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Decoupling and decomposition analysis of investments and CO₂ emissions in information and communication technology sector

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HIGHLIGHTS
• Carbon mitigation effect of information and communication technology (ICT) investment is assessed.
• ICT investment has an ideal decoupling state with carbon intensity in most economies.
• Emission intensity of ICT investment contributes an increase of carbon emissions.
• Efficiency of ICT investment is most significant factor in inhibiting emissions.
• ICT industrial structure should be further improved in the post-pandemic era.

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ABSTRACT
Organization of Economic Cooperation and Development (OECD) economies are facing a substantial increase in the information and communication technology (ICT) investments in the context of rapid spread of the Coronavirus Disease-2019 (COVID-19) pandemic and constraints of emissions reduction. However, the mechanism of the impact of ICT investments on carbon dioxide is still unclear. Therefore, by employing the decoupling-factor model and Generalized Divisia Index Method, we explore the decoupling states of ICT investments and emission intensity, and the driving factors of ICT investments’ scale, intensity, structure, and efficiency effects on carbon emissions in 20 OECD economies between 2000 and 2018. The results indicate that the number of economies with an ideal state of strong decoupling rose to nine between 2009 and 2018 compared to no economies between 2000 and 2009. The emission intensity of ICT investments contributes to a significant increase of carbon emissions, and the structure and efficiency of ICT investments always restrain the growth of carbon emissions. Significant emissions changes caused by the driving factors are shown in many economies before and after the crisis, reflecting the differences in the strategic choices of ICT investments and the impact on emissions due to the crisis such as the COVID-2019 pandemic. And policy implications for energy and carbon dioxide mitigation strategies in the post-COVID-2019 era are also provided.

1. Introduction
Many empirical studies have confirmed that information and communication technology (ICT) can promote the economic development of a nation, especially when a pandemic such as the Coronavirus Disease-2019 (COVID-19) is sweeping the world [1,2]. Both developing and developed countries have invested in ICT to resist the negative economic impact of the current COVID-19 pandemic [3], such as the “working from home” model via ICT equipment [4,5]. However, in the context of global warming, ICT investment may bring environmental issues, especially energy consumption and carbon emissions are concerned. According to Salahuddin and Alam [6], electricity consumption due to ICT devices is increasing at the rate of 7% per year, and promoting the growth of carbon emissions [7,8]. While others believe ICT investments can replace some high-energy-consuming industries, thereby reducing carbon emissions [9,10]. Therefore, the impact of ICT investments on carbon emission reduction is still uncertain.

For the developed economies, above issues are even more important. As an economic organization that accounted for about 63% of the world’s total GDP in 2019 [11], the Organization of Economic...
Cooperation and Development (OECD) economies have witnessed a rapid growth in ICT investments. According to the OECD’s telecommunications database, telecommunication investments by the OECD economies reached USD202.43 billion in 2018 [12]. And the Statista Research Department reported in its forecast of ICT investments in government markets from 2014 to 2025 that ICT investments in the United States will reach a peak of USD239.8 billion by 2025 [13]. In the meantime, the OECD economies are characterized by the highest level of energy consumption in the world, which has led to a sharp increase in carbon emissions [14]. According to statistics, OECD economies account for about 39% of the world’s total energy consumption in 2020 [15]. And carbon emissions from fossil fuel combustion in the OECD economies rose from 9340 billion kilograms (kg) in 1971 to 12620 kg in 2008, an average annual increase of 0.82% [16]. Moreover, since 2009, OECD countries affected by the global financial crisis have shown a fluctuating decline in carbon emissions, with an average annual decrease of 0.47%.

Some scholars have conducted preliminary explorations of the impact of ICT on carbon emissions in OECD economies [14,17]. However, to the best of the authors’ knowledge, it seems these scholars have not yet explored the relationship between ICT investments and carbon emissions in OECD economies, and the emission reduction mechanism of ICT Investments is still unknown. Especially in the era of global warming and post-COVID-19, how ICT investment balances the relationship between carbon emission reduction and economic growth becomes particularly important. Therefore, several questions have ignited our interest: (1) Is there a decarbonization trend in the ICT investments of OECD economies? (2) Through which mechanism does ICT investments contribute to carbon emission reduction? (3) To what extent have ICT investments and related emission-driving factors changed before and after the crisis, especially in the context of COVID-19 pandemic? To answer those questions, this study explores the decoupling relationship between ICT investments and carbon emission intensity, and the driving factors of ICT investments scale, emission intensity, structure, and efficiency effect on carbon emissions in OECD economies by using the Generalized Divisia Index Method (GDIM).

Accordingly, this study provides several novel contributions to the existing literature. First, we explore the decoupling relationship between ICT investments and emission intensity in OECD economies, and show the dynamic relationship between ICT investments and carbon emissions, which provides a basis for identifying the important effect of ICT investments on carbon emissions. Second, we discuss the impact of ICT investments’ scale and their emission intensity, structure, and efficiency factors on carbon emissions, which is helpful for understanding the mechanism of ICT investments affecting carbon emissions and proposing more targeted emission reduction measures. Finally, we explore the changes in the impact of ICT investments and other related factors on carbon emissions before and after the global financial crisis, which can provide OECD economies and other countries around the world with emission reduction measures before and after the crisis and pandemic.

The rest of the paper is organized as follows. Section 2 reviews the related literature. In Section 3, we illustrate the methodology and data in detail. Section 4 presents the results and discusses them. Section 5 concludes the paper and highlights some policy implications.

2. Literature review

In recent years, the issue of carbon emissions has caused great concern among scholars, such as the characteristics [18,19], causes [20] and effects of carbon emissions [21,22], and several studies have explored the relationships between carbon emissions and the ICT industry, particularly the drivers behind such emissions. This study discusses the existing literature under three strands of research: (1) providing research relating to the mechanism of carbon emission reduction, (2) studying the relationship between ICT investments and carbon emissions, and (3) providing an overview of carbon emissions studies in OECD economies and the impact of the global financial crisis.

2.1. Carbon emissions reduction mechanism

Since the issue of climate change first came to the world’s attention, many scholars have conducted research on carbon dioxide, an important greenhouse gas [23], and the growth trajectory of carbon emissions caused by fossil fuel combustion has received special attention [24,25]. In particular, some scholars have analyzed carbon emissions from a production perspective and a consumption perspective [26,27]. Other scholars have explored carbon emission reduction strategies from the perspective of carbon emission intensity or energy use [28,29]. However, the most crucial issue for policy makers and scholars is investigating mechanisms that reduce carbon emissions. Many scholars use different methods to explore the internal impact mechanism of carbon emissions and provide directions for reducing emissions [22]. Ehrlich and Holdren [30] first propose the IPAT model, pointing out that population, affluence, and technology can cause environmental changes. As research has continued, some scholars have recognized that economic factors are the primary contributors to increases in carbon emissions [21,32]. Chang and Lin [33] find that the primary factor for an increase in CO2 emissions is the level of final demand in Taiwan. Brizga et al. [34] show that final demand has been the main driving force for increasing emissions in the Baltic States and caused an 80%, 64%, and 143% increase in emissions in Estonia, Latvia, and Lithuania during 1995–2009. Some scholars further divide final demand factors into consumption, fixed capital formation, and exports, and explore their impact on carbon emissions [35,36]. For example, Wang et al. [37] show that fixed capital formation has a significant influence on changes in carbon emissions from energy consumption in Xinjiang, China. Zhou et al. [38] also point out that capital investment demand has largely affected the aggregate embodied carbon emissions in China, about 53% of emissions is caused by capital investment at a national level in 2012. Some scholars also focus on the industrial sector and point out that some high energy-consuming sectors are the main driving forces affecting carbon emissions [39,40]. Danish [41] also points out that the ICT sector has a significant effect on changes in carbon emissions. But the impact of investment within ICT on carbon emissions is more important.

2.2. Information and communication technology investments and carbon emissions

ICT investments are viewed as an important way to reduce carbon emissions. Consequently, many studies focus on the relationship between carbon emissions and ICT investments. For example, Cho et al. [42] believe ICT investments can reduce energy consumption by using new technology to replace old technology and reduce electricity consumption in innovative production processes. The reduction of carbon emissions thus obtained is called the “substitution effect.” Moreover, the substitution of virtual goods for physical goods, virtual mobility, e-commerce, and virtual meetings can also reduce carbon emissions [9]. Lu [8] suggests that ICT investments will raise productivity, boost economic growth, reduce energy intensity, and thus achieve carbon emissions reduction. Bieser and Hilty [43] point out that ICT investments allow people to work from home and have virtual meetings, thus avoiding travel-related carbon emissions. Zhang and Liu [44], using the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model, confirm that the ICT industry has a negative impact on CO2 emissions in China. They point out that the ICT industry provides technology that enhances energy efficiency, provides a low-carbon lifestyle, and provides a way to transition to a low-carbon economic environment. However, some scholars suggest ICT investments may increase energy consumption, electricity consumption, and carbon emissions [7]. For example, Cho et al. [42] point out that more electricity usage increases carbon emissions due to the new ICT equipment. Lee and Brahmamrene [45] use cointegrating regression estimation methods to show that ICT investments have a significant positive effect on both...
economic growth and CO₂ emissions. The impact of ICT investments on carbon emissions seems to be in a very vague state, and the above-mentioned scholars’ studies are limited to the overall level of ICT investments only. Scholars seem to have ignored ICT investments’ intensity, structure, and efficiency factors.

2.3. OECD economies’ carbon emissions and the global financial crisis

The OECD has received extensive attention from scholars since its establishment in 1961, particularly in relation to economic growth [46], public services [47], housing prices [48], and so on. At the same time, some scholars have expressed concern about energy and carbon emissions in OECD economies. For example, Wang et al. [49] study the impact of urbanization on carbon emissions in OECD economies by using the dynamic panel autoregressive distribution lag (ARDL) model. Their results show that CO₂ emissions decrease by 0.012% following each percentage point increase in the urbanization rate. Using the fully modified ordinary least square (FMOLS), dynamic ordinary least square (DOLS) and ARDL models, Wu and Xie [50] explore the relationship between income inequality and per capita CO₂ emissions, and show that higher income inequality promotes emission reductions in OECD countries. Some scholars have demonstrated the negative effect of advanced technology investments on carbon emissions in OECD countries [51]. For example, Paramati et al. [52] point out that green technology is a major factor helping to reduce carbon emissions in OECD economies. Zhang et al. [53] suggest that renewable energy investments can reduce emissions in the middle stage of economic development in OECD countries. Chen et al. [54] point out that the influence of technical factors on emissions is greater than that of non-technical factors in OECD countries, and their directions of influence are always opposite. But the impact of ICT investments on carbon emissions in OECD countries remains unknown.

It is not only the factors of OECD itself that lead to the change of carbon emissions, external shocks also have a significant impact on the process of carbon emission reduction. Throughout history, there have been several crises in the world, the most recent of which is the global financial crisis which began in 2008 [1]. This crisis has a negative effect on innovation and Research and Development (R&D) in OECD countries [55]. Similarly, this crisis has also had an impact on the OECD carbon emission-reduction process. Kim et al. [56] show that the trend of decoupling economic growth and energy use since the 2008 global financial crisis is evident in the power sector, and has resulted in changes in the energy industry.

Ali et al. [1] and Fernández-Portillo et al. [2] explore the impact of ICT on economic growth in OECD countries, and Salahuddin et al. [14] estimate a positive significant long-run relationship between Internet usage and CO₂ emissions in OECD countries. But few scholars have paid attention to the role of ICT investments in reducing carbon emissions in OECD economies and emission changes in response to the crisis.

2.4. Literature gaps

In analyzing the mechanisms of carbon emission reduction in the existing papers, there is a lack of exploration of the factors that combine the industrial sector and the role of the economy, and the factor of combining the ICT sector and investments, which are more important for reducing emissions. Second, many scholars have described the relationship between the ICT sector and carbon emissions, but there is no definite answer to whether ICT has promoted the growth of carbon emissions positively or reduced carbon emissions negatively. And they don’t properly explain the ways in which ICT investments affect carbon emissions reduction, especially in terms of ICT investments’ structure or efficiency. Finally, as OECD countries are the economic entities that are more severely affected by the economic crisis, it seems scholars have not yet explored the role of their ICT investments in the emission reduction process before and after the crisis, which would provide a good reference for a crisis response and emission reduction measures of OECD economies and even the whole world.

3. Methodology and data

This study mainly adopts the decoupling-factor model and the GDIM. First, the decoupling-factor method is used to investigate the relationship between ICT investments and carbon emissions intensity and to identify the decarbonization trends of OECD economies. Then we employ decomposition analysis to explore ICT investments-related factors that drove decarbonization between 2000 and 2018. The carbon emissions changes are divided into eight factors - the scale effect of ICT investments, ICT value added and gross investments; the intensity effect of ICT investments, ICT value added and gross investments; the structure effect of ICT investments, and the efficiency effect of ICT investments.

3.1. Decoupling-factor model

Two mainstream decoupling index methods exist in most related researches. One is Tapio’s decoupling index, which can help interpret the sensitivity of environmental pressure to minor economic changes based on elasticity [57,58]. The other is the OECD decoupling-factor model, which is developed by redefining Tapio’s decoupling index, and including a comprehensive index to indicate the marginal contribution [59]. Referring to Wu et al. [60] and Zhao et al. [32], we attempt to clarify the framework of the decoupling index and calculate according to the annual growth rate of ICT investments and the rate of carbon emissions per unit of ICT investments during the same periods.

\[ CE = IV \times CE_t \]  
\[ CE_t = CE_0 + CE_f \]  
\[ CE_0 = ICI_0 \times IV_0 \]  
\[ CE_f = ICI_1 \times IV_f \]  
\[ \Delta CE = CE_f - CE_0 \]

Where CE represents carbon dioxide emissions; IV represents the ICT investment; ICI = CE/IV represents the emission intensity of ICT investments.

To observe the changes of carbon emissions relative to ICT investments, we define the carbon emissions at the base year as CE₀ and at the targeted year t as CEₜ.

\[ CE₀ = ICI_0 \times IV_0 \]  
\[ CEₜ = ICI_1 \times IVₜ \]

And the changes of carbon emissions can be calculated as:

\[ \Delta CE = CEₜ - CE₀ \]

Considering the changes in emission intensity of ICT investments at an average annual decreasing rate \( f \), and changes in ICT investments at an average annual rate of growth of \( g \) during year \( t - t₀ \), the emission intensity of ICT investments and ICT investments for year \( t \) could be expressed as:

\[ ICI_t = ICI₀ \times (1 - f)^t \]

\[ IV_t = IV₀ \times (1 + g)^t \]

Based on the above equations, we bring Eqs. (5) and (6) into Eq. (3):

\[ CEₜ = ICI_t \times IVₜ = [I(1-f) \times (1+g)]^t \]

Therefore, the average annual growth rate of carbon emissions (\( t = 1 \)) could be expressed as:

\[ \rho = \frac{CEₜ - CE₀}{CE₀} = \frac{CEₜ}{CE₀} - 1 = \frac{ICI₀ \times IV₀ \times (1-f) \times (1+g)}{ICI₀ \times IV₀} - 1 \]

\[ = (1-f) \times (1+g) - 1 \]

Assuming that the average annual growth of carbon emissions is zero, based on Eq. (8), we can obtain a relationship between the average annual rate decrease of emission intensity of ICT investments (\( f \)) and the
average annual growth rate of ICT investments (g). We regard this average annual rate of the decrease in emission intensity of ICT investments (f) as the key point \( f_k \), which could be further calculated as:

\[
f_k = \frac{g}{1 + g}
\]  

(9)

By comparing \( f \) and \( f_k \), we could determine the decoupling relationship between the change in emission intensity and ICT investments, and obtain the decoupling index for a given period as:

\[
D = \frac{f - f_k}{f_k} \times (1 + g)
\]  

(10)

When \( D > 1 \), it indicates the decreased rate of emission intensity of ICT investments is higher than the critical value, the economy decreases the emission intensity of ICT investments more with the growth in ICT investments (Absolute decoupling); and when \( 0 < D < 1 \), it indicates the decreased rate of emission intensity of ICT investments is lower than the critical value and the economy decreases less in emission intensity of ICT investments with the growth of ICT's investments (Relative decoupling). Furthermore, when \( D < 0 \), it indicates the economy increases the emission intensity of ICT investments with ICT investments growth (Recession decoupling).

In order to show the decoupling relationship between ICT investments and emission intensity more clearly, based on Zhao et al. [32], we divide the decoupling index into nine possible states based on the change in directions of key points and the emission intensity of ICT investments (Table 1). And considering the calculation, the growth rate of ICT investments is higher than \(-1 \). Consequently, ignoring such situations, we could only consider six possible decoupling states, as shown in Fig. 1.

### 3.2. Generalized Divisia index method

Based on the above-mentioned decoupling-factor method, we further expand carbon emissions and conduct factor decomposition by using the GDIM, which is a commonly used approach to identify factors that contribute to changes of economic indicators [61]. Vaninsky [62] constructed the GDIM, which is different from log mean Divisia index (LMDI) method. On the one hand, the GDIM method can consider multiple absolute quantitative factors for simultaneous analysis. On the other hand, the decomposition result of LMDI is overly dependent on the initial factor identity represented by the multiplication, which will lead to different results due to the different decomposition equation [63]. Based on the fundamentals of the GDIM, the relationship between CO2 emissions and related factors can be expressed as:

\[
CE = IV \times \frac{CE}{IV} = VA \times \frac{CE}{VA} = GF \times \frac{CE}{GF}
\]  

(11)

\[
VA_{IV} = \left( \frac{CE}{IV} \right) \left( \frac{CE}{VA} \right)
\]  

(12)

\[
IV_{GF} = \left( \frac{CE}{GF} \right) \left( \frac{CE}{IV} \right)
\]  

(13)

where \( VA \) is the value added of ICT, and \( GF \) represents the gross investments. Meanwhile, suppose \( VCI = CE/VA \) represents the emission intensity of ICT value added; \( GCI = CE/GF \) represents the emission intensity of gross investments; \( IS = IV/GF \) represents the ICT investments’ structure; \( IE = VA/IV \) represents ICT investments’ efficiency. Eqs. (11)–(13) can be transformed into the following form:

\[
CE = IV \cdot ICI
\]  

(14)

\[
IV \cdot ICI - VA \cdot VCI = 0
\]  

(15)

\[
IV \cdot ICI - GF \cdot GCI = 0
\]  

(16)

\[
IV - GF \cdot IS = 0
\]  

(17)

\[
VA - IV \cdot IE = 0
\]  

(18)

Suppose factor \( X \)’s contribution to carbon emission changes is expressed as a function \( CE(X) \), Eqs. (14)–(18) construct a Jacobean matrix \( \Phi_x \) composed of relevant factors, as follows:

\[
\Phi_x = \begin{bmatrix}
ICI & IV & -VCI & -VA & 0 & 0 & 0 & 0 & 0 \\
ICI & IV & 0 & 0 & -GCI & -GF & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & -IS & 0 & -GF & 0 & 0 \\
-IE & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -IV
\end{bmatrix}^T
\]  

(19)

According to the principle of GDIM decomposition, the carbon emission change \( \Delta CE \) can be decomposed into the following factors to contribute to the total form:

\[
\Delta CE[X|\Phi] = \int_v CE(x) (I - \Phi \Phi_x) dx
\]  

(20)

where \( L \) represents the time span; \( CE = (ICI \ IV 0 0 0 0 0 0) \); \( I \) represents the identity matrix; and \( + \) represents the generalized inverse matrix. Meanwhile, if the column in Jacobean matrix \( \Phi_x \) is linearly independent, then \( \Phi_x^+ = (\Phi_x^T \Phi_x)^{-1} \Phi_x^T \). Thus, the carbon emission change \( \Delta CE \) can be decomposed into eight effects, with the following equation:

\[
\Delta CE = CE_{IV} + CE_{ICI} + CE_{VCI} + CE_{GI} + CE_{GCI} + CE_{IS} + CE_{IE}
\]  

(21)

where \( CE_{IV} \), \( CE_{VCI} \) and \( CE_{GCI} \) reflect the impact of changes in ICT investments, ICT value added, and gross investments on carbon emissions; \( CE_{GI} \) reflects the impact of changes in the low carbon level of ICT on carbon emissions or CO2 emissions intensity of ICT investments; \( CE_{GCI} \) reflects the impact of changes in the low carbon level of ICT on carbon emissions or CO2 emissions intensity of ICT investments; \( CE_{IS} \) reflects the impact of changes in the low carbon level of gross investments on carbon emissions or CO2 emissions intensity of gross investments; \( CE_{IE} \) reflects the impact of changes in ICT investments’ structure on carbon emissions; \( CE_{IE} \) reflects the impact of changes in ICT investments’ efficiency on carbon emissions.

### 3.3. Data

This study measures data spanning 19 years (2000–2018) from a
panel of 20 OECD economies due to the availability of data. The ICT investments of these economies come from the OECD Key ICT Indicator. We select investment in telecommunications in the OECD area as the proxy variation of ICT investments [12]. The value added of ICT from 2000 to 2014 is obtained from the World Input-Output database (WIOD) [64], and we assume that ICT sector data as a percentage of Gross domestic product (GDP) in each country over the four-year period (2015 to 2018) is the same as that in 2014. We select five sectors as ICT sectors, which are shown in Table 2. The gross fixed capital formation, as the proxy variation of gross investments, comes from World Bank Open Data [65]. In order to ensure the scientific nature of the data, this paper eliminates the impact of price factors on GDP, and selects the GDP index based on constant 2010 U.S. dollars. The carbon emissions of 20 OECD economies are selected from IEA [16]. The data-processing process is carried out in the R language.

4. Results and discussion

The decoupling state between the emission intensity of ICT investments and ICT investments at the national level is presented first, followed by the temporal decomposition analysis. The trends and mechanism of ICT investments that affect carbon emissions are considered here.

4.1. Decarbonization trends in information and communication technology investments

4.1.1. Changes of carbon emissions and decoupling values

Based on the Eqs. (4) and (10), the changes of carbon emissions and decoupling values of 20 OECD economies are shown in Fig. 2. Since the OECD has concentrated mostly on developed economies, these economies have reached a high level of industrialization, and the service industry occupies the main part of the economy, so carbon emissions have not shown an upward trend year by year [66]. For example, the decreases of carbon emissions in France – 13.13 Mt, 14.58 Mt, and 31.78 Mt during the periods 2008–2009, 2010–2011, and 2013–2014, respectively, far exceed the growth of carbon emissions. From the perspective of decoupling values, the decoupling index between emission intensity of ICT investments and ICT investments in France is hovering around 1.00, while recession decoupling is observed during 2012–2013 and 2014–2015, which suggests that the emissions intensity

![Fig. 1. Six states of decoupling. Note: The positive f value represents a negative change in emission intensity of ICT investments.](image)

| Table 2 |
|-----------------------------------------------|
| Sector names and ISIC code of ICT sectors in WIOD. |
| Sector names | ISIC Rev.4 |
| Manufacture of computer, electronic and optical products | C26 |
| Publishing activities | J58 |
| Motion picture, video and television program production, sound recording and music publishing activities; programming | J59-J60 |
| Telecommunications | J61 |
| Computer programming, consultancy and related activities; information service activities | J62-J63 |

Note: ISIC is abbreviation of International Standard Industrial Classification.

1. To be consistent with most research and IEA’s units [16], we used “million tons (Mt)” units, where 1Mt=10^9kg.
of ICT investments growth is accompanied by an increase in ICT investments. Also, absolute decoupling is observed for the period 2017–2018, which suggests that decreases in the emissions intensity of ICT investments is accompanied by a growth in ICT investments, and exceeds the reduction in emission intensity required to maintain the same amount of carbon emissions. Although Greece has also shown a downward trend in carbon emissions year by year, recession decoupling is observed between 2017 and 2018. The change in the decoupling index in the United States is more conducive to the development of ICT investment in carbon emissions, and changes to a higher index. We have observed that, except for the global financial crisis, which causes the United States to reach a recession decoupling (-3.04 during 2007–2008), then the United States shows a trend of volatility and rising. Strong decoupling is observed during the periods 2015–2016, 2016–2017, and 2017–2018. This suggests an obvious decline in the emissions intensity of ICT investments relative to ICT investments growth, which shows the high technology, high-quality development and continuous energy optimization of the ICT sector in the United States [67]. Although Korea and Turkey show a growth in carbon emissions, the decoupling value is almost between 0.00 and 1.00 (Relative decoupling). This suggests a slight decline in emissions intensity relative to ICT investments growth, although the magnitude of the decline in emissions intensity of ICT investments is lower than that of ICT investments growth.

4.1.2. Changes of decoupling status

Fig. 3 presents the outcome for 20 OECD economies between 2000 and 2009 and 2009 and 2018. A promising decarbonization trend for most economies, transitioning from weak to strong decoupling, is observed between 2009 and 2018. Between 2009 and 2018, nine economies demonstrate strong decoupling, while between 2000 and 2009, no economy demonstrates strong decoupling. Between 2009 and 2018, Australia and Austria demonstrate a transition from a strong negative decoupling state to a strong decoupling state, which indicates that both countries have shifted from a decline trend in ICT investments to an increase trend in ICT investments. This demonstrates a transition from an increase in emission intensity to a decline in emission intensity, achieving a low-carbon transformation of ICT investments. France, Germany, Italy, Spain, Switzerland, and the United States demonstrate a transition from a weak negative decoupling state to a strong decoupling state, which indicates that the above six countries have also achieved low-carbon transformation of ICT investments, but have already consciously reduced the emission intensity of ICT investments before the global financial crisis. Belgium demonstrates a transition from a recessive decoupling state to a strong decoupling state, which indicates that
with the rapid growth of ICT investments, its emission intensity has always been in a downward trend, and has realized the dual development of economic transformation and the tendency toward low-carbon use. Canada demonstrates a transition from a strong negative decoupling state to a weak decoupling state, which shows that its emission intensity has fallen at a rate less than that of the reduction in emission intensity required to maintain carbon emissions. Estonia, Japan, Korea, and Turkey show a strong negative decoupling state, and Greece, Luxembourg, The Netherlands, and Portugal show a weak negative decoupling state during the period 2009–2018. They all show that emissions intensity increased with the decline in ICT investments. These countries should pay attention to the low-carbon management of ICT investments, improve the energy efficiency and clean energy proportion of the ICT industry, and realize a low-carbon transition. The Czech Republic and Denmark demonstrate a transition from a weak negative decoupling state to a recession decoupling state, which suggests they achieve a reduction in emission intensity after the global financial crisis, but ICT investments decrease during the period 2000–2018.

4.2. Contributions of driving factors

Based on the results of decoupling, we further explore how ICT investment-related factors affect the low-carbon process of OECD economies. Based on Eq. (21), we decompose the changes in carbon emissions into eight factors, including ICT investments’ scale factors, ICT investments’ intensity factors, ICT investments’ structure factors, ICT investments’ efficiency factors, and the other four factors related to the ICT value added and investments. Fig. 4 shows the cumulative changes in the driving effects of carbon emissions in 20 OECD economies, and Fig. 5 shows the cumulative contribution ratio of carbon
emissions in eight driving effects of OECD economies.

4.2.1. Scale effect

The scale effect includes the scale effect of ICT investments (IV), the scale effect of ICT value added (VA), and the scale effect of gross investments (GF). For most economies, the IV has played a role in restraining carbon emissions. The increase in the scale of ICT investments has led to a reduction in carbon emissions. Among them, the more obvious effects have appeared in Italy, Japan, Korea, and Spain. Their cumulative carbon emissions reduction due to IV exceed other factors during the period 2000–2018. From the cumulative contribution ratio of carbon emissions, IV of Estonia and Japan have resulted in a higher ratio of carbon emission reductions. For example, from 2000 to 2018, the increase in Japan’s IV contributes to a total reduction of 339.0 Mt of carbon emissions, which is 5.05 times the change in Japan’s total carbon emissions. In Luxembourg, due to the increase in the scale of ICT investments, the country has promoted more significant carbon emissions. The cumulative increase in carbon emissions is 5.27 Mt, accounting for 5.96 times the cumulative carbon emissions change.

Moreover, the scale effect of ICT value added and gross investments for the period 2000–2018 demonstrate positive influences. For example, during the 2005–2015 period in Australia, the growth in GF contributes the largest increase in cumulative carbon emissions, and the cumulative increase in carbon emissions reaches 80.57 Mt in 2018, accounting for 167.41% of the change in total carbon emissions. Estonia’s effect of VA and GF are more obvious in promoting carbon emissions, their growth contributes 4.02 Mt and 5.22 Mt of cumulative carbon emissions between 2000 and 2018, and accounted for 6.22 times and 4.18 times the change in carbon emissions, respectively. The VA and GF of Greece, Italy, and Portugal’s growth contributes toward a decrease of carbon emissions change, which indicates that the ICT’s economy scale and gross investments are conducive to emission reduction.

Fig. 4. Cumulative changes in the driving effects of carbon emissions in 20 OECD economies.
4.2.2. Intensity effect

The intensity effect includes the emission intensity effect of ICT investments (ICI), the emission intensity effect of ICT value added (VCI), and the emission effect of gross investments (GCI). The ICI in most economies has led to a significant increase in carbon emissions. For example, the ICI of Japan contributes to an increase of 530.15 Mt of carbon emissions between 2000 and 2018, which is 7.90 times the changes in total carbon emissions. The ICI of The Netherlands contributes to an increase of 65.18 Mt of carbon emissions, which is 6.06 times the changes in gross carbon emissions during the 2000–2018. Only three countries (Australia, Belgium, and Luxembourg) show a decreasing trend of carbon emissions due to the effect of emission intensity of ICT investments during the period 2000–2018. This shows that the trend of carbon emission intensity in various economies is increasing, obviously driven by ICT investments. It also shows that the ICT industry doesn’t fulfill the low-carbon commitment well, uses more high-carbon energy such as coal and oil and its low-carbon technology is not mature enough [68].

In comparison, the VCI and GCI in most economies have caused a negative cumulative effect. For example, the VCI and GCI of Estonia contributes to a decrease of 3.42 Mt and 4.10 Mt of carbon emissions between 2000 and 2018, which are 2.75 times and 3.28 times the
changes in total carbon emissions. The VCI and GCI of the United States contributes to a decrease of 802.74 Mt and 834.56 Mt carbon emissions during the period of 2000–2018. This is 0.99 times and 1.03 times the changes in total carbon emissions. Turkey is the only country that has shown positive growth in carbon emissions under the effect of VCI. This shows that the country uses a lot of high-carbon energy, which leads to a continuous decrease in energy efficiency [69]. It should pay attention to the clean energy and improve technology of energy use [70]. The GCI of Greece and Portugal contributes to the growth of carbon emissions (30.92% and 7.80%, respectively) for the period 2000–2018. This shows that the energy and carbon emissions used by the above two countries have increased at a relatively high rate and should be taken seriously.

4.2.3. Structure effect

The structure effect of ICT investments (IS) is a major driving factor behind decreasing carbon emissions. In terms of the percentage of cumulative carbon emissions reduction, The Netherlands, Luxembourg, and Switzerland rank are the top three. For example, during the period 2000–2018, the IS of The Netherlands contributes to a sustained decline and cumulative total of 32.39 Mt of carbon emissions in 2018, accounting for 301.33% of carbon emissions change. The IS of Switzerland contributes to a decrease of 14.28 Mt of carbon emissions, which accounted for a 227.82% change of carbon emissions between 2000 and 2018. Fig. 6 shows the structure of ICT investments from 2000 to 2018, and presents the six countries where IS reduces carbon emissions by a relatively high proportion. Except for Luxembourg, the ICT investments’ structures of the other five countries have declined slightly as follows: The Netherlands, from 3.42% in 2000 to 1.35% in 2018; and Estonia, from 8.64% in 2000 to 1.15% in 2018. This indicates that a decrease in the proportion of ICT investments in gross investment can effectively reduce carbon emissions and achieve the effect of low-carbon development.

4.2.4. Efficiency effect

The ICT investments’ efficiency factor (IE) is expressed as the reciprocal of the share of ICT investments in the ICT value added. This factor reflects the contribution effect of reducing carbon emissions in all economies. For example, the IE of The Netherlands contributes to a decrease of 10.75 Mt of carbon emissions, accounting for a change of −310.32% of carbon emissions between 2000 and 2018. The IE of Switzerland contributes to a decrease of 6.27 Mt of carbon emissions, accounting for a change of −225.11% of carbon emissions in that period. And the IE of Japan contributes a decrease of 67.14 Mt of carbon emissions, accounting for a change of −214.78% of carbon emissions. This shows improved economic efficiency will help these economies achieve carbon emissions reduction.

4.3. Global financial crisis

Fig. 7 represents the cumulative contribution ratio of carbon emissions in eight driving effects between 2000 and 2009 and 2009 and 2018. The global financial crisis undoubtedly has a negative effect on innovation and research and development, specifically in the OECD countries [1]. From the perspective of the driving factors during the two time periods, the reduction in carbon emissions of Japan caused by IV increases after the global financial crisis, i.e., 1.77 times of carbon emissions between 2000 and 2009 and 43.29 times of carbon emissions between 2009 and 2018. Austria, Estonia, and Spain change from a negative effect of IV on carbon emissions between 2000 and 2009 to the effect of promoting carbon emissions between 2009 and 2018. This reflects the rapid development and a large amount of energy consumption of the ICT industry in the three countries after the financial crisis, which has led to more carbon emissions.

In most economies, the two factors of VA and GF have shown a trend of weakening the promotion effect after the global financial crisis. This shows that the effect of economic growth on carbon emissions is diminishing. The VA of Austria and Japan contributes to a decrease of carbon emissions between 2000 and 2009, but promotes the growth of carbon emissions between 2009 and 2018. The GF of Japan has also had the same effect. It reflects the rapid growth of Japan’s ICT value added and total investments after the global financial crisis and has driven a rapid increase in carbon emissions.

In most economies, the contribution of ICI to carbon emissions slowed down after 2009. For example, the ICI between 2000 and 2009 contributes to an increase of 50.71 times of carbon emissions in Spain, but between 2009 and 2018, ICI actually reduces carbon emissions by 43.65%. The same effect is also more obvious in Austria, Estonia, The Netherlands, and Switzerland. Japan is the only country in which ICI promotes an increased proportion of carbon emissions between 2009 and 2018 (75.90 times of carbon emissions change) compared to 2.29 times of carbon emissions change in the 2000–2009 period. After the global financial crisis, the massive ICT investments in Japan lead to a large amount of energy consumption. Ishida [71] confirms that ICT investments represent about 25% of total investments in Japan, and ICT has been one of the fastest-growing components of total investment. Optimizing the energy consumption of ICT investments and reducing
carbon emissions are the directions Japan needs to consider in the future. Japan is also a country in which the VCI and GCI factors have changed the most in the two periods, and both have transitioned from a promoting effect to an inhibiting effect, reflecting the obvious optimization of emission intensity in the overall consumption of Japan’s ICT industry and the investments of all industries.

In the two time periods, the effects of IS and IE on carbon emissions are both negative, which shows that optimizing ICT investments’ structure and improving the efficiency of ICT investments have always been the focus of all economies when developing the ICT industry. In terms of a decreasing proportion of structure and efficiency of ICT investments, the IS and IE of most economies contribute to a decrease of carbon emissions during the period 2009–2018 less than 2000–2009. For example, the IS and IE of Switzerland reduce carbon emissions by 82.31 times and 82.34 times, respectively, between 2000 and 2009, but only reduce such emissions by 13.98% and 11.12% between 2009 and 2018.

Fig. 7. The cumulative contribution ratio of carbon emissions in eight driving effects during 2000–2009 and 2009–2018.
2018. The decreasing contributions of IS and IE in Japan and Australia have significant amplification effects in 2009–2018 compared to 2000–2009. For example, Australia’s IS and IE cause a decrease of 190.07% and 133.74% of carbon emissions, respectively, between 2009 and 2018. But the decreasing effects of the above two factors between 2000 and 2009 reduce carbon emissions by only 16.78% and 20.35%.

5. Conclusions and policy implications

5.1. Conclusions

This paper explores the decoupling relationship between information and communication technology investments and emission intensity in 20 Organization of Economic Cooperation and Development (OECD) economies, and further explores the contribution of information and communication technology (ICT) investments’ scale, intensity, structure, and efficiency effects on carbon emissions through the Generalized Divisia Index Method. The following conclusions are obtained:

(1) OECD economies show different decoupling states between ICT investments and emission intensity during different periods of time. France’s recession decoupling state shows that emission intensity is increasing along with the growth of ICT investments. The decoupling state and development trend of the United States are more conducive to the growth of ICT investments, which changes gradually to a higher index as time progresses. From a comparison before and after the global financial crisis, we see that no country is in a state of strong decoupling between ICT investments and emission intensity before 2009. This indicates that the economies selected in the study have not fully realized the rapid growth of ICT investments, accompanied by the trend of decreasing emission intensity. However, between 2009 and 2018, the number of economies with a strong decoupling state rise to nine, showing that these economies have achieved significant results in the mutual game between ICT investments growth and emission reduction, and energy utilization has been optimized and adjusted.

(2) Judging from the driving factors of carbon emissions, the emission intensity of ICT investments contributes to a significant increase of carbon emissions in many economies, which indicates that the rapid expansion of ICT investment scale has led to unreasonable energy utilization. The factors of scale of ICT value added and the scale of gross investments play a role in promoting carbon emissions in most economies, and their emission intensities show a significant inhibitory effect. The growth of the economic scale of the ICT industry and the effect of investments contribute to an increase of carbon emissions to a certain extent, but the emission intensities of ICT value added, and gross investments significantly inhibit the growth of carbon emissions, which shows that the consumption of the ICT industry and the energy use of the total investments of the whole industry are developing in a direction conducive to emission reduction. The structure and efficiency of ICT investments always restrain the growth of carbon emissions. In all the selected economies, both factors show a cumulative negative emission reduction effect, and will continue to bring about emission reduction effects in the future.

(3) In the two periods around 2009, Japan is the country with the most significant changes in the impact of various factors on carbon emissions. For example, the effect of ICT investments in the period 2000–2018 contributes to a decrease of 43.92 times carbon emission change, while the decreasing effect of carbon emissions only accounts for 1.77 times from 2000 to 2009. The impact of ICT investments’ structure and ICT investments’ efficiency also contribute to the decrease from 40.87% and 40.01% of carbon emissions change between 2000 and 2009 to 9.51 times and 23.96 times of total emissions change between 2009 and 2018. But, relatively speaking, the effect of promoting carbon emissions has become more significant. For example, the effect of the emission intensity of ICT investments on carbon emissions increases from 2.29 times in 2000–2009 to 75.90 times in 2009–2018. But the situation of Switzerland is the opposite; after 2009, the carbon emissions change caused by various factors become small. This shows that the impact of ICT investments on carbon emissions in different economies is disparate before and after the global financial crisis. In addition, the driving factors of some economies’ carbon emissions have shown changes in direction. For example, the effect of ICT investments on carbon emissions changes from suppression to promotion in Spain between 2009 and 2018, while the emission intensity of ICT investments factor changes from a promotion effect to a suppression effect. This suggests these economies should have paid attention to ICT investment-related strategies and clean energy policy before and after the crisis such as pandemic of Coronavirus Disease-2019 (COVID-2019) to achieve common development and carbon emission reduction.

5.2. Policy implications

We also put forward some policy implications according to the conclusion:

(1) Some OECD economies have shown strong decoupling states between emission intensity and ICT investments since the global financial crisis. The rapid development of ICT investments has been accompanied by a decline in emission intensity. But economies that have not been in a state of strong decoupling need to pay attention to the changes in ICT investments for carbon emissions. For example, the Czech Republic and Denmark need to pay attention to the growth of ICT investments and increase the proportion of ICT investments. While ensuring the growth of ICT investments, Greece and The Netherlands should increase the proportion of clean and renewable energy, and promote energy optimization to achieve carbon emission and intensity reduction. The situation in the United States seems to be optimistic. At the end of the research period, that country is developing toward a higher decoupling relationship, which shows its ICT investments and emission intensity change are developing harmoniously and can provide references for other economies’ governments.

(2) The impact of ICT investments on carbon emissions is inconsistent for different economies, but the emission intensity of ICT investments plays a role in promoting carbon emissions for most OECD economies. In contrast, the emission intensity of ICT’s value added and emission intensity of gross investments have had a strong decreasing effect for most economies. This requires these economies to focus on the energy used for ICT investments when deploying ICT-related industries. The ICT investments’ structure and efficiency of these economies have a significant inhibitory effect, which suggests that these economies can increase the proportion of ICT investments to gross investment and increase the proportion of ICT investments in the economy to promote the effect of emission reduction. Governments should also realize that scaling up the deployment of the digital economy will have huge benefits for future energy optimization and low carbon. While expanding the investment scale of digital industry, governments of all countries are using technological progress and energy innovation to transform energy utilization, increase the proportion of clean energy and renewable energy, and improve energy utilization efficiency, so as to form an obvious advantage in energy utilization compared with traditional industries.

(3) Under the influence of the financial crisis, reducing carbon emissions in Japan has become more effective, but Japan needs to
pay special attention to the rapid growth of emission intensity of ICT investments on carbon emissions promotion. This reveals that while relevant economies have been vigorously developing the digital economy after COVID-2019 pandemic, investment in related industries will need to pay special attention to the externalities of carbon emissions. It is worth mentioning that the structure and efficiency factors of ICT investments have shown a relatively significant negative effect before and after the crisis, which also provides relevant economies with directions for reducing emissions after COVID-2019 pandemic. The COVID-2019 pandemic has greatly dampened the economic development of most economies, and the layout of the ICT industry and joint development of information technology and industrialization are powerful driving force for economic development. Under the dual influence of environmental constraints and economic recovery, optimizing the structure of ICT investments and improving the efficiency of ICT investments will be the most important means to reduce emissions in the post-COVID-2019 era. Increasing the proportion of ICT investment and clean energy is particularly important to reduce emissions in the post-pandemic era.

CRediT authorship contribution statement

Jianda Wang: Data curation, Software, Writing – original draft. Qingzhe Jiang: Methodology, Validation. Xiucheng Dong: Conceptualization, Writing – review & editing. Kangyin Dong: Methodology, Validation, Funding acquisition.

Declaration of Competing Interest

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

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Ali MA, Alam K, Taylor B, Rafiq S. Does ICT maturity catalyse economic growth in Australia: A time series evidence. Telemat Inform 2015;32:862-78. https://doi.org/10.1016/j.telem.2015.04.011.
[2] Chen X, Gong X, Li D, Zhang J. Can information and communication technology reduce CO2 emission? A quantile regression analysis. Environ Sci Pollut R 2019;26: 120588. https://doi.org/10.1007/s11356-018-9798-z.
[3] Wang M, Yao M, Wang S, Qian H, Zhang F, Wang Y, et al. Study of the emissions and spatial distributions of various power-generation technologies in China. J Environ Manage 2021;278:111401. https://doi.org/10.1016/j.jenvman.2021.111401.
[4] Lu W. The impacts of information and communication technology, energy consumption, financial development, and economic growth on carbon dioxide emissions in 12 Asian countries. Mitig Adapt Strateg Gl 2018;23. https://doi.org/10.1007/s11027-018-9787-7.
[5] Shahnazi R, Dehghan Shabani Z. The effects of spatial spillover information and communications technology on carbon dioxide emissions in Iran. Environ Sci Pollut R 2019;26:24196–212. https://doi.org/10.1007/s11356-019-10652-7.
[6] World Bank Open Data. GDP (constant 2010 US$). 2021. https://data.worldbank.org./.
[7] OECD. “Telecommunications database”, OECD Telecommunications and Internet Statistics (database); 2020.
[8] Adedayomi FF, Bekun VF, Driha OM, Balsalobre-Lorente D. The effects of air transportation, energy, ICT and FDI on economic growth in the industry 4.0 era: Evidence from the United States. Technol Forecast Soc Change 2020;166:120297. https://doi.org/10.1016/j.techsoc.2020.120297.
[9] Salahuddin M, Alam K, Ozturk I. The effects of Internet usage and economic growth on CO2 emissions in OECD countries: A panel investigation. Renew Sustain Energ Rev 2016;62:1226–35. https://doi.org/10.1016/j.rser.2016.04.018.
[10] Bi J. hp Statistical Review of World Energy. 2021. https://www.bp.com/statisticalreview.
[11] IEA. CO2 emissions from fuel combustion; 2020.
[12] Sinha A. Impact of ICT exports and internet usage on carbon emissions: a case of OECD countries. Int J Green Econ 2018;12:229–57. https://doi.org/10.1142/S021759081849769X.
[13] Huang L, Liao Q, Yan J, Liang Y, Zhang H. Carbon footprint of oil products pipeline transportation. Sci Total Environ 2021;783:146906. https://doi.org/10.1016/j.scitotenv.2021.146906.
[14] Pei J, Meng B, Wang F, Yue J, Zhao Z. Production sharing, demand spillovers and CO2 emissions: the case of Chinese regions in global value chains. Singapore Econ Rev 2016;63(3):1740011. https://doi.org/10.1142/S0217590817400112.
[15] Qiu R, Liao Q, Yan J, Yan Y, Guo Z, Liang Y, et al. The coupling impact of subsystem interconnection and demand response on the distributed energy systems: A case study of the composite community in China. Energy 2021;228:120588. https://doi.org/10.1016/j.energy.2021.120588.
[16] Dong K, Dong X, Ren X. Can expanding natural gas infrastructure mitigate CO2 emissions? Analysis of heterogeneous and mediation effects for China. Energy Econ 2020;90:104830. https://doi.org/10.1016/j.eneco.2020.104830.
[17] Dong K, Hochman G, Zhang Y, Sun R, Li H, Liao H. CO2 emissions, economic and population growth, and renewable energy: Empirical evidence across regions. Energy Econ 2018;75:180–92. https://doi.org/10.1016/j.eneco.2018.08.017.
[18] Wei W, Li J, Chen B, Wang M, Zhang P, Guan D, et al. Embodied greenhouse gas emissions from building China’s large-scale power transmission infrastructure. Nat Sustain 2021;1–9. https://doi.org/10.1038/s41895-021-00704-8.
[19] Dong K, Hochman G, Timilsina GR. Do drivers of CO2 emission growth alter over time and by the stage of economic development? Energy Policy 2020;140: 114200. https://doi.org/10.1016/j.enpol.2020.114200.
[20] Zhang H, Chen J, Li W, Song X, Shibasaki R. Mobile phone GPS data in urban ride-sharing: An assessment method for emission reduction potential. Appl Energy 2020;299:115038. https://doi.org/10.1016/j.apenergy.2020.115038.
[21] Liu L, Huang G, Baetz B, Zhang K. Environmentally-extended input-output simulation for analyzing production-based and consumption-based industrial greenhouse gas mitigation policies. Appl Energy 2018;223:69–78. https://doi.org/10.1016/j.apenergy.2018.09.192.
[22] Peters GP. From production-based to consumption-based national emission inventories. Ecol Econ 2008;65:13–23. https://doi.org/10.1016/j.ecolecon.2007.10.014.
[23] Chang WS, Tohno S, Shim SY. An estimation of energy and GHG emission intensity caused by energy consumption in Korea: an energy IO approach. Appl Energy 2009;86:1902–14. https://doi.org/10.1016/j.apenergy.2009.02.001.
[24] Dong F, Long R, Li Z, Dai Y. Analysis of carbon emission intensity, urbanization and energy mix: evidence from China. Nat Hazards 2016;82:1375–91. https://doi.org/10.1007/s11069-016-2402-8.
[25] Ehrlich PR, Holdren JP. Impact of population growth. Science 1971;171:1212–7. https://doi.org/10.1126/science.2073166.
[26] Liu B, Shi J, Wang H, Su X, Zhuo F. Driving factors of carbon emissions in China: A joint decomposition approach based on meta-frontier. Appl Energy 2019;256:11420. https://doi.org/10.1016/j.enpol.2019.11420.
[27] Zhao L, Zhao Y, Yuan R. Drivers of household decarbonization: Decoupling and decomposition analysis. J Clean Prod 2021;289:125154. https://doi.org/10.1016/j.jclepro.2021.125154.
[28] Chang YF, Lin SJ. Structural decomposition of industrial CO2 emission in Taiwan: an input-output approach. Energy Policy 1998;26:5–12. https://doi.org/10.1016/S0301-4215(97)00049-1.
[29] Briza J, Feng K, Hubacek K. Drivers of greenhouse gas emissions in the Baltic States: A structural decomposition analysis. Ecol Econ 2014;98:22–8. https://doi.org/10.1016/j.ecolecon.2013.12.001.
[30] Meng D, Wang J, Andrews R, Xie H, Yue J, Peters GP. Spatial spillover effects in determining China’s regional CO2 emissions growth: 2007–2010. Energy Econ 2017;63:161–73. https://doi.org/10.1016/j.eneco.2017.02.001.
Zhang C, Liu C. The impact of ICT industry on CO2 emissions: A demand-side decomposition analysis. Energy Econ 2020;85:104600. https://doi.org/10.1016/j.eneco.2019.104600.

Zhao Y, Wang S, Zhang Z, Liu Y, Ahmad A. Driving factors of carbon emissions embodied in China’s US trade: a structural decomposition analysis. J Clean Prod 2020;131:678-89. https://doi.org/10.1016/j.jclepro.2019.04.114.

Dijstler. Effects of information and communication technology and real income on CO2 emissions: The experience of countries along Belt and Road. Telemat Inform 2019; 45: 101300. doi: 10.1016/j.tielle.2019.101300.

Chen J, Wang P, Cui L, Huang S, Song M. Decomposition and decoupling analysis of CO2 emissions in OECD countries using panel data. Energy Policy 2018;231:937-48. https://doi.org/10.1016/j.enpol.2018.01.047.

Li L, McMurray A, Li X, Gao Y, Xue J. The diminishing marginal effect of R&D input and carbon emissions in China - an empirical study using a nonparametric additive regression model. Environ Sci Polym 2021;280:111818. https://doi.org/10.1016/j.envsci.2021.111818.

Paramati SR, Mo D, Huang R. The role of financial deepening and green technology on carbon emissions: Evidence from major OECD economies. 101794 Finance Res Lett 2020. https://doi.org/10.1016/j.frl.2020.101794.