Interface between energy consumption, CO_2 emissions, economic growth, and macroeconomic openness in financial action task force countries through the lens of a causality approach

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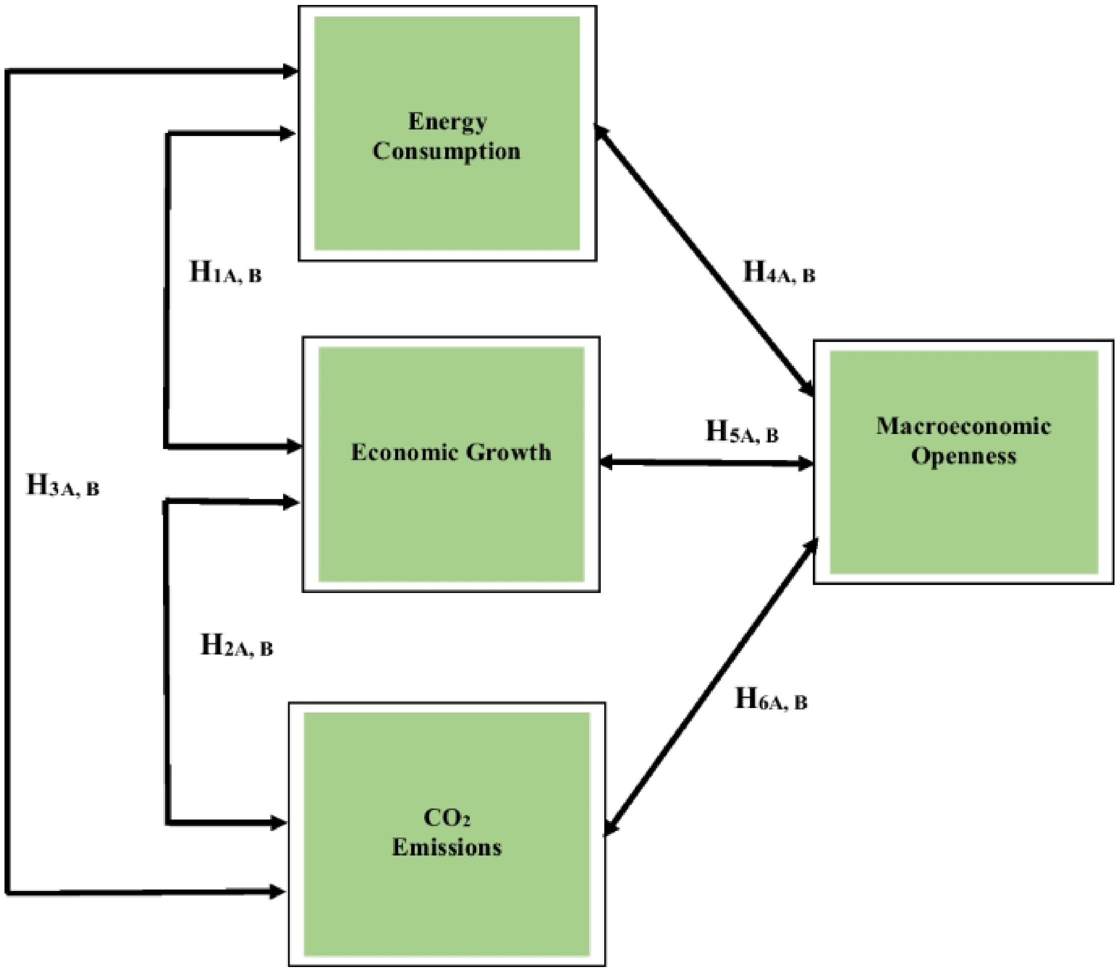
Abstract

There is strong scientific evidence to suggest that carbon dioxide (CO_2) emissions are one of the key drivers of global warming. Rising CO_2 emissions across the globe have been traced back to increasing global trade and rapid industrial development powered by fossil fuels. High CO_2 emissions have had an adverse effect on the quality of life and economic growth of communities across the globe. In this study, the Granger causality approach is used to examine scientifically some causal relationships between energy consumption, CO_2 emissions, economic growth, and key macroeconomic variables (trade openness and foreign direct investment) in the panel of Financial Action Task Force (FATF) countries. FATF countries are signatories to agreements to adhere to good financial practices to ensure sustainable development of their economies. The empirical analysis was conducted for the period 1980 to 2020. Results indicate a strong endogenous relationship between the variables in the short and long run. The analysis suggests that careful *co-curation* of economic, trade, energy, foreign direct investment, and environmental management policies is needed to ensure sustainable economic development in the FATF countries. Global trade and foreign direct investment policies must foster new environmental-friendly industries and greater use of clean renewable energy among these countries.

Graphical abstract



Note: Arrows indicate direction of possible causal links between the variables.

Keywords: CO 2 emissions; Energy consumption; Foreign direct investment; Financial Action Task Force countries; Openness to trade

Introduction

Climate change [1] is currently the greatest threat to humankind and our planet. Efforts and methods to mitigate climate change have therefore been intensively discussed at numerous international governmental and multilateral summits. In particular, global warming, as one effect of climate change, has attracted much attention from the scientific community, as well as from policy-makers (Acheampong 2018; Alola 2019a, b; Wang et al. 2011), as one of the most pressing topics of the last two decades (Jafari et al. 2012). Numerous studies have recognised that increased levels of greenhouse gases, especially CO_2 emissions, are critical contributors to climate change (IPCC 1996; Yeh and Liao 2017; Shabani and Shahnazi 2019; Nair et al. 2021).

Since the Industrial Revolution, there has been an 80% increase in the atmospheric absorption of carbon dioxide (CO_2)—from 280 ppm in 1750 to 504 ppm in 2020—because of CO_2

emissions (GML 2021). The most significant cause of these emissions is the burning of fossil fuels. Nearly half of CO_2 emissions remain in the atmosphere as one of the main greenhouse gases, contributing to a rise in global temperatures (Ekwurzel et al. 2017), whilst the remaining CO_2 emissions are absorbed by land and oceans (Putman et al. 2016). Hence, the atmospheric CO_2 concentration serves as a key indicator of global warming (Halicioglu 2009; NOAA 2019). Not surprisingly, the failure to address factors that cause climate change has been recognised as a major source of disruption of sustainable and healthy living (World Economic Forum 2019). Moreover, the failure to slow climate change has been listed every year from 2015 to 2019 as one of the top five global risk factors (IEA 2019a, b; World Economic Forum 2019).

Numerous studies have reported that energy consumption is a primary source of CO_2 emissions (Saidi et al. 2017; Cai et al. 2018; Chen et al. 2019; Radmehr et al. 2021). It has been projected that the repercussions of global warming might shrink countries gross domestic product (GDP) globally by about 25% by 2050, whereas reducing greenhouse gas emissions may cost only 1% of GDP by the same date—a cost that is not negligible, but manageable (see Stern 2007). It has been argued that CO_2 emissions are inextricably tied to the demand for energy, which is why it is critical to address the energy consumption problem to diminish humanity's carbon footprint (Martinho 2016). However, there are several unknown macroeconomic costs to mitigation initiatives. Hence, it is not entirely clear whether individual strategies proposed to reduce energy consumption are an effective way of dealing with environmental degradation issues (Jafari et al. 2012) because energy consumption and economic growth are probably entangled. Consequently, reducing energy consumption to decrease CO_2 emissions may hinder economic growth (Sadorsky 2012; Omri et al. 2014; Omri et al. 2015; Agboola et al. 2021; El-Karimi and El-Houjjaji 2022; Khan et al. 2022). Conversely, it is true that an increase in economic and industrial development may lead to higher energy usage. Therefore, establishing the connection between energy consumption, CO_2 emissions, and growth is of interest to scientists and policy-makers, as has been noted by Ang (2007), Bekun et al. (2019a, b), Bekun et al. (2019a, b), IEA (2019a, b), and İnal et al. (2022), *inter alia*. Hence, the present study assesses these linkages for the Financial Action Task Force (FATF) countries. [2]

The present study adds value to the existing literature on both development economics and environmental economics in various ways, in the specific context of macroeconomic openness. This is the first attempt to investigate the inter-linkages between CO_2 emissions, growth, and energy consumption in the context of two key macroeconomic openness indicators, namely the degree of trade openness (hereafter OPE) and foreign direct investment (hereafter FDI) inflows. Although the inter-linkages between energy consumption and growth are well-trodden ground in the academic literature (Śmiech and Papież 2014; Khan et al. 2020), there has been significantly less research on the interactions between the triad of energy consumption, CO_2 emissions, economic growth, and the two macroeconomic openness indicators, OPE and FDI. The incorporation of these variables offers valuable insights into the impact of increased global trade and FDI flows on energy consumption patterns and CO_2.

The second original contribution of this paper is the argument that, since the empirical analysis shows that macroeconomic openness does indeed influence energy growth and the CO_2 nexus, a key policy implication from this study is that policy-makers must ensure that trade and FDI policies are congruent with weaning economies away from fossil fuels and transitioning them to environmentally friendly renewable energy sources.

The third contribution is that these links are explored in the context of FATF countries, a group of countries that are signatories to agreements to adhere to global best practices to ensure the integrity of their financial systems, so as to prevent these countries' economies from using their financial resources sub-optimally. Doing so might lead to market failures arising from global financial crimes and unsustainable economic practices. This cluster of countries has been understudied in the economic growth literature. This study thus provides valuable insights on how well the FATF countries are addressing climate change issues, in particular CO_2 emissions, and ensuring sustainable economic growth rates. Our conclusions may assist governments, conservationists, and firms engaging in FDI to formulate and institute environmental management policies and regulations to reduce the carbon footprint, whilst concurrently taking economic growth into account. In short, this study provides suitable policies for the group of FATF economies, which may be generalised to other emerging and/or developing economies.

This paper is structured into six sections. Following on from this introduction, the 'Development of the hypotheses and literature review' section develops our hypotheses and reviews the relevant literature. The 'Data and sample description' section explains our data sources and comments on the sample of FATF countries. The 'Preliminary requirements' section presents the results of our stationarity and cointegration tests, which are preliminary requirements for our subsequent analyses. This section concludes with a presentation of our econometric model to establish the causality between the variables. The 'Temporal causality results' section discusses the main results of our empirical analysis, and the 'Conclusion and policy implications' section sets out a summary, makes policy recommendations, and notes the limitations of this study.

Development of the hypotheses and literature review

We use a *unified* outline to unravel the possible relations among energy consumption patterns, CO_2, and growth, with two indicators for macroeconomic openness (OPE and FDI). The study attempts to discover possible linkages between all these variables. This section reviews the possible relationships between the variables, based on the literature, and also presents the various related hypotheses.

The link between energy consumption and economic growth

Does energy consumption affect growth? This question has been of interest to policy-makers and the research community since the ground-breaking efforts of Kraft and Kraft (1978). They found that the causal connection tracks from growth to energy consumption and not the reverse. An explanation for this relationship is that, as the economy develops and grows, more energy is needed to improve general living standards (Darmstadter et al. 1979; Rosenberg 1998; Wu and Chen 2017; Zhang and Cheng 2009; Carfora et al. 2019; Nair et al. 2021; Le et al. 2021; El-Karimi and El-Houjjaji 2022).

Alternatively, energy consumption may be regarded as an important foundation of economic growth, since energy is a basic factor of production. Therefore, additional energy usage in manufacturing may be connected to increased industrial growth and industrial productivity (Azam et al. 2015; Pradhan et al. 2018; Alola 2019a, b; IEA 2019a, b; Akadiri et al. 2020; Khan et al. 2020; Le et al. 2021; Acheampong et al. 2021; Adom et al. 2021; İnal et al. 2022). However, one could hypothesise that there may be little or no link between energy consumption and growth, if one is dealing with countries that are generally not heavily reliant on (fossil fuel) energy. As already indicated, there is some uncertainty concerning the direction of causation between energy consumption patterns and growth. We therefore examined the following hypothesis:

- *$H_{1A, B}$: Energy consumption Granger-causes economic growth, and vice versa.*

$H_{1A,B}$ has already been examined in various studies. For example, support for this hypothesis is available from Saidi et al. (2017: Table 1) and Pao and Chen (2019: Table 2). The FATF countries are, however, not the focus of these prior studies, nor are OPE and FDI included in their studies.

The link between CO_2 and economic growth

As noted in the introduction, environmental degradation is a serious global problem. There is ample scientific evidence to show that global warming and premature deaths are both a result of emissions, especially carbon particles that accumulate in the atmosphere (De Sario et al. 2013; McIntosh and Pontius 2017; Saidi et al. 2017; Nair et al. 2021). The first of two significant effects of global warming is that, as global temperatures increase, the Arctic ice melts at a much faster pace, which raises the ocean levels (see, for instance, McMichael et al. 2006). Higher sea levels will have an adverse impact on highly populated cities in coastal areas across the globe. A second significant outcome of global warming is the increased risk of droughts throughout the world (Dai 2013). Hence, addressing the carbon footprint problem has become increasingly important, as rising CO_2 emissions have a large impact on both societal well-being and the survival of all biological species (including humans) on Earth.

Several in-depth studies have been conducted based on the concept of the environmental Kuznets curve (EKC) developed by Grossman and Krueger (1991). The EKC posits that there is an inverted-U curve in respect of the relationship between economic development and environmental degradation. In pre-industrial economies, the level of economic growth is low, and so is the level of environmental degradation. Once economies begin to move towards achieving stronger growth, setting more ambitious targets and often growing through FDI, they are more likely to focus on the industrial sector. As they become more industrialised, their economies tend to grow without paying much attention to protecting the environment; hence, they can have high economic growth but poor environmental quality. However, over time, once economies achieve a target level of economic growth, they often start focusing on environmental degradation and on reducing pollution by investing in the service sector and/or enforcing strict environmental regulations. In the modern era, innovative technologies and methods enable stronger economies to implement new ways to decrease CO_2 emissions.

Many studies discuss the EKC construct (for instance, Sun et al. 2022). It must be noted, however, that the validity of the EKC can be tested easily for a single country, but that it is not so simple to test this hypothesis with a panel data model in which the sample countries are at different stages of development. Thus, there is still some controversy regarding the validity of the EKC: some studies have found evidence of the inverted U-curve, whereas others' data do not support the EKC (see, for example, Jain and Nagpal 2019; Harbaugh et al. 2002).

Notwithstanding the lack of conclusive evidence on the correctness of the EKC, it is widely acknowledged that, at least to a certain point in economic development, increased industrial and economic activities may be regarded as significant causal agents for escalating environmental degradation and global warming, even if a closer enquiry of the connection between environmental quality and growth demonstrates that this relationship is remarkably complex. Some studies show that there is an association between economic growth and increased environmental pollution across the globe. Conversely, other studies show that in many developed economies, increased economic wealth has resulted in wider use of energy-efficient devices and appliances. [3] The increased use of renewable energy has also reduced carbon emissions in these countries. Studies that confirm these complex relationships include those by Dinda (2004), Arvin et al. (2015), Andlib and Khan (2021), Chien et al. (2021), Sun et al. (2021), and Wangzhou et al. (2022). To understand the connection between CO_2 emissions and growth, we tested the following hypothesis:

- *$H_{2A,\,B}$: Economic growth Granger-causes CO_2 emissions, and vice versa*.

This hypothesis has previously been tested by various researchers, with varying results. These studies include those by Criado et al. (2011), Arvin et al. (2015), Ito (2017), Saidi et al. (2017), Cai et al. (2018), Le and Quah (2018: Table 1), Mardani et al. (2019: Table 1), and Agboola et al. (2021).

The link between energy consumption and CO_2 emissions

Numerous studies have investigated the connection between CO_2 and energy consumption. The factors causing CO_2 emissions can be categorised into indirect and direct factors. The direct factors include energy consumption (see Wang et al. 2014; Kais and Ben Mbarek 2017; Radmehr et al. 2021). The indirect factors mainly relate to socio-economic development issues [4] (see, for example, Wang et al. 2016). In this study, we focused on the direct factors, in particular, how energy consumption patterns affect CO_2 emissions (Ang, 2007; Zhang and Cheng 2009; Ito 2017; Boutabba et al. 2018; Zhu et al. 2019; Akadiri et al. 2020; Hao et al. 2020; Li et al. 2020a, b; Wu et al. 2020; Khan et al. 2021; Chien et al. 2021; Sohail et al. 2022; Chien et al. 2022; Sun et al. 2022).

There are two views on the connection between CO_2 and energy consumption. First, rapid industrialisation, powered by the use of carbon-based energy across the globe, is regarded as an important cause of climate change due to the increased CO2 emissions resulting from industrialisation (Callan et al. 2009; Wu and Chen 2017). According to the Intergovernmental Panel on Climate Change (2006), carbon emissions vary in different countries and regions according to the type of energy used for industrial and other economic activities. Second, in some countries, the level of CO_2 emissions may influence energy consumption patterns—for example, in several countries where CO_2 emissions are very high, governments have intervened by limiting the amounts of CO_2 emissions allowed in industries and by providing greater incentives for firms and consumers to use renewable energy sources (see, for example, Apergis and Payne 2012, 2014). As was the case for economic growth and environmental quality, the relationship between energy consumption and emissions is complicated by the fact that the relationship may change, depending on the state of economic growth in the country (Kaya and Yokobori 1997). Based on the view that rapid industrialisation accelerates climate change resulting from CO_2 levels, we tested the following hypothesis:

- *$H_{3A,\,B}$: Energy Granger-causes CO_2 emissions, and vice versa.*

$H_{3A,\,B}$ has been tested by various prior researchers; relevant results are summarised in Lin and Raza (2019: Table 1a). [5]

The link between energy consumption and macroeconomic openness

The potential connection between energy consumption and macroeconomic openness is especially interesting. Nasreen and Anwar (2014) have identified two steps through which this nexus occurs. Firstly, energy is a necessary and important production input needed to run the machinery and other equipment used in manufacturing. Secondly, fuel (energy) is needed to transport, export, and import produced goods. Without energy for transport, a country's openness to trade could be hampered. A key factor for attracting foreign investors to a country is thus an uninterrupted supply of energy for the production and transportation of goods and services. Nasreen and Anwar (2014) speculate that there is a feedback connection between trade openness and energy consumption.

One of the contributions of this work is the simultaneous consideration of economic growth, macroeconomic openness, and their relationships with energy consumption. To date, there have been only a few studies that investigated the linkages among these variables. The results are mixed. Cole (2006) found that trade openness gears to economic growth: as growth intensifies, energy consumption increases. Jena and Grote (2008) found that openness to trade contributes to energy consumption. Several studies have shown a bidirectional relationship (see, for example, Sadorsky 2011; Shahbaz et al. 2013; Tan et al. 2021; Safdar et al. 2022), but others have reported no connection between the variables (Narayan and Smyth 2009). Given the mixed results of previous studies, we tested the following hypothesis:

- *$H_{4A,\,B}$: Energy consumption Granger-causes macroeconomic openness, and vice versa.*

The link between economic growth and macroeconomic openness

The dynamics between macroeconomic openness and growth have been well studied and documented (see, for example, Tang and Tan 2014; Pradhan et al. 2017a, b; Stern 2000). It is thought that trade openness affects economic growth via four channels: (1) increased trade openness increases exports and imports between countries, which stimulates economic growth in those economies; (2) depending on the development stage of their local industries, countries tend to focus on the production of goods and services in areas where they have a comparative advantage and can participate in the global value chain; (3) improved terms of trade between countries have a positive effect on foreign exchange markets; and (4) increased diffusion of knowledge and technology enables countries to increase their intellectual and technological capabilities (Kugler 1991; Giles and Williams 2000; Pradhan et al. 2021). Similarly, FDI contributes to economic development via a transfer of technology, expertise, and capital. These factors are critical for enhancing economic activities between participating countries (Findlay 1978; Wang 1990).

Some studies demonstrate unidirectional causality (Gries et al. 2009; Hossain 2011; Nasreen and Anwar 2014; Pradhan et al. 2015; Menyah et al. 2014; Safdar et al. 2022). Others report a feedback connection between macroeconomic openness and growth (Chow and Fung 2011; Omri et al. 2014; Sakyi et al. 2014; Pradhan et al. 2016; Huchet-Bourdon et al. 2018; Arvin et al. 2021). Due to these mixed results, we tested the following hypothesis:

- *$H_{5A,\,B}$: Economic growth Granger-causes macroeconomic openness, and vice versa.*

The link between macroeconomic openness and CO_2 emissions

Finally, we examined the connection between CO_2 emissions and macroeconomic openness. The seminal work of Grossman and Krueger (1991) explains why trade globalisation can cause environmental degradation and contribute to an increase in greenhouse gases. Their study listed three paths through which increased trade openness and environmental degradation are linked. The first is the 'scale effect', which refers to the argument that increased trade openness causes an expansion of economic activity, thus increasing pollution through the increased burning of fossil fuels. The second is the 'composition effect': competitive advantage may arise from differences in countries' environmental regulations. In this case, increased trade can intensify environmental degradation, because global firms may move their environment-polluting operations to nations or regions with less stringent environmental standards. The third is the 'technique effect'—after increased trade liberalisation, products do not need to be manufactured using exactly the same process as before trade liberalisation. Interestingly, in some countries, this could mean decreased environmental degradation, as foreign producers usually transfer knowledge regarding the use of new techniques and/or devices that reduce pollution.

Studies on this link have yielded interesting but mixed results. For example, Baek et al. (2009) found that the influence of openness to trade on the environment in a country differs, subject to a country's level of development. In advanced countries, trade liberalisation may improve environmental quality. However, the opposite was found in many developing countries, where trade liberalisation has had an adverse impact on the environment. For example, studies have found a similar effect in OECD countries, where trade liberalisation benefits the environment, whilst the opposite is true for non-OECD countries; see Managi et al. (2009), Chien et al. (2021), Sun et al. (2021), Tan et al. (2021), Li et al. (2022), and Safdar et al. (2022), for example. Overall, there is little consensus on the connection between macroeconomic openness and CO_2 (or more generally, environmental quality). In other groups of countries, Nakano et al. (2009) and Aïssa et al. (2014) report a negative linkage. Antweiler et al. (2001) found a positive link between macroeconomic openness and CO_2 emissions. Akin (2014: Table 1) summarises the literature on the connection between environmental quality (primarily in terms of CO_2 emissions) and trade openness. To contribute to these debates, we examined the following hypothesis:

- *$H_{6A,\,B}$: Macroeconomic openness Granger-causes CO_2 emissions, and vice versa.*

Data and sample description

The data for this study were obtained from the *U.S. Energy Database* of the Inter-American Development Bank and the *World Development Indicators* of the World Bank. We studied data on the FATF countries from 1980 to 2020. The FATF mix of countries includes developed countries, newly industrialised economies, as well as developing nations. These countries are listed in the World Bank database. We selected this group for four reasons.

First, as already indicated, the FATF member countries are committed to implementing global best practices to ensure the integrity of financial systems, working together to prevent global financial crimes emanating in member countries; to promote greater macroeconomic openness; and to promote optimal use of financial resources to enhance the economic sustainability of the countries. These practices also include ensuring that their financial systems enable these countries to transition towards cleaner energy sources.

Second, the group consists of countries in different stages of development with different fossil fuel consumption patterns to power their economies. Geographically, FATF countries are in different regions and have different income levels. This selection of countries is interesting in that the impact of globalisation on environmental integrity/degradation is of particular interest to researchers and policy creators. For example, Doytch and Uctum (2016) claim that foreign direct investment in the areas of manufacturing and non-service industries have a positive impact in wealthier nations, but a negative impact in low-income countries.

Third, climate change is taking a toll on every country globally, including the FATF countries. Some of the countries in this group are suffering many climate shocks—extreme heat, extreme cold, very little or no rainfall, droughts, etc. These now increasingly common phenomena pose a threat to agricultural productivity and animal and human lives. Most of the economies in FATF countries face the challenges of large populations and rapid rates of urbanisation, putting increasing high pressure on natural resources. Additionally, the FATF countries tend to contain current urban hotspots or ones likely to emerge over the next decade, as the rapid growth of urban populations puts pressure on the economy and the environment.

Fourth, we can examine if adherence to good financial practices translates to better environmental management practices in respect of reducing CO_2 emissions. Hence, the empirical analysis provides valuable insights into the effects of the macroeconomic openness policy dynamics between CO_2, energy consumption, and growth among this group of countries. Furthermore, to confront the detrimental impact of climate change and fulfil the demand and supply gap of energy use, FATF economies need to focus on this empirical investigation process, particularly with reference to the use of renewable energy in these economies.

To our knowledge, this study is the first to deploy the Granger approach to investigate *simultaneously* the temporal causal connection between these five variables (the dynamics among energy consumption (ENG), CO_2 emissions (CO_2), and economic growth (PEG) in the presence of two macroeconomic openness indicators, namely OPE and FDI) for the FATF group of countries. [6] Figure 1 summarises the hypotheses that are tested.

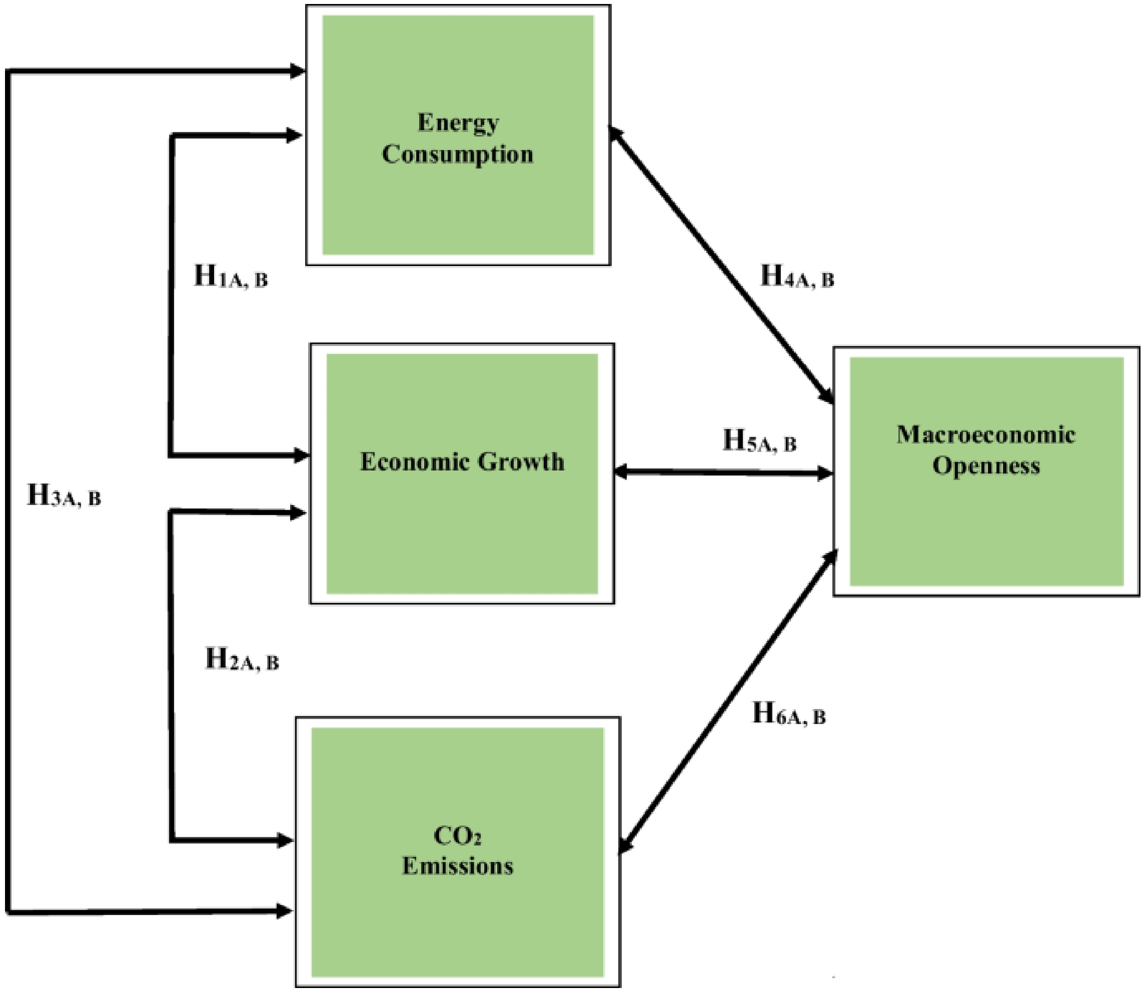


Fig. 1. Conceptual framework

Preliminary requirements

The Granger causality employed in this study displays *temporal* or *predictive* causality between the five variables. [7] To confirm which technique(s) would be the most appropriate to conduct Granger causality, some preliminary analyses were necessary. We analysed six different cases using six different energy consumption indicators: coal energy (CEC), oil energy (OEC), gas energy (GEC), electricity energy (EEC), biomass energy (BEC), and non-biomass energy (NEC). In Appendix 1, Table 5, we describe all the variables. All the data series were transformed into their natural logarithmic form for our empirical investigation. [8] Table 1 provides descriptive statistics and correlation among these variables.

We examined the dynamics among CO_2 emissions, growth, openness to trade, energy consumption, and FDI, with a specific focus on the short- and long-run dynamic associations between the chosen variables. Our analysis proceeded as follows.

Table 1. Descriptive statistics

Variables	CEC	OEC	GEC	EEC	BEC	NEC	PEG	CO2	OPE	FDI
Part 1: Summary										
Mean	−0.32	0.32	−0.09	−0.40	−1.93	−0.43	4.33	0.84	1.82	0.43
Median	−0.35	0.48	0.08	−0.32	−1.77	−0.36	4.52	0.90	1.78	0.41
Maximum	1.85	1.61	1.40	1.16	0.72	0.89	5.05	1.39	3.65	1.94
Minimum	−3.80	−0.92	−1.50	−5.28	−5.05	−5.00	2.66	−0.05	1.34	−0.92
Standard dev	0.99	0.55	0.66	1.21	1.25	0.82	0.51	0.28	0.26	0.50
Skewness	−0.23	0.16	0.10	−2.78	−0.17	−1.68	−1.42	−0.79	0.60	0.32
Kurtosis	3.39	2.66	2.63	11.9	2.53	9.58	4.52	3.73	4.81	373
JB	4.01	2.41	1.88	120.1	3.66	590.9	112.5	33.2	22.7	10.4
Part 2: Correlation matrix										
CEC	1.00									
OEC	0.82*	1.00								
GEC	0.69*	−0.86*	1.00							
EEC	0.38*	0.39*	0.34*	1.00						
BEC	0.39*	0.48*	0.42*	0.63*	1.00					
NEC	0.46*	0.57*	0.47*	0.29*	0.49*	1.00				
PEG	−0.46*	−0.36*	0.20*	−0.19*	−0.31*	−0.27*	1.00			
CO2	−0.44*	−0.10	0.10	−0.14	−0.10	−0.22*	0.76*	1.00		
OPE	−0.53*	−0.61*	−0.92*	−0.26*	−0.30*	−0.72*	0.44*	0.34*	1.00	
FDI	−0.34*	−0.32*	−0.46*	−0.21*	−0.26*	−0.36*	0.20*	0.13	0.61*	1.00

Variables are defined in Table 5 (Appendix 1)

JB is the Jarque-Bera statistics

*Statistical significance at the 1% level

We first examined the cross-sectional dependence and the stationarity of these variables. The cross-sectional dependency (CD) test (Pesaran 2003) was deployed to report the cross-sectional dependence of these variables; the cross-sectional Im–Pesaran–Shin (CIPS) unit root test (Pesaran 2007) was used to check the stationarity properties. Table 2 sets out the results of the CD and the CIPS tests. Based on these results, we rejected the null hypothesis of cross-sectional independence, as all ten variables analysed (CEC, OEC, GEC, EEC, BEC, NEC, PEG, CO_2, OPE, and FDI) are cross-sectionally dependent. We also rejected the non-stationarity hypothesis for the differenced data, as the tests confirmed that the variables are first difference stationary and thus integrated of order one (denoted by I [1]).

Table 2. Results of panel unit root test

Variables	BPL	PCL	BSL	PCD	Level	CIPS	Unit root inference
CEC	6141*	160.8*	160.2*	20.83*	1	−15.2*	**1 [1]**
OEC	9377*	254.6*	254.1*	58.64*	1	−7.56*	**1 [1]**
GEC	10,987*	311.3*	310.8*	97.69*	1	−8.88*	**1 [1]**
EEC	16,365*	457.2*	456.8*	126.0*	1	−11.3*	**1 [1]**
BEC	13,188*	365.1*	364.8*	109.2*	1	−7.19*	**1 [1]**
NEC	7761*	207.7*	207.2*	75.23*	1	−13.1*	**1 [1]**
PEG	29,160*	828.1*	827.7*	169.7*	1	−22.9*	**1 [1]**
CO2	13,696*	379.8*	379.4*	63.52*	1	−12.8*	**1 [1]**
OPE	17,331*	485.2*	484.8*	116.9*	1	−27.7*	**1 [1]**
FDI	4853*	123.5*	123.1*	54.4*	1	−16.2*	**1 [1]**

Variables are defined in Table 5 (Appendix 1)

BPL is the Breusch-Pagan Lagrange multiplier (LM); PCL is the Pesaran scaled LM; BSL is the Bias-corrected scaled LM; PCD is the Pesaran Cross-Section Dependence Test; CIPS is the cross-sectional augmented Im-Pesaran-Shin test; I [1] is integrated of order one

*Statistical significance at the 1% level

We then checked for the feasibility of a long-run stable connection between CO_2, growth, energy consumption, openness to trade, and FDI, using the Fisher cointegration test (Maddala and Wu 1999). Table 3 reports the panel cointegration results for the six cases under review, showing that the chosen variables are cointegrated, indicating a long-run connection between the five variables.

Table 3. Results of the cointegration tests

Table 3 Results of the cointegration tests

Hypothesised no. of CE(s)	With linear deterministic trend		Inference
	λ_{Trace}	$\lambda_{Max\text{-}eigen}$	
Case 1: *CEC, PEG, CO2, OPE, FDI*			
None ($k \leq 0$)	363.3*	252.5*	
At most 1 ($k \leq 1$)	219.4*	150.9*	
At most 2 ($k \leq 2$)	154.7*	126.5*	Cointegrated [3]
At most 3 ($k \leq 3$)	68.23	66.91	
At most 4 ($k \leq 4$)	62.76	62.76	
Case 2: *OEC, PEG, CO2, OPE, FDI*			
None ($k \leq 0$)	391.0*	299.8*	
At most 1 ($k \leq 1$)	214.6*	170.5*	
At most 2 ($k \leq 2$)	120.1*	112.7*	Cointegrated [3]
At most 3 ($k \leq 3$)	54.70	53.88	
At most 4 ($k \leq 4$)	51.91	51.91	
Case 3: *GEC, PEG, CO2, OPE, FDI*			
None ($k \leq 0$)	412.9*	282.2*	
At most 1 ($k \leq 1$)	295.1*	220.7*	
At most 2 ($k \leq 2$)	142.2*	121.2*	Cointegrated [3]
At most 3 ($k \leq 3$)	64.87	64.09	
At most 4 ($k \leq 4$)	54.41	54.41	
Case 4: *EEC, PEG, CO2, OPE, FDI*			
None ($k \leq 0$)	388.0*	288.4*	
At most 1 ($k \leq 1$)	258.3*	199.6*	
At most 2 ($k \leq 2$)	138.9*	113.9*	Cointegrated [3]
At most 3 ($k \leq 3$)	67.55	57.41	
At most 4 ($k \leq 4$)	63.55	53.55	
Case 5: *BEC, PEG, CO2, OPE, FDI*			
None ($k \leq 0$)	510.4*	355.0*	
At most 1 ($k \leq 1$)	278.1*	200.3*	
At most 2 ($k \leq 2$)	136.4*	107.7*	Cointegrated [3]
At most 3 ($k \leq 3$)	82.87	77.80	
At most 4 ($k \leq 4$)	62.07	62.07	
Case 6: *NEC, PEG, CO2, OPE, FDI*			
None ($k \leq 0$)	287.3*	199.0*	
At most 1 ($k \leq 1$)	186.9*	138.2*	
At most 2 ($k \leq 2$)	119.4*	103.5*	Cointegrated [3]
At most 3 ($k \leq 3$)	55.99	54.88	
At most 4 ($k \leq 4$)	53.57	53.57	

Variables are defined in Table 5 (Appendix 1)

λ_{Trace} is the trace statistics; $\lambda_{Max\text{-}eigen}$ is the Max-Eigen statistics, and CE(s) is the number of cointegrating equations

*Significance at the 1% level

Appendix 2 Fig. 2 presents a flow chart to explain the analyses step by step. After determining the nature of stationarity and cointegration, we used the following vector error-correction model (VECM) to explore possible Granger causality between the chosen variables [9]:

$$\begin{bmatrix} \Delta Energy\ consumption_{it} \\ \Delta Economic\ growth_{it} \\ \Delta CO2\ emissions_{it} \\ \Delta Trade\ openness_{it} \\ \Delta Foreign\ direct\ investment_{it} \end{bmatrix} = \begin{bmatrix} \alpha_{1j} \\ \alpha_{2j} \\ \alpha_{3j} \\ \alpha_{4j} \\ \alpha_{5j} \end{bmatrix}$$

$$+\sum_{k=1}^{q} \begin{bmatrix} \mu_{11ik}(L) & \mu_{12ik}(L) & \mu_{13ik}(L) & \mu_{14ik}(L) & \mu_{15ik}(L) \\ \mu_{21ik}(L) & \mu_{22ik}(L) & \mu_{23ik}(L) & \mu_{24ik}(L) & \mu_{25ik}(L) \\ \mu_{31ik}(L) & \mu_{32ik}(L) & \mu_{33ik}(L) & \mu_{34ik}(L) & \mu_{35ik}(L) \\ \mu_{41ik}(L) & \mu_{42ik}(L) & \mu_{43ik}(L) & \mu_{44ik}(L) & \mu_{45ik}(L) \\ \mu_{51ik}(L) & \mu_{52ik}(L) & \mu_{53ik}(L) & \mu_{54ik}(L) & \mu_{55ik}(L) \end{bmatrix}$$

$$\begin{bmatrix} \Delta\ Energy\ consumption_{it-k} \\ \Delta Economic\ growth_{it-k} \\ \Delta CO2\ emissions_{it-k} \\ \Delta Trade\ openness_{it-k} \\ \Delta Foreign\ direct\ investment_{it-k} \end{bmatrix} + \begin{bmatrix} \rho_{1i} ECT_{it-1} \\ \rho_{2i} ECT_{it-1} \\ \rho_{3i} ECT_{it-1} \\ \rho_{4i} ECT_{it-1} \\ \rho_{5i} ECT_{it-1} \end{bmatrix} + \begin{bmatrix} \psi_{1it} \\ \psi_{2it} \\ \psi_{3it} \\ \psi_{4it} \\ \psi_{5it} \end{bmatrix}$$

where α is the constant term; q is the highest lag length; and ψ is the error term.

ECT_{it-1} refers to the error-correction term. These lagged ECTs normally capture Granger causality in the long run. The ECT coefficients of differenced variables record short-run causality between the covariates, whilst the F-statistics show the short-run association between them. The lagged ECT coefficients measure the rate of change at which the dependent variable returns to a path of equilibrium if disturbed from the long-run path.

Temporal causality results

Our temporal causality outcomes are shown in Table 4 and are discussed in the next two sub-sections.

Table 4. Granger causality results

Dependent variable	Independent variables					ECT_{-1} coefficient	Short-run inference
Case 1: VECM with CEC, PEG, CO2, OPE, FDI							
	ΔCEC	**ΔPEG**	**ΔCO2**	**ΔOPE**	**ΔFDI**	**ECT_{-1}**	
ΔCEC	—	6.11**	15.5*	1.54	0.56	−0.002**	CEC↔PEG
						(−4.26)	CEC↔CO2
ΔPEG	9.35*	—	3.67***	4.59**	2.36	−0.13	CEC ∤ OPE
						(−0.22)	CEC ∤ FDI
ΔCO2	21.4*	10.1*	—	12.1*	3.89***	−0.001***	PEG↔CO2
						(−3.64)	PEG↔OPE
ΔOPE	0.21	14.2*	0.52	—	4.08***	−0.002	PEG→FDI
						(−0.39)	CO2←OPE
ΔFDI	1.48	8.49*	3.94***	5.29**	—	−0.003*	CO2↔FDI
						(−8.84)	OPE↔FDI
Case 2: VECM with OEC, PEG, CO2, OPE, FDI							
	ΔOEC	**ΔPEG**	**ΔCO2**	**ΔOPE**	**ΔFDI**	**ECT_{-1}**	
ΔOEC	—	4.44***	1.16	2.80	10.4*	−0.001***	OEC←PEG
						(−4.32)	OEC→CO2
ΔPEG	0.86	—	2.35	4.72**	3.20	−0.001	OEC→OPE
						(−0.89)	OEC↔FDI
ΔCO2	19.1*	7.44*	—	11.3*	3.82***	−0.001***	PEG→CO2
						(−4.20)	PEG↔OPE
ΔOPE	10.4*	21.4*	2.38	—	4.69***	−0.001	PEG→FDI
						(−0.28)	CO2←OPE
ΔFDI	3.93***	10.4*	1.63	5.56**	—	−0.04*	CO2←FDI
						(−8.27)	OPE↔FDI
Case 3: VECM with GEC, PEG, CO2, OPE, FDI							
	ΔGEC	**ΔPEG**	**ΔCO2**	**ΔOPE**	**ΔFDI**	**ECT_{-1}**	
ΔGEC	—	0.07	5.01**	5.40**	4.11**	−0.003**	GEC→PEG
						(−4.10)	GEC↔CO2
ΔPEG	3.69***	—	3.70***	5.13**	1.87	−0.006	GEC↔OPE
						(−0.11)	GEC←FDI
ΔCO2	3.73***	13.5*	—	10.9*	2.88	−0.001***	PEG↔CO2
						(−3.30)	PEG↔OPE
ΔOPE	3.80***	15.2*	1.17	—	3.88***	−0.002	PEG→FDI
						(−0.65)	CO2←OPE
ΔFDI	1.95	7.27*	1.53	4.51***	—	−0.003*	CO2 ∤ FDI
						(−7.69)	OPE↔FDI
Case 4: VECM with EEC, PEG, CO2, OPE, FDI							
	ΔEEC	**ΔPEG**	**ΔCO2**	**ΔOPE**	**ΔFDI**	**ECT_{-1}**	
ΔEEC	—	0.96	4.74***	0.97	7.35*	−0.003**	EEC→PEG
						(−4.66)	EEC↔CO2
ΔPEG	3.51***	—	1.58	3.80***	3.70***	−0.001	EEC→OPE
						(−0.60)	EEC↔FDI

ΔCO2	19.1*	11.9*	—	6.55**	2.56	−0.003***	PEG→CO2
						(−3.92)	PEG↔OPE
ΔOPE	6.27**	14.5*	1.35	—	4.87***	−0.009	PEG↔FDI
						(−0.67)	CO2←OPE
ΔFDI	13.5*	12.2*	0.99	5.64**	—	−0.001*	CO2 ∤ FDI
						(−8.67)	OPE↔FDI
Case 5: VECM with BEC, PEG, CO2, OPE, FDI							
	ΔBEC	**ΔPEG**	**ΔCO2**	**ΔOPE**	**ΔFDI**	**ECT_{-1}**	
ΔBEC	—	0.93	5.60**	4.84**	6.87*	−0.005***	BEC→PEG
						(−3.33)	BEC↔CO2
ΔPEG	5.00**	—	9.82*	11.1*	7.36*	−0.002	BEC↔OPE
						(−2.37)	BEC↔FDI
ΔCO2	8.95*	3.96***	—	6.45**	6.50**	−0.002***	PEG↔CO2
						(−3.98)	PEG↔OPE
ΔOPE	3.90***	11.8*	0.06	—	4.68***	−0.001	PEG←FDI
						(−2.17)	CO2←OPE
ΔFDI	6.33**	0.56	0.65	3.71***	—	−0.002*	CO2←FDI
						(−8.26)	OPE↔FDI
Case 6: VECM with NEC, PEG, CO2, OPE, FDI							
	ΔNEC	**ΔPEG**	**ΔCO2**	**ΔOPE**	**ΔFDI**	**ECT_{-1}**	
ΔNEC	—	4.30***	9.99*	1.15	1.99	−0.001***	NEC←PEG
						(−3.96)	NEC←CO2
ΔPEG	0.42	—	4.30***	4.37***	4.37***	−0.001	NEC→OPE
						(−0.12)	NEC ∤ FDI
ΔCO2	0.96	14.1*	—	10.8*	3.69***	−0.0001***	PEG↔CO2
						(−3.31)	PEG↔OPE
ΔOPE	4.40***	14.9*	0.58	—	4.11***	−0.002	PEG↔FDI
						(−0.38)	CO2←OPE
ΔFDI	2.98	8.47*	1.87	4.87***	—	−0.004*	CO2←FDI
						(−8.85)	OPE↔FDI

VECM is the vector error-correction model, ECT-1 is the lagged error-correction coefficient; other variables are defined in Table 5 (Appendix 1)

*, **, and *** indicate significance at the 1%, 5%, and 10% levels, respectively

←/→/ ↔ arrows indicate the direction of Granger causality, while ∤ indicates the absence of causality

Long-run causality results

The long-run results are uniform. When *energy consumption* is the dependent variable, the lagged ECT coefficients are uniformly significant for all the energy consumption indicators. Consequently, in each case, energy consumption tends to gravitate to its long-run stability path in response to changes in the factors (which in this study are economic growth, CO_2 emissions, trade openness, and FDI). The rate of return to equilibrium varies between 1 and 5%. Therefore, we can establish that economic growth, CO_2 emissions, and macroeconomic openness indicators are significant drivers of energy in the long run.

When CO_2 *emissions* is the variable under review, the lagged error-correction coefficients are uniformly significant for all six cases. In each case, CO_2 emissions tend to converge to their long-run stability path in reaction to deviations in energy consumption, economic growth, FDI, and openness to trade. The convergence rate back to long-run equilibrium varies from 1 to 5%. Based on these findings, we can deduce that economic growth, energy consumption, trade openness, and FDI are notable drivers of CO_2 in the long run.

When *FDI* is the variable tested, the lagged ECT coefficients are significant for all six cases. In each case, FDI tends to converge to its long-run stability path if there are fluctuations in energy consumption, CO_2 emissions, economic growth, and openness to trade. The rate of return to equilibrium varies between 1 and 5%. These findings confirm that economic growth, energy consumption, CO_2 emissions, and openness to trade are considerable drivers of FDI in the long run.

In summary, we observe there are three significant results regarding the long-run dynamics. Firstly, economic growth, CO_2 emissions, openness to trade, and FDI are indeed drivers of energy consumption. Secondly, energy consumption, openness to trade, FDI, and economic growth are causal agents of CO_2 emissions. Thirdly, economic growth, openness to trade, CO_2 emissions, and energy consumption elevate FDI.

Short-run causality results

Unlike with the three uniform long-run outcomes, the results for the short-run differed in the six cases. However, we did observe two consistent short-run results. First, for all six cases, we found that there is a feedback association between economic growth and trade openness in the short run. Second, in all six cases, we found support for the hypothesis that trade openness Granger-causes CO_2 emissions. The remaining short-run results are summarised as follows.

We first considered $H_{1A,B}$, that energy consumption Granger-causes economic growth, and vice versa. We found two cases that support the theory that economic growth Granger-causes energy consumption, namely cases 2 and 6 (OEC and NEC). In three cases, namely cases 3, 4, and 5 (GEC, EEC, and BEC), we found evidence for the hypothesis that energy consumption Granger-causes economic growth. Finally, in case 1 (CEC), we found a feedback association between economic growth and energy consumption.

$H_{2A,B}$ states that economic growth Granger-causes CO_2 emissions, and vice versa. There were two cases, namely cases 2 and 4 (OEC and EEC), where economic growth Granger-causes CO_2. There were four cases, namely cases 1, 3, 5, and 6 (CEC, GEC, BEC, and NEC), which showed a feedback association between CO_2 and economic growth.

Next, we considered $H_{3A,B}$, which states that CO_2 emissions Granger-cause energy consumption, and the converse. Case 2 (OEC) demonstrated that energy consumption causes CO_2. Case 6 (NEC) showed that CO_2 emissions Granger-cause energy consumption. The remaining cases (CEC, GEC, EEC, and BEC) indicated a feedback association between these two variables.

$H_{4A,B}$ states that macroeconomic openness Granger-causes energy consumption, and vice versa. Here, the results were mixed. First, we inspected the connection between energy consumption and openness to trade. Cases 2, 4, and 6 (OEC, EEC, and NEC) supported the hypothesis that energy consumption Granger-causes trade openness. Two cases, namely cases

3 and 5 (GEC and BEC), showed a feedback relationship. Finally, case 1 (CEC) supported a neutral relationship. Next, we inspected the connection between energy consumption and FDI. Case 3 (GEC) supported the hypothesis that FDI Granger-causes energy consumption. Three cases, namely cases 2, 4, and 5 (OEC, EEC, and BEC), supported the feedback hypothesis, but two cases, cases 1 and 6 (CEC and NEC), supported the neutrality hypothesis.

Next, we looked at $H_{5A,B}$, which states that economic growth Granger-causes macroeconomic openness. We found one set of uniform short-run results regarding this hypothesis. In all six cases, we found support for the feedback hypothesis when we used trade openness as our measure for macroeconomic openness. However, when we considered FDI as the proxy for macroeconomic openness, the results were inconsistent. In three cases, namely cases 1, 2, and 3 (CEC, OEC and GEC), we found evidence supporting the hypothesis that growth Granger-causes FDI. Two cases, namely cases 5 and 6 (BEC and NEC), supported the hypothesis that FDI Granger-causes economic growth. In case 4 (EEC), we found support for the feedback hypothesis.

Finally, $H_{6A,B}$ states that macroeconomic openness Granger-causes CO_2 emissions. We again had one set of uniform short-run results: all six cases supported the hypothesis that openness to trade Granger-causes CO_2 emissions. When we replaced OPE with FDI as the variable, the results were no longer uniform: cases 2, 5, and 6 (OEC, BEC and NEC) supported the hypothesis that FDI causes CO_2 emissions; case 1 (CEC) supported the feedback hypothesis; cases 3 and 4 (GEC and EEC) showed no causality.

In summary, the short-run results varied from case to case when FDI (rather than OPE) was used as the macroeconomic openness variable. We found bidirectional causality (supporting the demand-following as well as the supply-leading hypotheses), but also unidirectional causality (supporting either the supply-leading or the demand-following hypothesis) between CO_2 emissions, energy consumption, and growth. Thus, the short-run dynamics differ in the six cases. These short-run causality results are summarised in the last column of Table 4.

Robustness and stability of results

Five robustness checks were performed to test the validity and stability of our results. First, we engaged the Pedroni and the Westerlund cointegration tests to observe the strength of the Fisher cointegration outcomes. The test outcomes confirmed a long-run equilibrium association between CO_2 emissions, energy consumption, openness to trade, economic growth, and FDI. These outcomes were uniform for all six cases (the results are not included because of space limitations, but may be requested from the authors).

Second, we obtained dynamic ordinary least squares and fully modified ordinary least squares estimates to determine the magnitude of the stimulus of economic growth, CO_2 emissions, OPE, and FDI on energy consumption. The results displayed a positive association with energy consumption in all six cases. These estimates are reported in Appendix 3, Table 6.

Third, we performed generalised methods of moments (GMM) estimations to check the causality between CO_2 emissions, OPE, FDI, economic growth, and energy consumption. These results also confirmed that economic growth, CO_2 emissions, OPE, and FDI have a considerable impact on energy consumption in all six cases. The GMM estimates are set out in Appendix 4, Table 7. [10]

Fourth, we applied variance decomposition analysis (VDA) to test the endogenous association between the chosen variables. This analysis provided supplementary support for the stability of the VECM results and confirmed the existence of relationships between CO_2 emissions, energy consumption, OPE, economic growth, and FDI. The VDA results for all six cases are reported in Appendix 5.

Fifth, we used generalised impulse response functions (GIRFs) to confirm the existence of dynamic associations between CO_2 emissions, openness to trade, economic growth, FDI, and energy consumption. GIRFs provided another lens for gaining insights into how shocks affect each endogenous variable and further supported our earlier findings. The results for GIRFs for all six cases are reported in Appendix 6.

Overall, these robustness results confirm that economic growth, CO_2 emissions, and macroeconomic openness are drivers of energy consumption, in both the short and the long run.

Conclusion and policy implications

Summary and policy implications

Many studies have analysed the interactions among energy consumption, economic activities, and growth, but in this study, we examined the simultaneous causal associations between CO_2 emissions, energy consumption, growth, and two macroeconomic openness variables—trade openness (OPE) and FDI—in the FATF countries from 1980 to 2020. Unlike previous research, we studied the links between all these variables simultaneously. The nexus between these variables is complex but of strong interest to policy-makers. Using advanced panel estimation techniques, we discovered a number of important facts.

The main finding is that there is a robust endogenous association between these macroeconomic variables in both the short and long run. In particular, policies that stimulate economic growth have a profound effect on CO_2 emissions and energy consumption in the FATF economies. This finding confirms that global economic growth has a substantial influence on the world's carbon footprint.

For the long run, the results show that (1) economic growth, CO_2 emissions, FDI, and openness to trade are key drivers of energy consumption; (2) energy consumption, economic growth, openness to trade, and FDI are causal agents of CO_2 emissions; and (3) economic growth, openness to trade, CO_2 emissions, and energy consumption accelerate FDI. In the short run, we also observed solid endogenous associations between all the variables. These results have important policy implications in respect of CO_2 emissions in FATF countries.

First, governments should put in place prudent FDI policies to attract energy-efficient industries into these countries to intensify the use of clean renewable energy to power industrial and economic development. Whilst these initiatives have been undertaken by some FATF countries, the policies are not yet widely implemented among all member states. For example, in many developed economies, there are government regulations, incentives, and support services that assist and enable firms and consumers to reduce their carbon footprint through a smooth transition to renewable energy sources. Such initiatives have had positive effects in many FATF member countries. For example, European member countries have increased their renewable energy use by 5.1% per annum from 2007 to 2017 (European Commission 2019b).

The increased use of renewable energy has resulted in a significant decline in CO_2 emissions by consumers and firms, especially in the three industry sectors with the highest carbon footprints. From 2007 to 2017, in the electricity, gas, steam, and air-conditioning industries, CO_2 emissions dropped from 1052 kg CO_2 per person to 771 kg per person; in construction industries, CO_2 emissions decreased from 920 kg CO_2 per person to 644 kg CO_2 per person; and in the food, beverage and tobacco sectors the reduction was from 453 kg CO_2 per person to 393 kg CO_2 per person (European Commission 2019a).

Second, a troubling trend that has emerged as trade across the FATF members intensified over the years is the export of polluting industries from more developed to less developed FATF countries. Whilst many of the developed FATF member countries have transitioned to more eco-friendly energy resources, they have also exported their high-carbon-based industries and products to the less developed FATF countries. The export of 'polluting' industries and products has had a positive stimulus on the growth of less developed FATF countries in the short run, but at the expense of their increased dependency on carbon-based energy. This has contributed to an escalation in CO_2 emissions in these countries. For example, the transportation sector is a key contributor to CO_2 emissions. Many developed economies, such as the USA, Japan, Germany, and South Korea, encourage the use of energy-efficient vehicles in their countries, but export second-hand vehicles with high CO_2 emissions to developing countries. As trade between developed and developing nations increases, vehicle industry experts have warned that the second-hand vehicle market will increase fourfold by 2050 (Macias et al. 2013; Edwards 2017). This has the potential to increase CO_2 emissions significantly in most developing and emerging countries.

Third, the empirical findings show robust long-run endogenous associations between FDI and CO_2 emissions. This suggests that governments in FATF states should be more selective in the types of industries that they permit to invest in their countries. Greater trade incentives and support (through taxes and subsidies) should be given to encourage FDI that is energy efficient and uses renewable energy for its production processes. In other words, whilst many studies argue that FDI inflows are crucial for economic growth, the empirical findings of our research show that FDI should not always be encouraged if these investments are harmful to the environment. Thus, developing countries should be careful to attract only desirable types of FDI. Prudent choices will have a desirable long-term impact on the state of the environment in these countries, which will have a direct impact on the health and well-being of their population and labour force—as well as a knock-on effect on their economic growth rates. The beneficial effect will be enhanced if developing countries use environmental standards as tariff barriers to ensure that only products and services that adhere to environmentally friendly input standards are permitted to enter their jurisdictions.

Fourth, given that CO_2 emissions are transboundary and that these emissions are closely associated with international trade legislation, macroeconomic policies, and economic growth, policy-makers in the FATF countries should pay careful attention to co-developing policy initiatives regarding trade openness and economic policies, especially in establishing environmentally sustainable strategies. These include ensuring that there is greater awareness regarding the influence of economic-driven activities on CO_2 emissions, and putting the relevant support systems in place to assist firms and consumers in using renewable energy sources. The following measures should be considered in member countries: the introduction of smart electricity metres for households and businesses to enable consumers to monitor their electricity consumption; the promotion of 'green buildings' which incorporate energy-efficient lighting, air-conditioning, and other uses of renewable energy sources; a shift in the transportation sector from carbon fuels to the use of clean renewable energy, for example, by reducing taxed and duties on energy-efficient vehicles, and by developing and maintaining public transport infrastructure.

Fifth, developed FATF member countries that have the advantage of higher levels of technology and innovation should assist less-developed FATF member countries to adopt energy-efficient and renewable energy sources to create economies that are less dependent on carbon-based energy. Assistance can take the form of financial incentives, technical expertise, and help to less-developed countries to undertake regulatory reforms regarding their local and regional power grid systems, and enabling them to connect to renewable energy sources (UNEP 2017). These measures would provide developing countries with more cost-effective and environmentally sound methods to advance their economic development. Wider use of energy-efficient technology will enable firms to achieve greater economies of scale, reducing the cost of these new technologies and the production of renewable energy. Increasing the use of eco-friendly fuels will not only be good for the environment, but will also initiate new green industries that may create high-paying jobs to raise the economic growth of member countries in more environmentally sustainable ways.

The results of this study highlight several important points. In the context of the rapid expansion of a global economy and trade, it is vital to implement effective carbon emission control policies to reduce the greenhouse effect, one of the five biggest global risks (Stern 2007; NBS 2018). Policy-makers need to take an integrative approach to balance economic growth imperatives with the need to reduce the carbon footprint caused by economic activities.

Our study shows that the nexus of environmental effects and economic activities requires trade-offs, and that increasing growth rates and well-diffused macroeconomic openness are inevitably major causes of environmental degradation. The policy implication of this finding is that we need to encourage governments to adopt political choices that tackle environmental issues and the trade-offs between the environment and economic growth congruent with the arguments presented in Sohail et al. (2022). Additionally, there should be a benefit from firms/consumers in developed countries meaningfully and purposefully investing in developing countries with a *corporate environmental responsibility* (CER) or *corporate social responsibility* (CSR) framework. In other words, given that trade openness and FDI in emerging nations tend to lead to increases in energy consumption and emissions, steps should be taken by firms investing in developing countries to invest more purposefully in manufacturing policies and practices that promote the use of more efficient and renewable energy sources and more efficient and environmentally friendly manufacturing processes. For example, Dögl and Behnam (2015) have reported that CER practices actually have a more positive meaningful impact on business outcomes in emerging countries than in developed countries, which seems to support the argument that consumers in developed nations might be willing to pay a premium for goods produced and services provided in an environmentally friendly way.

Limitations and suggestions for future research

Although this article reports on several encouraging outcomes, there are some limitations. First, although we offer insights into indicators of short-term and long-term energy consumption in the FATF countries, several additional indicators could not be included. Examples are income, energy price, quality of institutions, and social factors in this group of economies. We acknowledge that not including these indicators in an econometric model could generate estimates suffering from *omitted variable bias*. We recommend the inclusion of these variables in future research.

Second, the VECM model considers linear associations between the chosen variables. This approach could be too selective to identify and link the complex associations between these variables. Moreover, if the association between these variables is strongly non-linear, different econometrics tools such as the non-linear autoregressive distributive lag (NARDL) model could be employed to ensure better outcomes, another area of investigation suggested for further research.

Third, our empirical process deals with FATF countries and annual data between 1980 and 2018. Our results could perhaps have been more nuanced if we had used more countries and included more data in this empirical processing, including world panel data analysis. With more countries and more data, we could undertake a comparative analysis to gain more insights into the relationship between these variables, which is an avenue to pursue in future.

Fourth, our current analysis offers valuable highlights into likely causal associations among energy consumption, CO_2, economic growth, and macroeconomic openness (trade and FDI). Our outcomes suggest that co-developing the right policies concerning energy consumption, CO_2, and macroeconomic economic openness, as well as economic growth, could offer a multiplier outcome, pushing the socio-economic development of the selected FATF countries towards participation in a network-based world economy. Findings from this cluster of FATF economies could be pertinent for other groups of economies and clusters. Subsequent research can also take into account other macroeconomic/socio-economic factors due to significant differences in the social, economic, and institutional across the FATF countries. Future studies might also include the impact of infrastructure, particularly the institutional infrastructure [11] and ICT infrastructure, [12] financial development, [13] and technological innovation [14] to investigate the dynamics between energy consumption, CO_2 emissions, economic growth, and macroeconomics openness. Other recommendations include modelling the non-linear dynamics between these variables using the quantile autoregressive distributive lag (QARDL), the cross-sectional augmented autoregressive distributive lag (CS ARDL), and the non-linear autoregressive distributive lag (NLARDL) models. The latter two approaches may provide additional insights into the dynamic relationships between these variables and may offer valuable new information in future enquiries.

Availability of data and materials

This paper has no attachment to data and materials.

Notes

1. This is one of the most severe challenges faced throughout the world today. Consequently, the phenomenon is studied and analysed by academics, environmentalists, and policymakers. Climate change has been attributed to greenhouse gases, to which carbon emissions contribute significantly (see, for instance, Uzar 2020; Chien et al. 2021; Sun et al. 2021; Sun et al. 2022; Sohail et al. 2022; Wangzhou et al. 2022).
2. The FATF includes various jurisdictions and regional organisations (the Gulf Cooperation Council and the European Commission). The countries included in our analysis are Argentina, Australia, Austria, Belgium, Brazil, Canada, China, Denmark,

Finland, France, Germany, Greece, Hong Kong, Iceland, India, Ireland, Italy, Japan, the Republic of Korea, Luxembourg, Malaysia, Mexico, the Netherlands, New Zealand, Norway, Portugal, the Russian Federation, Singapore, South Africa, Spain, Sweden, Switzerland, Turkey, the UK, and the USA.

3. The use of more efficient technologies may be one reason that some studies do not find the inverted U-curve.
4. Rapid socio-economic development can increase the demand for energy, which in turn raises CO_2 emissions (Yu et al. 2014).
5. The studies mentioned appear to indicate a strong positive nexus between energy consumption and CO_2. Their results support the argument that cities with high energy consumption have higher carbon emissions (see, for example, Salahuddin and Gow, 2014). When cities have high carbon emissions, governments react by attempting to implement regulatory measures to discourage fuel consumption and reduce carbon emissions. One such measure is to impose strong restrictions on energy consumption. Such policies are implemented by various means, for example, by raising the price of fossil fuels (natural gas, coal, and oil), imposing tolls on private vehicles (particularly, through high tolls during business hours), encouraging public transport, and introducing alternates such as electrical vehicles. Governments may not impose restrictions on energy consumption or implement any of these policies if a country does not have unacceptably high carbon emissions. This then implies strong causality between energy consumption and emissions, leading to significant consequences for and actions in an economy.
6. Trade openness (OPE) refers to the ratio between imports and exports (exports + imports) over real GDP. This measure captures a country's trade flows. There are some limitations to using this measure to capture trade openness, but the other measures proposed in the literature all display other disadvantages and weaknesses, such as data limitations and difficulties in expanding data series over a reasonable timespan (Gräbner et al. 2021). In other words, there is no consensus on the best measure to capture trade openness. Therefore, we selected the most commonly used measure in the literature, namely the abovementioned trade flow variable, as a proxy for trade openness, as our study requires a readily available data for a long time span.
7. The advantages of our chosen methodology are that it is designed to establish the long-run relationship and joint behaviour between these variables, and it takes care of the "endogeneity issue" between the variables analysed. The disadvantage of the technique is that it cannot capture possible non-linear relationships between the variables.
8. The transformation smooths the data and also helps reduce the pernicious effect of heteroscedasticity (Huh, 2011; Roberts and Nord, 1985).
9. Granger causality results depend on the number of chosen lags. In common with many papers reporting on temporal causality investigations, we determined the number of lags optimally using the Akaike Information Criterion (see, for example, Auffhammer and Carson, 2008 for discussion).
10. The reported results follow the Arellano-Bond dynamic panel data estimation procedure, which we believe to be a valid procedure to identify energy consumption in the sample countries. Normal panel methods could pose a problem because of country-specific impacts in a sample comprising many different countries, such as our sample. We employ the twin specification tests developed by Arellano and Bond (1991). The first test is a Hansen J-statistic, which identifies conditions that test the validity of the instruments. The second test checks that the residuals are not serially correlated. It shows that GMM can be deployed either in a one-step or in a two-step process. A two-step process uses residuals derived from the first-step process to build a weighted

variance–covariance (VC) matrix when homoscedasticity to the parameters is absent (Arellano and Bond, 1991). In this work, and in line with most papers in the academic literature, a two-step GMM estimator is used.

11. Institutional quality seems to play a considerable role in the use of natural resources and the sustainability of the environment (Abdala, 2008).
12. Information and communication technologies (ICT) infrastructure can help to identify advanced, more efficient ways to use energy. ICTs make it possible to find new channels to reduce environmental pollution and promote investment in new and cleaner technologies (Andlib and Khan, 2021).
13. Financial development (particularly banking and insurance activities) offers effective means to reduce carbon emissions from the environment to improve air quality in various economies (Tan et al. 2021).
14. Technology plays a crucial role in reducing emanations and to achieve energy conservation targets (Chien et al. 2021).

Credit author statement

Rudra Prakash Pradhan: conceptualization, writing—reviewing and editing.

Mak Arvin: conceptualization, writing—reviewing and editing.

Mahendhiran Sanggaran Nair: conceptualization, writing—reviewing and editing.

Sara Bennett: conceptualization, writing—reviewing and editing.

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Contributions

All authors have equal credit with reference to conceptualization and writing—reviewing and editing.

Ethical approval

We declare that authors have no conflict of interest with respect to funding source declaration, author agreement, and permission note.

Consent to participate

All authors give consent to this paper to participate for publication.

Consent to publish

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Competing interests

The authors declare no competing interests.

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Appendices

Appendix 1. Definition of variables

Table 5. Notation and definitions

Variable acronym	Definition
CEC	**Coal energy consumption**: energy use measured in Quadrillion British Thermal Units (QBTU)—calculated on a per capita basis
OEC	**Oil energy consumption**: energy use measured in QBTU—calculated on a per capita basis
GEC	**Gas energy consumption**: energy use measured in QBTU—calculated on a per capita basis
EEC	**Electricity energy consumption**: energy use measured in QBTU—calculated on a per capita basis
BEC	**Biomass energy consumption**: energy use measured in QBTU—calculated on a per capita basis
NEC	**Non-renewal energy consumption**: energy use measured in QBTU—calculated on a per capita basis
CO2	**CO_2 emissions**: carbon dioxide emissions measured in metric tons—calculated on a per capita basis
PEG	**Per capita economic growth**: growth rate of per capita gross domestic product
OPE	**Trade openness**: total trade (exports plus imports) as a % of gross domestic product
FDI	**Foreign direct investment**: inflows quantified as a % of gross domestic product

Monetary measures are in constant US dollars

Variables are defined in the *World Development Indicators* of the World Bank and the *U.S. Energy Database* of the Inter-American Development Bank

The source of data is the *World Development Indicators* of the World Bank and the *U.S. Energy Database* of the Inter-American Development Bank

The natural logarithm of the variables is used in the estimation process

Appendix 2. Flow chart of the analysis

To assist the reader, we present a flow chart of the analysis. Given our finding that the chosen variables are cointegrated, we follow the left-hand route towards the end of the flow chart, thus proceeding with a Vector Error-Correction Model (VECM) deployment in place of a Vector Autoregression (VAR) model analysis. Following the VECM analysis to establish causality, several other tests are performed, as discussed in the 'Robustness and stability of results' section.

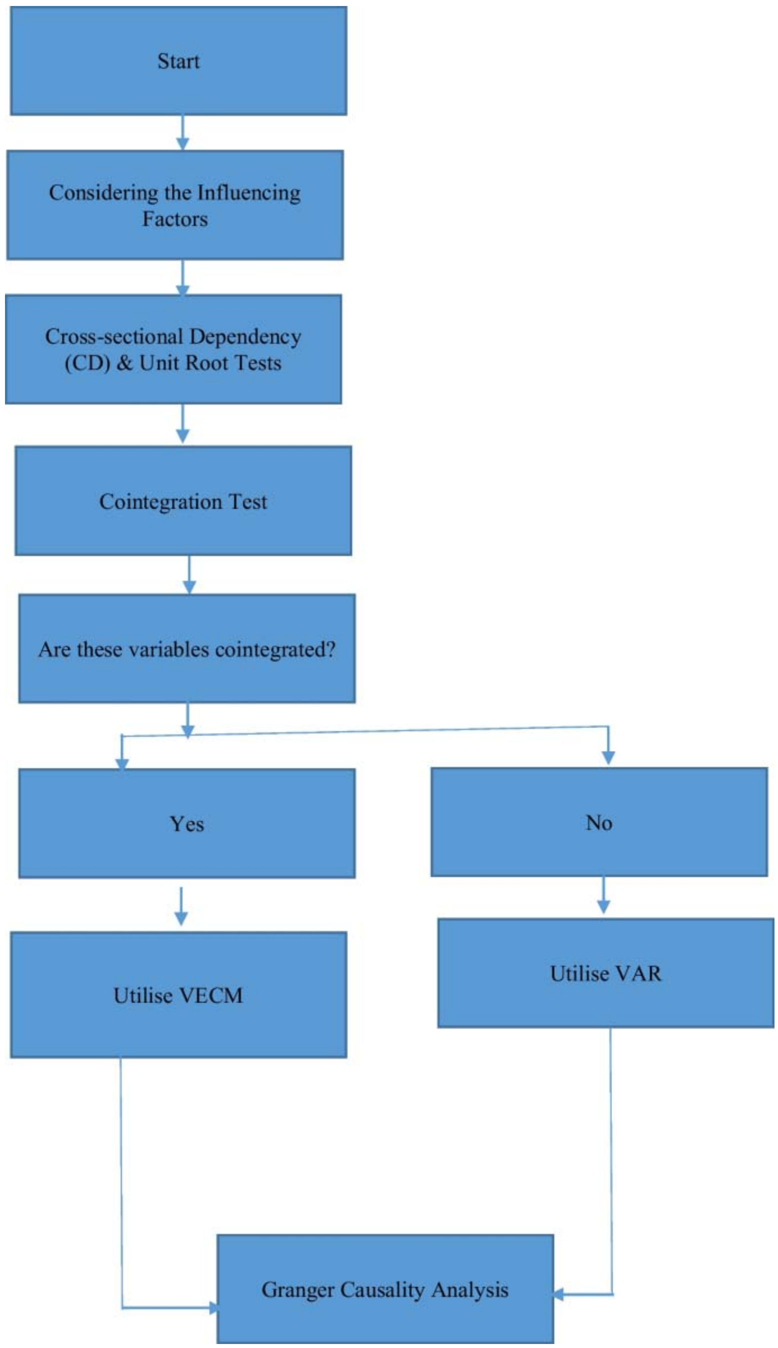

Fig. 2. Flow chart of the analysis

Appendix 3. FMOLS and DOLS estimation results

Table 6. Results of FMOLS and DOLS estimations

Dependent variable: ENG						
IVs	Case 1: CEC	Case 2: OEC	Case 3: GEC	Case 4: EEC	Case 5: BEC	Case 6: NEC
Part A: FMOLS estimation results						
PEG	0.072*	0.251*	0.723*	0.431*	0.339*	0.453*
CO2	0.122*	0.395*	0.773*	0.501*	0.612*	0.337*
OPE	0.359*	0.231*	0.694*	0.492*	0.379*	0.439*
FDI	0.036*	0.018*	0.040*	0.006*	0.050*	0.083*
R^2	0.98	0.99	0.91	0.99	0.98	0.95
Part B: DOLS estimation results						
PEG	0.115*	0.283*	0.635*	0.435*	0.409*	0.404*
CO2	0.129*	0.410*	0.136*	0.480*	0.309*	0.254*
OPE	0.651*	0.254*	0.849*	0.609*	0.695*	0.227*
FDI	0.094*	0.043*	0.037*	0.038*	0.445*	0.179*
R^2	0.99	0.99	0.96	0.99	0.96	0.96

Notations are defined in Table 5 (Appendix 1)

ENG denotes energy consumption and is used for CEC, OEC, GEC, EEC, BEC, and NEC

*Significant at the 1% probability level

Appendix 4. Mixed effects generalised methods of moments (GMM) estimation results

Table 7. Results of dynamic GMM estimation

Dependent variable: ENG						
IVs	Case 1: CEC	Case 2: OEC	Case 3: GEC	Case 4: EEC	Case 5: BEC	Case 6: NEC
ENG (-1)	0.681*	0.700*	0.685*	0.698*	0.676*	0.702*
PEG	0.017*	0.013*	0.018*	0.001*	0.354*	0.065*
CO2	0.219*	0.215*	0.254*	0.114*	0.099*	0.012*
OPE	0.061*	0.016*	0.061*	0.017*	0.098*	0.024*
FDI	0.026*	0.001*	0.047*	0.061*	0.147*	0.001*
NC	35	35	34	35	33	35
NO	1855	1855	1855	1855	1855	1855
AR1 (*P*-value)	0.09	0.03	0.02	0.01	0.07	0.01
AR2 (*P*-value)	0.29	0.25	0.41	0.24	0.43	0.28
HJS (*P*-value)	0.00	0.00	0.00	0.00	0.00	0.00

Variables are defined in Table 5 (Appendix 1)

ENG denotes energy consumption and is used for CEC, OEC, GEC, EEC, BEC, and NEC

*Significant at the 1% probability level

Appendix 5. Variance decomposition analysis (VDA) results

Case 1: With CEC, PEG, CO2, OPE, FDI

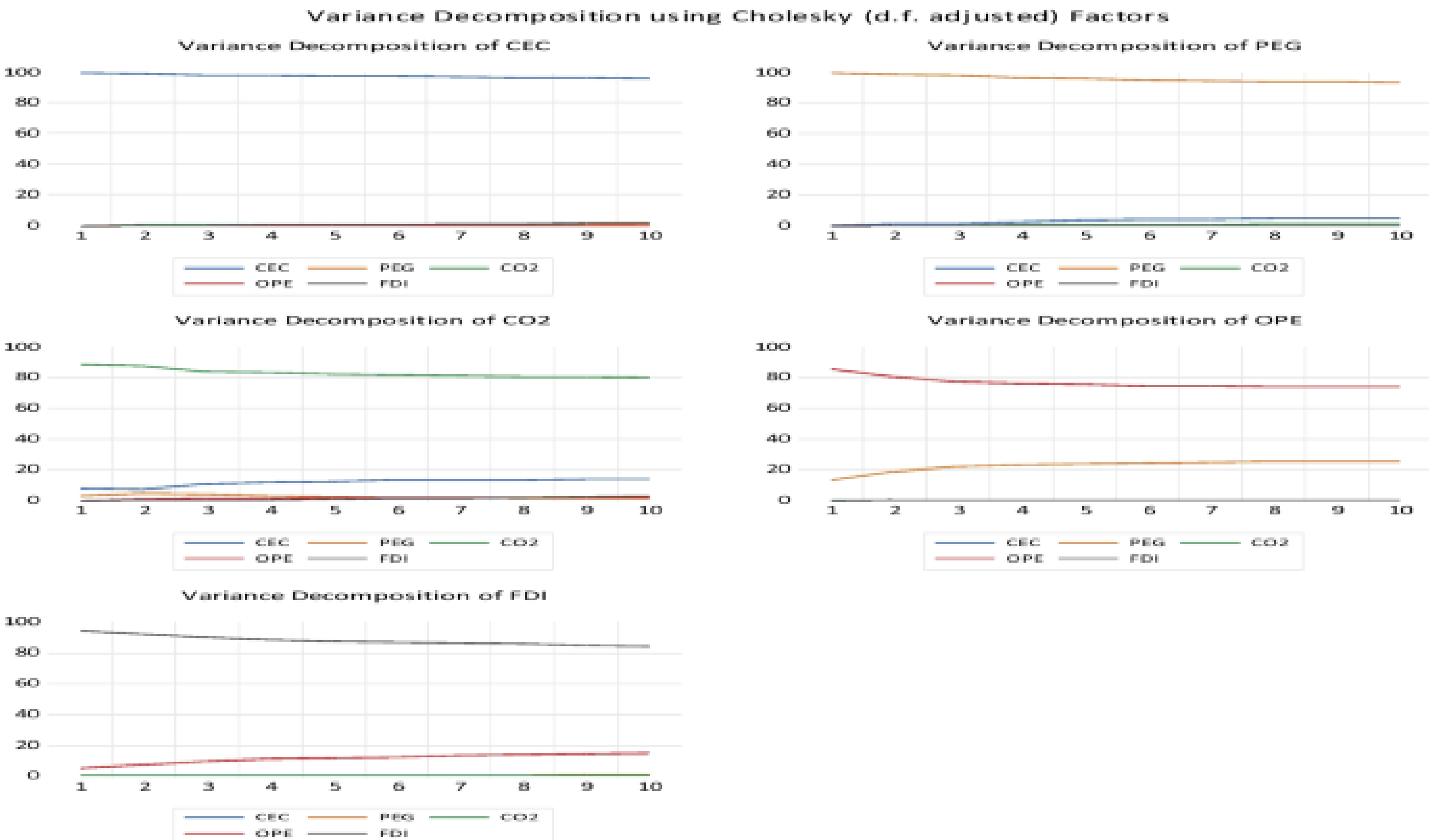

Fig. 3. Case 1: With CEC, PEG, CO2, OPE, FDI. Variables are defined in Table 5 (Appendix 1)

Case 2: With OEC, PEG, CO2, OPE, FDI

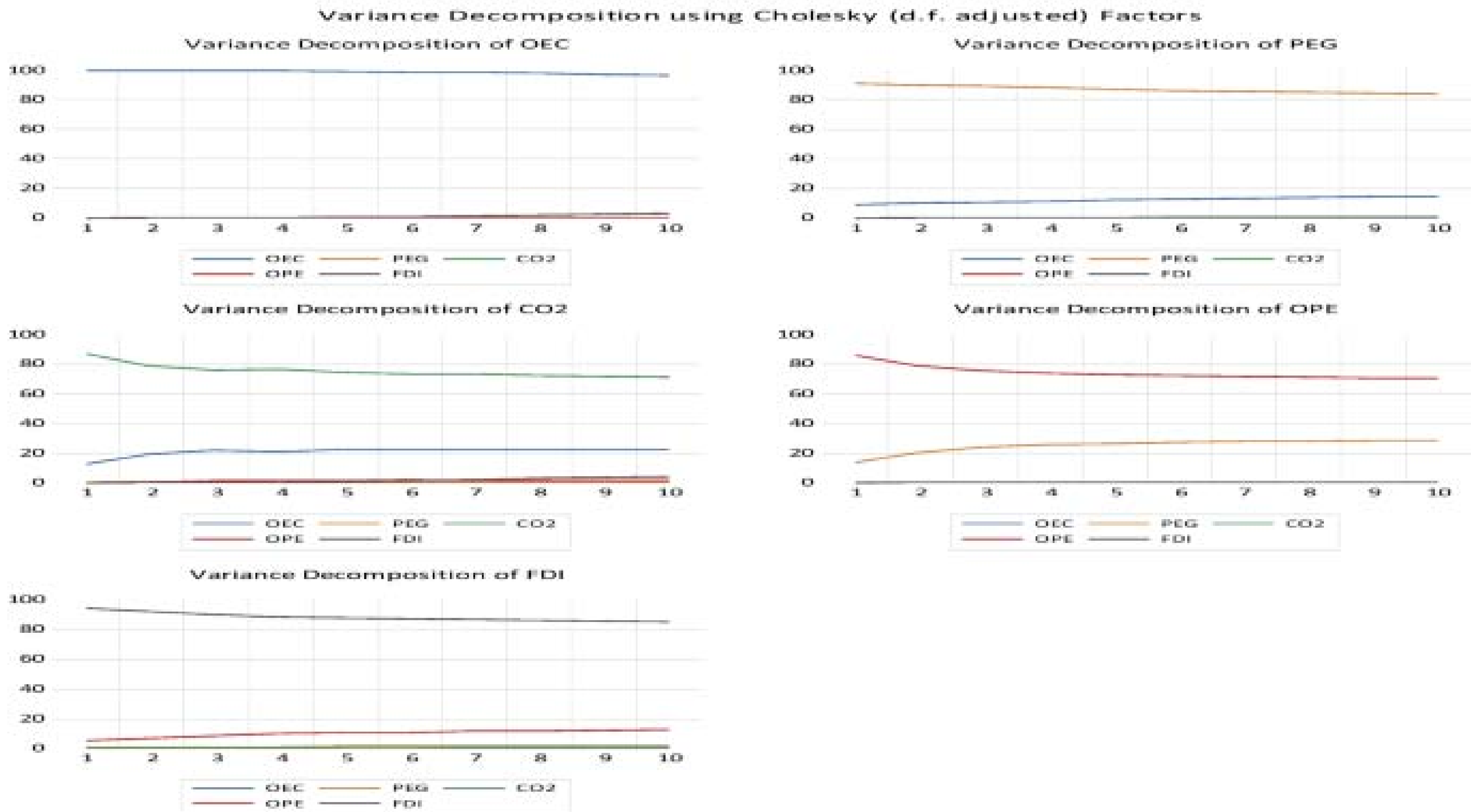

Fig. 4. Case 2: With OEC, PEG, CO2, OPE, FDI. Variables are defined in Table 5 (Appendix 1)

Case 3: With GEC, PEG, CO2, OPE, FDI

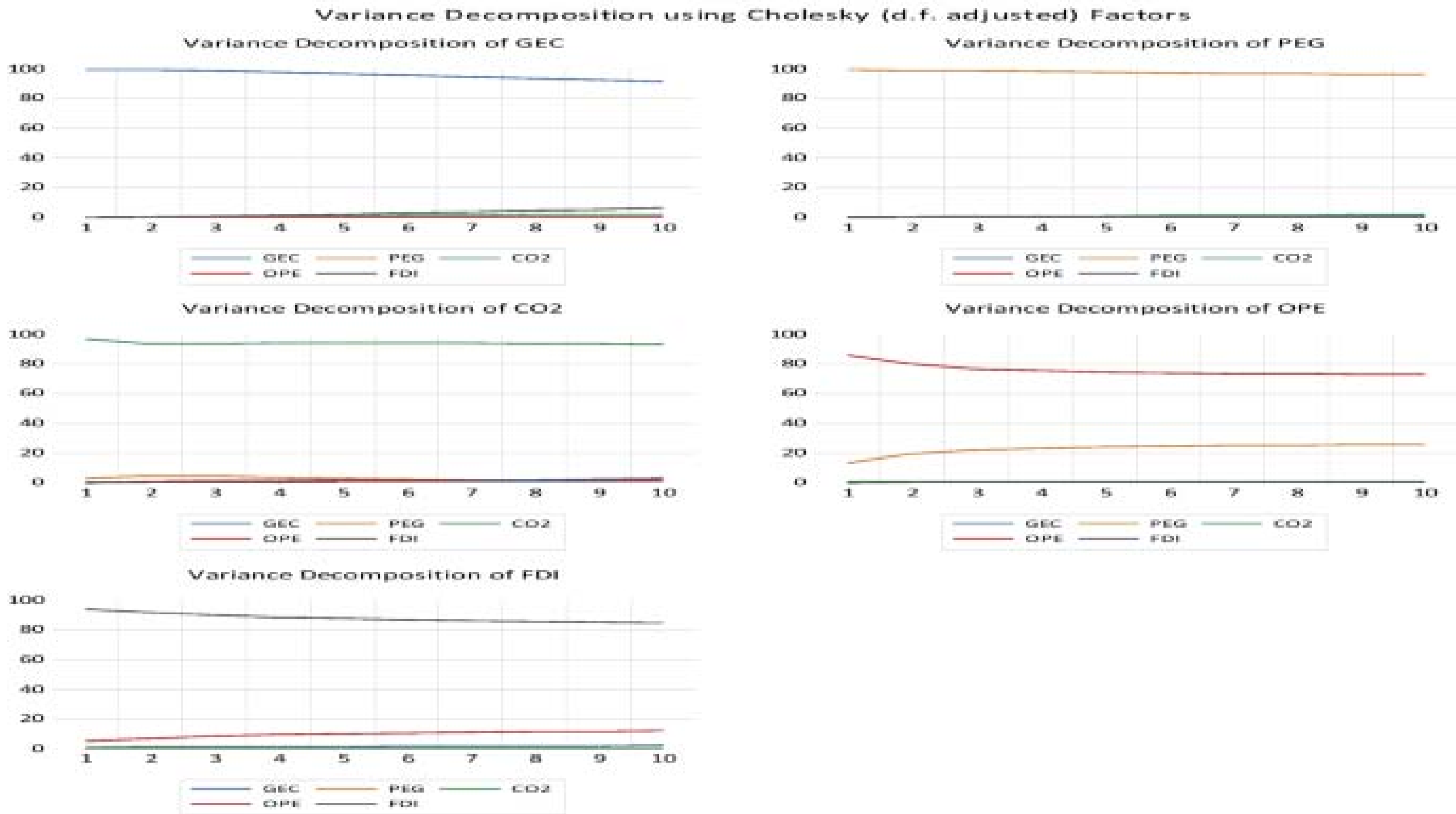

Fig. 5. Case 3: With GEC, PEG, CO2, OPE, FDI. Variables are defined in Table 5 (Appendix 1)

Case 4: With EEC, PEG, CO2, OPE, FDI

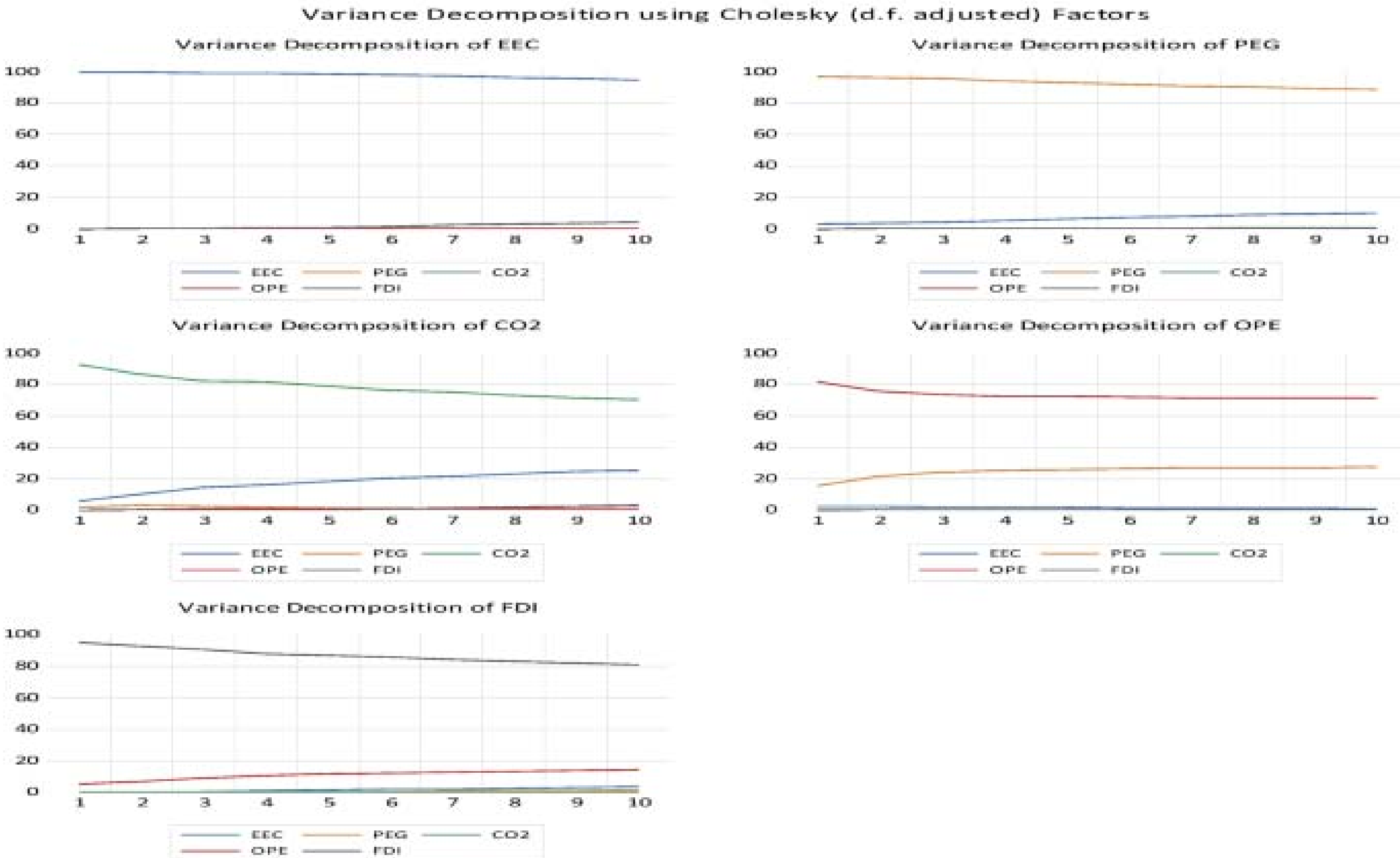

Fig. 6. Variables are defined in Table 5 (Appendix 1)

Case 5: With BEC, PEG, CO2, OPE, FDI

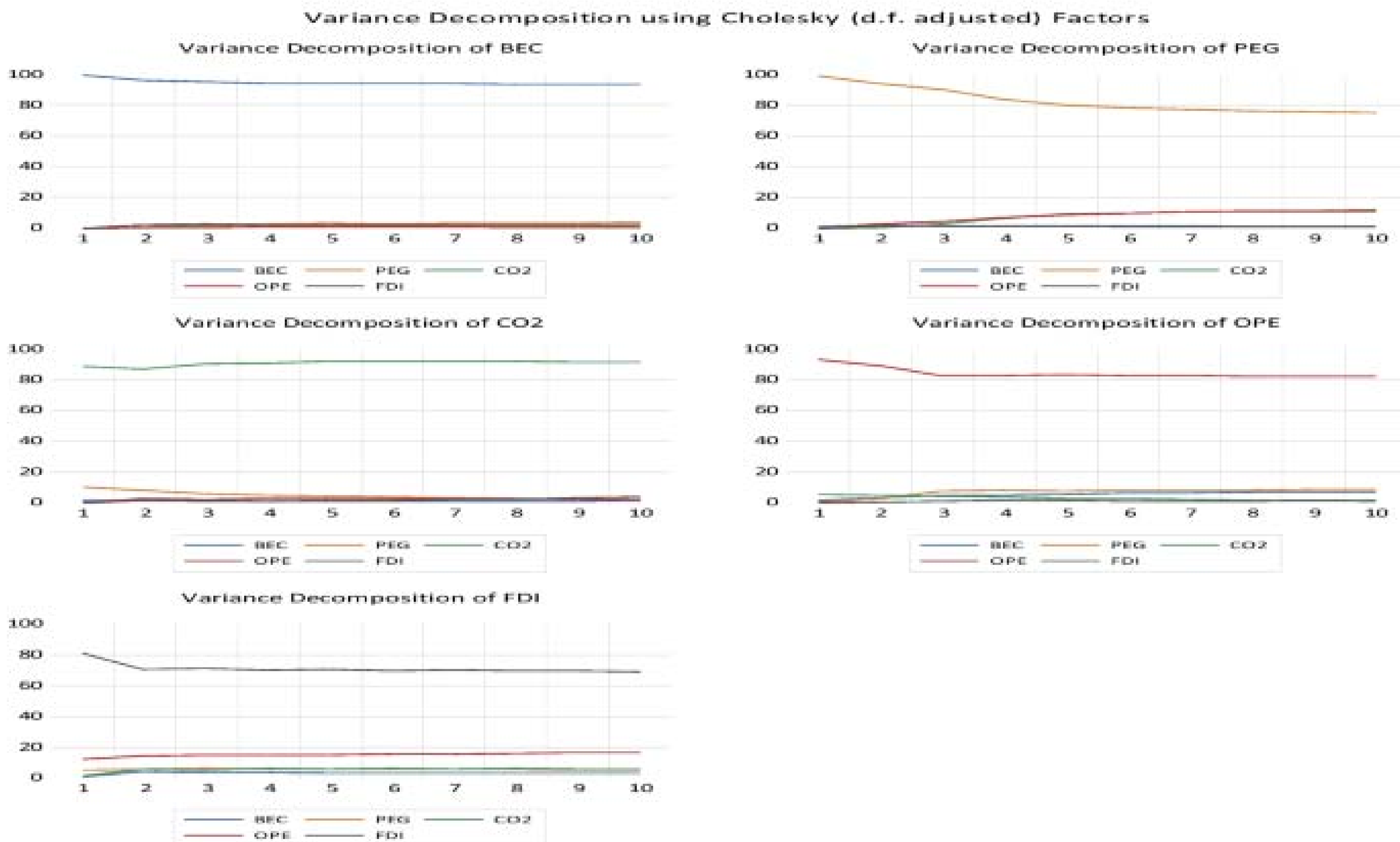

Fig. 7. Case 5: With BEC, PEG, CO2, OPE, FDI. Variables are defined in Table 5 (Appendix 1)

Case 6: With NEC, PEG, CO2, OPE, FDI

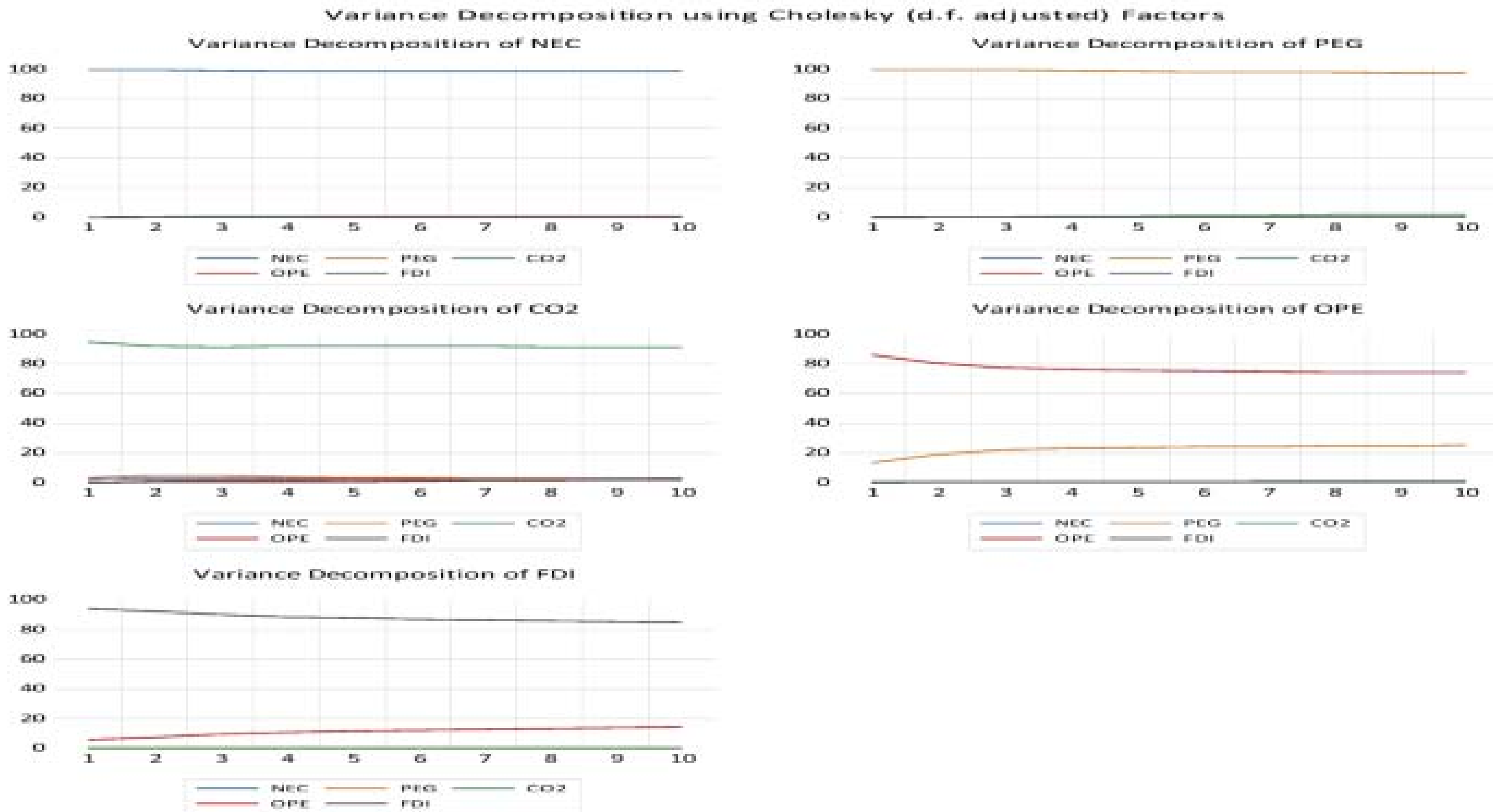

Fig. 8. Case 6: With NEC, PEG, CO2, OPE, FDI. Variables are defined in Table 5 (Appendix 1)

Appendix 6. Generalised impulse response functions (GIRFs) results

Case 1: With CEC, PEG, CO2, OPE, FDI

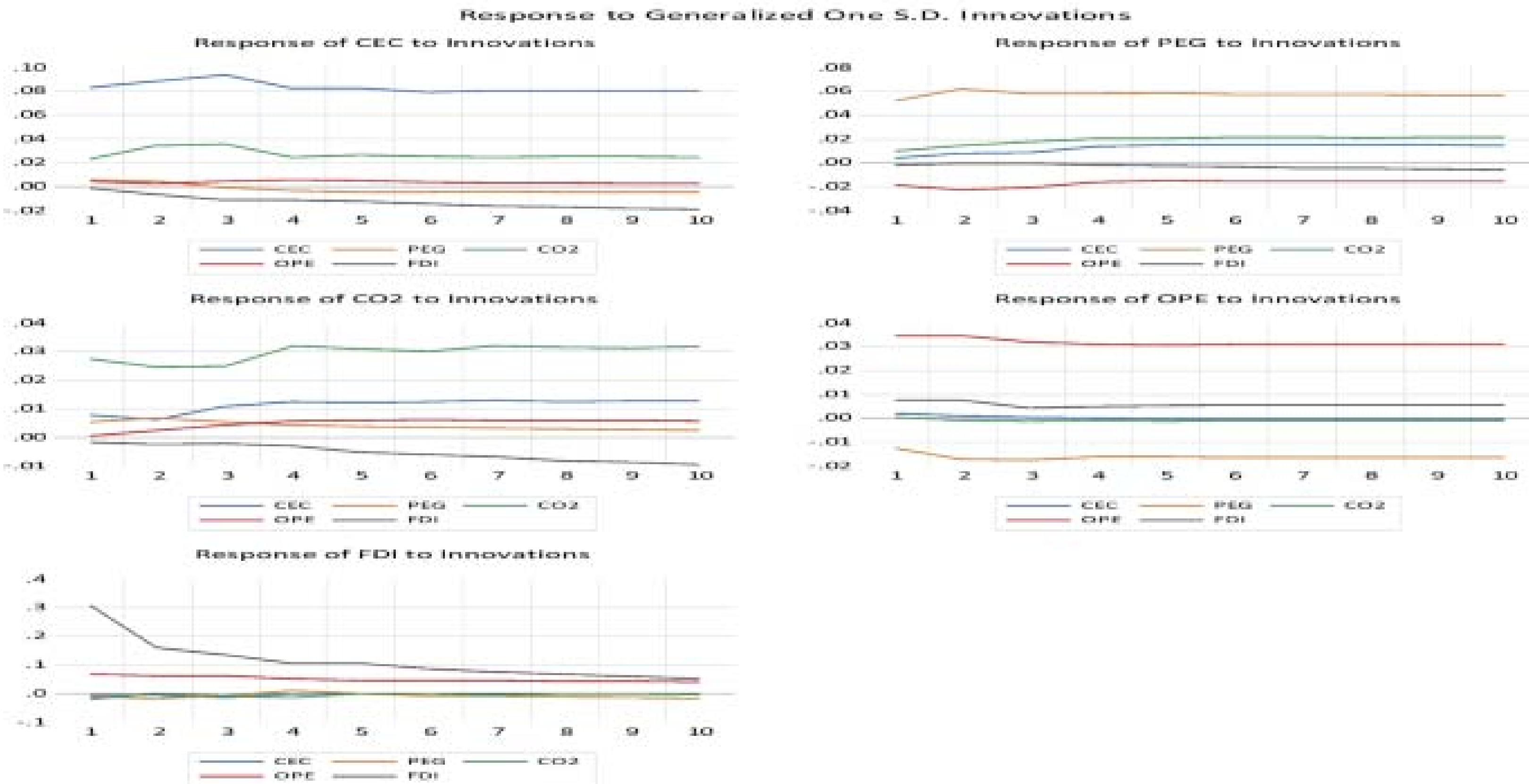

Fig. 9. Case 1: With CEC, PEG, CO2, OPE, FDI. Variables are defined in Table 5 (Appendix 1)

Case 2: With OEC, PEG, CO2, OPE, FDI

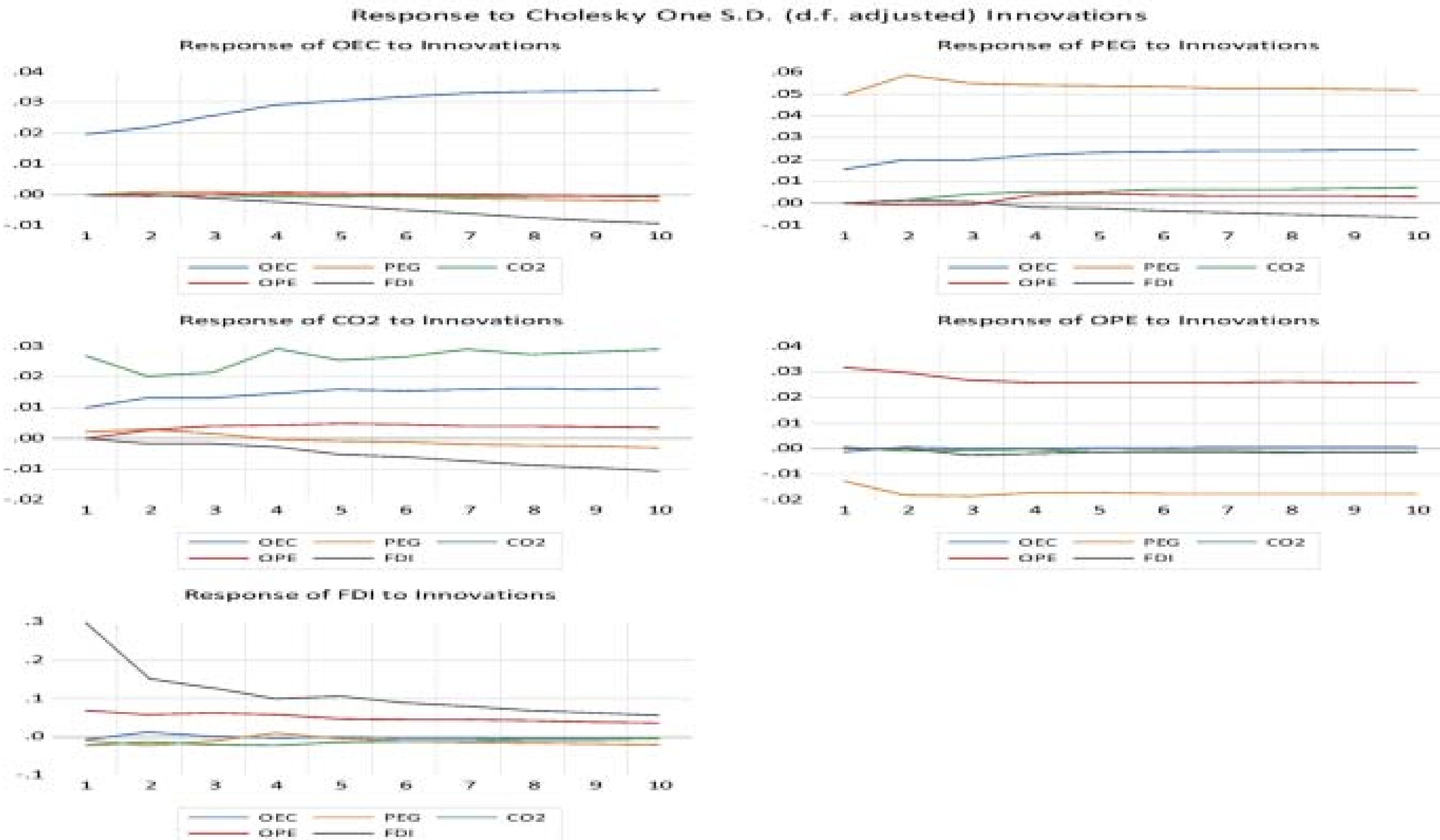

Fig. 10. Variables are defined in Table 5 (Appendix 1)

Case 3: With GEC, PEG, CO2, OPE, FDI

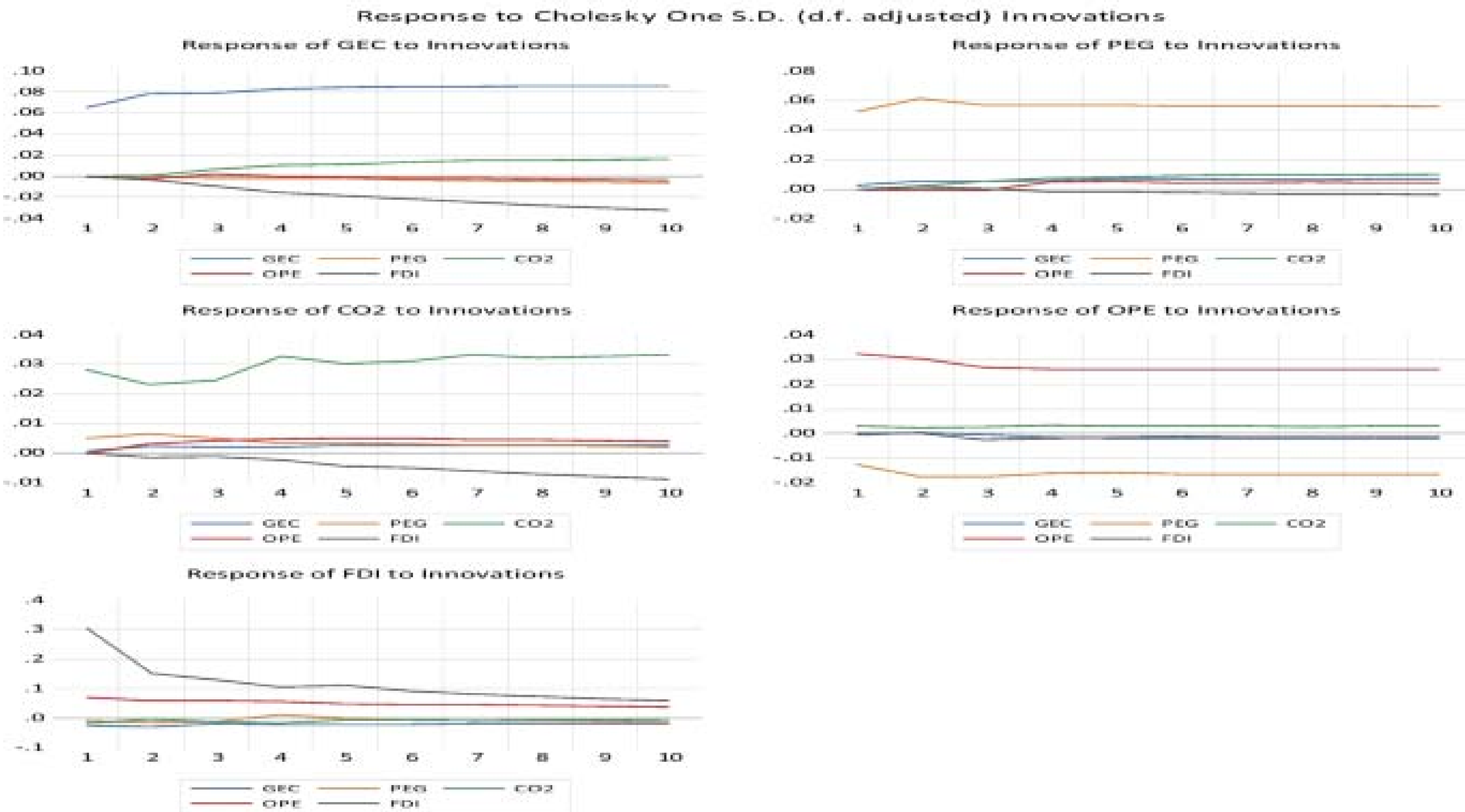

Fig. 11. Variables are defined in Table 5 (Appendix 1)

Case 4: With EEC, PEG, CO2, OPE, FDI

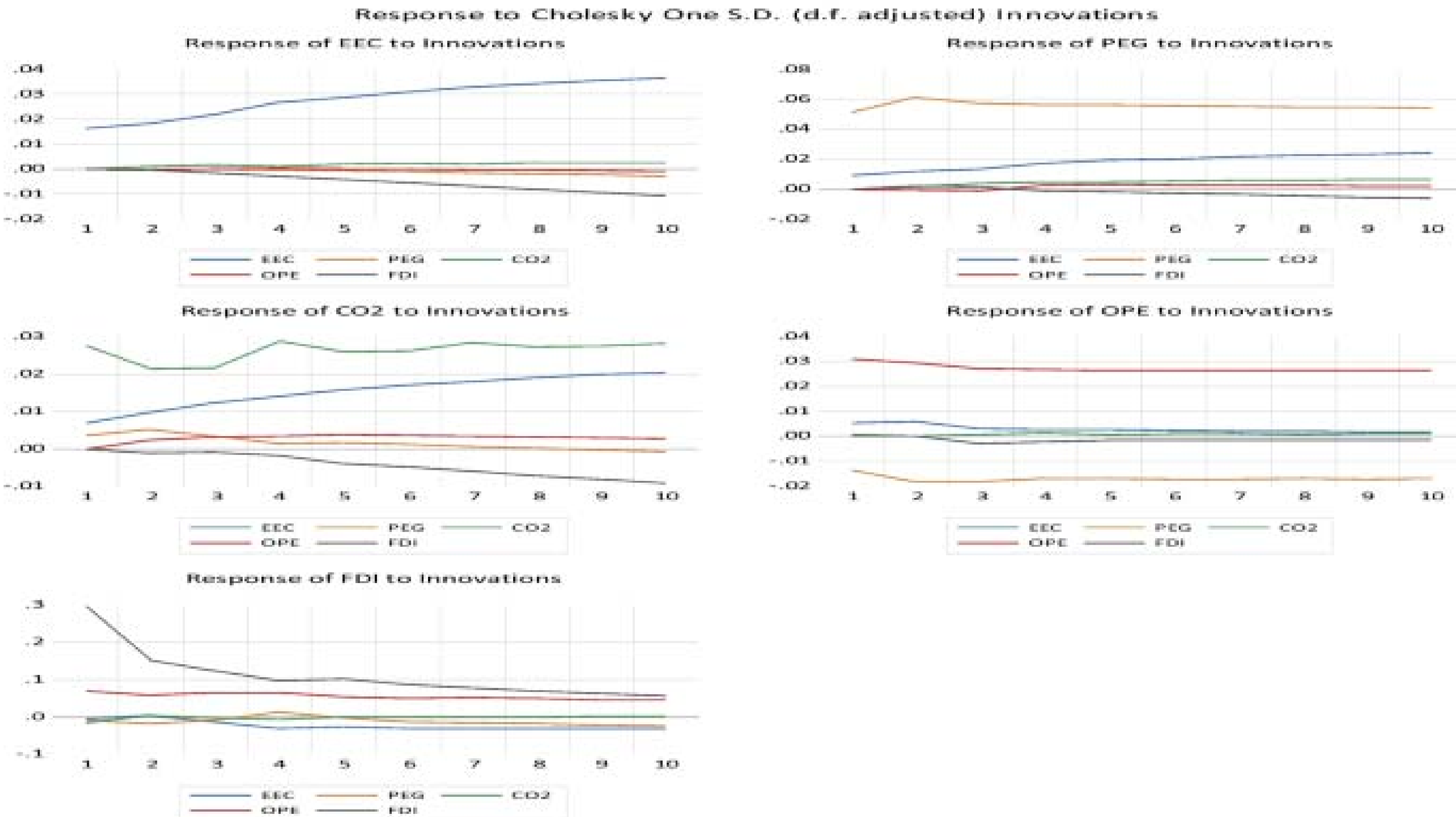

Fig. 12. Case 4: With EEC, PEG, CO2, OPE, FDI. Variables are defined in Table 5 (Appendix 1)

Case 5: With BEC, PEG, CO2, OPE, FDI

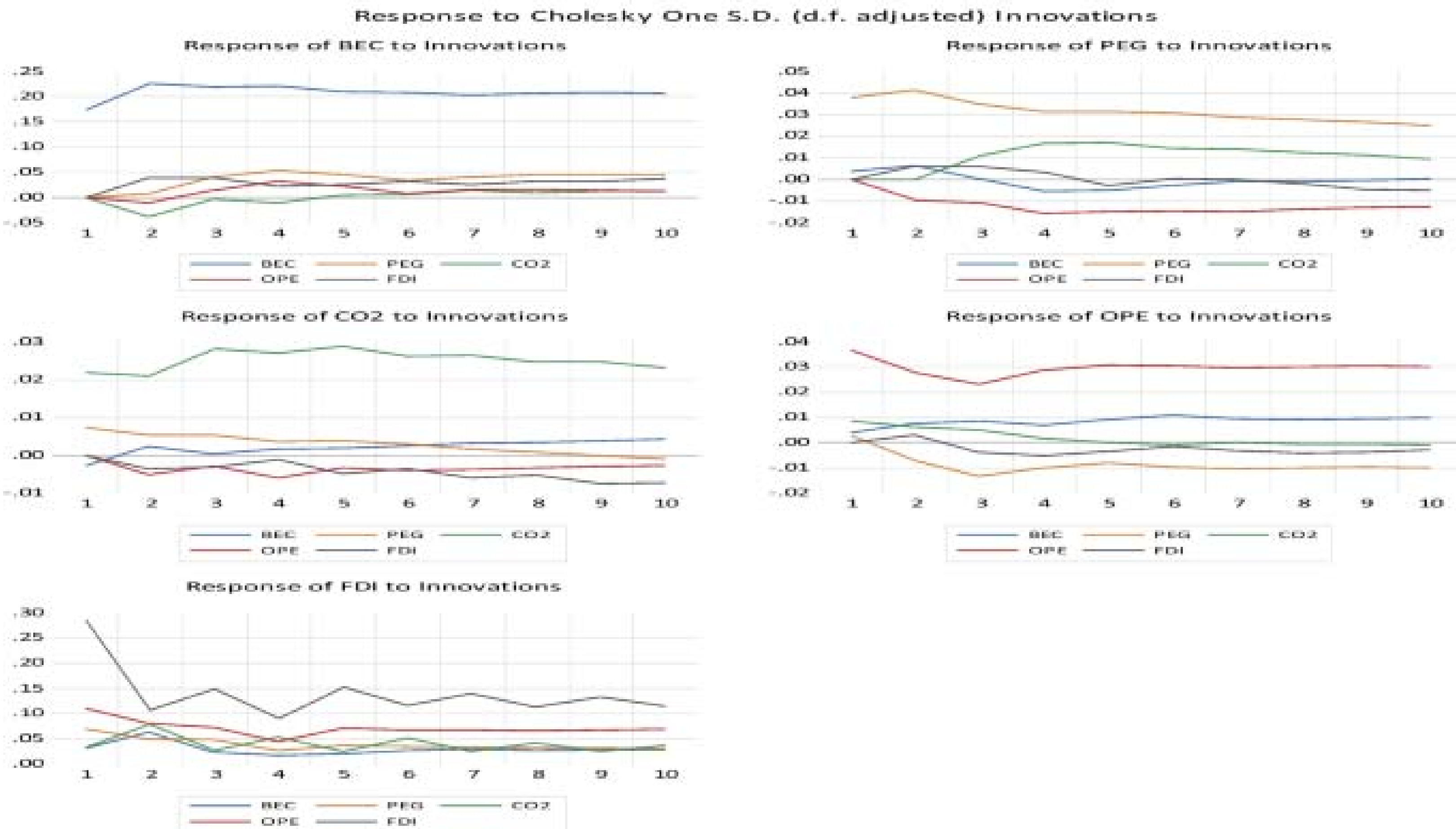

Fig. 13. Case 5: With BEC, PEG, CO2, OPE, FDI. Variables are defined in Table 5 (Appendix 1)

Case 6: With NEC, PEG, CO2, OPE, FDI

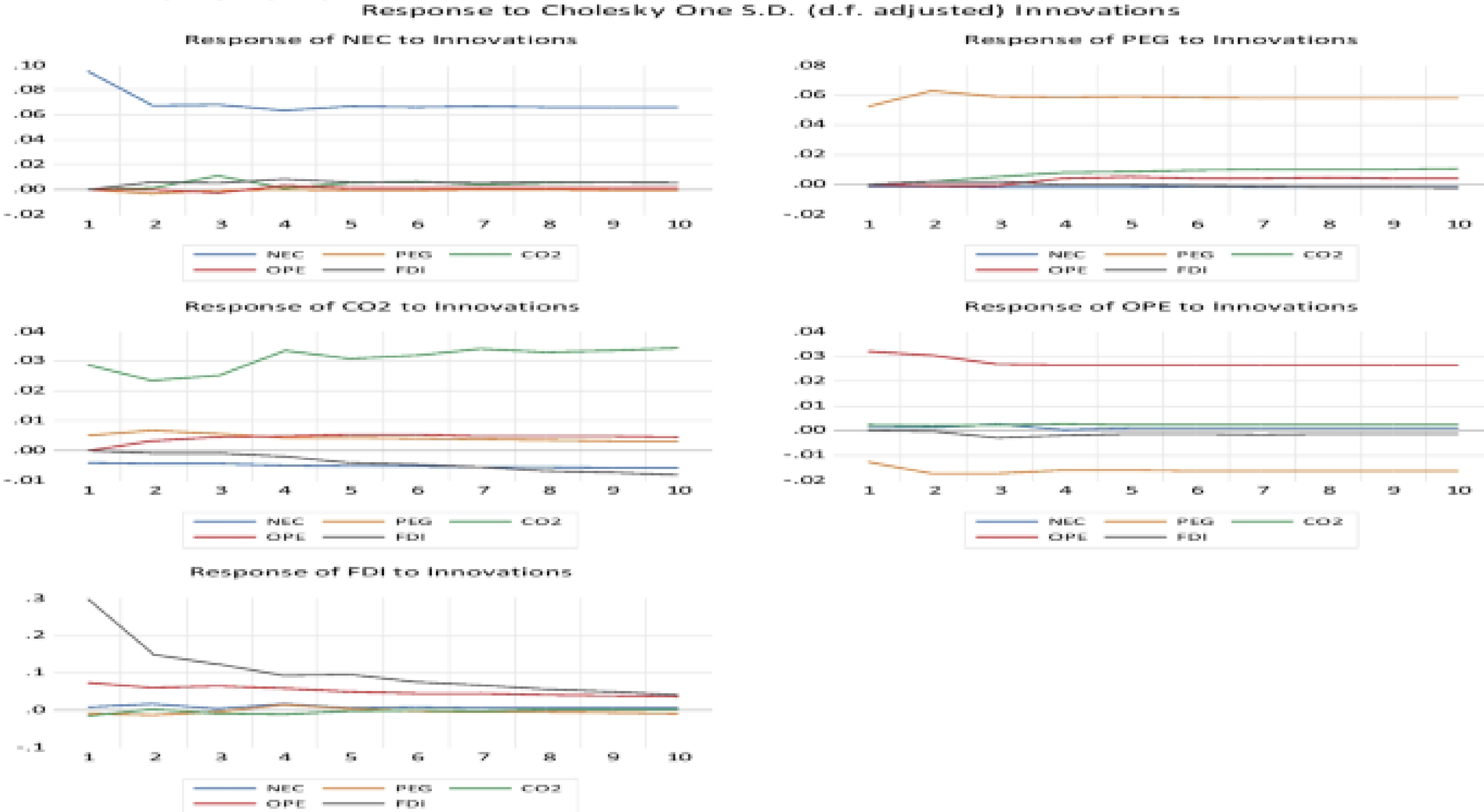

Fig. 14. Case 6: With NEC, PEG, CO2, OPE, FDI. Variables are defined in Table 5 (Appendix 1)