies in OECD countries fully moderate the innovation-energy nexus.

From a policy perspective, this study developed some set of crucial policy to support policymakers, energy institutions, and other government agents toward improving their energy efficiency strategies in line with the sustainable development goals (SDGs) vision 2030 (OECD, 2016; OECD, 2017). The recommended sets of policies are as follows: Policymakers are advised to strengthen the policy guidance to integrate outward FDI spillover and trade policies to domestic technological innovation as well as promote green technology innovation, would help fast track national energy saving, and emission reduction goals. The cross-sectional dependence of the variables supports common policies among OECD countries directed toward reducing energy consumption in order to achieve sustainability. Common energy regulations and policies would promote greater research and development of advanced energy friendly technologies as well as development of renewable energy infrastructure. OECD members must ensure that MNC affiliates comply with investment and regulation policies, especially policies related to energy conservation. Energy-saving incentive and other stimulus funding maybe initiated to encourage firms that follows the combination of FDI, energy-saving and carbon emission reduction. Public awareness on the need for renewable energy and clean environment should be increased among OECD countries. Thus, government should formulate policies and programs to drive the green technology campaign. It is expected that our findings may not be the same with other countries samples, therefore future research may examine other group of countries with different moderating factors.

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7. DECLARATION OF COMPETING INTEREST

The authors declare that there are no competing personal or financial interests that influences this research work.

8. DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: (https://databank.worldbank.org/source/world-development-indicators).

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