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Research article

How does financial development influence carbon emission intensity in the OECD countries: Some insights from the information and communication technology perspective

Miaomiao Tao, Mingyue Selena Sheng *, Le Wen

Energy Centre, Department of Economics, Business School, The University of Auckland, Auckland, New Zealand

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ABSTRACT

Based on an extended STIRPAT framework, this paper investigates the effects of financial development on carbon emission intensity in OECD countries from linear and non-linear perspectives, where financial development is proxied by three dimensions: financial deepening, financial deepening, and financial size, and financial efficiency. Fortunately, three types of financial development significantly alleviate carbon emission intensity. An extended moderation effect model is built to estimate the effect of financial development via information and communication technology on carbon emission intensity. The results reveal that internet-based information and communication technology and service-based information and communication technology are positively correlated with carbon emission intensity. To effectively handle the endogeneity issue triggered by causal relationships between variables and allow potential non-linear nexus, an advanced dynamic panel threshold model incorporating the generalised method of moments is employed to investigate how financial development affects carbon emission intensity under different types of information and communication technology. Empirical evidence demonstrates the significance of the non-linear nexus between financial development and carbon emission intensity. Lastly, heterogeneity analysis demonstrates the existence of heterogeneity associated with institutional quality, degree of economic development, and resource endowment concerning the effect of financial development on carbon emission intensity among the OECD countries.

1. Introduction

Climate change brings a global symmetric risk to human society. It has posed the most significant threats and challenges to all people's essential aspects of life: food production, land use, water access, and physical and human capital. Undauntedly, inadequate attention to climate change would cause unpredictive socio-economic consequences for humans and nature, hinder long-term sustainable economic development, and heighten the risk of abrupt to our environmental and ecological systems. Global warming and environmental degradation are two of the most pressing issues confronting all economies worldwide, especially for emerging markets. Therefore, the core solution is to prioritise green development and foster a new development pattern towards a low-carbon economy. Global carbon dioxide emissions (CE) decreased in 2019 by 1.5% compared to last year due to the sluggish growth of the global economy, contributing to approximately 75% of the world's total greenhouse gas (GHG) emissions. Still, GHG emissions tend to be increased by another 50% by 2050, and the substantial increase will be primarily led by projected growth in CEs from energy use.[1]

However, trends varied depending on the country's context: emissions from developed economies fell dramatically – 6.5% while developing economies' emissions grew by 3%, driven by India and China (IEA, 2011). The Organisation for Economic Co-operation and Development (OECD) countries tremendously influence the global greenhouse effect. As shown in Table 1, CEs in OECD countries reached 10,778.1 million tonnes (Mt) in 2020, accounting for a nearby 33.66% of the global amount. Fortunately, OECD countries are motivated to lower CEs to about 20% by 2020 and between 80 and 95% by 2050 (EIA,[2] 2013). The purpose for choosing OECD countries as the primary context is motivated by the fact that their economic characteristics were

* Corresponding author.
E-mail addresses: taomiaomiao12311@outlook.com (M. Tao), m.sheng@auckland.ac.nz (M.S. Sheng), l.wen@auckland.ac.nz (L. Wen).

[1] See https://www.oecd.org/env/.

[2] EIA (Energy Information Administration): https://www.eia.gov/.

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well-suited to our objectives. Specifically, OECD countries enjoy energy-induced economic growth and remain the highest energy consumption, with 41% of the global energy depletion (Duffour, 2012). In fact, these countries have joined the international community to mitigate emissions, as evidenced by the fact that most OECD members have signed the 1997 Kyoto Protocol and committed to their CE reduction targets at the 2015 Paris Climate Change Conference (Dong et al. (2017) and Yousefi et al. (2019).

Therefore, some robust countermeasures have been formulated to better fulfil their reduction targets and proactively tackle climate change, among which, sustaining financial development (FDT) has emerged as a widely admitted solution for addressing environmental issues (Wang et al., 2022a, b) in addition to technological innovations. Specifically, FDT endorses and permits economic activities (i.e., FDI, stock market activities), as well as amplifies business activities in banking and financial sectors that entail one possible channel to foster income growth. Simultaneously, well-functioning financial systems provide credits for alternative power systems and offer capital for carbon-free and environmentally friendly projects at a shadow rate. These cheap financing overheads may avoid excessive resource and energy utilisation by strengthening innovative capabilities in the domestic energy-intensive sectors (Khan et al., 2020). Therefore, FDT may adversely affect environmental quality. However, the opposite viewpoint highlights that FDT degrades the environment. For example, low-yielding enterprises (or the so-called "zombie enterprises") may have free access to adequate financial resources, and this phenomenon is particularly common, especially in the context of the widespread prevalence of corruption in a specific country.

The rapid development in information and communication technology (ICT) has ushered in a new era of globalisation, in which the linkages between various economies are increasingly sophisticated. Concisely, ICT's development promises to introduce user-friendly communication networks through e-commerce platforms, which will assist in removing entry barriers in the domestic and international markets, easing economic and social transmission in the education, trade and health sectors, reducing information asymmetries, and making production processes more efficient (Zafar et al., 2022). Therefore, the bonus derived from ICT's development entails its potential effect in stimulating sustainable economic development and determining possible economic prosperity in the long run. Bastida et al. (2019) investigated how energy sector digitalisation affects electricity consumption among residents by creating new opportunities. Consumers may therefore realise more efficient energy decisions by enabling interventions in household electricity usage (Laitner and Ehrhardt-Martinez, 2007). Additionally, high-resolution sorting and measuring electricity data ensures that energy enterprises provide real-time consumption data to households and utility enterprises. This can provide strong incentives to apply more responsible behaviours regarding electricity usage. The production function initiated by Cobb and Douglas (1928) includes three crucial factors: capital, labour, and technology. Theoretically, FDT is seen as the representative of capital among production conditions, whereas ICT refers to technological advancement (Cheng et al., 2021). Therefore, the endogenous growth model considered ICT as an essential determinant stimulating economic growth. In fact, ICT's promoting effect is mainly manifested in developing innovative and capital-intensive products and cultivating new business patterns (Czernich et al., 2011). Fortunately, this conjecture was verified in the work of Yang et al. (2021) who emphasised that corporate transaction costs and information asymmetries could be significantly reduced because enterprises can directly complete data filtering and matching by connecting with the supply and demand data of energy enterprises.

However, ICT's effect on environmental protection in the past literature is debatable. One standpoint highlights ICT's direct substitution effect, implying that electricity-based equipment can be substituted by ICT penetration (Cai et al., 2013) and, thereby, certifying ICT's positive effect on environmental protection. Another viewpoint asserts that accelerating the adoption of information technology systems raises excessive electricity consumption, thereby consolidating ICT's direct but adverse impact. Considering ICT's indirect but positive effects on CEs, seminal work provided by Cho et al. (2007) demonstrated the compensation effects that ICT diffusion occurs. For instance, the South Korean economy has substituted labour with information technology to lower production costs in the first production stage; however, a positive correlation between electricity consumption and CEs was identified in later economic development.

Similarly, trade liberalisation, FDT, and income effect attract foreign investors to emerging markets, where the initial industrialisation process offers an ideal platform for a low start-up. Simultaneously, easy access to financial resources nourishes traded commodities. Under certain technology conditions, the sharp increase in aggregate output means massive investments in production factors, emitting more CEs and exposing the economy to the residual effect (Frankel and Romer, 1999). In contrast, a relatively low-interest rate regime helps enterprises cultivate a new business mode to acquire more profit at the lowest costs. New production plants may therefore improve resource utilisation efficiency by adopting advanced technologies. However, the absence of stringent environmental regulations gives these firms leverage that allows them to save their profits, which should be put toward reducing CEs (Dogan and Turkekul, 2016).

This paper contributes to the following aspects. *First*, the nexus between carbon emission intensity (CEI), FDT, and ICT is explored based on an extended STIRPAT framework. Specifically, FDT is gauged by three dimensions: financial deepening (FDT_FD), financial size (FDT_SZ), and financial efficiency (FDT_EY), thereby yielding more reliable results. *Second*, given the growth dilemma between economic growth and environmental deterioration (Table 1) facing OECD countries, we should get deeper into the internal transmission mechanism of FDT in order to adhere to the guiding ideology of sustainable development. Hence, a moderation effect model is built to investigate the moderation effect of ICT between FDT and CEI, where ICT is composed of internet-based ICT and service-based ICT. Furthermore, a panel threshold regression (PTR) model incorporating the lagged period of explained variables and the generalised method of moment (GMM) is employed to investigate the potential non-linear nexus between FDT and CEI. The resulting conclusions gain insight into the internal mechanisms between FDT and CEI in OECD countries. *Third*, FDT's heterogeneous effect on CEI associated with institutional quality (IQ), economic development (ED), and resource endowment (RE) is also presented.

As for the novelty, this paper, for the first time, examines the joint

Table 1
Economic indicators of the OECD countries in 2010 and 2020, respectively.

Indicators	2010			2020		
	OECD	World	Ratio	OECD	World	Ratio
GDP	15.43	41.37	37.30%	51.82	86.65	59.80%
Primary energy consumption	234.19	505.38	46.24%	217.11	557.10	38.97%
CE	13046.1	31045.1	42.02%	10778.1	32018.2	33.66%

Notes: GDP: trillion; primary energy consumption: million tonnes; CE: million tonnes.
Data source: BP (2021); *World Bank Database*.

reduction effect of FDT and ICT on CEI in OECD countries.[3] *Second*, the non-linear nexus between FDT and CEI is captured from a dynamic perspective by performing a dynamic PTR model and, therefore, the derived results can comprehensively uncover the linkage among FDT, ICT, and CEI. *Lastly*, the legal system origin (LSO) acting as the instrument variable (IV) along with GMM and newly designed IV are utilised to conduct the robustness checks, thereby producing convincing results and more robust policy recommendations.

In summary, the objectives of this paper include.

- ✓ Modelling the effect of FDT on CEI in OECD countries.
- ✓ Investigating the joint reduction effect of FDT and ICT (including internet-based ICT and service-based ICT) on CEI.
- ✓ Assessing the non-linear nexus between FDT and CEI from a dynamic perspective.
- ✓ Capturing the heterogeneity analysis associated with IQ, ED, and RE with respect to FDT's effect on CEI.

The paper consists of six parts. Part 2 recaps the past literature. Part 3 describes the methodology. Part 4 presents the empirical findings. Part 5 conducts the mechanism analysis. Conclusions and policy recommendations are presented in Part 6.

2. Literature review

2.1. FDT-CEs nexus

Steered by the EKC hypothesis (Grossman and Krueger, 1995), an array of studies have examined FDT's effect on CEs. However, the empirical conclusions vary from studies regarding FDT's effect on environmental quality. The first strand of literature contented that although FDT's effect on economic growth is imperative, it degrades the environment (Ouyang and Li, 2018). For example, Charfeddine and Kahia (2019) posited that financial institutions provide a low-interest regime of borrowing with lesser barriers to the household and investors, resulting in increased energy consumption and CEs. Similarly, Khan et al. (2017) explored FDT's effect on CEs in 34 upper-middle-income countries and further reported that FDT depresses environmental quality. Taking N-11 countries during 1990–2017 as an example, Wang et al. (2020) certified the positive nexus between FDT and CEs (Shahbaz et al., 2013). Specifically, according to Sadorsky (2010), FDT increases CEs through four potential channels. First, the development of the stock market aids listed enterprises in lowering financial costs, reducing information asymmetries, optimising liability structure, and dispersing operating risks, thereby purchasing new installations, and investing more in new projects. These aspects are expected to increase CEs. Second, foreign investors are more likely to raise investment in domestic and, thus accelerating the rapid expansion of the domestic economy. Third, prosperous financial intermediations benefit households' loan activities, making it easier for households to purchase large ticket items (i.e., air conditioners and refrigerators), which implies an increase in energy consumption (Zhang, 2011). Fourth, firms featured by high resource consumption and high-polluting emissions may obtain scarce financial resources through corruption behaviour.

Instead, studies also shared their accumulated wisdom to demonstrate the FDT's promoting effect on environmental quality. For instance, Zioło et al. (2020) posited that green finance replaced convention finance by imposing a carbon tax on carbon-oriented projects and providing financial resources for developing low-carbon technologies. Similarly, Sheraz et al. (2021) scrutinised the link between FDT and CEs and further declared that FDT significantly decreases CEs in G20 countries. As a matter of fact, to proactively tackle climate change, the global economies are shifting financial investment from high-polluting projects to low ones while prioritising cleaner investment solutions (Zerbib, 2019).

Financial tools, such as green bonds and credits, are essential in addressing climate-related problems by stratifying the vital demand for low-carbon projects (Yao et al., 2020). Therefore, another wisdom is that green finance helps mitigate CEs. For instance, Saeed Meo and Karim (2022) certified the restricting effect of green finance on CEs in the selected top economies with the highest CEs. This evidence aligns with Li et al. (2019) who emphasised the essential role of green investment in achieving low-carbon transition and lowering CEs. In addition, Zhang et al. (2021) also verified the reduction effect of green credit on CEI in China, but the corresponding reduction effect has significant regional heterogeneity.

2.2. ICT-CEs nexus

The introduction of cloud computing and blockchain technology has raised wide attention from scholars concerning energy issues. However, such technologies' fast diffusion and expansion could increase energy needs, becoming one of the most significant challenges for realising energy-related sustainable development goals (Aste et al., 2017). For simplicity, applying information technology and adopting ICT-based equipment to foster economic growth promote the scaling-up use of non-renewable energy (Zhou et al., 2018). In contrast, ICT's application promotes the replacement of traditional technology and, thereby improving energy efficiency and reducing CEs. This is because most of ICT's products can be regarded as less energy-intensive (Takase and Murota, 2004). However, ICT's effect in different countries may differ due to the heterogeneity such as institutional quality, development status or even geographical locations. Moreover, the directional impact is highly contingent upon that country's dominant element (Han et al., 2016).

In short, there are two opposite viewpoints concerning ICT's impact. One is the energy-saving effect of ICT. Asongu et al. (2017) investigated how ICT complements CEs by adopting the GMM method in Sub-Saharan, and further contented that ICT's reduction effect on CEs is significant after crossing the threshold. Añón Higón et al. (2017) verified an inverted "U-shaped" relationship between ICT and CEs in 142 countries. In summary, the application of ICT equipment can help improve ICT equipment efficiency on the one hand (Ashiq et al., 2022); on the other hand, ICT helps to address environmental issues through environmental supporting models related to environmental-friendly project applications (Houghton, 2010). Fortunately, both channels are expected to reduce energy consumption and decrease CEs.

The second point states that ICT's application increases pollution emissions. Salahuddin and Alam (2016) explored the short- and long-run impacts of ICT and economic growth on electricity consumption from OECD countries. The results showed that both ICT and economic growth contribute to electricity consumption in both the short- and the long run. Findings from Danish et al. (2018) showed that CEs in N-11 countries are positively influenced by ICT, economic growth, and the moderating effect of FDT and ICT. Similarly, Lee & Brahmasrene (2014) confirmed the positive relationship between ICT and CEs in N-11 countries. Preceding work from Afzal and Gow (2016) certified a positive association between ICT use and electricity in N-11 countries, which aligns with Cho et al. (2007). A different perspective regarding ICT's impact on CEs provided by Danish et al. (2019) revealed that ICT's reduction effect varies from income level (i.e., ICT increased CEs in countries with the low-income level but decreased in high and middle-income countries).

2.3. FDT-ICT nexus

The pioneering studies on economic growth or environmental quality, whether concentrating on the effect of FDT or ICT, rarely focus on the combined effects of the two. It is argued that financial industries

[3] The detailed information can be found in Appendix A.

have a broader and deeper application of ICT products as ICT's application significantly enhances the operating efficiency of financial sectors through the so-called ICT's diffusion effect. The seminal work of Shamim (2007) revealed that in the long run, the financial sector and better telecommunications infrastructure are beneficial in driving economic growth. Unfortunately, Shamim's (2007) study failed to consider the joint effect between FDT and ICT on economic growth. Later evidence from Sassi and Goaied (2013) demonstrated the positive joint effect between FDT and ICT on economic growth in 17 MENA economies. However, the positive joint effect between FDT and ICT on economic growth is heterogeneous with respect to income levels (Das et al., 2018).

2.4. Literature gaps

In short, although current studies have offered fruitful information to uncover FDT's effect on CEs, relevant studies on assessing the FDT-CEs nexus in OECD countries are scant. *Second*, one of the crucial gaps is that studies ignore the essential role of ICT when assessing FDT's effect on CEs from the moderation and non-linear perspectives. *Third*, the heterogeneous analysis associated with institutional quality, economic development, and resource endowment is also conducted, which may be helpful to formulate differentiated development plans towards low-carbon transition by deepening the financial system in OECD countries.

3. Methodology

3.1. Model derivation

We aim to capture FDT's effect on CEs by constructing econometric model. Specifically, the IPAT model is a common procedure applied to assess the impact of human activities on environmental quality, with the following mathematical format: I = PAT. This particular form entails that environmental impact is the function of P (population), A (affluence), and T (technology). Although the IPAT model has a distinct structure because it is a parsimonious specification of crucial deriving elements behind the environmental change, but it has several limitations. For example, IPAT as an accounting equation is not sensitive to conducting hypothesis testing because the known values of some terms determine the value of the missing term (York et al., 2003). Dietz and Rosa (1994) developed a stochastic version (i.e., the STIRPAT model) by extending the IPAT model, which can effectively control stochastic elements, thereby accurately assessing the driving elements of environmental impacts. Specifically, the standard STIRPAT model is set as follows:

$$I = \alpha P^{\beta_1} \bullet A^{\beta_2} \bullet T^{\beta_3} \bullet \varepsilon \tag{1}$$

Where α, β_1, β_2, and β_3 are parameters, representing the environmental impacts of driving elements; ε is a residual term. Subsequently, we can get a linear form by taking the natural logarithm on both side of Eq. (1). This can help to reduce data volatility and avoid the potential heterogeneity, as arranged in Eq. (2):

$$\ln I_{it} = \alpha + \beta_1 \ln P_{it} + \beta_2 \ln A_{it} + \beta_3 \ln T_{it} + \varepsilon_{it} \tag{2}$$

To better reveal FDT-CEs nexus and follow Yan et al. (2022), *I* is measured by the proportion of total CEs to GDP. And the driving factors (i.e., *P*, *A*, and *T*) are decomposable (Chikaraishi et al., 2015). Thus, urbanisation rate (UR) is employed to represent population factor (Guo et al., 2019). *A* is quantified by economic growth (PGDP) (constant $2017); simultaneously, its quadratic term (PGDP2) is also introduced to verify the occurrence of the EKC hypothesis.

Referring to Adom et al. (2018), *T* can be expressed by three ways.

First, *T* captures the inputs into production. To this end, we treat non-renewable energy consumption (NE) as an essential input factor. Specifically, NE is evaluated by the proportion of NE to total energy consumption. The variable NE mainly refers to various fossil fuels, including coal, petroleum, and natural gas. These factors are the most fundamental components in the formation of CEs. Indeed, Ali et al. (2022) displayed that renewable energy consumption, NE, and R&D expenditure positively affect CEs in the long run, with NE contributing approximately 0.75% to CEs (Kuriqi et al., 2021).

Second, *T* reveals a transformational process between production and consumption. The status of a country's financing is fundamental because it determines which investments are undertaken in the transition process of production and consumption. For brevity, FDT is essential for low-carbon transition in the country. Specifically, FDT in our paper is assessed by three aspects: financial deepening (FDT_DP), financial size (FDT_SZ), and financial efficiency (FDT_EY). First, with reference to Salahuddin et al. (2018), FDT_DP is denoted by the proportion of domestic credit in the private section of GDP. Paramati et al. (2021) contented that well-designed financial markets and institutions improve economic conditions by facilitating intermediary financial sources and services and enhancing environmental quality by reallocating financial funds for environmentally-friendly ventures. Moreover, the size of financial markets and institutions could be expanded along with FDT_DP, thereby accelerating the ease of access to low-cost credits for households, investors, and business investments and, consequently, proliferating economic development (Hou et al., 2021). Second, FDT_SZ is proxied by the bank's credit scale ratio to GDP. This is because the financial scale may degrade environmental quality (Zhang, 2011). Third, FDT_EY represents the share of total capital formation to domestic savings (Yang and Ni, 2021).

Third, Amuakwa-Mensah and Adom (2017) proclaimed that *T* also expresses the institutional quality (i.e., governance). With this regard, *T* is also expressed by government intervention (GI). Importantly, GI is expressed by the share of total government consumption expenditure to GDP. According to Zhou et al. (2023), governments worldwide put more emphasis on vigorously addressing environmental problems by initiating standards and guidelines to keep economies on track for long-term inclusive development while mitigating pollution emissions. In other words, governments may force firms to actively repones to emission compliance towards eco-friendly projects by raising stringent environmental regulations.

Fourth, we also incorporate foreign capital usage (FCU) into the STIRPAT model, where FCU is gauged by the ratio of the net inflow of FDI to GDP. Theoretically, FDI's impact may be twofold. First, FDI could reduce pollution emissions of the OECD countries by absorbing more mature technologies and advanced management experience through the flow of technical talents triggered by the learning effect (Kim et al., 2015). In contrast, FDI may degrade environmental quality because the rise of preferential regulations and policies may squeeze the market share of domestic enterprises and lead to the possibility of exchanging advanced technologies, which may attract foreign enterprises with lower innovation capacity and high pollution emissions, thus, aggravating environmental deterioration (Shahbaz et al., 2015; Alalawneh et al., 2021).

Therefore, the extended STIRPAT model is finally specified as

$$\ln CEI_{it} = \alpha + \beta_1 \ln FDT_{it} + \beta_2 \ln UR_{it} + \beta_3 \ln PGDP_{it} + \beta_4 \ln PGDP2_{it} + \beta_5 \ln NE_{it} + \beta_6 \ln GI_{it} + \beta_7 \ln FCU_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{3}$$

Where μ_i and λ_t are country-fixed effect and time-period fixed effect, respectively; α_0 is the intercept; $\beta_1 - \beta_7$ denote parameters to be identified.

3.2. Channel analysis model

As mentioned earlier, FDT and ICT are crucial factors influencing CEs, and they are often incompletely independent but interdependence. In other words, FDT's effect on CEI is subject to ICT's advancement. To explore the effects of FDT and ICT on CEI simultaneously, the interaction term between FDT and ICT is included in Eq. (1). We specialise the FDT data and ICT data to ensure better the estimated parameters of FDT are economically meaningful. Thus, the moderating effect model is specified as

$$\ln CEI_{it} = \alpha_0 + \beta_1 \ln FDT_{it} + \beta_2 ICT_{it} + \beta_3 \ln FDT_{it} * ICT_{it} + \sum_{i=1}^{6} \beta_i * Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

Where $\ln FDT_{it} * ICT_{it}$ denotes the interaction term between FDT and CEI; β_3 is the corresponding regression coefficient. Z_{it} is the selected interference variables. The interaction term is derived by first normalising the raw data of FDT and ICT, respectively, and then multiplying them together to handle the multicollinearity. For the channel analysis, two indicators are selected to express ICT. Overall, ICT is evaluated by individuals using the internet, computer, communications, and other services. According to World Bank (2018), this indicator contains the internet application by individuals through computers, personal digital assistants, mobile phones, digital television and game consoles. To this end, we adopt internet usage as a percentage of total population (ICT1[4]) to proxy internet-based ICT. The ratio of computer, communications and other services to total commercial service exports is treated as trade-based ICT, indexed as ITC2.[5]

3.3. Non-linearity

To further investigate the effect of FDT on CEI levels under different types of ICTs, a dynamic PTRmodel is employed based on the traditional static PTR model proposed by Hansen (1999). Following Tao et al. (2023) and Hao et al. (2020), the dynamic PTR model takes the following form:

$$\ln CEI_{it} = \alpha_0 + \beta_1 \ln CEI_{it-1} + \beta_2 \ln FDT_{it} * I(q_{it} \le \lambda) + \beta_2 \ln FDT_{it} * I(q_{it} > \lambda) + \sum_{i=1}^{6} \beta_i * Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

Where q_{it} is a threshold variable, including ICT1 and ICT2. I(•) indexes the indicator function; λ is the threshold value. CEI_{it-1} is the lagged period of CEI, capturing the possible "accumulation effect". The estimation procedure contains the following steps. First, λ is measured using a grid search over the specified interval; simultaneously, nearby 11% data endpoints are dropped in the grid search, therefore, the estimated λ falls within a ICT range of roughly 15 percent to 105 percent (Arčabić et al., 2018). Second, a wild bootstrap procedure with 1000 replications is applied to determine the 95 percent confidence interval (CI) for λ, as the threshold estimate is a nuisance parameter that exists only under the non-linearity alternative. Note that the optimal estimate, λ, is identified by minimising residual sum of square, where the GMM estimation procedure is employed to estimate the model. Third, the Wald statistic is introduced to identify the significance of the threshold effect (Wu et al., 2019). The smaller the *p*-value is, the more significant the threshold effect. Notably, if $p < 0.10$, suggesting that there is an asymmetry in FDT's effect on CEI. Lastly, we adopt the two-step GMM-IV procedure to determine the regressors' coefficients.

Table 2
Descriptive statistics.

variables	definition	mean	sd	min	max	unit
CEI	Carbon intensity	0.372	0.221	0.063	1.624	%
FDT_FD	Financial deepening	1.024	0.457	0.002	3.046	%
FDT_SZ	Financial size	0.952	0.429	0.002	3.046	%
FDT_EY	Financial efficiency	0.950	0.250	0.334	2.141	%
GI	Government intervention	0.192	0.038	0.103	0.279	%
UR	Urbanisation rate	0.771	0.113	0.513	0.980	%
LNPGDP	Economic growth (logarithm)	10.451	0.406	9.304	11.670	US $
FCU	Foreign capital utilisation	0.412	0.143	0.071	0.690	%
NE	Non-renewable energy consumption	0.059	0.052	0.0003	0.291	%
ITC1	Internet-based ICT	0.720	0.184	0.141	0.990	%
ICT2	Service-based ICT	0.395	0.170	0.006	0.796	%

3.4. Robustness checks

First, the robustness tests in this paper are conducted by three ways. Taking the potential endogeneity into consideration, the GMM method (Blundell and Bond, 1998) is introduced with the following form:

$$\ln CEI_{it} = \alpha_0 + \beta_1 \ln CEI_{it-1} + \beta_2 \ln FDT_{it} + \sum_{i=1}^{n} \beta_i * Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (6)$$

Second, the legal system origin (LSO) of the OECD countries is treated as FDT's IV. Theoretically, an ideal IV should satisfy two conditions: relevance and exogeneity (1) *Relevance*. La Porta et al. (1998) expounded that the protection of investors' rights and property rights is rooted in one country's legal system, which is essential in enhancing financial operation efficiency. This standpoint is further verified by Levine et al. (2000) who held that an efficient legal system becomes increasingly essential for refining the financial system, thereby promoting inclusive economic development. However, different LSO (i.e., common-law tradition, civil-law tradition) tends to trigger heterogeneous impacts on economic growth through FDT. To this end, the selection of LSO satisfies the precondition of relevance. (2) *Exogeneity*. Following La Porta et al. (1998), most economies can be categorised into four types regarding the source of law: French, Anglo-American, German or Scandinavian. Importantly, the adoption of a specific legal system in the country lies in colonisation or occupation. Therefore, LSO also meets the condition of exogeneity.

[4] This indicator is known as internet-based ICT. One the one hand, internet-based ICT helps reduce information asymmetries and lower transaction costs by providing user-friendly platform for consumers or investors. In other words, its development helps adapt the existing business model by cultivating new ones. On the other hand, ICT may increase energy consumption (i.e., electricity consumption) in a shooter period, thereby degrading the environment.

[5] This indicator is also known as service-oriented ITC. According to World Bank (2018), service-oriented ITC contain such activities as international telecommunications, and postal and courier services, etc. Therefore, the restraining effect of service-oriented ITC may be more significant than ICT1.

Fig. 1. CEI and FDT in OECD countries in the selected years.

Third, we further design one IV to verify the reliability of the estimated results. Specifically, the average FDT, including FDT_FD, FDT_SZ, and FDT_EY, of all countries except for the country is treated as IVs. The corresponding estimations are performed by employing 2SLS and GMM.

3.5. Descriptive statistics

This paper selects 35 OECD countries during 2004–2018 to comprehensively assess the role of FDT on CEI from a dynamic perspective. Appendix B lists the selected OECD countries. The data are collected from the *World Bank database*. The country-level LSO data are extracted from La Porta et al. (2008). The interpolation method is employed to fulfil missing values for several variables before estimation. The statistical description of each variable is listed in Table 2.

The spatial distribution characteristics of country-level CEI and FDT (i.e., FDT_FD, FDT_SZ, and FDT_EY) are plotted in Fig. 1.[6] Overall, CEI in the selected OECD countries has presented a declining trend during the research period. Specifically, the CEI level of the US, Japan, Germany, Canada, and Australia is significantly higher than that of other OECD members, with Germany having the highest average CEI level during the sample period. Notably, the aforementioned countries also performed better than other OECD countries concerning FDT.

4. Empirical findings

4.1. Benchmark regression results

Table 3 shows the results estimated using Eq. (1), whereas columns (2), (4), and (6) show the results without controlling the time-period fixed effect. In contrast, columns (1), (3), and (5) display the results controlling the time-period fixed effect and country fixed effect. According to Ramos and Veiga (2013), a two-way fixed effect model considering time-period and individual fixed effects could improve both the quantity and quality of the data and yield more accurate model interference. Apart from the characteristics mentioned above, taking the IPTA model for example, this particular model emphasises modelling driving elements behind pollutant emissions. With this regard, the country fixed effect could be sought from the country's unobservable endowment. However, resource endowment acting as a typically time-invariant variable determines the energy utilisation of one country in the long run because the use of different energy could exert completely different effects on pollutant emissions, which vary intensely from other countries. Therefore, the implementation of the two-way

[6] More information can be found in Appendix C.

Table 3
Benchmark regression.

	(1)	(2)	(3)	(4)	(5)	(6)
lnFDT_FD	−0.0642***	−0.0518***				
	(0.015)	(0.014)				
lnFDT_SZ			−0.0698***	−0.0547***		
			(0.015)	(0.014)		
lnFDT_EY					−0.0459**	−0.0533**
					(0.023)	(0.024)
lnGI	−0.2833	0.8324***	−0.2592	0.8412***	−0.6414**	−0.7589***
	(0.294)	(0.309)	(0.292)	(0.308)	(0.268)	(0.277)
lnUR	2.0025***	2.6837***	2.0289***	2.7071***	0.8341***	1.9601***
	(0.276)	(0.279)	(0.276)	(0.280)	(0.192)	(0.280)
lnPGDP	−1.8046***	−1.8324***	−1.8109***	−1.8486***	−2.2359***	−1.9611***
	(0.388)	(0.358)	(0.387)	(0.358)	(0.394)	(0.392)
lnPGDP2	0.0632***	0.0742***	0.0633***	0.0749***	0.0866***	0.0711***
	(0.019)	(0.018)	(0.019)	(0.018)	(0.019)	(0.019)
lnFCU	−0.0931	−0.0314	−0.0894	−0.0293	−0.1218*	−0.1343*
	(0.076)	(0.067)	(0.076)	(0.067)	(0.074)	(0.077)
lnNE	5.3946***	5.4367***	5.5098***	5.5141***	3.5148*	4.7013**
	(1.807)	(1.590)	(1.804)	(1.590)	(1.845)	(1.824)
_cons	5.5418*	3.9329	5.4546*	3.9304	10.3126***	7.1095**
	(2.994)	(2.654)	(2.986)	(2.651)	(3.004)	(3.011)
μ_i	√	√	√	√	√	√
λ_t	×	√	×	√	×	√
Obs.	525	525	525	525	525	525
R-squared	0.6324	0.7274	0.6344	0.7280	0.6097	0.6224

Notes: Figures reported in ( ) are standard errors; *p < 0.10, **p < 0.05, ***p < 0.01.

fixed panel data model is more suitable. As can be seen that three dimensions of FDT, including FDT_FD, FDT_SZ, and FDT_EY, have significant negative effects on CEI, which aligns with Saidi and Mbarek (2016) who demonstrated FDT's promoting effect on CEs. This outcome highlights that vigorously promoting FDT is conducive to reducing CEI in OECD countries. To be specific, FDT's essential role lies in its function as a leading production factor in guiding various financial resources to where productivity is high and the regions or countries wish to improve substantially. Fortunately, FDT in OECD countries is far more developed than in other countries worldwide. Not surprisingly, the financial sector's contribution in OECD countries constitutes nearly 80% of the global amount, and the global share of FDI inflows accounting for approximately 63% (World Bank, 2015). Moreover, the induced FDI inflows could attract multinational enterprises to transfer their cleaner and greener technologies to the host countries, thereby reducing CEs, which is caused by the "pollution halo hypothesis".

As for interference variables, the correlation between GI and CEI varies from models under different FDT's measurements. First, Fredriksson and Millimet (2002) stressed that the effectiveness of local environmental regulation heavily depends on the local government's attitude toward environmental protection. If local governments lower the threshold for environmental protection,[7] this will attract the "zombie enterprises" and thus trigger excessive energy consumption and pollution emissions (Copeland and Taylor, 1994). In contrast, Fischer and Fox (2012) disclosed that government subsidies could mitigate pollutant emissions. And Qian and Roland (1998) further complemented that under a multi-objective institutional arrangement, local government's decision-making should align with the willingness of residents to pursue specialised social welfare; subsequently, the government will provide the best environmental quality for local residents.[8] Second, the rapid urbanisation process has enhanced people's material living standards and intensified the conflicts between humans and nature. Our findings align with Rehman and Rehman (2022) and Duan et al. (2022), displaying that urbanisation significantly promotes CEI. Third, the estimated coefficients for the linear term (PGDP) are significantly positive and negative for the quadratic term (PGDP2), forming an inverted "U-shaped" trend between economic growth and CEI. Thus, the EKC hypothesis is captured in OECD countries. Fourth, FCU plays an important restraining role in CEI. As mentioned earlier, a sound financial mechanism could correct and guide the reallocation of scarce financial resources from regions with low-productivity levels to high-yielding ones. The well-designed financial mechanisms could absorb foreign enterprises to invest more in projects, especially green-oriented projects, by providing cleaner technologies to the host country, with apparent environmental spillovers, thereby showing a declining trend in CEs of the host country and thus exerting a "pollution halo" effect (Ran et al., 2020). Lastly, similar to Wang et al. (2022a, b),[9] results uncover that the share of NE to total energy consumption significantly contributes to CEI.

4.2. Robustness checks

We check the robustness of baseline results from three perspectives, as reported in Table 4. First, columns (1)–(3) display the results estimated by the GMM procedure. Evidently, FDT_FD, FDT_SZ, and FDT_EY significantly alleviate CEI, with a significance level of 1%. Still, the coefficients of CEI's lag period are significantly positive, thereby certifying the "accumulation effect". Second, columns (4)–(6) of Table 4 report the results estimated adopting the IV method, where country-level LSO is treated as IV. Fortunately, our results also demonstrate the significant restriction effect of FDT_FD, FDT_SZ, and FDT_EY on CEI.

Third, we further examine the reliability of baseline results by constructing the IVs; simultaneously, both 2SLS and GMM procedures are employed to estimate the results. We first conduct a set of tests to validate the IVs, as shown in Table 5 (Appendix D). (1) The first-stage F-statistics are greater than 10 (Brunello et al., 2022), designating that endogenous variables are highly associated with IVs. (2) The Wald F

[7] For example, high-polluting firms could obtain market shares by bribing local government officials.

[8] For example, the cap-and-trade environmental regulation (i.e., carbon trading scheme) promulgated by the government is helpful in CE reduction compared with common-and-control environmental regulation (Tao et al., 2022).

[9] Wang et al. (2022a, b) found that renewable energy consumption positively affects total factor carbon productivity. In contrast, NE's consumption hinders the improvement of total factor carbon productivity.

Table 4
Robustness test I.

	(1)	(2)	(3)	(4)	(5)	(6)
	GMM procedure			IV procedure		
ln $CEI_{i,t-1}$	0.6464***	0.6341***	0.6389***			
	(0.013)	(0.012)	(0.013)			
lnFDT_FD	−0.0488***			−0.3606***		
	(0.008)			(0.137)		
lnFDT_SZ		−0.0664***			−0.6879***	−0.0014***
		(0.007)			(0.210)	(0.0002)
lnFDT_EY			−0.0421***			
			(0.006)			
_cons	2.9409	1.3549	4.3107	−1.1905	10.7905	9.3650**
	(2.552)	(1.105)	(4.267)	(9.282)	(10.423)	(4.6383)
μ_i	√	√	√	√	√	√
λ_t	√	√	√	√	√	√
Obs.	490	490	490	525	525	525

Notes: Figures reported in ( ) are standard errors; *p < 0.10, **p < 0.05, ***p < 0.01.

statistics in all columns are greater than the critical value. Hence, the newly designed IVs pass the weak IV test. The KP rk LM statistic rejects the original assumption at a 1% significance level (i.e., the IV satisfies the identifiability). Simultaneously, the robustness check shows no overidentification problem as Hansen J statistics are insignificant through all estimations. In short, the reported estimations align with the results documented in Table 3. Therefore, FDT indeed plays an inhibitory role in CEI.

4.3. Heterogeneity analysis

We further explore the heterogeneity concerning IQ, ED, and RE in OECD countries.

(1) **IQ.** Lau et al. (2014) held that IQ plays a vital role whereby it could help mitigate environmental degradation in a country despite its relatively low-income level. This implies that countries can enjoy a favourably ecological environment with higher income levels. This is because countries with better IQ could offset the negative externalities imposed by rapid economic expansion, such as environmental loss (Panayotou, 1997). Law et al. (2013) further contented that FDT has more cumulative effects on economic growth when FDT is developed within a sound institutional system. Note that legal systems of different origins have tremendous differences in protecting investor rights, resulting in differences in FDT between countries (Beck and Levine, 2003). Bekaert et al. (2011) contented that the better the IQ is, the more significant the promoting effect of financial openness on economic growth will be. Their findings also showed that FDT helps improve environmental quality in countries with stringent institutions by mitigating CEs. However, it is also noted that FDT might degrade the environment when countries have a weak IQ (Tamazian et al., 2009). Thus, to capture FDT's impact on CEI under IQ's conditions and follow Amighini et al. (2011), we first calculate a comprehensive index[10] by collecting data from the *Global Governance Index database*, including corruption control, the rule of law, voice rights and accountability, rule quality, government efficiency and political stability. Lastly, the sample is divided into two subgroups (i.e., low IQ and high IQ) according to the median level of the comprehensive index.

(2) **ED.** It is commonly believed that there is a significant difference between developed and underdeveloped economies concerning economic performance, innovative capability, and the maturity of the financial system. Compared with developing economies, developed economies are more likely to have better IQ, a higher degree of the financial system, more achievements in technological innovation, and a higher level of green development. To this end, the related analysis is also performed to capture the potential heterogeneity concerning ED.

(3) **RD.** Resources, as a crucial component of one country's wealth, are essential in driving economic growth. The existing powers have all enjoyed resource gains in the rapid economic growth period (Shahbaz et al., 2019). However, the conclusions of whether natural resources are a "curse" or a "blessing" for a country's FDT in current studies are debated. For example, Smith (1776) highlighted that abundant resource endowment sustains economic growth and booms FDT; In contrast, the "resource curse" hypothesis was identified in the work of Tiba (2019). Thus, heterogeneity analysis is performed by classifying the sample into two categories: the resource endowment group and the non-resource endowment group.

The corresponding results are presented in Table 6 (Appendix E).

Columns (1), (3) & (5) in **Panel A** are the estimated results of subgroups with low-level IQ, whereas columns (2), (4) & (6) display the results with high-level IQ. Under the lower IQ, FDT_FD, FDT_SZ, and FDT_EY negatively affect CEI of OCED countries. In contrast, FDT's restraining effect tends to be dramatically improved with further improvement of IQ. Logically, a high-level IQ means open financial markets, a competitive and fair economic environment, and a mature governance system. However, it is hard for governments in countries with low-level IQ to provide sufficient financial resources and economic security services because of the restriction of the institutional system and unsuitable political environment. As a result, the road to the low-carbon economic development of a country is full of thorns because the harsh FDT environment has loosed investors' confidence.

Panel B displays the heterogeneity analysis considering the country's ED. Compared with developing economies, the reduction effect of FDT_FD, and FDT_SZ in developed economies is more predominant (Columns (1) & (2)). While FDT_EY exerts a weak promoting impact on the developing economics of OCED countries, we all understand that FDT_EY in developing economies is relatively backward. At the same time, the financial market is comparatively immature. This could explain the dilemma that FDT of developing economies hinders inclusive economic development (Nanda and Kropf, 2016). Besides, due to the limitation of internal and external influences (i.e., insufficient financial resources, inadequate innovative capability), developing economies mainly concentrate more on resource- or labour-intensive production activities, thus, triggering pollutant emissions. They also

[10] The entropy method is a representative objective weighting determination procedure, which is adopted to construct the IQ comprehensive index in OECD countries.

focus on traditional and mature technologies for their production. At the other extreme of the development spectrum, developed economies present an entirely different scenario. The relative abundance resource endowment in developed economies is typically specialised by capital (including physical capital and human capital), not natural resources or labour. In other words, they specialise in capital- and skill-intensive products.

Comparing results in columns (1), (3) & (5) and columns (2), (4), and (6) in Panel C,[11] our findings entail that FDT's on CEI is tremendous in non-resource-based countries. According to Berglof and Lehmann (2009), abundant natural resources could reduce people's demand to return capital into the future, which implies that natural resources will reduce investment and savings, resulting in the sluggish growth of FDT. Sachs and Warner (2001) also asserted that high resource prices and abundant natural resources are prone to attack labour to engage in those resource extraction production activities, resulting in a slowdown in technological advancement, especially in green technologies. Moreover, Gylfason & Zoega (2006) further complemented that sufficient natural resources in a given economy could drive the financial industry to invest in industries lacking innovative capabilities, which will stagnate or slow long-term sustainable economic development.

5. Mechanism analysis

5.1. Moderating effect of ICT

Using Eq. (5), we further verify the moderating effect of ICT, as reported in Table 7 (Appendix F). First, FDT reduces CEI, which aligns with the baseline results. Promoting FDT is conducive to lowering CEI in OECD countries. Second, the coefficient of ICT1 and ICT2 in all models is positive, excluding FDT_FD model, suggesting that ICT's development in OECD countries contributes to CEI. Third, the interaction term between FDT and ICT is negative, with the estimated coefficient in column (4) showing a significant reduction effect. A strong belief is that ICT helps handle energy over-consumption for everyday and economic activities (Ishida, 2015). At the same time, it also helps to solve the environment-growth dilemma through two pivotal channels (Laitner and Ehrhardt-Martinez, 2007). (1) ICT may improve the efficiency and reliability of the gird transmission and boom power redistribution and storage (which refers to the efficiency channel). (2) ICT may boost knowledge creation, cause networks and spillover effects, and lower transaction costs, thereby driving national productivity (the productivity channel).

Though the important role of ICT in sustaining economic growth cannot be overlooked considering its widespread function in advanced economies, unfortunately, its impact on environmental quality is contestable. Notably, energy consumption is growing at a rapid rate of approximately 7 percent per annum due to ICT rapid expansion in the past few decades (Chaabouni and Saidi, 2017) and the world's total energy consumption due to ICT-oriented products has amounted to 4.7 percent by 2012 which was 4% in2007.[12] As a result, the contribution of the ICT sector in world's CEs is continuously growing because, on one side, the ICT-oriented production activities are degrading the environment (Chen et al., 2019) whereas, on the other side, increased usage of computers, internet has swelled the excessive energy demands (Chien et al., 2021), especially the scaling-up use of electricity, which is the main source of degrading the environment.

Nonetheless, our results align with the work of Salahuddin and Alam (2016) for 26 OECD economies and the study of Saidi et al. (2017) for 67 economies as the empirical evidence certified the direct causality from ICT to electricity consumption. This viewpoint is further complemented by Magazzino et al. (2021) who held that internet penetration and electricity consumption improve each other, suggesting that the dramatic improvements in ICT have substantially expanded power needs in OECD countries. Besides, electricity consumption is also found to be a crucial driver of CEs (Liu et al., 2022). Therefore, the positive correlation between ICT and CEI is identified in this paper.

5.2. Dynamic PTR results

A dynamic PTR model is employed to capture the threshold effect, where ICT1 and ICT2 are considered as threshold variables. Table 8 (Appendix G) includes the traditional serial autocorrelation and IV's validity tests. Specifically, AR (1) and AR (2) tests as well as the Hansen test cannot be rejected at a 10% significance level, verifying the suitability of the selected IVs. The *p*-value of the Wald statistics through all models reject the original assumption of no threshold effect. Particularly, the estimated λ of ICT1 under three types of FDT is 0.8981, 0.8981, and 0.7650, with 95% CI of [0.3500, 0.9478], [0.3500, 0.9478], and [0.3500, 0.9478], respectively. When treating ICT2 as threshold variable, the estimated λ of ICT1 under three dimensions of FDT is 0.0194, 0.0101, and 0.1799, with 95% CI of [0.0057, 0.1979], [0.0057, 0.1979], and [0.0057, 0.1979], accordingly. Therefore, the nexus between FDT and CEI is non-linear.

Subsequently, the sample is categorised into subgroups with low- or high-level ICT1 and ICT2. Specifically, the top five countries with the highest ICT1 score include Greece (0.7239), Mexico (0.7270), Portugal (0.7769), Finland (0.8093), Japan (0.8388), and Turkey (0.8389). In contrast, countries with the lowest ICT1 contain Norway (0.1410), the United Kingdom (0.1458), Ireland (0.2142), Korea, Rep. (0.2277), and Israel (0.2774). The average ICT1 score was 0.5127 in 2004 and all countries failed to surpass λ in FDT_FD and FDT_SZ models, with only four countries crossing 0.7650 (under FDT-EY model), accounting for 11.43% of the whole sample. Fortunately, the internet-based ICT index of all OECD countries in 2018 has significantly improved, with the average ICT1 being 0.8577. Specifically, countries above λ under FDT_FD, FDT_SZ, and FDT_EY models include 10, 10, and 29, respectively, which represent 28.57%, 28.57%, and 82.86% of the whole sample accordingly. The average service-based ICT score in 2004 was 0.0903. In particular, there were 29, 33, and 5 countries above the corresponding λ, representing 82.86%, 94.29%, and 14.29% of the whole sample. However, the average ICT2 (=0.0584) and classified countries under each model have sharply decreased, with each subgroup containing 24, 30, and 1 countries, respectively.

One interesting point can be identified by checking the threshold regression. The restraining effect of three types FDT indices tends to be weakened when internet-based ICT crosses the corresponding λ, with FDT_SZ's coefficient in column (2) being insignificant. In contrast, FDT's inhibitory effect is more prone to be tightened because the threshold coefficients for FDT_FD, FDT_SZ and FDT_EY are higher than those below the corresponding λ. Note that the service sector's advancement depends on information, knowledge, local market scale, and human capital, and it presents significant spatial clustering characteristics (Kim et al., 2021; Niebuhr et al., 2020). In recent years, more attention has been given to developing and constructing service clustering regions. Service firms have been guided to focus on specific clustering regions with diversified services and high-productivity characteristics. Therefore, OECD countries should form a sound financial mechanism and prioritise service-oriented ICT development. Besides, our results align with Salahuddin et al. (2016) who demonstrated a significant positive relationship between internet usage and CEs. However, to better play the incentive role of FDT to CEI reduction, OECD countries should spare no effort to concentrate more on promoting two types of ICT.

[11] We classify the resource-based and non-resource-based countries by referring to the 2019 BP Statistical Yearbook World Energy. A total of 51 countries' proven reserves of gas, oil, and coal accounted for a share of the world's total. Countries that have none of these three components were considered non-resource-based countries.

[12] See https://issafrica.org/iss-today/achieving-effective-national-environmental-governance-in-africa.

6. Conclusions and policy implications

By employing a panel data from the OECD countries during 2004–2018, this paper examines FDT's effect on CEI and the corresponding mechanisms based on the extended STIRPAT model. The moderating effect of ICT on CEI from FDT has also been verified under the methodological framework. A dynamic PTR model is employed to investigate the non-linear nexus between FDT and CEI under different ICTs, where ICT includes internet-based ICT and service-based ICT. The heterogeneity analysis associated with IQ, ED, and RE is also conducted. The main conclusions are summarised below.

(1) FDT significantly mitigates CEI in OECD countries irrespective of which indicators of FDT are chosen.
(2) The moderating effect results show that internet-based and service-based ICT positively correlate with CEI in OECD countries. Still, the collaborative effect between FDT and ICT exerts a weak restriction effect on CEI.
(3) A non-linear nexus exists between FDT and CEI in OECD countries under different ICTs.
(4) The reduction effect of FDT on CEI also varies from countries with different IQ, ED, and RE. It is interesting to conclude that the corresponding inhibitory effect of FDT is significant in countries with high-level IQ, developed economies, and non-resourced-based countries.

Based on the research findings, several policy recommendations are derived.

First, prioritising technological advancement and improving energy utilisation efficiency. To successfully achieve a low-carbon transition, OECD countries can start by reducing CEs and lower fossil energy intensity (see Fig. 1) while simultaneously improving energy utilisation efficiency.[13] Moreover, technological innovation (especially low-carbon technologies) is essential in improving the efficiency of fossil fuels, such as mining, coal, and natural gas, thereby reducing CEs. Considering specific technical investment risks, policymakers should formulate powerful, robust policies for relevant authorities to provide long-term stable technical investment funds to enterprises, scientific and research institutions, and universities through budgetary allocations.

Second, from the perspective of FDT, strategies like refining domestic financial market mechanisms, deepening financial cooperation, and attracting international capital inflows can be adopted by OECD countries. In the meantime, IQ is also essential in FDT and sustainable development. Relevant authorities of the OECD countries can establish a better institutional environment by controlling corruption, reinforcing the legal system's construction, and improving government management efficiency to provide a fair, effective and safe investment environment, attracting foreign enterprises to settle in, thereby injecting validity into the domestic markets. Developed economies may support the economic development of developing economies by providing low-carbon technologies and personnel support. And developing economies should vigorously conduct R&D activities to strengthen their innovative capabilities by absorbing advanced management experience. Besides, OECD countries, especially resource-based countries, should also optimise their energy consumption structure from existing consumption structures to sustainable ones. On the one hand, the governments of OECD countries should promote the broad utilisation of clean energy (i.e., solar energy) in residents' daily life and production activities. On the other hand, it is also necessary to introduce targeted policies in regions with different economic development stages and resource endowments.

Third, the collocative effect between FDT and ICT needs further improvement. In order to achieve sustainability objectives, OECD countries should focus on reaching the required threshold levels of ICT in various forms. Specifically, related economies should implement policies related to ICT in an environmentally responsible way. Moreover, domestic countries should establish strict environmental regulations to avoid the "pollution haven" phenomenon.

It is argued that economic activities (i.e., financial liberalisation and trade liberalisation) have accelerated linkages between economies worldwide. Therefore, the change in FDT in a specific unit may therefore generate a certain effect on other units trigged by the spatial spillover effects. To this end, further analysis is suggested to conduct from a spatial perspective, thereby presenting an integrated scenario of the FDT-ECI nexus.

[13] Studies (Duan et al., 2017; Emodi and Boo, 2015) highlighted that improving energy efficiency is conducive to mitigating CEs.

Credit author statement

Miaomiao Tao: Conceptualization, Methodology, Formal analysis, Data Curation, Investigation, Writing – Original Draft, Writing - review & editing. **Mingyue Selena Sheng**: Writing - Original Draft, Writing - review & editing. **Le Wen**: Formal analysis, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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