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RESEARCH IN ENVIRONMENTAL PLANNING AND MANAGEMENT

The effect of information and communication technologies and total factor productivity on CO_2 emissions in top 10 emerging market economies

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Abstract
The aim of this paper is to investigate the nexus among information and communication technologies (ICT), total factor productivity (TFP), and carbon dioxide (CO_2) emissions in the top 10 emerging market economies for the period from 1995 to 2014 using the panel vector autoregressive (PVAR) approach. Analysis results suggest that the internet usage and fixed telephone subscriptions have a positive impact on environmental pollution, although mobile cellular subscriptions and TFP have a negative impact on carbon emissions. According to causality test results, there is bidirectional causality between CO_2 and all independent variables. Consequently, the results justified the use of TFP instead of GDP as an indicator of the economic development and the importance of ICT in environmental problems since ICT has proven to be undeniable in environmental policies. Thus, possible policies prioritize environmental sustainability in the digitalization of the economy, which ensures both a pollution-reducing effect and an increase in TFP.

Keywords ICT · TFP · CO_2 emissions · PVAR · Causality · Technology

Introduction

With the industrial revolution, the changing production structure throughout the world has led to an increase in both energy consumption and environmental pollution. The dependence on energy in production and the widespread use of fossil fuel consumption have further deepened environmental degradation (Li et al. 2019). Carbon dioxide (CO_2) emissions are considered to result from the increased economic activities and to be of much concern for policymakers (Auffhammer and Carson 2008; Ozturk and Acaravci 2010). Though there are many sorts of emissions, CO_2 emissions are known to pollute the environment. According to the previous studies (Costantini and Monni 2008; Zhang et al. 2017; Inglesi-Lotz and Dogan 2018), these emissions have been associated with different factors such as gross domestic product, financial development, technological innovation, renewable energy consumption, and human capital.

This study focuses on information and communication technologies (ICT) and total factor productivity (TFP) rather than traditional factors affecting CO_2 emissions. In recent years, the Internet, computers, and related applications, which are known as ICTs, have been adopted as the main factor that causes social change, growth, and innovation. First of all, it is known that there are different theoretical approaches to the relationship between ICT and TFP. There is an opinion that developments in firm-level ICT add up extra costs. This means that ICT requires additional capital such as R&D investments. On the other hand, the widespread use of ICT plays a role in increasing productivity in production by spreading a positive externality to the economy (Ram and Acharya 2016). These two different views are confirmed by empirical analysis that ICT affects TFP positively (Venturini 2015; Gehringeer

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et al. 2015; Edquist and Henrekson 2017) and/or negatively (Basu and Fernald 2007). Although the direct connection of TFP with technological advances, explanations, and research on the effect of ICT on TFP is popular in the economic literature, recently, the environmental dimension of ICT has been under discussion. For instance, ICT is required for accurate tracking energy-related processes from production to consumption and effective management of these processes. In addition, emission monitoring through environmental screens and electronic waste recycling are positive ICT activities (Raghupathi et al. 2014). Using ICT for environmental management is said to contribute to environmental quality. The view that ICT causes pollution to decrease is related to the decrease in transaction and travel costs of households and companies as a result of ICT deeping. Hilty (2007) discussed the importance of using ICT in combating climate change from a theoretical perspective. In particular, it is emphasized that turning to energy efficiency in these areas due to the intensive use of energy by transceivers in data centers and communication networks significantly reduces carbon emissions (Hilty 2007). Contrary to this view, the impact of the rapid development of the ICT industry on global emissions in the period up to 2040 is predicted by Belkhir and Elmeligi (2018). Their results implied that the uncontrolled development of ICT will take global carbon emissions seriously. According to another view, although ICT is not directly effective in combating climate change, it is important to adapt to this process by implementing it more effectively (Sala 2010). Empirical results for ICT, both in terms of its contribution to environmental quality (Asongu 2018) and its effect on increasing pollution (Lee and Brahmasrene 2014; Raheem et al. 2019), can be found in the literature.

The present study is aimed at investigating the nexus among TFP, ICT, and CO_2 emissions in the top 10 emerging market economies for the period from 1995 to 2014. Ten emerging market economies are selected considering the nominal GDP they have in the selection of these countries. They are China, India, Brazil, Russia, Mexico, Indonesia, Turkey, Thailand, South Africa, and Malaysia. By selecting this country group, the aim is to guide the pollution reduction policies of these 10 countries with high carbon emissions in the context of TFP and ICT. Especially, China, India, and the Russian Federation are the three countries that produce the most carbon dioxide emissions. The top 10 emerging market economies are the largest carbon emitter and energy-consuming countries. These countries contribute significantly to global economic output. Hence, it is worth investigating the effect of TFP and ICT on CO_2 emissions in these countries. Moreover, given the rapid global integration in the emerging market economies, where communication technologies are accelerating the dissemination of information, the discussion of whether ICT development is a factor affecting carbon emissions is justified in this study. Thus, this study contributes to the literature by choosing more up-to-date indicators instead of traditional factors affecting CO_2. Another contribution is methodology. We employ panel vector autoregressive (PVAR) methodology to explore the above links and serve the goal of the empirical analysis as well. One of the most important advantages of this method is that it tries to capture the dynamic relationship between variables by using the minimum constraint set. Besides, PVAR, which enables to conduct impulse-response and shock analysis, is useful for identifying possible policy effects. Also, testing the causality relationship between all variables is another factor in the selection of the method.

The main contribution of this study is to confirm the presence of a common correlation between ICT, TFP, and CO_2 emissions and assess the effect of ICT and TFP on carbon dioxide (CO_2) emissions in the top 10 emerging market economies. The ultimate motivation for this research is to achieve consistent evaluation of the impact of ICT and TFP on carbon dioxide (CO_2) emissions in the top 10 emerging market economies in a single model. The originality of our work consists of the introduction of TFP instead of GDP as an alternative indicator of economic development in order to complete and create an added value to the previous literature.

The rest of the study is structured as follows. "Literature review" examines the literature review. In "Data, model specification, and methodology," the model, dataset, and methodological explanations are presented. Empirical findings are evaluated in "Empirical findings." Our conclusions and policy implications are drawn in "Conclusion."

Literature review

With the understanding of the seriousness of the environmental situation, a growing body of literature has started to examine the environmental effects of economic activities. Environmental Kuznets curve (EKC) hypothesis is widely discussed in this area. In studies that test this hypothesis, which is an important turning point in the field of sustainable development, the relationship between GDP and CO_2 is widely adopted. Some of the studies confirmed the validity of the EKC hypothesis investigating the relationships between different variables including CO_2 emissions, energy consumption, coal consumption, economic growth, trade openness, GDP growth, changes in the price of fuel, income, foreign trade, urbanization, renewable and non-renewable energy, and real income (Lindmark 2002; Saboori and Sulaiman 2013; Nasir and Rehman 2011; Shahbaz et al. 2012; Shahbaz et al. 2013; Tiwari et al. 2013; Heidari et al. 2015; Kasman and Duman 2015; Dogan and Seker 2016; Rauf et al. 2018; etc.). The other studies achieved the opposite result refuting the EKC hypothesis, assuming an inverted U-shaped relationship between environmental degradation and income, proposing the idea that the decrease in energy consumption will hinder economic growth (Basar and Temurlenk 2007; Ang 2008; Akbostanci et al. 2009; Esteve and Tamarit 2012; Saboori et al. 2012; Jebli and Youssef 2015; Ozturk and Al-Mulali 2015; Lopez-Menendez et al. 2014; etc.). Despite the contradictory approaches, they are both targeted at giving the policymakers the opportunity to formulate different types of growth policies to endure environment to its original position taking into consideration different strategies to increase the environmental protection, strengthening the environmental regulations.

While it is discussed whether GDP is a good indicator of economic development recently, the opinion that TFP can be used as an alternative has become widespread in the literature on environmental economics. In particular, studies focusing on the nexus between TFP and energy are found in the current literature (Tugcu 2013; Ackah and Adu 2014; Ladu and Meleddu 2014; Rath et al. 2019). The link between TFP and CO_2 is investigated by Amri et al. (2019). Therefore, few studies have examined TFP as an indicator of the economic development. Also, recently, different variables that affect carbon emissions have been included in the models. ICT is one of these variables. Therefore, this section includes the studies on the ICT–TFP–CO_2 relationship.

Table 1 indicates the existence of a very limited number of studies investigating the ICT–TFP–CO_2 relationship. Therefore, it is necessary to fill the gaps in the current literature in accordance with the importance of the issue. In addition, the disputed results in the studies inspired to consider the relationship from a different perspective. In particular, some of the studies dealing with the ICT–CO_2 relationship have revealed that ICT causes pollution (Lee and Brahmasrene 2014; Raheem et al. 2019) while others have achieved the opposite result (Zhang and Liu 2015; Ozcan and Apergis 2017; Asongu 2018). Based on this literature, we hypothesize that TFP and ICT are positively associated with reduction in CO_2 emissions in the top 10 emerging market economies with high carbon emissions. In summary, our research is aimed at examining the nexus between TFP, ICT, and CO_2 emissions in the top 10 emerging market economies for the period from 1995 to 2014, using the PVAR approach. Since this relationship has not been previously addressed with PVAR analysis in the existing literature, fresh evidence is presented in the literature in terms of empirical analysis.

Data, model specification, and methodology

This paper investigates the connection between information and communication technologies (*ICT*), total factor productivity (*TFP*), and carbon dioxide (*CO_2*) emissions, using yearly dataset for the top 10 emerging market economies[1] from 1995 to 2014. Our model is inspired by Amri et al. (2019) and Raheem et al. (2019) taking into consideration the model in the function which is as follows:

$$\mathrm{CO}_{2it} = f\left(\mathrm{ICT}_{it}, \mathrm{TFP}_{it}, \mathrm{TFP}^{2}{}_{it}\right) \quad (1)$$

$$\mathrm{CO}_{2it} = \alpha_{it} + \beta_1 \mathrm{INT}_{it} + \beta_2 \mathrm{TEL}_{it} + \beta_3 \mathrm{CELL}_{it} + \beta_4 \mathrm{TFP}_{it} + \beta_5 \mathrm{TFP}^2_{it} + \varepsilon_{it} \quad (2)$$

where CO_2 is CO_2 emission metric tons per capita. Individuals using the Internet (INT), fixed telephone subscriptions (TEL), and mobile cellular subscriptions (CELL) are used as a proxy for information and communication technologies. Finally, TFP denotes total factor productivity and is collected from Penn World table, version 9.1. TFP^2 is the square of TFP. Other variables are obtained from the World Bank database. The natural logarithm of all variables is calculated and used in the analysis.

At the initial stage of the analysis, we examine the presence of unit roots. A second-generation panel unit root test is employed to determine the degree of integration of the respective variables. The Pesaran (2007) panel unit root test does not require the estimation of the factor loading to eliminate cross-sectional dependence. Specifically, the usual ADF regression is augmented to include the lagged cross-sectional mean and its first difference to capture the cross-sectional dependence that arises through a single-factor model. The null hypothesis is a unit root for the Pesaran (2007); the CIPS test is specified as follows:

$$\mathrm{CIPS}(N, T) = N^{-1}\sum_{\mathrm{I}} = 1^{N} t_i(N, T) \quad (3)$$

where CIPS(N, T) is the cross-section augmented form of the IPS unit root test developed by Im et al. (2003) and t_i (N, T) is the cross-section augmented Dickey–Fuller statistic.

Next, we use the panel VAR method to determine the long-run relationship between variables. It is generally assumed that all variables in VAR models are endogenous and interdependent and a panel VAR model consists of a combination of traditional VAR method and panel data models (Canova and Ciccarelli 2013). A basic panel VAR equation can be written as (Abrigo and Love 2015):

$$Y_{it} = Y_{it-1}A_1 + Y_{it-2}A_2 + \ldots + Y_{it-p}A_{p-1} + Y_{it-p}A_P + X_{it}B + u_{it} + e_{it} \quad (4)$$

where Y_{it} is (kxk) vector of independent variables, X_{it} is (1xl) vector of exogenous covariates and u_{it} and e_{it} are vectors of dependent variable-specific panel fixed-effects and

[1] China, India, Brazil, the Russian Federation, Mexico, Indonesia, Turkey, Thailand, South Africa, and Malaysia.

Table 1 Empirical studies focusing on ICT–TFP–CO_2 nexus

Study	Main variables	Country	Date	Method	Findings
Lee and Brahmasrene (2014)	CO_2 emissions, ICT, GDP, human capital development	ASEAN countries	1991–2009	FMOLS, CCR	ICT has a positive impact on CO_2
Zhang and Liu (2015)	CO_2 emissions, ICT, urbanization, energy intensity, industrial structure	China	2000–2010	STIRPAT model	ICT has a negative impact on CO_2 emissions
Higon et al. (2017)	CO_2 emissions, ICT, GDP, industry share, education, government effectiveness, rule of law, number of passenger cars	142 economies	1995–2010	POLS, DF-FE, IV-FE	There is an inverted U-shaped relationship between ICT and CO_2
Ozcan and Apergis (2017)	ICT, CO_2, GDP, FD, trade, energy consumption	20 emerging economies	1990–2015	Augmented Mean Group	Internet usage has a negative impact on air pollution
Asongu (2018)	CO_2 emissions, globalization, and ICT	44 Sub-Saharan African countries	2000–2012	GMM	ICT has a negative impact on CO_2 emissions
Amri (2018)	CO_2 emissions, TFP, ICT, trade, financial development, energy consumption	Tunisia	1975–2014	ARDL	ICT has an insignificant effect on CO_2 emissions
Amri et al. (2019)	CO_2 emissions, TFP, and ICT	Tunisia	1975–2014	ARDL model with the breakpoint	ICT has an insignificant effect on CO_2 emissions
Raheem et al. (2019)	CO_2 emissions, GDP, FD, and ICT	G7 countries	1990–2014	PMG	ICT has a positive effect on emissions in the long run
Tzeremes (2020)	CO_2 emissions, TFP, CO_2	G20 countries	1971–2017	Time-varying VAR model	EKC hypothesis is valid in Turkey. There is an inverted U-shaped relationship between TFP and CO_2 in Argentina and Saudi Arabia. N-shaped relationship is determined in France, Italy, and South Africa

Table 2 Unit root test results

Variable	Intercept	Trend	None
CO_2	− 2.417**	− 2.063	− 0.834
INT	− 2.586**	− 3.069**	− 1.729**
TEL	− 2.193	− 1.669	− 1.045
CELL	− 2.173	− 1.049	− 1.187
TFP	− 0.757	− 1.885	− 0.443
TFP2	− 1.363	− 2.166	− 0.735
ΔCO_2	− 4.129*	− 4.906*	− 3.007*
ΔINT	− 2.405**	− 3.071*	− 0.687
ΔTEL	− 2.385**	− 3.732*	− 1.855**
ΔCELL	− 2.441**	− 1.419	− 0.854
ΔTFP	− 2.471**	− 5.312*	− 3.206*
ΔTFP2	− 3.318*	− 5.365*	− 3.601*

* and ** denotes 1% and 5% statistical significance levels, respectively

idiosyncratic errors, respectively.

There are a number of econometric advantages within the panel VAR method. This method is effective in analyzing the transmission of shocks that may occur within a unit and time. The panel VAR models are suitable for creating average effects in groups of non-homogeneous units and analyzing specific differences relative to the mean. The panel VAR method can also be used to analyze the importance of interdependencies and check whether the feedback is generalized. Also, this approach tries to capture the dynamic relationship between variables by using minimum constraint set (Canova and Ciccarelli 2013). The PVAR approach combined panel data methodology with the traditional VAR approach, which handles all variables in the model endogenously, and provides consistent estimates, allowing individual heterogeneity that cannot be observed (Love and Zicchino 2006). Moreover, this approach allows obtaining impulse–response functions and investigating variance decomposition. Impulse–response functions illustrate that the effect of a standard deviation shock that occurs in one of the random error terms on endogenous variables. Variance decomposition implies the sources of shocks in variables themselves and other variables as a percentage. Hence, this approach provides effective and consistent empirical results by allowing the relationship under consideration to be evaluated from a detailed perspective.

Empirical findings

This study applies the CIPS unit root test which considers the presence of heterogeneity in the dataset. Table 2 reports the results of the panel unit root test based on CIPS testing procedures and different deterministic components. The results indicate that all variables are integrated at first difference. Therefore, all variables are adopted as I (1) because the series must be stationary at the same level, which is a prerequisite for the panel VAR approach.

The first step of the PVAR analysis is to determine the optimal lag length. Table 3 shows that the first-order panel VAR is the preferred model, since it has the smallest MBIC, MAIC, and MQIC.

In the next stage, the panel VAR method is applied using GMM style estimation according to 1 lag. Panel estimation results based on the GMM approach are given in Table 4.

Table 4 illustrates that the internet usage, and fixed telephone subscriptions have a positive impact on environmental pollution. This result is compatible with Raheem et al. 2019, although mobile cellular subscriptions and total factor productivity decrease emissions. The significant effect of ICT on emissions is incompatible with the results of Amri et al. (2019). While the results for the internet usage and fixed telephone subscription are consistent with Lee and Brahmasrene (2014) and Raheem et al. (2019), the result for mobile cellular subscriptions is compatible with Asongu (2018). But the result of the internet usage is incompatible with Ozcan and Apergis (2017). Moreover, as TFP continues to increase, the emission-reducing effect of this increase is higher. Therefore, an increase in productivity in the economy without depending on inputs contributes to environmental quality. This result obtained for TFP, which has increased due to technological progress, expresses that the technologies used in production of these countries contribute to sustainable development. Also, total factor productivity causes an increase in ICT, its biggest positive impact being on the internet usage. When examining the situation where TFP is a dependent variable, the results show that the increase in CO_2 decreases TFP while an increase in INT, TEL, and CELL stimulate TFP. Thus, the increased use of ICT has a positive effect on productivity in the manufacturing sector. Thanks to ICT, information flow and market limits expand and costs decrease, which leads to the economic growth.

Table 3 PVAR lag length selection results

Lag	CD	*J*	*J* value	MBIC	MAIC	MQIC
1	1	110.8895	.4051022	− 430.2591	− 105.1105	− 237.208
2	1	73.81449	.4186171	− 286.9512	− 70.18551	− 158.2505
3	1	26.17311	.8856435	− 154.2098	− 45.82689	− 89.8594

Table 4 PVAR GMM style estimation results

Variable	CO_2	INT	TEL	CELL	TFP	TFP2
L.CO_2	0.6354493*	− 2.744231*	− 0.5471752*	− 2.582949*	− 0.0617643*	0.0616335*
L.INT	0.125531*	3.095916*	0.1166289*	2.006236*	0.0272054*	0.0020106
L.TEL	0.1424424*	1.179148*	1.041377*	1.439763*	0.0196766	− 0.026431*
L.CELL	−0.1600561*	− 2.692*	− 0.1421093*	− 1.599605*	0.0236994*	0.0010673
L.TFP	−0.5781688*	18.03369*	1.723489*	12.9691*	− 1.143033*	1.069834
L.TFP2	−2.681431*	− 1.108437	0.6836113**	− 5.969515***	− 2.894959*	2.553997*

*, **, and *** denotes 1%, 5%, and 10% statistical significance levels, respectively

Interestingly, empirical results have confirmed inaccuracy of the view that theoretically, ICT may be beneficial for environmental quality. Although information and communication technologies are needed to implement environmental policies, these technologies have an uncontrolled usage area (Ruchkina et al. 2017). On the other hand, the emission-reducing effect of mobile cellular subscriptions is of much interest. However, it should be noted that electricity consumption is lower in mobile technologies especially when compared to the internet usage. In addition, developments such as the use of smartphones in connection with mobile cellular subscriptions allow for extra energy savings as some activities (especially such as banking transactions) can be carried out via mobile phones. In this case, the emissions-causing part of the internet usage is the use of the internet via computer.

Next, we estimate causal dynamics. According to Table 5, there is bidirectional causality between carbon dioxide emissions and all independent variables. Also, there is bidirectional causality between the internet usage and fixed telephone subscriptions, mobile cellular subscriptions, total factor productivity, and fixed telephone subscriptions and mobile cellular subscriptions, and mobile cellular subscripts and total factor productivity. Finally, we found unidirectional causality running from total factor productivity to fixed telephone subscriptions.

After estimating the coefficient and investigating the causality, the stability condition is checked. The resulting graphs of eigenvalues above confirm that the estimate is stable. Ensuring the stability condition, we move to the next stage of the research (Fig. 1).

Impulse–response graphs are presented in Fig. 2. Accordingly, a standard deviation shock of total factor productivity, mobile cellular subscriptions, the internet usage, and fixed telephone subscriptions increase CO_2 emissions. On the contrary, a standard deviation shock of square of TFP decreases CO_2 emissions. These results are in line with the long-run coefficient estimation results. Therefore, TFP, TEL, CELL, and INT increase carbon emissions, while TFP^2 reduces emissions.

Another important component of the analysis is variance research. The variance decomposition obtained from the moving average section of the VAR model indicates the source of the shocks that occur in the variables themselves and other (explanatory) variables as a percentage. Table 6 demonstrates that variation of carbon dioxide emissions is explained about 91% by past own changes at 1 period ahead. However, when each period is analyzed, while the share of CO_2 decreases gradually, especially, the share of internet usage and TFP increases significantly. Impressively, the variation of CO_2 emissions is explained about 10% by past own, 32% by past internet usage, and 19% total factor productivity changes at 10 periods ahead. Therefore, this result confirms that the increasing spread of ICT inevitably has environmental impacts. Specifically, the importance of the internet usage is undeniable. One of the biggest factors here is that data centers are becoming more and more

Table 5 PVAR causality results

Variable	CO_2	INT	TEL	CELL	TFP	TFP2
CO_2		49.236*	220.442*	50.506*	23.903*	80.308*
INT	211.084*		202.616*	491.776*	22.375*	0.381
TEL	55.548*	18.580*		36.083*	2.631	16.258*
CELL	298.077*	472.752*	276.267*		12.949*	0.080
TFP	24.626*	52.810*	107.065*	42.949*		324.243*
TFP2	104.919*	0.068	5.848*	2.894*	224.536*	

* and ** denotes 1% and 10% statistical significance levels, respectively

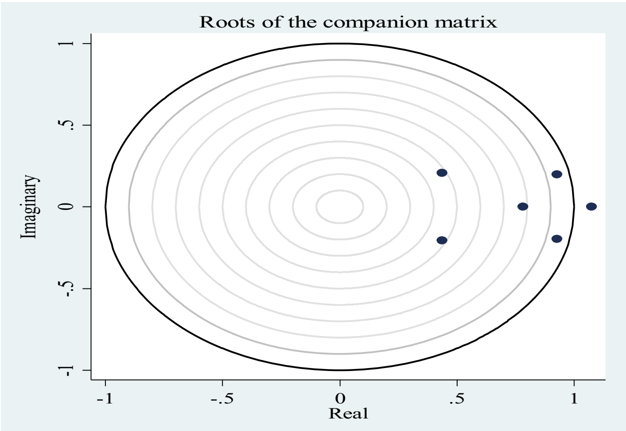

Fig. 1 Roots of companion matrix

widespread. The fact that these data centers meet the conditions of providing high availability and fault tolerance leads to the excessive energy consumption of these centers. Therefore, this large share of the internet usage in explaining an increase in CO_2 emissions over time is not surprising.

Conclusion

In this study, we evaluated the impact of information and communication technologies (ICT) and total factor productivity (TFP) on carbon dioxide (CO_2) emissions in top 10 emerging market economies between 1995 and 2014. In doing so, we applied a panel vector autoregressive (PVAR) approach to determine the long-run relationship between variables in the context of the 10 big emerging countries by using minimum constraint set. Our investigation confirms the presence of a common correlation among ICT, TFP, and CO_2 emissions and over time. We have applied an econometric approach to conduct an impulse–response and shock analyses for identifying possible policy effects and test the causality relationship between all variables which proved to be bidirectional between CO_2 and all independent variables. This study demonstrates that the internet usage and fixed telephone subscriptions have a positive impact on environmental pollution, although mobile cellular subscriptions and TFP have a negative impact on carbon emissions. Also, while ICT has a positive impact on TFP, CO_2 emissions have a negative impact on it. Interestingly, our empirical findings reveal that there is bidirectional causality between CO_2 and all independent variables.

Therefore, our empirical findings provide several policy implications:

(i) ICTs are to promote a decrease in excessive energy consumption of data centers and CO_2 emissions; the policy must be designed so that it encourages the

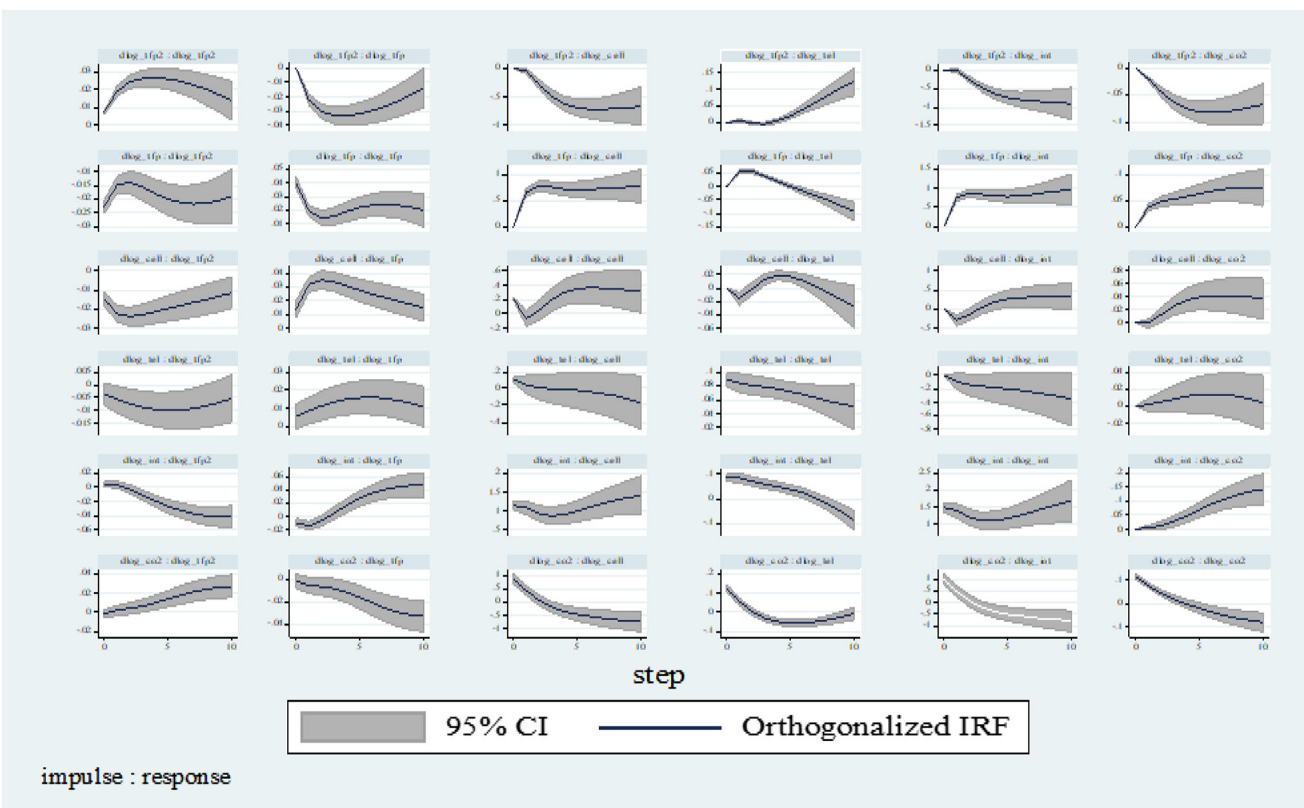

Fig. 2 Impulse–response Graphs

Table 6 Variance decomposition results

CO_2 (response)	Impulse					
Forecast horizon (years)	CO_2	INT	TEL	CELL	TFP	TFP2
0	0	0	0	0	0	0
1	1	0	0	0	0	0
2	0.9107635	0.0012741	0.0001275	0.0001785	0.0680812	0.0195751
3	0.7606553	0.0064941	0.0009469	0.0054787	0.1386082	0.0878168
4	0.5865874	0.0251074	0.0026776	0.0223377	0.1850586	0.1782313
5	0.4347247	0.0640575	0.0046846	0.0413281	0.2071901	0.2480151
6	0.3257107	0.1189825	0.0061809	0.0542715	0.213498	0.2813564
7	0.2567105	0.179419	0.0068403	0.0600265	0.211513	0.2854907
8	0.2168264	0.2368059	0.0067537	0.0607487	0.2057769	0.2730885
9	0.1957338	0.2869217	0.006177	0.0587406	0.1986756	0.2537514
10	0.1859668	0.3287486	0.0053715	0.0555378	0.1914028	0.2329725

environmentally positive impacts of ICTs, while inhibiting the negative ones. In other words, considering the fact that digitalization is inevitable, the environmental sustainability of this digitalization within the industry should not be neglected.

(ii) Since we found the importance of ICT in environmental problems, there is a need in the proper implementation of the undertaken policies towards the sustainable development agenda, especially in terms of technical infrastructure.

(iii) When the contribution of ICT to TFP is considered an important economic result, the structural transformation mechanisms of the industrial economy need to be applied to the new ICT-based economy.

(iv) The result that ICT–CO_2–TFP balance is in a close relationship makes it necessary to correctly prioritize in emerging market economies. When the priority is TFP and thus production growth, support should be provided to invest in ICT, especially for the implementation of micro-scale projects. Moreover, the minimum energy consumption and maximum digitalization criteria around the sustainability condition of the established modern ICT will be the infrastructure of these countries for the new industrial structure of world.

The use of TFP instead of GDP would be a good policy variable as an indicator of the economic development for further research. In addition, existing literature may be expanded by addressing this relationship with different other explanatory variables and a new econometric approach.

Author contributions All authors contributed to the study conception and design. Material preparation and data collection and analysis were performed by Buket Altinoz, Dinara Vasbieva, and Olga Kalugina. The first draft of the manuscript was written by Buket Altinoz and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. Conceptualization was done by Buket Altinoz, Dinara Vasbieva, and Olga Kalugina Data curation was performed by Buket Altinoz. Methodology was done by Buket Altinoz. Formal analysis and investigation were performed by Buket Altinoz. Writing and original draft preparation were done by Buket Altinoz. Writing and review and editing were done by Dinara Vasbieva and Olga Kalugina. Dinara Vasbieva and Olga Kalugina supervised the study.

Data availability Data is available at https://e.mail.ru/cgi-bin/getattach?file=dataset.xlsx&id=16027625180277863852;0;1&mode=attachment&notype=1&x-email=dinara-va%40list.ru.

Compliance with ethical standards

Ethical approval and consent to participate Not applicable.

Consent for publishing Not applicable.

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

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