Energy Economics 109 (2022) 105994

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Financial development, renewable energy and CO2 emission in G7 countries: New evidence from non-linear and asymmetric analysis

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A R T I C L E I N F O

Keywords:
Carbon emission
Financial development
Renewable energy
NARDL
SDG

A B S T R A C T

The G7 countries have not yet been able to make a discernible impact in achieving the Sustainable Development Goal (SDG) 13 and 7. This situation could be ascribed to the underlying financialization issue in these countries, along with the implementation issues with renewable energy generation. In the wake of these two scenarios, the G7 countries are struggling to reduce carbon emissions (CO_2). Handling this issue might require a policy reorientation, which is what this study focuses on. More specifically, it analyzes the nonlinear and asymmetric effects of financial development and renewable energy generation on CO_2 emissions. The study, which encompassed the 1986–2019 period, adopts non-linear Autoregressive distributed lag (NARDL) and two-stage least square (2SLS) techniques. An SDG-oriented policy framework has been recommended based on these study outcomes. While this policy framework is aimed at addressing the objectives of SDG 13 and 7, the framework is generalizable to other nations. The contribution of the present study is an emphasis on the environmental policy issues of the G7 countries, and the accompanying recommendation of this SDG-oriented policy framework.

1. Introduction

The prevailing economic growth pattern is causing environmental degradation in different forms, which has emerged as a contentious policy debate. With the advent of the Sustainable Development Goals (SDGs), the world is witnessing the need to bring reorientation in their existing economic growth pattern, to restore the ecological balance. Now, reorienting the economic growth pattern will necessarily entail reorientation of the economic growth drivers, a process that would necessitate the revamped contribution of financialization channels. During the 47th G7 Summit, held in Cornwall, the criticality of financialization was discussed, following the report of the Swiss Re Institute (2021). It has been postulated that G7 economies might lose 8.5% of their wealth if the climatic actions are avoided, and climatic funding has been identified as one of the major drivers to tackle this situation. Moreover, the 47th G7 Summit was critical in the background of the COP26 summit, as the USA has rejoined the Paris accord. Hence, the financial mobilization might prove to be critical for the G7 economies from the perspective of environmental sustainability. The argument is fortified by the recent SDG progress report 2021, where the G7 countries are struggling to achieve the objectives of climatic action, namely, SDG 13 (Sachs et al., 2021). This report also reflects the inability of the G7 countries to mobilize the finances so as to reiterate their growth strategies to tackle climate change (Bargout, 2012). Under such circumstances, it might be necessary to develop a new SDG-oriented policy framework involving financial development. The need for this policy reorientation is the first stepping stone of the present study.

Concerning this policy issue, a special mention needs to be made of the stock indices in the G7 countries. Just prior to the 47th G7 Summit, a report published by Science Based Targets initiative (SBTi, 2021) revealed these economies' private sectors are not in alignment with the SDG objectives. Moreover, these indices are on temperature pathways of over 2.95 degrees Celsius. A scrutiny of the sectors consisting of these indices revealed that the sectors are primarily driven by fossil fuel-based solutions. This situation is pivotal for policymakers, as the prevailing financialization channels have caused these countries to tread along the growth trajectory, which is not environmentally sustainable. Hence, in addition to bringing a transformation in the financial development

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https://doi.org/10.1016/j.eneco.2022.105994
Received 19 April 2021; Received in revised form 17 March 2022; Accepted 21 March 2022
Available online 31 March 2022
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pattern, policy intervention is also essential for transforming the energy consumption pattern in these countries. This issue dates back to the Rome G7 Energy Initiative in 2014, which aimed to reorient the domestic policies for developing inexpensive, diversified, and low-carbon energy systems (European Commission, 2014). These principles involved the diversification of energy sources and bringing energy efficiency in the production processes. Despite this much-needed initiative, the SDG progress report 2021 does not show a favorable scenario for the G7 countries, in terms of making the energy sources accessible and cleaner, i.e., SDG 7 (Sachs et al., 2021). As per the recent global energy sector assessment report published by International Energy Agency (2021), the achievement of net-zero by 2050 requires the G7 countries to have 60% of the energy mix to have renewable energy solutions by 2030. As of 2021, the energy mix stands at only 48%. Hence, the G7 countries need to bring changes in their existing energy mix by enhancing the share of renewable energy sources to achieve environmental sustainability. Both financial development and renewable energy generation need to be harmonized within a unified policy framework as this transformation might have an impact on the economic growth pattern. The present study is aimed at addressing this particular policy void.

This discussion puts forth the following observations about the environmental sustainability in the G7 countries:

- The G7 countries are still struggling to achieve the objectives of SDG 7 and 13.
- The prevailing financial development pattern in G7 countries is not conducive for achieving environmental sustainability.
- The prevailing renewable energy generation pattern in G7 countries is not adequate to achieve environmental sustainability.

In view of these observations, a pertinent question before the G7 countries is "*How to achieve environmental sustainability?*" Given the existing policies in these countries are proving to be ineffective in answering this question, a policy reorientation is necessary by taking the financial development and renewable energy generation process into account. In line with the international environmental policy discourse, this policy reorientation is necessary attaining the objectives of SDG 7 and 13. If the level of per capita emissions of the G7 countries is benchmarked with developing economies such as China and India, it becomes apparent that the majority of G7 member countries have reported higher levels of per capita carbon dioxide (CO_2) emissions than these two countries (refer to Fig. 1). This comparative scenario indicates the ecologically unsustainable environmental policy regime in the G7 countries, and the present study can contribute to the literature by addressing this problem through policy reorientation. Accordingly, the research question of the study is as follows:

Research Question: *Can reorientation in financial development and renewable energy generation process ensure environmental sustainability in the G7 countries?*

The academic literature has by far not been able to give a conclusive solution to this pressing issue in the G7 countries. In view of the identified policy void prevailing in these countries, a policy reorientation is necessary for achieving environmental sustainability. In this process, financial development and renewable energy generation might be taken as policy instruments. Based on these two policy instruments, the present study aims at recommending an SDG-oriented policy framework for internalizing the negative environmental externalities exerted by the economic growth pattern in the G7 countries. Though this policy framework is aimed the G7 countries, it is also generalizable to the other developed nations aiming at policy reorientation for attaining environmental sustainability. As this policy framework also aims at attaining the objectives of SDG 7 and 13, it can serve as a benchmark for the other countries to adopt. Moreover, the context of the G7 countries has also been strategically chosen, so that the policy reorientation exercise carried out in this study for the leading economies of the world can initiate a discussion in the global environmental policy forum. Initiation of this discussion is important for adhering to the goals set during the 47th G7 Summit, followed by COP26 Summit. By far, this multipronged SDG-oriented policy design for achieving the environmental sustainability has not been addressed in the academic literature, and there lies the contribution of the present study. This study can contribute to the literature of the energy economics not only by recommending this policy framework, but also initiating a discussion in the global environmental policy forum about the possible directions for reorienting the prevailing policy regimes across the countries to achieve the environmental

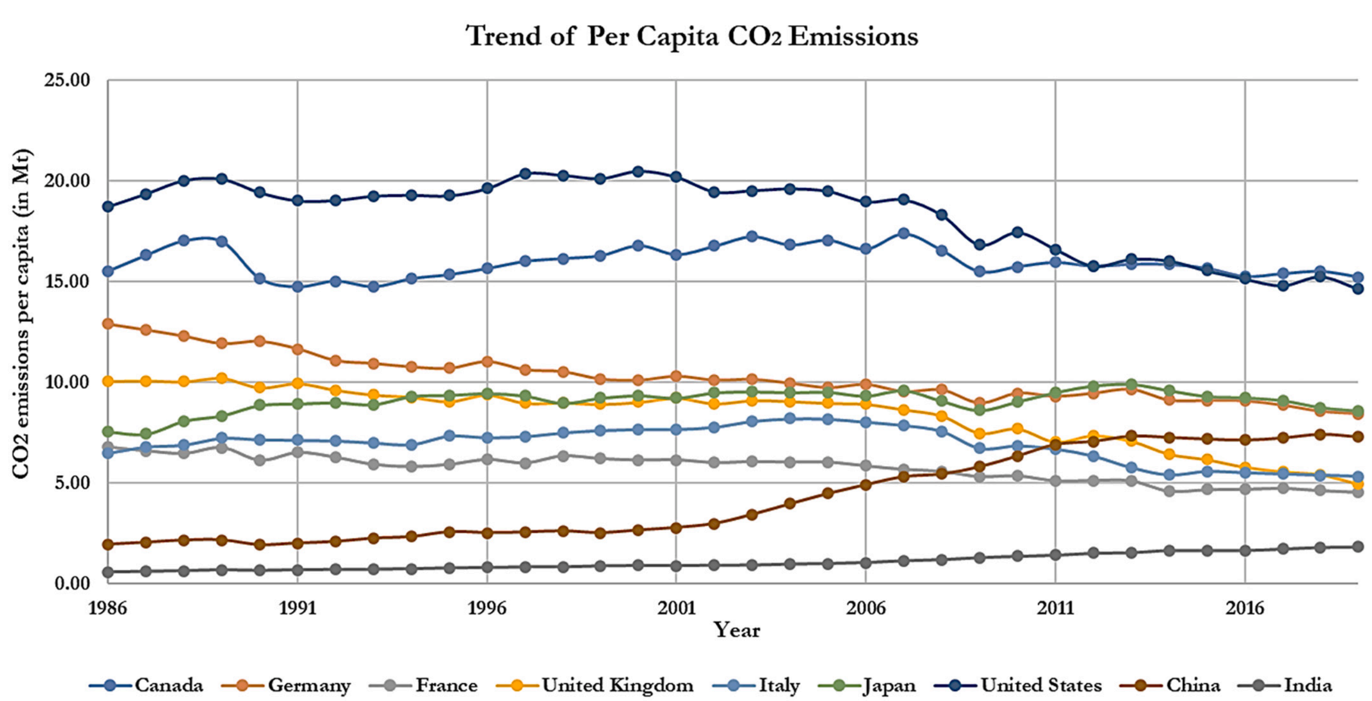

Fig. 1. Trend of CO_2 emissions per capita (Source: World Development Indicators, 2021).

sustainability.

At the same time, it is necessary to remember that the methodological adaptation needs to complement the contribution of the study. It is not unrealistic to infer that the upward or downward movements in policy instruments might not impact the target policy parameter unilaterally (Sinha et al., 2021). However, the impacts of these movements could be varied. Hence, it is possible to make the policy framework more robust by assuming a nonlinear association between the policy instruments and the target policy parameter that might reflect the camouflaged dimensions of policy instruments. Moreover, not all the policy instruments may be able to simultaneously affect the policy parameters as there might be certain lags in their impacts, based on the contextual setting. Therefore, the method to be chosen for the study needs to consider these two elements. Therefore, the Non-Linear Autoregressive Distributed Lag (NARDL) technique (Shin et al., 2014) has been used in the present study. This econometric technique helps in capturing the asymmetric relationship between policy instruments and the target policy parameter, especially for small data sets. Unlike Autoregressive Distributed Lag (ARDL), NARDL captures the long and short-run asymmetries. To check the robustness of the outcomes in presence of possible endogeneity, this study also employed a two-stage least square estimation method (2SLS) for panel estimation. In this manner, the present study has maintained methodological complementarity.

The study is organized as follows: the second section reviews the existing literature, while the third section reports data sources and outlines the methods. Similarly, the fourth section discusses the empirical results, whereas the fifth section concludes the study with policy recommendations.

2. Brief literature review

This section is based on the literature on the nexus between financial development, renewable energy consumption (REC), human capital (HC), and carbon dioxide (CO2) emissions.

2.1. Financial development and CO2 emission

Since the idea of an Environmental Kuznets Curve (EKC) was put forward (Grossman and Krueger, 1995), many empirical studies have investigated the impact of financial development (FD) on CO2 emissions. However, past studies have not reached any consensus about the previous findings of FD impact on environmental quality. As per one school of thought, FD is imperative for economic growth, but it also adversely affects the environment (Khan et al., 2017; Ouyang and Li, 2018). Due to FD, financial institutions offer a low cost of borrowing with lesser constraints to the investors and household sectors, thus raising the demand for energy and causing CO2 emissions (Charfeddine and Kahia, 2019; Zhang, 2011). In a similar vein, Khan et al. (2017) analyzed FD's impact on CO2 emissions from 34 upper-middle-income countries. Using a sample of 13 years from 2001 to 2014, the authors revealed that the FD adversely affects environmental quality. Renewable energy reduces environmental degradation in African and American countries. Likewise, Shahbaz et al. (2013a, 2013b) and Wang et al. (2020) underscored a strong relationship between FD and environmental quality.

In contrast, other schools of thought assert that FD improves the quality of the environment. For example, Zioło et al. (2020) contended that green or sustainable finance replaced conventional finance by imposing taxes on CO2 emission projects and providing efficient technology and research and development. Similarly, Shahbaz et al. (2013a, 2013b) opined that FD and trade openness reduced environmental degradation in Indonesia's case. On a similar note, Ang (2007), Cardenas et al. (2016), and Shahbaz et al. (2018) investigated the impact of FD on CO2 emissions in France. Likewise, Sheraz et al. (2021a, 2021b) scrutinized FD's link with CO2 emission and confirmed that FD mitigates CO2 emissions in the case of G20 countries. However, Ozturk and Acaravci (2013) did not report any impact of FD on CO2 emissions.

To address the climate issues, world economies are shifting investments in high polluted projects to low polluting projects while implementing green investment strategies (Wang and Zhi, 2016; Zerbib, 2019). Financial instruments such as green and blue bonds can play a vital role in combating climate-related issues by meeting the financing demand for low CO2 emission projects (Li et al., 2019; Mumtaz and Yoshino, 2021; Xu et al., 2020).

In this regard, another contentious issue is that of green finance, which helps lower CO2 emissions. Studies have shown that green investment plays a key role in achieving sustainable growth while reducing CO2 emission levels (Li et al., 2019). In the broader context, green investment denotes investments in projects that are not only crucial for sustainability and environmental protection but also deal with the preventive measures relating to carbon emissions (Li and Wei, 2021; Zerbib, 2019). Green investment enables the debt capital markets to mobilize the funds for low CO2 emission projects (Saeed Meo and Karim, 2021). Furthermore, Mumtaz and Yoshino (2021) studied how the green investment at the firm level affects the short and long-run performance of initial public offering (IPOS). Results indicate that firms with green investment perform better and are known to elicit investors' participation.

Meanwhile, Huang and Du (2020) investigated the effect of the CO2 emissions trading pilot program on the land supply of energy-intensive industries. According to the findings of this study, CO2 emission programs reduce the supply of energy-intensive industries by 25% which then promulgates green development.

2.2. Renewable energy consumption and CO2 emission

To resolve the issue of climate change and global warming, in particular, the world is making concerted efforts (Kahouli, 2017). One of the important factors that can improve the environment's quality is to shift toward renewable energy consumption (REC). Several past studies keep an eye effect of REC on the environment and economic growth. On the other hand, Balsalobre-Lorente et al. (2018) and Shao et al. (2019) argued that REC and energy innovation have improved the quality of the environment in the European Union. Khan et al. (2020) studied the linkage between REC, CO2 emissions, and environmental innovation. By employing the Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CCEMG) tests, results indicate that environmental innovation and REC enhance the quality of the environment. Similarly, Bhattacharya et al. (2017) found by using a sample of 85 countries and the Generalized Methods of Moment (GMM) and Ordinary least Square (OLS) technique that renewable energy consumption negatively impacts CO2 emissions as well as the GDP. Other research studies have also found evidence of REC improving the environment's quality from China, MENA region, N-11 countries, European Union, and South Asia (Balsalobre-Lorente et al., 2018; Bao and Xu, 2019; Charfeddine et al., 2018; Charfeddine and Kahia, 2019; Rahman and Velayutham, 2020; Wang et al., 2020; Zheng and Paul, 2019).

2.3. Human capital and CO2 emission

Human Capital (HC) is considered vital for the improvement of environmental quality. Costantini and Monni (2008) underscore the significance of investing in HC. The impact of FD and foreign direct investment (FDI) on CO2 emission relies on the HC (Lan et al., 2012). Similary, Baiardi and Morana (2021) and Bashir et al. (2019) examined the relationship between HC and CO2 emissions and confirmed that HC helps mitigate CO2 emissions. Khan et al. (2020) argued that the impact of GDP on CO2 emissions is predicated on the level of HC. This study used a sample of 122 countries from 1980 to 2014. Results showed an increase in the level of education or HC led to a decline in CO2 emissions. Similarly, Bano et al. (2018) and Danish et al. (2017) evaluated the impact of HC on the environment in Pakistan's case. Using the ARDL technique, HC reduced CO2 emission in the long run and has bidirectional causality. Besides that, Sarkodie et al. (2020) used the dynamic ARDL technique to report the effect of energy consumption, HC, trade, and income level on CO2 emissions in the case of China. Results have indicated that HC and fossil energy consumption negatively affect the environment, whereas renewable energy improves its quality Yao et al. (2020) also conducted research related to HC and environmental quality. Long-run relationships showed additional tertiary schooling cause of environmental degradation, but another additional tertiary schooling mitigates the CO2 emission (Yuan et al., 2017).

2.4. Research gap

The above literature of past studies indicates mixed explanatory variables (FD, REC, HC) on carbon emissions (See Table 1). Some studies claimed that FD improves environmental quality (through making an investment in green projects and new technology), whereas others contended that FD causes environmental degradation (CO2 emission projects). Similarly, many past studies showed that REC and HC improve the environment's quality by switching toward green energy and investing in human education. However, the majority of studies have investigated the linear nature of the relationship between these explanatory variables and CO2 emission in different frameworks. In contrast, this study formulates a new framework to explore the nonlinear relationship between FD, REC, and HC when it comes to CO2 emission (Yuan et al., 2017).

3. Data and econometric technique

3.1. Data source and theoretical background

This empirical study is based on secondary data from 1986 to 2019, which is selected based on data availability. This annual time series data for G7 countries is collected from World Bank development indicators (WDI) and our world data website. All the variables except FD and HC index are transformed into logarithm form.

$$CO2_t = f(FD_t, REC_t, HC_t) \tag{1}$$

On the basis of past studies (Shahbaz et al., 2013a, 2013b; Shahbaz et al., 2018), this study assumes FD as the primary explanatory variable of the study, which improves the quality of the environment in G7 developed economies (Inglesi-Lotz and Dogan, 2018). This study expects a negative correlation between REC and CO2 emissions. To reduce environmental degradation and efficient consumption of REC, HC is considered a vital factor. HC is associated with the level of education that reduces the environment's degradation. Adopting a similar stance, we also expect a negative relationship between HC and CO2 emissions.

As human capital is an endogenous regressor, and it might create multicollinearity issues in the empirical model. Hence, assessing the plausibility of the model is important before the empirical estimation. To check the model fitment, Lasso and Ridge models are used. The reason behind using this algorithm is to shrink the coefficient of the less contributing variable during the regularization process. In order to maintain parsimony, only the summary of models is provided in Table 2. The Square Root, Adaptive, and Elastic Net Lasso estimators are used, and the Ridge estimator is used to validate the outputs of the Lasso estimators. The model outputs suggest the selection of all the variables within the empirical framework.

In order to check the robustness of the parameter selection, Least Angle Regression with the Lasso algorithm is used. The model will select the variables until the lowest value of Mallow's Cp is reached. The model output reported in Table 3 shows the selection of all the three variables in the model. Based on the model output, the further estimations can be carried out.

Table 1
Past literature on financial development, renewable energy consumption, human capital and Co2 emission.

Name of author and year	Sample of study and region	Econometric technique	Outcomes
Shahbaz et al. (2018)	1955 to 2016 in France	Bootstrapping ARDL technique	FD improve the quality of the environment
Shahbaz et al. (2013a, 2013b)	1975 to 2011 from Indonesia	ARDL and Vector Error Correction Model (VECM) Granger causality	FD leads to reduce CO2 emission; FD Granger causes CO2 emission.
Khan et al. (2017)	2001 to 2014 with 34 countries	GMM, Granger causality, VECM	FD cause of environmental degradation, although renewable energy minimizes the CO2 emission.
Zhang (2011)	China	Granger casualty, variance decomposition	FD has a direct relation with CO2 emission
Wang et al. (2020)	1990 to 2017 from N-11 countries	CCEMG and AMG	FD increases the CO2 emission whereas REC and HC reduce
Charfeddine and Kahia (2019)	1980 to 2015 from MENA	Panel Vector Autoregressive (PVAR)	FD and REC slightly improve the quality of the environment
Ozturk and Acaravci (2013)	1960 to 2007 from Turkey	ARDL	FD has no impact on CO2 emission
Balsalobre-Lorente et al. (2018)	1986 to 2016 European form union	AMG	REC and energy innovation improve the quality of the environment
Khan et al. (2020)	1990 to 2017 from G7 countries	AMG and CCMG	REC improve the quality of the environment
Bhattacharya et al. (2017)	1991 to 2012 from 85 countries	GMM and OLS	REC improve the quality of the environment without decreasing GDP
Bao and Xu (2019)	1997 to 2015	Bootstrap Panel causality test	REC and GDP growth influence other regions
Rahman and Velayutham (2020)	1990 to 2014 from South Asia	Fully Modified Ordinary Least Square (FMOL) and Dynamic Ordinary Least Square (DOLS)	REC has a positive impact on growth
Bano et al. (2018)	1971 to 2014	ARDL and VECM	HC improve the environmental quality and also have a bidirectional relationship
Sarkodie et al. (2020)	1961 to 2016 from china	Dynamic ARDL technique	HC and fossil energy degrade the environment, whereas REC improves its quality.
Yao et al. (2020)	1996 to 2006 from chain	Local Linear Estimation Dummy Variable Estimation (LLDVE)	HC improve the quality of the environment
Bashir et al. (2019)	1985 to 2017 from Indonesia	VECM	There is no Causality between HC and CO2 emission

3.2. Research methodology

3.2.1. NARDL asymmetric co-integration test

Unseen and uncertain events, like economic recessions, fluctuation in financial markets, and political revolutions, can affect linear approaches when it comes to estimating the relationship between economic time series data. As was done in the study carried out by Haug and

Table 2
Model summary of Lasso and Ridge estimations.

Variables	Square root Lasso		Adaptive Lasso		Elastic net Lasso		Ridge	
	Statistic	Post-est OLS	Statistic	Post-est OLS	Statistic	Post-est OLS	Statistic	Post-est OLS
FD	−0.6584	−0.6586	−0.6584	−0.6586	−0.6479	−0.6586	−0.5617	−0.6586
REC	−0.2446	−0.2447	−0.2445	−0.2447	−0.2410	−0.2447	−0.2126	−0.2447
HC	−9.1604	−9.1637	−9.1582	−9.1637	−8.9006	−9.1637	−6.7757	−9.1637

Note: All the models estimated using extended Bayesian information criterion.

Table 3
Model summary of Least Angle Regression with Lasso algorithm.

Step	Mallow's Cp	R-Square	Action
1	75.4815	0.0000	
2	59.2199	0.0586	Add HC
3	51.2377	0.0907	Add FD
4	4.0000	0.2488	Add REC

Model summary	
Variables	Coefficient
FD	−0.6586
REC	−0.2447
HC	−9.1637

Ucal (2019), this study employs a multivariate NARDL approach to estimate the long and short-run asymmetric co-integration between FD, REC, HC, and CO2 emissions. Moreover, this technique gets validated if the variables are stationary at the level I (0) or first difference I (1). It allows for reporting the functional relationship between CO2 emission, FD, REC, and HC. NARDL is a better approach than the VECM due to the convergence issues in large parameters and having the same kind of integrated order.

$$\Delta CO2_t = +\rho CO2_{t-1} + \theta_1^+ FD_{t-1}^+ + \theta_2^+ FD_{t-1}^- + \theta_3^+ REC_{t-1}^+ + \theta_4^- REC_{t-1}^- + \theta_5^+ HC_{t-1}^+ + \theta_6^- HC_{t-1}^- + \sum_{i=t}^{P} \alpha_1 \Delta CO2_{t-1} + \sum_{i=t}^{P} \alpha_2 \Delta FD_{t-1}^+ + \sum_{i=t}^{P} \alpha_3 \Delta FD_{t-1}^- + \sum_{i=t}^{P} \alpha_4 \Delta REC_{t-1}^+ + \sum_{i=t}^{P} \alpha_5 \Delta REC_{t-1}^- + \sum_{i=t}^{P} \alpha_6 \Delta HC_{t-1}^+ + \sum_{i=t}^{P} \alpha_7 \Delta HC_{t-1}^- + \mathrm{Dt} + \mu_t \tag{2}$$

In equation number 1, αi represents the short-run asymmetry coefficients, whereas θi indicates long-run asymmetry coefficients with $i = 1\ldots0.8$. Coefficients for the long run capture the time of reaction and speed of adjustment toward the equilibrium level. Meanwhile, the short-run coefficient estimates the quick effect of independent variables on dependent variables. Further, the Wald test is used to report the long-run ($\alpha = \alpha^+ = \alpha^-$) and short-run asymmetries ($\theta = \theta^+ = \theta^-$) for financial development ($FD_{t)}$), renewable energy consumption ($REC_{t)}$), Human Capital ($HC_{t)}$) and Carbon Emission ($CO2_t$). The Akaike information criteria, p, and q facilitate the selection of optimal lags for dependent and independent variables. Further, all variables are decomposing the independent into positive and negative sums as follow:

$$x_t^+ = \sum_{j=1}^{t} \Delta x_t^+ = \sum_{j=1}^{t} max(\Delta x_j, 0) \text{and } x_t^- = \sum_{j=1}^{t} \Delta x_t^- = \sum_{j=1}^{t} min(\Delta x_j, 0) \tag{3}$$

Where X_t represent the independent variables FD_t, REC_t, and HC_t.

We employ the ARDL bounds test developed by (Shin et al., 2014) to capture the asymmetric (non-linear) co-integration among variables. It is a combined test for all the regressors of lagged levels. F-statistic test (null hypothesis is $\theta = \theta^+ = \theta^- = 0$) and t-statistic (null hypothesis $\theta = 0$) employed against the (alternative hypothesis $\theta < 0$). Rejection of the null hypothesis and acceptance of the alternative hypothesis indicates the long-run relationship between the variables. Moreover, we use ($lm_h^+ = \theta_{/p}^+$) and ($lm_h^+ = \theta_{/p}^-$) to capture the long-run asymmetric co-efficients, which is why long-run co-integration estimates the negative and positive shocks of the exogenous and shows the long-run relationship between the variables.

Below given equation capture the asymmetric dynamic multiplier effects.

$$m_h^+ = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial FD_t^+}, m_h^- = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial FD_t^-}, m_h^+ = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial REC_t^+}, m_h^- = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial REC_t^-} \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial HC_t^+}, m_h^- = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial HC_t^-} \tag{4}$$

Here, $h \to \infty$ $m_h^+ \to m_h^+$ *and* $m_h^- \to m_h^-$ represent the asymmetric response of the exogenous variables to positive and negative fluctuation on the independent variable. It is also possible to capture the constant dynamic change from the initial point of equilibrium to the new point of adjustment in system variables.

3.2.2. Two-Stage Least Square (2SLS) estimation

While we use NARDL estimation for obtaining the individual country results, further understanding whether renewable energy, human development, and financial development can affect the carbon emission at the panel level, we implement the two-stage least square estimation method. This method assumes significance for estimation when the error term of the dependent variable is associated with the independent variables used in the study. Ignoring this problem may provide us with biased estimation results, thus further violating the assumption of exogeneity (Shittu et al., 2021). To address the endogeneity issue, this study uses the 2SLS estimation developed by (Cumby and Obstfeld, 1981) to ascertain the relationship of carbon emission with renewable energy, human capital, and financial development for the seven countries as a whole.

As HC is an endogenous variable, including it directly within a panel data framework might lead to spurious outcomes. To tackle this issue, education policy has been used as an instrument of human capital. For empirical purposes, education policy has been parameterized by public expenditure on education (Patron and Vaillant, 2012; Apergis et al., 2021). Choosing this proxy will encapsulate the impact of human capital, without triggering endogeneity in the model outcome.

3.2.3. Hatemi-J causality test

This study uses the asymmetric causality test proposed by Hatemi-J

(2012) to estimate the asymmetric causal direction between variables. Capturing the asymmetric effects and differentiating between positive and negative shocks is one plausible reason to use the technique (Toda and Yamamoto, 1995).

$$Y_t = Y_{t-1} + e_{1t} = y_0 + \sum_{i=1}^{t} e_{1i} \text{and } X_t = X_{t-1} + e_{2t} = x_0 + \sum_{i=1}^{t} e_{2i} \quad (5)$$

This equation indicates that variables have a random walk process (Hatemi-J, 2012). Here $t = 1, 2 \ldots T$, X0, and y0 and show the initial values, whereas e_{2t} *and* e_{1i} are the error terms. Further, positive and negative shocks are represented by $e_{1i}{}^{+} = \max(e_{1i}{}^{+}, 0)$ and $e_{2i}{}^{+} = \max(e_{2i}{}^{+}, 0)$, $e_{1i}{}^{-} = \max(e_{1i}{}^{-}, 0)$ and $e_{2i}{}^{-} = \max(e_{2i}{}^{-}, 0)$.

The asymmetric framework for positive and negative shocks is given below:

$$Y_t = Y_{t-1} + e_{1t} = y_0 + \sum_{i=1}^{t} e_{1i}^{+} + \sum_{i=1}^{t} e_{1i}^{-} \text{and } X_t = X_{t-1} + e_{2t} = x_0 + \sum_{i=1}^{t} e_{2i}^{+} + \sum_{i=1}^{t} e_{2i}^{-} \quad (6)$$

Moreover, cumulative forms for positive and negative shocks for all the variables are given in the following equation in our estimation framework:

$$CO2^{+} = \sum_{i=1}^{t} e_{1i}^{+}, CO2^{-} = \sum_{i=1}^{t} e_{1i}^{-}, FD^{+} = \sum_{i=1}^{t} e_{2i}^{+}, FD^{-} = \sum_{i=1}^{t} e_{2i}^{-}, REC^{+} = \sum_{i=1}^{t} e_{3i}^{+}, REC^{-} = \sum_{i=1}^{t} e_{3i}^{-}, HC^{+} = \sum_{i=1}^{t} e_{4i}^{+}, HC^{-} = \sum_{i=1}^{t} e_{4i}^{-} \quad (7)$$

For asymmetric causality for positive and negative shock, the study uses the approach recommended by (Hatemi-J, 2012). However, it is also necessary to adopt a vector autoregressive (VAR) model with order p to estimate asymmetric causal relationships. For optimal lag selection for the VAR model, the criterion suggested by Hatemi-J (2008, 2010) can be used. The below given Hatemi-j Criterion (HJC) model is used for the lag selection:

$$\text{HJC} = ln(|AJ|) + q\left(\frac{n^2\, lnT + 2n^2 ln(lnT)}{2T}\right), q = 0, \ldots p \quad (8)$$

Ln indicates the natural logarithm and also represents an element of estimated $|AJ|$ variance-covariance matrix for the error term in the VAR model with q lag order and numbers of equations. Furthermore, n refers to the number of variables; T represents the number of observations. K^{th} element of $\sum x +$ it denotes the null hypothesis does not granger w^{th} element of $y_t{}^{+}$. Null hypothesis H0: ω, column k element is equal to zero where r = …, p. By employing the Wald test (Hatemi-J, 2012), we can also test this hypothesis.

3.2.4. Dumitrescu and Hurlin (D-H) panel causality test

This study also employs a pairwise non-causality test for panel data (Dumitrescu and Hurlin, 2012). This test is useful when the time period (T) is greater than the cross-sections (N) in balanced and heterogeneous panels (Sheraz et al., 2021a, 2021b). The Null hypothesis assumption in the Dumitrescu and Hurlin (D-H test) is as follows: no causal association exists between the variables and in the alternative hypothesis, there is a causal relationship between variables. The numerical representation of D-H causality is as follows:

$$y_{it} = \alpha_i + \sum_{j-1}^{J} \lambda_j^i y_{i(t-j)} + \sum_{j-1}^{J} \beta_j^i X_{i(t-j)} + \mu_{it} \quad (9)$$

Here λ *and* β_{ji} denote the coefficients of regression and autoregressive parameters, whereas X and Y show the numbers of observations.

4. Results and discussion

4.1. Descriptive summary and unit root test

The road map of results potation is as follows: first, we report a descriptive summary and stationarity of all the variables using unit root tests. Furthermore, to estimate the causal relationship between the variables, NARDL, 2SLS, and the asymmetric causality test proposed by (Hatemi-J, 2012), and pair-wise (Dumitrescu and Hurlin, 2012) (D-H) non-causality test is used.

Descriptive statistic summary for G7 countries is reported in Table 4.

While performing the NARDL and 2SLS, it is essential to have all the variables stationary at level I(0) or the first difference I(1). To confirm the stationary of data for NARDL, the study implies Augmented Dickey-Fuller (ADF) Dickey and Fuller (1979) by Taylor et al. (2012) and Phillips and Perron (PP) (Phillips and Perron, 1988). Results in Table 5A indicate that CO2, FD, REC, and HC (form G7 countries) are stationary at level I(0) or the first difference I(1). Lastly, with the null hypothesis of stationarity, the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test results illustrate the fact that model parameters are both I(0) and I(1) for the various G7 member countries.

Similarly, Table 5B shows the results of the second-generation (CIPS and CADF) unit root test proposed by Pesaran (2007). Results confirm that all the variables are stationary at the level and the first difference.

To confirm non-linear behavior variables, we use Brock-Dechert-Scheinkman (BDS), a nonparametric test by Broock et al. (1996).

Table 4
Descriptive statistics.

Countries	Descriptive	CO2	FD	REC	HC	Countries	Descriptive	CO2	FD	REC	HC
	Mean	6.27	0.74	10.34	1.58	Japan	Mean	7.08	0.74	7.75	1.55
	Median	6.33	0.78	10.33	1.64		Median	7.11	0.74	7.72	1.51
	Max	6.38	0.99	10.43	1.75		Maxi	7.18	0.89	8.24	1.93
	Mini	6.00	0.47	10.26	1.27		Mini	6.80	0.57	7.44	1.21
Canada	Std.D	0.10	0.15	0.04	0.16		Std.D	0.09	0.10	0.16	0.17
	Mean	5.96	0.65	8.14	1.56	UK	Mean	6.26	0.79	6.58	1.59
	Median	5.98	0.72	8.13	1.65		Median	6.34	0.86	6.22	1.56
	Maxi	6.05	0.84	8.48	1.74		Maxi	6.41	0.94	8.44	2.04
	Mini	5.81	0.41	7.78	1.15		Mini	5.92	0.57	5.32	1.23
France	Std.D	0.07	0.15	0.16	0.18		Std.D	0.14	0.11	0.99	0.18
	Mean	6.79	0.71	7.54	1.56	USA	Mean	8.61	0.80	8.35	1.57
	Median	6.80	0.73	7.38	1.58		Median	8.61	0.87	8.28	1.53
	Maxi	6.95	0.79	8.94	1.81		Maxi	8.72	0.90	8.84	1.84
	Mini	6.62	0.52	6.41	1.19		Mini	8.40	0.57	7.97	1.40
Germany	Std.D	0.09	0.06	0.87	0.18		Std.D	0.07	0.12	0.23	0.12
	Mean	6.04	0.64	7.93	1.53						
	Median	6.07	0.74	7.76	1.53						
Italy	Maxi	6.20	0.80	8.57	1.56						
	Mini	5.81	0.32	7.43	1.65						
	Std.D	0.12	0.16	0.34	1.74						

Note: CO2, FD, REC, and HC represent carbon dioxide, financial development, renewable energy consumption, and human capital.

Table 5A
ADF, PP and KPSS unit root test for time series data.

Variables	Test	Canada	France	Germany	Italy	Japan	UK	USA
	ADF	I(0)	I(1)	I(0)	I(1)	I(0)	I(0)	I(0)
CO2	PP	I(0)	I(1)	I(0)	I(1)	I(0)	I(0)	I(0)
	ADF	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)
FD	PP	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)
	ADF	I(0)	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)
REC	PP	I(0)	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)
	ADF	I(0)	I(1)	I(0)	I(0)	I(1)	I(0)	I(1)
HC	PP	I(0)	I(1)	I(0)	I(0)	I(1)	I(0)	I(1)
KPSS Test Result								
CO2		0.235***	0.228	0.104	0.237***	0.042	0.068	0.112
FD		0.082	0.242	0.222***	0.249***	0.305***	0.238***	0.246***
REC		0.112	0.217	0.283***	0.278***	0.279***	0.241***	0.239***
HC		0.069	0.223	0.024	0.119	0.272***	0.032	0.367***

Note: ADF and PP represent Augmented Dickey-Fuller, Phillips, and Perron, whereas I(0) and I(1) represent level and first difference. Moreover, ***, ** and ** indicate the level of significance at 1%, 5%, and 10%. The critical values for KPSS test statistics are 0.216, 0.146, and 0.119 at 1%, 5% and 10% level.

Table 5B
CPIS and CADF unit root test for panel data.

Variables	Level	First difference	Order	Level	First difference	Order
CO2	−2.343***	–	I(0)	−2.343***	–	I(0)
FD	−3.078**	–	I(0)	−2.987	−2.342***	I(1)
REC	−2.654**	–	I(0)	−2.346*	–	I(0)
HC	−2.876***	–	I(0)	−2.098***	–	I(0)

Note: CPIS and CADF represent Cross-sectional Augmented Im-Pesaran-Shin and Cross-sectional Augmented Dicky-fuller Statistic. ***, **, and * indicate the level of significance at 1%, 5%, and 10%.

Table 6
BDS test.

Countries		CO2	FD	REC	HC	Countries		CO2	FD	REC	HC
		BDS	BDS	BDS	BDS			BDS	BDS	BDS	BDS
	2	0.192***	0.173***	0.079***	0.277***	Japan	2	0.146***	0.149***	0.084***	0.119***
	3	0.329***	0.302***	0.118***	0.215***		3	0.276***	0.242***	0.098***	0.033***
Canada	4	0.425***	0.401***	0.138***	0.441***		4	0.385***	0.288***	0.052***	0.022***
	5	0.487***	0.466***	0.137***	0.317***		5	0.474***	0.319***	0.013***	0.357***
	6	0.527***	0.514***	0.119***	0.356***		6	0.545***	0.336***	0.167***	0.042***
	2	0.123***	0.179***	0.050***	0.212***	UK	2	0.135***	0.163***	0.174***	0.011***
	3	0.183***	0.306***	0.031***	0.221***		3	0.191***	0.293***	0.282***	0.015***
FRANCE	4	0.220***	0.393***	0.027***	0.235***		4	0.198***	0.377***	0.343***	0.004***
	5	0.212***	0.459***	0.013***	0.383***		5	0.158***	0.436***	0.373***	0.017***
	6	0.167***	0.501***	0.004***	0.423***		6	0.065***	0.473***	0.371***	0.035***
	2	0.147***	0.129***	0.183***	0.237***	USA	2	0.177***	0.192***	0.112***	0.216***
	3	0.239***	0.227***	0.299***	0.122***		3	0.296***	0.327***	0.163***	0.006***
Germany	4	0.314***	0.298***	0.376***	0.316***		4	0.362***	0.421***	0.172***	0.001***
	5	0.366***	0.343***	0.427***	0.242***		5	0.398***	0.481***	0.158***	0.034***
	6	0.401***	0.356***	0.458***	0.419***		6	0.419***	0.521***	0.146***	0.028***
	2	0.142***	0.191***	0.145***	0.208***						
	3	0.212***	0.326***	0.231***	0.356***						
Italy	4	0.244***	0.416***	0.282***	0.459***						
	5	0.247***	0.478***	0.295***	0.532***						
	6	0.231***	0.515***	0.272***	0.582***						

Note: BDS test, based on residual values for all the variables at *, **, and***, explains the rejection of null hypothesis at 10%, 5%, and 1%.

Table 6 presents the BDS test results, which confirm non-linearities in CO2 emission, FD, REC, and HC. The null hypothesis for the linearity of variables is rejected as an alternative hypothesis for non-linearity is accepted.

4.2. Asymmetric co-integration (bound and diagnostic test)

To confirm the long-run relationship between CO2 emission, FD, REC, and HC by using the optimal lag run, the study employs the NARDL model for each country of the G7 block. Firstly, the study uses the proposed bound test to capture the short-run and long-run co-integration results (Narayan, 2005), as reported in Table 7. Moreover, Table 8 shows several diagnostic tests for model efficiency, which include serial correlation (SC), heteroscedasticity (HT), and Ramsey's RESET statistic (RR). The study also reports the Durbin Watson test for no auto-correlation, $R^{2,}$ and Adj-R^2 for the goodness of the model for each country. Furthermore, cumulative sum (CUSUM) and cumulative sum of square (CUSUMSQ) are reported for the model's stability (S represents stable and NS refers to not stable) (Table 9). Tables 9 and 10 illustrated co-integrations for the long and short-run and asymmetry effects for G7 countries.

Table 7 reveals the existence of the long-run relationship between

Table 7
Bound test for asymmetric co-integration.

Countries	F-Statistics	Outcome	Model Selection
Canada	3.39***	Co-integration	ARDL(1,1,0,0,0,1,0)
France	9.32***	Co-integration	ARDL(1,3,3,3,1,3,2)
Germany	3.31***	Co-integration	ARDL(7, 2, 2, 2, 2, 2, 2)
Italy	16.64***	Co-integration	ARDL(1,3,2,2,2,3,3)
Japan	25.14***	Co-integration	ARDL(3,3,3,2,3,3,0)
UK	6.99***	Co-integration	ARDL(2,2,2,1,1,1,1)
USA	7.86***	Co-integration	ARDL(2,3,2,3,1,0,2)
			Critical values (k = 6)
Sig		I0 Bound	I1 Bound
10%		2.12	3.23
5%		2.45	3.61
2.50%		2.75	3.99
1%		3.15	4.43

Note: bound test, which is a selection of a model (lag) based on AIC at *, **, *** explain the rejection of the null hypothesis of no-cointegration at 10%, 5%, and 1%.

CO2 emission, FD, REC, and HC as the null hypothesis of no long-run co-integration is rejected and accepted the alternative hypothesis at 1% for all the G7 countries. Moreover, it can be seen that the error correction coefficient results in Table 9 are negative and significant, thereby supporting the adjustment process of equilibrium.

Table 8 shows that the diagnostics test results, which indicate all the variables, including CO2, FD, REC, and HC for G7 countries, are normal. Results show the absence of SC, HT, and RR, as all the variables from 1986 to 2019 for G7 countries are insignificant. Table 9 depicts the stability test (CUSUM and CUSUMSQ) and adjusted R^2 for the goodness of fit of the model, which qualified the criteria and indicated the model's fitness for all countries.

4.3. Long run and short run co-integration

After confirming long-run co-integration, the next step is to identify the positive and negative shocks of FD, REC, and HC on CO2 emission for the long and short-run and confirm the asymmetries in G7 countries. The findings of long and short-run co-integration and asymmetric behavior are reported in Table 9. In the long-run, positive and negative shocks to FD hurts CO2 emission for UK and USA, as a positive and negative change in the cumulative function of FD, which increases CO2 emissions by (1.56 and 0.41) and (2.06 and 2.14), for a 1% change. However, in the case of France, Germany, and Italy, positive and negative shocks to FD positively and negatively impact the environment, thus indicating a positive cumulative function of FD decrease the CO2 emissions by (−0.16), (−1.22), and (−1.61) for a 1% change, but the negative cumulative function of FD increases CO2 emissions by (1.78), (0.71) and (0.05) for a 1% change. Further, for Canada, a positive shock to FD exacerbates environmental degradation, as the cumulative function of FD increases CO2 emissions (1.64)) at 1% change; however, coefficients are insignificant in the case of adverse shocks (0.02). However, in France, positive and negative shocks to FD are insignificant so do not affect CO2 emissions.

In the short-run, positive and negative shocks of FD hurt CO2 emission for Japan and USA. However, as far as France is concerned, a positive and negative shock to FD improves and degrades the environment's quality, respectively, but FD has a negative and positive change in CO2 emissions in Italy's positive and negative cumulate function. Similarly, in Canada and UK, a positive shock is insignificant, but negative shocks cause environmental degradation. Further, by employing the Wald test for both the long and short run, positive shocks on CO2 emission are not parallel to negative shocks, which indicates asymmetric impact for Canada, France, Italy, Japan, the UK, and the USA.

In the long-run coefficients for Italy, Japan, and the USA, positive and negative shocks to REC have a positive effect on the environment (CO2 emission), as cumulative positive and negative functions of renewable consumption (coefficients of positive shocks −0.24, −0.17, and −0.28) improve the quality of environment (coefficients for negative shocks −0.89, −0.85, and −0.20) at 1% change. Further, in the case of Canada and Germany, positive shocks are statistically insignificant but an adverse shock to REC have a positive impact on environmental quality, as positive and negative cumulative functions changes have positive (coefficients 0.22 and 0.02) and negative (−1.13 and 3.20) impact on CO2 emission at 1% change. Similarly, positive shocks to REC improve the quality of the environment, as the cumulative function of REC decreases CO2 emissions (−0.29 and − 0.43) at a 1% change for France and the UK, but adverse shocks have insignificant coefficients (0.12 and 0.17).

However, for Italy, positive and negative shocks to REC in the short-run have a positive impact on the environment, as cumulative functions of positive and adverse cumulative have a positive effect on environmental quality. Similarly, in the case of Japan, a positive shock to REC is insignificant but negative shocks reduce carbon emissions. Conversely, for USA positive shocks to REC improve the quality of the environment but negative shocks remain insignificant. Further, we reported the Wald test result for the long-run and short-run asymmetry relationship between REC and CO2 emissions. The impact of positive shocks on CO2 emissions is different from adverse shocks across all G7 countries.

The result of the long-run relationship for Canada, Germany, and Italy indicates that positive and negative shocks to HC have a positive impact on environmental quality, as cumulative functions of positive and negative change have positive (coefficient of positive shocks −0.23, −0.05, and − 0.18) impact on CO2 emissions (coefficient of negative shocks −0.10, −0.09, and − 0.36) due to 1% change. However, in the case of Japan and the USA, positive shocks to HC have a positive impact on environmental quality, while negative shocks are insignificant. The cumulative functions of positive changes have a positive environmental impact (−0.09, and −0.20) and adverse cumulative functions have negative but statistically insignificant effects (0.02 and 0.05) on CO2

Table 8
Diagnostics test.

Countries	Diagnostics	Coefficient	*P*-value	Countries	Diagnostics	Coefficient	P-value
	SC	2.26	0.2201	Japan	SC	5.53	0.9084
Canada	HT	1.25	0.3143		HT	0.57	0.8376
	RR	0.60	0.1204		RR	0.15	0.7165
	SC	1.53	0.3024	UK	SC	1.24	0.3236
	HT	0.42	0.2142		HT	0.94	0.5514
France	RR	0.58	0.5768		RR	0.006	0.9369
	SC	0.32	0.5215	USA	SC	1.06	0.3728
	HT	0.23	0.9812		HT	0.48	0.9125
Germany	RR	0.03	0.2124		RR	0.30	0.3229
	SC	8.85	0.1804				
Italy	HT	1.58	0.2746				
	RR	0.77	0.4664				

Note: SC, HT RR represent serial correlation, heteroscedasticity, and Ramsey's RESET statistic.

Table 9
Co-integration results.

Variables	Canada	France	Germany	Italy	Japan	UK	USA
Short-run coefficients							
$CO2_{t-1}$			6.62		0.46**	−0.20**	0.17*
$CO2_{t-2}$			8.88**		0.49***		
FD^+	−0.05	−1.03***	−8.91	0.73*	0.95**	−0.12	0.22*
FD^+_{t-1}		−0.19	1.65	−1.87**	0.06	−0.53	−0.10
FD^+_{t-2}		−0.48		0.90**	0.31	−0.72*	
FD^-	0.007*	2.29**	0.86	−0.50*	0.86*	1.23*	0.83**
FD^-_{t-1}		−1.35	−4.58	−1.41**	1.04**	0.59	1.21***
FD^-_{t-2}		2.33**			−1.13**		
REC^+	0.07	−0.09	0.34	−0.38***	−0.12	−0.08	−0.25***
REC^+_{t-1}		0.06	0.07	−0.26***	−0.24*	0.12	
REC^+_{t-2}		0.17				0.09	
REC^-	0.35	0.07	0.19	−0.20**	−0.42**	−0.18	0.01
REC^-_{t-1}			9.26	0.43***	−0.23*		−0.12**
REC^-_{t-2}					0.33**		
HC^+	0.008	−0.11**	0.04	−0.03	−0.11**	−0.01	−0.02*
HC^+_{t-1}		−0.02	−0.10	−0.11**	−0.05**		0.03
HC^+_{t-2}		−0.10**		0.14**	−0.04*		
HC^-	−0.03**	−0.02	−0.35*	−0.03***	0.01	0.01	0.04
HC^-_{t-1}		0.07	0.82	−0.25***		−0.12*	
HC^-_{t-2}				−0.15***			
ECM	−0.30***	−1.31***	−1.40***	−1.16***	−0.84***	−0.87**	−0.88***
Long-run coefficients							
FD^+	1.64**	−0.16*	−1.22*	−1.61***	0.05	1.56**	0.41***
FD^-	0.02	1.78**	0.71*	0.05*	1.04	2.06*	2.14***
REC^+	0.22	−0.29**	0.02	−0.24***	−0.17*	−0.43***	−0.28***
REC^-	−1.13**	0.12	−3.20*	−0.89***	−0.85*	0.17	−0.20***
HC^+	−0.23*	0.008	−0.05*	−0.18**	−0.09*	−0.01	−0.20***
HC^-	−0.10*	−0.27**	−0.09*	−0.36***	0.02	−0.21*	0.05
C	6.23***	6.22***	6.23***	5.96***	7.02***	6.53***	8.64***
R^2	0.965	0.994	0.998	0.998	0.988	0.993	0.98
Adj-R^2	0.950	0.976	0.969	0.994	0.944	0.981	0.97
D-W Stat	2.34	2.37	2.86	3.31	3.09	2.66	2.76
CUSUM	S	S	S	S	S	S	S
CUSUMSQ	S	S	S	S	S	S	S

Note: + and – indicate the partial sum of positive and negative change in variables, CUSUM and CUSUMSQ represent the cumulative sum of the recursive residual and cumulative sum of the squares of recursive residuals (stable S, not stable NS). *, ** and *** indicate the level of significance at 1%, 5%, and 10%.

Table 10
Results for asymmetries and symmetries restrictions.

Countries	Wald test	FD	causal	REC	causal	HC	causal
Canada	WLR-E	28.35(0.0000)	A	17.9(0.0001)	A	25.6(0.0000)	A
	WLR-S	8.2(0.0161)	A	11.7(0.0028)	A	4.7(0.0939)	A
France	WLR-E	23.9(0.0000)	A	18.4(0.0001)	A	8.5(0.0137)	A
	WLR-S	19.3(0.0001)	A	6.3(0.0960)	A	5.6(0.0586)	A
Germany	WLR-E	12.2(0.0003)	A	3.01(0.005)	A	7.7(0.0207)	A
	WLR-S	9.3(0.0045)	A	2.1(0.0008)	A	17.02(0.0002)	A
Italy	WLR-E	33.2(0.0003)	A	35.4(0.0002)	A	19.9(0.0013)	A
	WLR-S	5.5(0.0218)	A	29.3(0.0002)	A	13.2(0.0017)	A
Japan	WLR-E	0.95(0.3257)	S	22.6(0.0016)	A	2.78(0.0031)	A
	WLR-S	10.2(0.0062)	A	9.68(0.0077)	A	7.58(0.0182)	A
UK	WLR-E	12.6(0.0018)	A	7.94(0.0086)	A	1.82(0.0007)	A
	WLR-S	3.17(0.0564)	A	1.51(0.0421)	A	1.3(0.1950)	S
USA	WLR-E	28.03(0.0000)	A	19.73(0.0001)	A	15.03(0.0005)	A
	WLR-S	48.2(0.0000)	A	7.2(0.0260)	A	7.1(0.0300)	A

Note: WLR-E and WLR-S represent the Wald test for long-run and short-run symmetries and where the null hypothesis of symmetries is rejected, and the alternative hypothesis of asymmetry is accepted at a significant level 1%,5%, and 10%, which represent as *, ** and *** respectively.

emissions on a variation of 1%. Lastly, positive shocks are insignificant in France and UK, but negative shocks to HC reduce the CO2 emissions. Results are indicative of a cumulative function of positive change (0.008, and − 0.01) and cumulative functions of negative change (−0.27, and −0.21) improve the environmental quality at 1% change.

In the short-run, positive shocks to HC improve the environment's quality for France, Japan, and the USA, but negative shocks are insignificant. Conversely, in the case of Canada, Germany, and Italy, positive shocks to HC are insignificant. Having said that, negative shocks to HC can be seen to improve the environmental quality. Finally, the Wald test results for long-run and short indicate asymmetries behavior for HC and CO2 emissions, since a coefficient that makes a positive change on CO2 emission is not similar to the coefficients of adverse change in the case of all G7 countries.

Finally, the results of dynamic multipliers adjustment (see Figs. 2 to 22 in Appendix A) reveal that CO2 emission adjustment toward its new equilibrium in terms of positive and negative shocks in FD, REC, and HC over 34 years. The positive shock (continuous black line) and negative

Table 11
Results for 2SLS estimation.

Variables	Coefficient	p-value
FD	−0.3820***	0.008
REC	−0.3285***	0.002
HC	−1.3851	0.593
Constant	0.0086**	0.031
Number of obs	–	231
Wald chi2	10.23**	0.0167
Sargan test of overidentification	6.253	0.2824
Basmann test of overidentification	6.176	0.2895
Breusch-Pagan test of heteroskedasticity	0.080	0.7833

***, ** and * indicate the level of significance at 1%, 5%, and 10%.

shock (dashed black line) capture the change of curve, thus revealing the adjustment of FD, REC, and HC to a positive and negative effect of multipliers to shocks CO2 emission at the given period. The dashed red line, which denotes the asymmetry, indicates the positive and negative effects multipliers to shocks of FD, REC, and HC.

4.4. Two-Stage Least Square (2SLS) estimation

To understand the impact of FD, REC, and HC on CO2 emission at the panel level, we further implement the 2SLS test. Table 11 shows the results of this test. The coefficient value of FD is negatively correlated with CO2 emission, which suggests a 1% increase of FD can decrease −0.3820% of carbon emission in G-7 countries. It indicates the block of G-7 countries which comprises developed economies, a shift from conventional sources of financing to green and sustainable financing. Moreover, these countries provide funds to encourage research and development and impose tax restrictions on fossil fuel consumption industries, which improves the quality of the environment. These findings are in line with the past studies Shahbaz et al., 2013a, 2013b; Shahbaz et al., 2018; Sheraz et al., 2021a, 2021b). Similarly, the role of REC exerts a negative and significant effect on CO2 emission, which shows that a 1% consumption of REC can reduce −0.3285% of CO2 emissions in G-7 countries. It shows a shift toward REC while reinforcing that sustainable economic growth can improve the quality of the environment and it is consistent with the findings of previous studies (Balsalobre-Lorente et al., 2018; Bao and Xu, 2019; Charfeddine and Kahia, 2019; Khan et al., 2019; Rahman and Velayutham, 2020; Wang et al., 2020).

In addition, the coefficient of HC, instrumented by the public expenditure on education, shows a negative and but statistically insignificant effect on CO2 emission. It suggests that a 1% increase of HC can reduce the CO2 emissions by −1.3851% in G-7 countries. These findings reveal that an increase in the level of education (technical training and R & D), public awareness improves the environmental quality but lowers CO2 emission levels, which is consistent with these studies (Bashir et al., 2019; Costantini and Monni, 2008; Lan et al., 2012; Yao et al., 2020).

4.5. Asymmetric and symmetric Hatemi-J time series causality test

We employed the asymmetric causality test (Hatemi-J, 2012) to capture the asymmetric and symmetric causal relationship between CO2, FD, REC, and HC. Table 12 showed an asymmetric bidirectional causality between CO2 → FD and FD → CO2 (row 1, 4) for all the G7 countries. We noted bidirectional asymmetric causality between positive shocks (row 2, 5) running from $CO2^{+}$ → FD^{+} and FD^{+} → $CO2^{+}$ in Canada, France, Germany, Italy, and the USA. Meanwhile, in Japan and the UK, the neutral effect is positively asymmetric to $CO2^{+}$ → FD^{+} is neutral (row2) and unidirectional for FD^{+} → $CO2^{+}$ (row 5). Similarly, asymmetric bidirectional nexus is noted for negative shocks (row 3, 6) running from $CO2^{-}$ → FD^{-} to FD^{-} → $CO2^{- \text{ in}}$ Canada, France, Germany, Italy, and Japan, respectively.

The results indicate the bidirectional causal relationship between CO2 emission and REC (for both symmetric and asymmetric for negative shock) running from CO2 → REC and REC → CO2 (row 7, 10), and $CO2^{-}$ → REC^{-} and REC^{-} → CO2 (row 9, 12) for G7 developed economies. Moreover, a bidirectional asymmetric nexus is observed between positive shocks in $CO2^{+}$ → REC^{+} and REC^{+} → $CO2^{+}$ (rows 8 and 11) for Canada, France, Germany, Japan, and the USA. There is a unidirectional asymmetric causal relationship between positive shocks in $CO2^{+}$ → REC^{+} (row 8); however, the neutral effect is noted for a positive shock in REC^{+} → $CO2^{+}$ (row 11).

There is a bidirectional symmetric causal relationship between CO2 → HC and HC → CO2 (row 13, 16) for the G7 developed countries. Furthermore, findings reveal that a bidirectional asymmetric relationship exists between positive shocks running from $CO2^{+}$ → HC^{+} and HC^{+} → $CO2^{+}$ (row 14, 17) in Canada, Italy, the UK, and the USA. Although we reported a unidirectional causal relationship between a positive shock in $CO2^{+}$ → HC^{+} for Germany and Japan, there is a neutral relationship between $CO2^{+}$ → HC^{+} (row 14) in France. Similarly, we have also reported a bidirectional asymmetric causal relationship for a negative shock in $CO2^{-}$ → HC^{-} and HC^{-} → $CO2^{-}$ (row 15, 18) for France, Italy, Japan, the UK, and the USA. However, we found a neutral

Table 12
Asymmetric and symmetric causality test.

	Countries	Canada	France	Germany	Italy	Japan	UK	USA
	Variables	Wald test	Wald test	Wald test	Wald test	Wald test	Wald test	Wald test
1	CO2 → FD	1.746***	3.507***	0.327***	3.853***	0.438***	1.893***	7.756*
2	$CO2^{+}$ → FD^{+}	0.697***	0.902***	1.324***	7.516*	11.063	3.94	0.524***
3	$CO2^{-}$ → FD^{-}	0.972***	1.983***	4.726*	2.178***	3.56***	18.988	0.618
4	FD → CO2	2.193***	1.731***	0.412***	0.035***	0.091***	0.165***	2.212***
5	FD^{+} → $CO2^{+}$	9.005*	10.559	1.515***	7.639*	2.938***	0.381***	0.32***
6	FD^{-} → $CO2^{-}$	33.342	6.874*	3.595***	3.951**	0.694***	0.46***	5.729**
7	CO2 → REC	1.746***	2.589***	4.149**	8.075*	0.664***	8.359***	0.837***
8	$CO2^{+}$ → REC^{+}	0.388***	1.384***	9.459*	1.396***	2.879***	0.523***	7.095*
9	$CO2^{-}$ → REC^{-}	16.139*	3.737***	2.379**	7.429*	9.846*	5.975*	8.67*
10	REC → CO2	2.636***	6.553*	5.554*	0.225***	0.022***	1.35***	0.514***
11	REC^{+} → $CO2^{+}$	9.915*	2.322***	0.065***	9.068	1.75***	24.428	3.418***
12	REC^{-} → $CO2^{-}$	3.678***	2.452***	0.073***	0.328***	0.009***	0.429***	0.83***
13	CO2 → HC	0.014***	2.752***	10.534*	5.122**	3.105***	2.303***	2.239***
14	$CO2^{+}$ → HC^{+}	4.39***	14.36	1.538***	1.538***	1.375***	1.457***	2.355***
15	$CO2^{-}$ → HC^{-}	17.273	1.513***	23.382	1.72***	10.74*	1.443***	4.053**
16	HC → CO2	2.455***	1.102***	1.036***	0.465***	0.786***	0.315***	0.041***
17	HC^{+} → $CO2^{+}$	14.202**	3.661***	15.637	2.333***	60.865	5.762*	8.533*
18	HC^{-} → $CO2^{-}$	0.317***	1.464***	3.174***	7.564**	13.274*	3.348***	0.544***

Note → represent unidirectional causality, *, **, *** indicates the significance level at 1%, 5% and 10% respectively. For the selection of lag, we used HJC information criteria, while unrestricted extra lag is included in the VAR model for unit root effects, proposed by (Toda and Yamamoto, 1995).

Table 13
Dumitrescu and Hurlin (D-H) panel causality test.

Null Hypothesis:	W-Stat.	Zbar-Stat.	P-value
CO2 → FD	3.600	1.628	0.1034
FD → CO2	4.031*	2.115	0.0344
CO2 → RE	2.719	0.632	0.5273
RE → CO2	4.277*	2.393	0.0167
CO2 → HC	1.817	−0.387	0.6987
HC → CO2	6.278***	4.656	0.0000

Note → represent unidirectional causality, *, **, *** indicates the significance level at 1%, 5% and 10% respectively.

and asymmetric unidirectional relationship between $CO2^{-}$ → HC^{-} and HC^{-} → $CO2^{-}$ (row 15, 18) in Canada and Germany.

4.6. Dumitrescu and Hurlin (D-H) panel causality test

To estimate the panel causality effect between CO2, FD, REC, and HC, this study employed a pair-wise (Durusu-ciftci et al., 2020) (D-H) non-causality test. Estimated results are presented in Table 13, which illuminates diverse findings. In the case of FD and CO2, we found a unidirectional causal relation running from FD to CO2 emission. This reveals that a change in FD significantly affects CO2 emission levels in the case of G7 countries, consistent with the past findings (Sheraz et al., 2021a, 2021b). Likewise, in the case of REC to CO2, a unidirectional casualty relationship exists that runs from REC to CO2. It reveals the impact of REC on CO2 and it is in line with the study of Toumi and Toumi (2019). Moreover, there is a one-way causality relationship between HC and CO2 emissions, which implies that HC significantly affects CO2 emission levels.

4.7. Discussion of the results

Findings of study related to FD, REC, HC, and CO2 emission would be useful for researchers, policymakers, and governments of G7 countries alike in more ways than one. A comparative analysis of past and current studies could help scholars understand the role of asymmetric and panel modeling in investment, consumption, the development of HC, and emissions nexus. By employing the bound test for time-series analysis, country-specific results show a non-linear co-integration for a long-run relationship between FD, REC, HC, and CO2 emissions for G7 developed economies.

Table 9 shows a diverse asymmetric co-integration relationship between the variables for G7 countries. In the long run, for the UK and the USA, positive and negative shocks to FD negatively impact environmental quality, which is in line with prior studies (Charfeddine and Kahia, 2019; Wang et al., 2020) as additional investments in CO2 emission projects cause environmental degradation. In addition, mixed results are reported in the case of France, Germany, and Italy, as an asymmetric effect of FD due to positive shock improves the environmental quality and reduces CO2 emission. This is congruent with a previous study (Shahbaz et al., 2018) as a change in technology and investing in environmentally-friendly projects improve the quality. However, negative shocks are known to cause environmental degradation. Moreover, the Wald test confirms asymmetric behavior (long and short-run) in Canada, France, Germany, Italy, Japan, the UK, and the USA.

In the long run, in the case of Italy, Japan, and the USA, we have noticed positive and negative shocks to REC which have a positive impact on the environment which also support the findings of past studies (Balsalobre-Lorente et al., 2018; Bao and Xu, 2019; Charfeddine and Kahia, 2019; Khan et al., 2019; Rahman and Velayutham, 2020; Wang et al., 2020) as the switch toward the REC can reduce CO2 emissions. At the same time, France and the UK have positive shocks to REC, but in the case of Canada and Germany negative shocks to REC improve the quality of the environment by reducing the CO2 emission. Further, in Canada, France, Japan UK, and the USA, long and short-run asymmetric behavior is reported.

In the long run, for Canada, Germany, and Italy, positive and negative shocks to HC reduce CO2 emission by creating awareness and improving the skills through training, which is in line with prior studies (Bashir et al., 2019; Costantini and Monni, 2008; Lan et al., 2012; Yao et al., 2020). Further in the case of Japan and the USA, positive shocks to HC and negative shocks to HC in the case of France and the UK improve the environmental quality. Moreover, the study also reported the asymmetric (long and short-run) behavior in G7 countries.

Moreover, the study also employed a statistical technique of 2SLS to estimate the panel effect for G-7 countries. Table 11 presents the panel results for G-7 countries. As per the findings of this study, FD and REC improve the quality of the environment by making investments in green projects, shifting toward green or renewable energy. However, HC is negative but statistically insignificant with a correlation to CO2 emissions.

Further, by employing the asymmetric causality test (Hatemi-J, 2012), it was found that the results of an asymmetric and symmetric causal relationship between variables are volatile and quite interesting. There is an asymmetric bidirectional relationship between CO2 emission, FD, REC, and HC for G7 countries (Sadorsky, 2011). In Canada, France, Germany, and Italy, bidirectional asymmetric casualty running in positive and negative shocks of CO2 emission to FD, and vice versa. The study also noted a bidirectional asymmetric causal relationship for positive and negative running from CO2 emission to REC for Canada, France, Germany, Japan, and the USA, which is in line with the views of Toumi and Toumi (2019).

Moreover, the pair-wise panel non-causality test for G7 countries indicates a unidirectional causal relationship running from FD to CO2 emission which is similar to the past study of Sheraz et al. (2021a, 2021b). In addition, results show that REC and HC also have a unidirectional causal relationship with CO2 emission which is in line with the past findings of Toumi and Toumi (2019) and Wang et al. (2020).

5. Conclusion and policy implications

This study analyzed the nonlinear impacts of financial development and renewable energy generation on CO_2 emissions for G7 countries over 1986–2019. By adopting the NARDL and 2SLS approach, the study outcomes revealed the asymmetric impacts of financial development and renewable energy generation on CO_2 emissions. The study outcomes reveal certain characteristics, which might be utilized for recommending a policy framework for the G7 countries.

5.1. Core policy framework

As the impacts of financial development and renewable energy generation on CO_2 emissions are not consistent across the countries and different lag specifications, it indicates that both these policy instruments need a standardized harmonization in the policy framework. It might lead to a consistent and expected impact on the CO_2 emissions. Therefore, the policy framework needs to consider both these parameters, while controlling for the effects of human capital. The policy framework needs to be designed in a way so that while having the potential environmental benefits, the economic growth pattern remains intact (Sinha et al., 2022a, b, c). Hence, the policy framework needs to follow a phase-wise implementation approach. In the first phase, the policymakers could aim at reducing the demand for fossil fuel solutions, as the industrial sectors in the G7 countries are majorly driven by it. To reduce this demand, the policymakers might choose to utilize the financialization channel, for which the financial institutions might be used as the intermediaries (Sharma et al., 2021). First, policymakers would do well to ensure a mandate to replace the existing fossil fuel-based technologies within a certain period. Some of the firms might be reluctant to undergo this process. To overcome this barrier, the financial institutions might be instructed to provide credits to the firms against a differential rate of interest, depending on the carbon footprint of the firms, i.e., firms with higher carbon footprint will have to pay a higher rate of interest. This might gradually discourage the firms to use fossil fuel-based solutions, as the credit burden will eventually increase their cost of operations. Design of this phase has extended the finding of Knittel (2012) on the imposition of Pigouvian taxes on petroleum products used in transportation in the OECD countries and its consequences. After this phase becomes operational, the demand for fossil fuel solutions will start declining, and resultantly, the demand for renewable energy solutions will rise.

Following the first phase of implementation, the second phase needs to focus on the development and deployment of renewable energy solutions. An incisive policy intervention is necessary to safeguard the interests of the firms as the high implementation cost of the renewable energy solutions might negatively impact the cash flow of the firms (Sinha et al., 2020a, b). The policymakers need to make the renewable energy technologies available to the firms at a subsidized rate and on a pro-rata basis, based on the revenue stream of the firm. However, this rate will be lower than the maximum value of the differential interest rate levied during the first phase, because a higher rate might discourage the firms to continue their operations, and thereby, the overall economic growth pattern might be impacted (Sinha et al., 2020c, d). During the financial appraisal of a petrochemical firm in South Africa, this phenomenon was observed, and this finding was validated against the depreciation allowance under the *Renewable Energy Sources Act* of Germany (Govender et al., 2019). The rationale of the design of this phase of the policy framework has been adopted from the findings of this study. Policymakers might also choose to provide certain interest rate holidays to the firms so that the firms might get some relaxation from the burden of credit. While this move will gradually smoothen the implementation of renewable energy solutions at the firm level, the fiscal loss borne by the countries might be settled against the interest income earned during the first phase (Cheng et al., 2021). In fact, the second phase of the implementation process should commence after the cumulative interest income in the first phase reaches a threshold level, at which the policymakers can subsidize the renewable energy solutions.

While the implications drawn from the empirical outcomes of the study details about the firm-level activities, the policy framework also needs to take account of the households. Creating a demand of the renewable energy and energy efficient solutions will not only help in reducing the CO_2 emissions at household level, but also will help in sustaining the renewable energy demand at the grassroots level (Sinha et al., 2017, 2018). Hence, these two phases will have an impact on the renewable energy adoption at the household level, as well. With the rise in the demand of renewable energy solutions, the renewable energy generation will be able to achieve economies of scale. This will lead to reduction in the price of these solutions. Extending the finding of Dato (2018) for the OECD countries, the demand for renewable energy in the households will tend to rise, leading to a reduction in the CO_2 emissions. With the price reduction, the risk associated with the renewable energy projects might go down, and this might open up the avenues for the household investments in energy efficiency and renewable energy solutions. This phenomenon was observed by Ameli and Brandt (2015), while observing the roadblocks in household investment in energy efficiency and renewable energy in the OECD countries. However, in order to rationalize the income disparity in the households, the policymakers might choose to use differential subsidy mechanism for procuring the solutions, as the willingness to pay for the energy efficiency and renewable energy solutions might differ based on the household income level (Alberini et al., 2018). This subsidized pricing will also help these households to be proactively responsive to the international market movements (Böhringer et al., 2021). Moreover, the policymakers also consider the energy efficiency measures while the construction of the houses to reduce the future possibilities of CO_2 emissions (Nishioka et al., 2000).

Once these two phases of the policy framework are operational, the countries will start making a progression toward reducing CO_2 emissions and improving environmental quality. The revamped production processes will be able to gradually internalize the negative environmental externalities exerted by the industrial growth pattern. This move might enable the policymakers to progress toward the accomplishment of SDG 13 goals. On the other hand, the steady rise in the demand for renewable energy solutions will start making the energy solutions cleaner. This policy move will make a way to attain the objectives of SDG 7.

5.2. *Tangential policy framework*

As the core policy framework is operation, it might require a support mechanism for sustenance. In this pursuit, the tangential policy framework is developed, which might act as the third phase of the policy framework (Zafar et al., 2020, 2021). This particular phase of the policy framework should aim at the development of human capital for sustaining the first two phases. As the demand for renewable energy starts rising, the existing renewable energy generation infrastructure might be inadequate to support the demand. Hence, these nations need to focus on developing the capacity to innovate by promoting human capital. By bringing changes in the educational curricula and by providing training, the policymakers might create an environment of sustainable entrepreneurship, which can not only facilitate economic growth but also ensure environmental sustainability. Policymakers in the G7 countries need to encourage entrepreneurship ventures for generating renewable energy solutions. The resulting economies of scale might help reduce the price of renewable energy solutions. By this key policy move, cleaner energy solutions will also become affordable, as a result of which progression of these nations toward the achievement of SDG 7 will be stronger.

5.3. *Limitations and future projections*

As the study is focused on the G7 countries and has considered two policy instruments, i.e., financial development and renewable energy generation, the policy framework might appear to be inconclusive. Admittedly, the consideration of other growth aspects of the G7 countries might have contributed to the multidimensionality of the recommended policy framework. However, the parameters were chosen within the theoretical boundaries of the research problem, and expanding the scope of the problem could have incorporated other growth drivers. However, the policy framework has been developed considering the context of other developed and developing nations, which might require a policy revamp to encounter the environmental degradation issues. There lies the generalizability of the policy framework recommended in the study. Further studies would do well to explore the comparative scenario between the developed and the developing countries to provide policy directions from a broader perspective.

Consent to participate section

All authors participated in the process of draft completion. All authors have read and agreed to the published version of the manuscript.

Ethical approval

The study did not use any data which need approval.

Consent to publish

All authors agree to publish.

Authors contributions

All Authors contributed conceptually, formally and in original drafting. All Authors contributed. Responsibilities are as follows; Deyi Xu: supervision, funding acquisition, validation, writing—review and editing. Muhammad Sheraz: conceptualization, formal analysis, methodology, writing—original draft, writing—review and editing. Arshad Hassan: conceptualization, methodology, results validation, writing—review and editing. Avik Sinha: conceptualization, methodology, software, writing—original draft, writing—review and editing. Saif Ullah: conceptualization, methodology, validation, writing—review and editing.

Funding

Project Name: Major Program of the National Natural Science Foundation of China, "Supply Security and Management Policy of Strategic and Critical Mineral Resources in the New Era" (Grant No: 71991482), National Natural Science Foundation of China, Natural Science Foundation of China (No. 72074197, & No. 71991480). The Open Fund Project of Hubei Provincial Research Base for Regional Innovation Capacity Monitoring and Analysis Soft Science (No. HBQY2020z10) and the Major Research Projects of Guangxi Department of Natural Resources in 2019 (Sub-bid C) (No. GXZC2019-G3-25122-GXGL-C).

Availability of data and materials

Data available upon request.

CRediT authorship contribution statement

Xu Deyi: Supervision, Funding acquisition, Validation, Writing – review & editing. **Muhammad Sheraz:** Conceptualization, Formal analysis, Methodology, Writing – original draft. **Arshad Hassan:** Conceptualization, Methodology, Validation, Writing – review & editing. **Avik Sinha:** Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **Saif Ullah:** Conceptualization, Writing – original draft, Methodology, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors reported no potential conflict of interest concerning the research, authorship, and/or publication of this article.

Acknowledgment

We are very grateful to Dr. Jaleel Ahmad for their helpful comments and suggestions which improved the draft.

Appendix A

Canada.

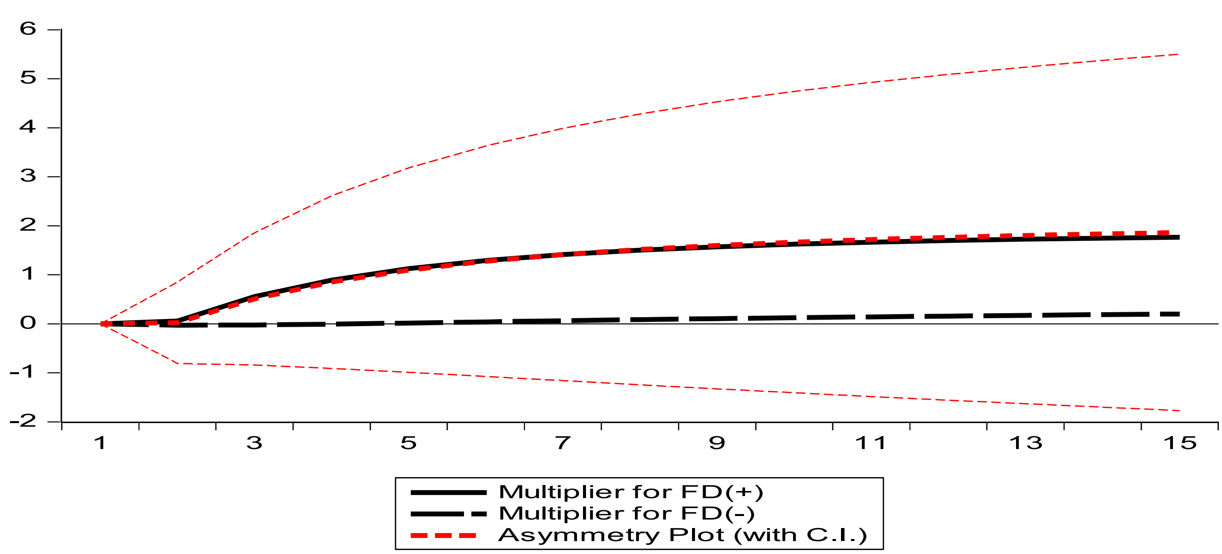

Fig. 2. The cumulative effect of FD on CO2.

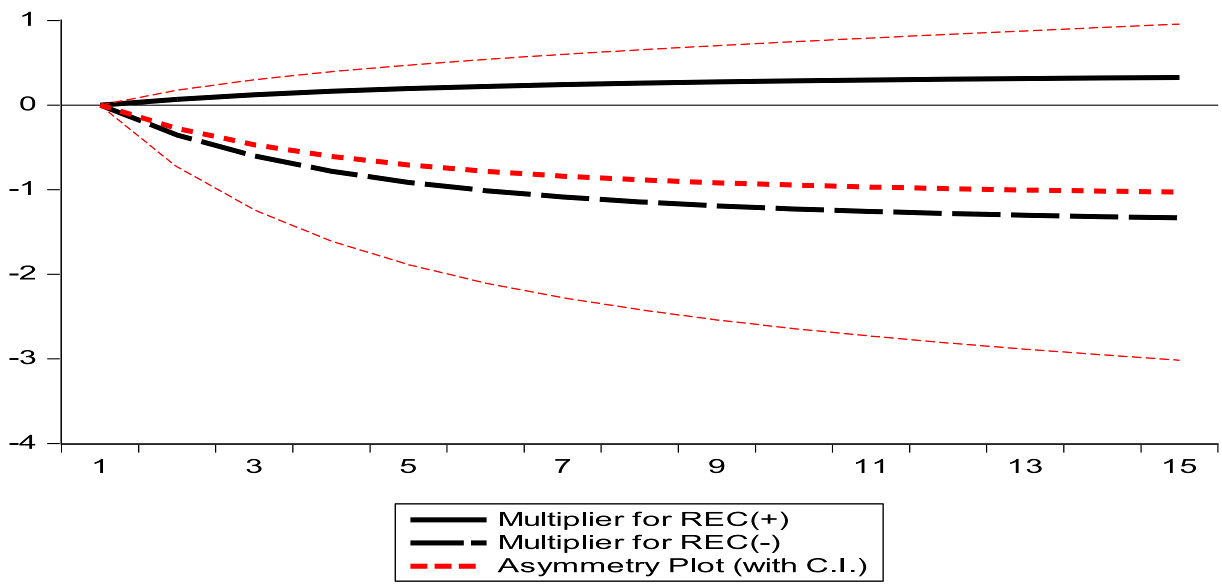

Fig. 3. The cumulative effect of REC on CO2.

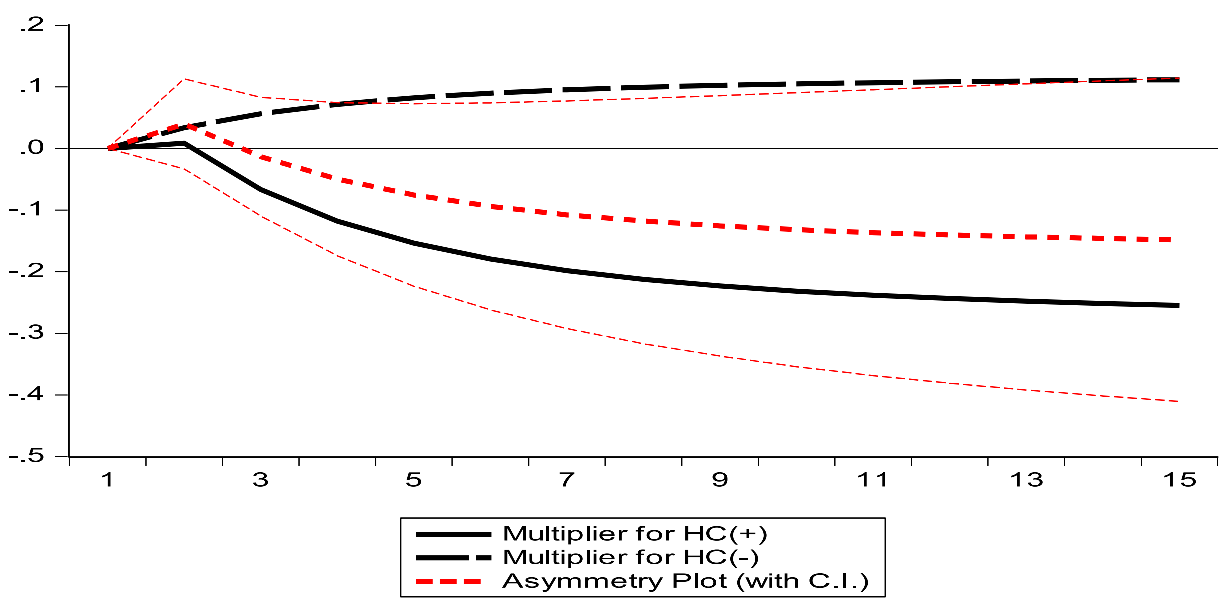

Fig. 4. The cumulative effect of HC on CO2.

France.

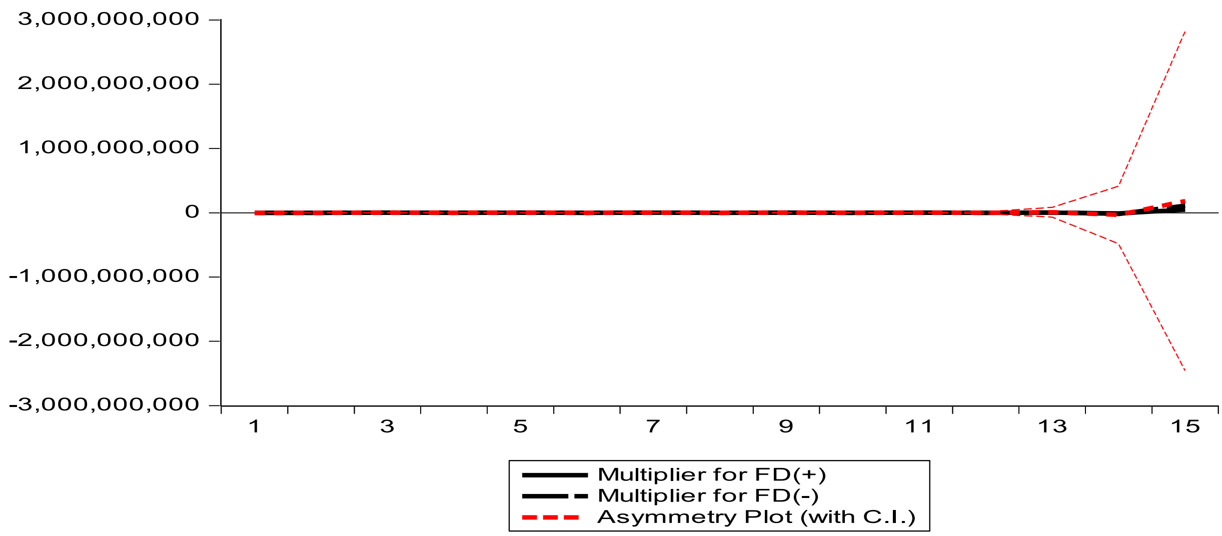

Fig. 5. The cumulative effect of FD on CO2.

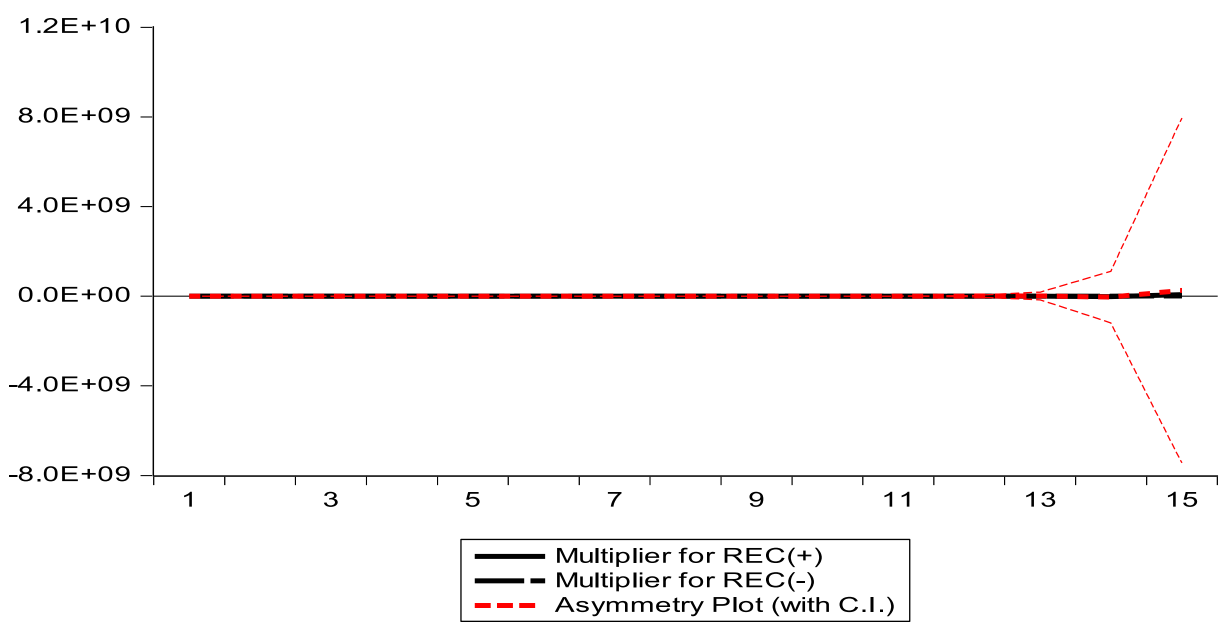

Fig. 6. Cumulative effectiveness of REC on CO2.

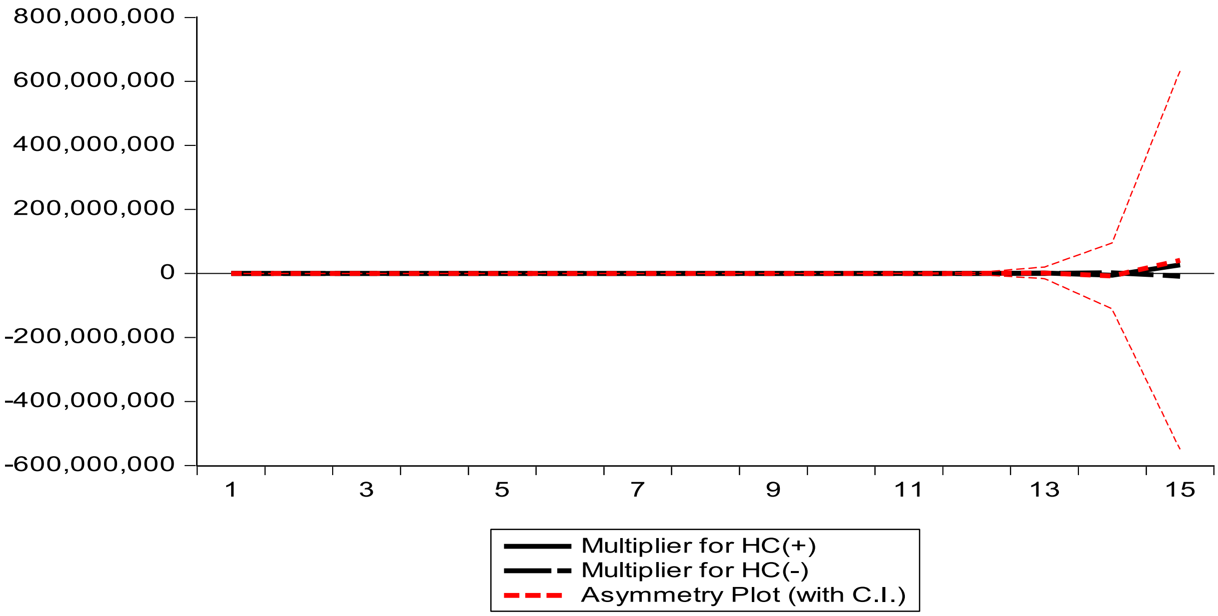

Fig. 7. Cumulative effectiveness of HC on CO2.

Germany.

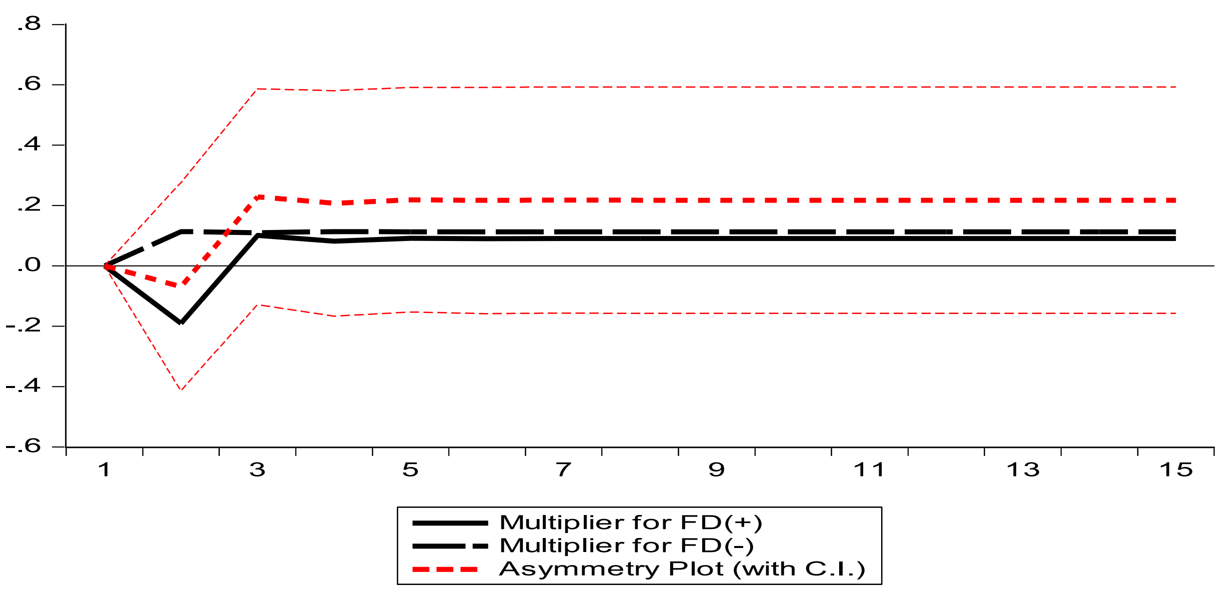

Fig. 8. The cumulative effect of FD on CO2.

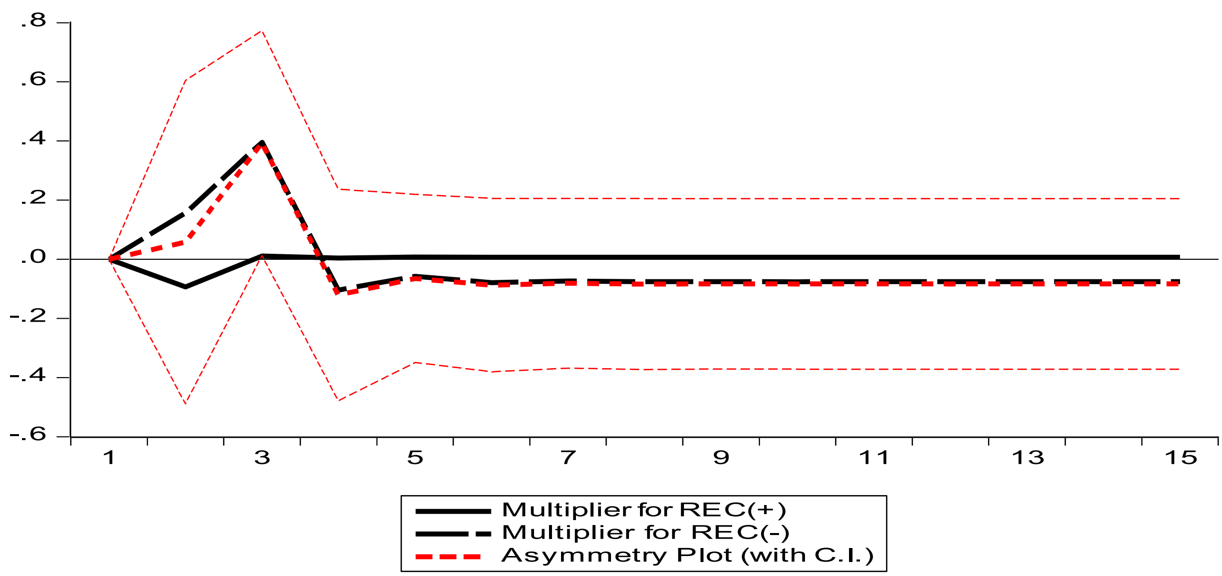

Fig. 9. Cumulative effect REC on CO2.

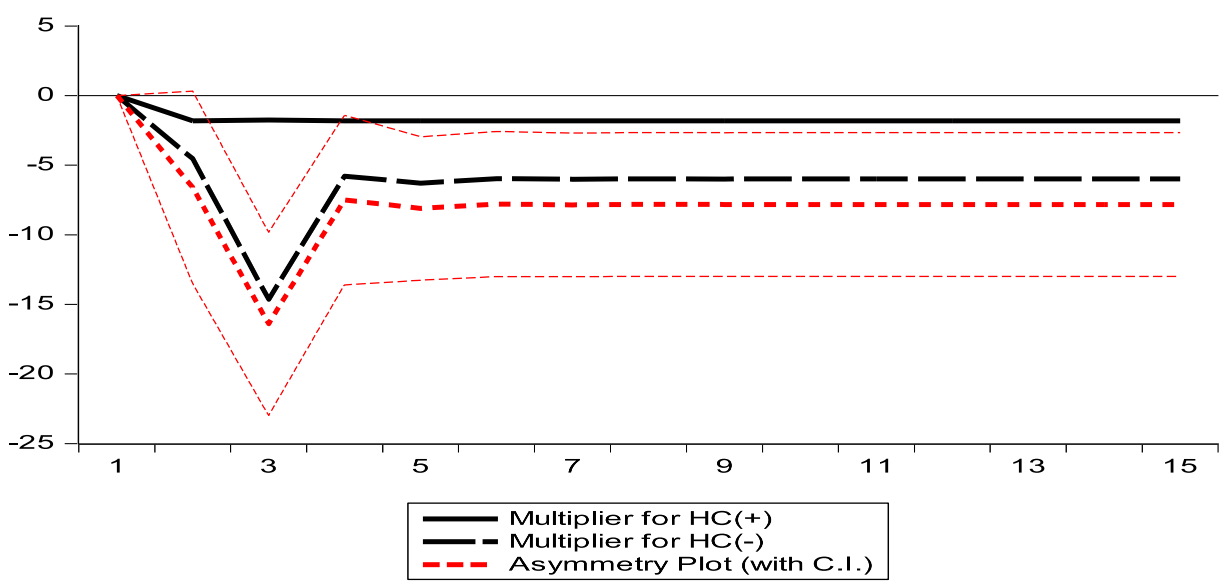

Fig. 10. The cumulative effect of HC on CO2.

Italy.

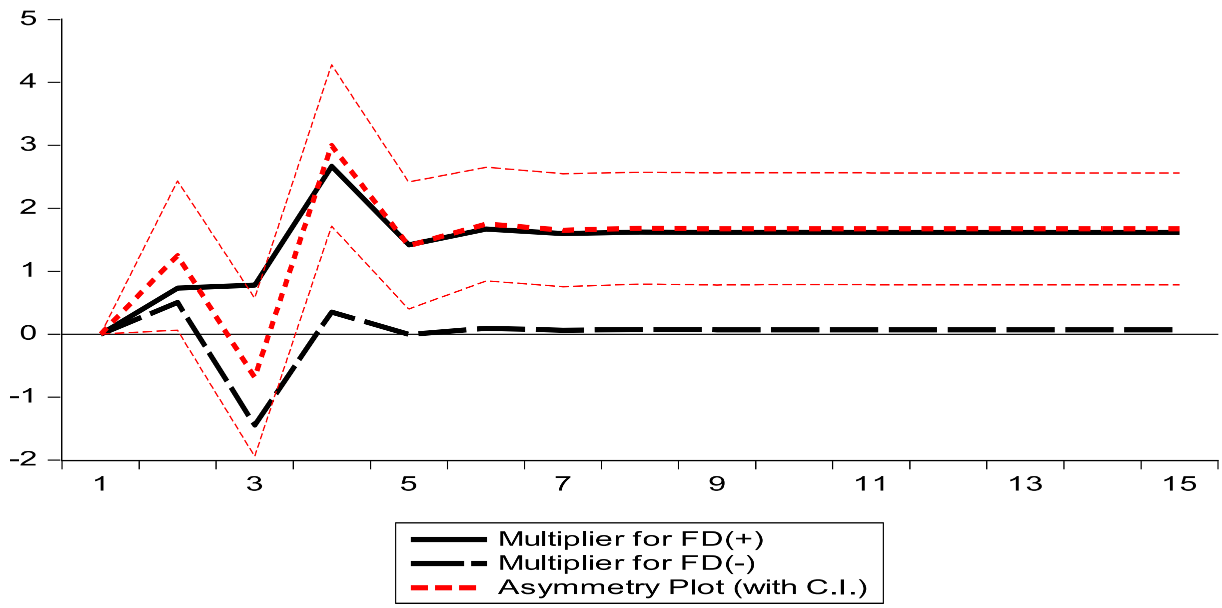

Fig. 11. The cumulative effect of FD on CO2.

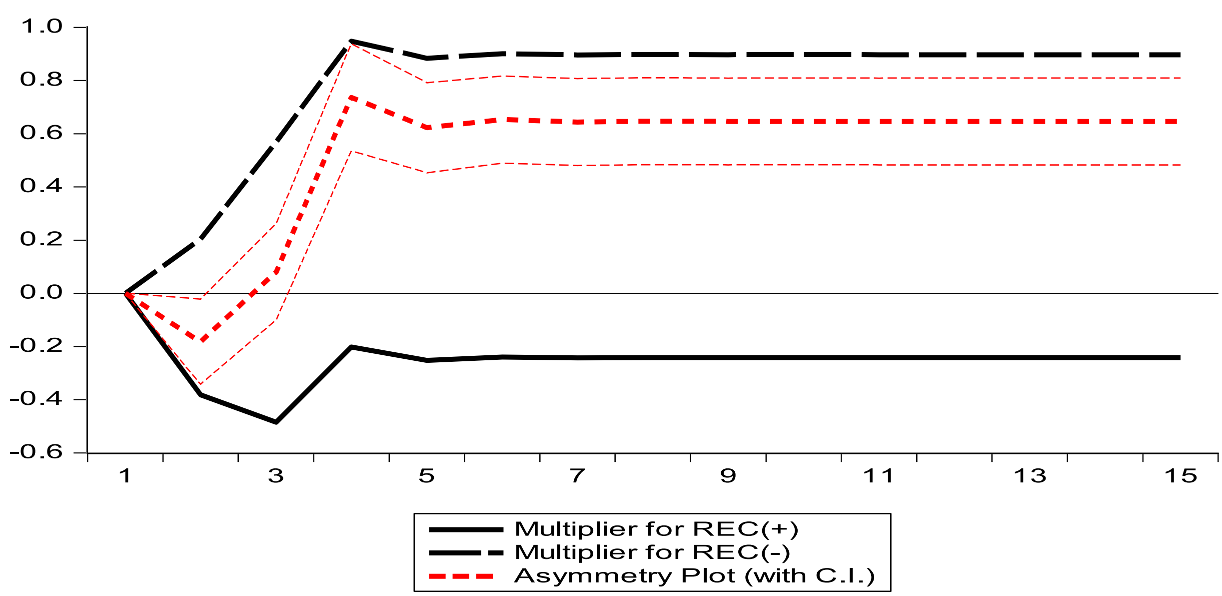

Fig. 12. The cumulative effect of REC on CO2.

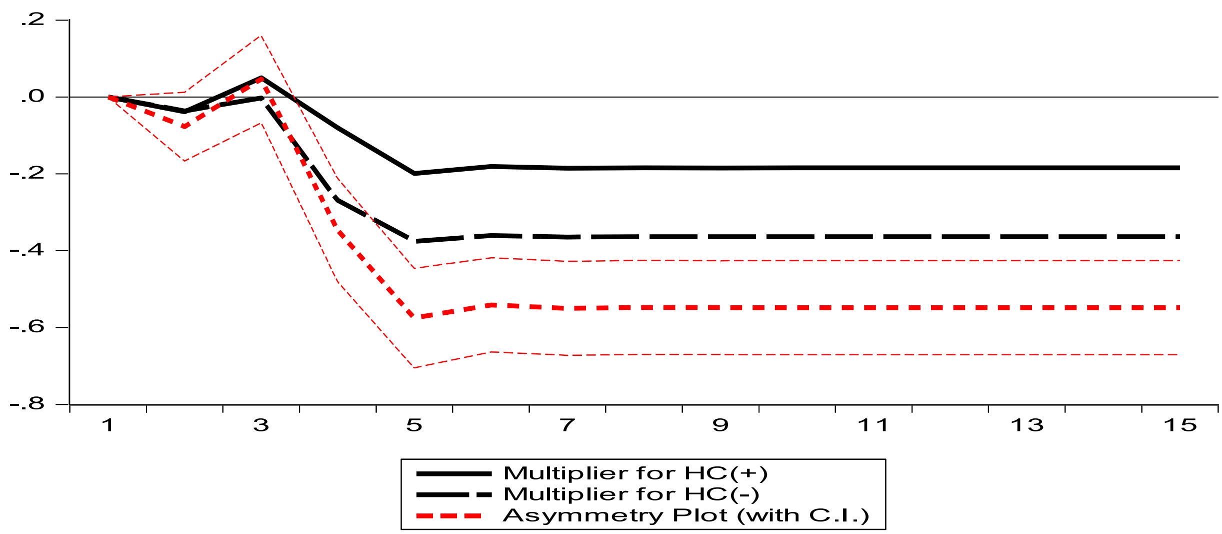

Fig. 13. The cumulative effect of HC on CO2.

Japan.

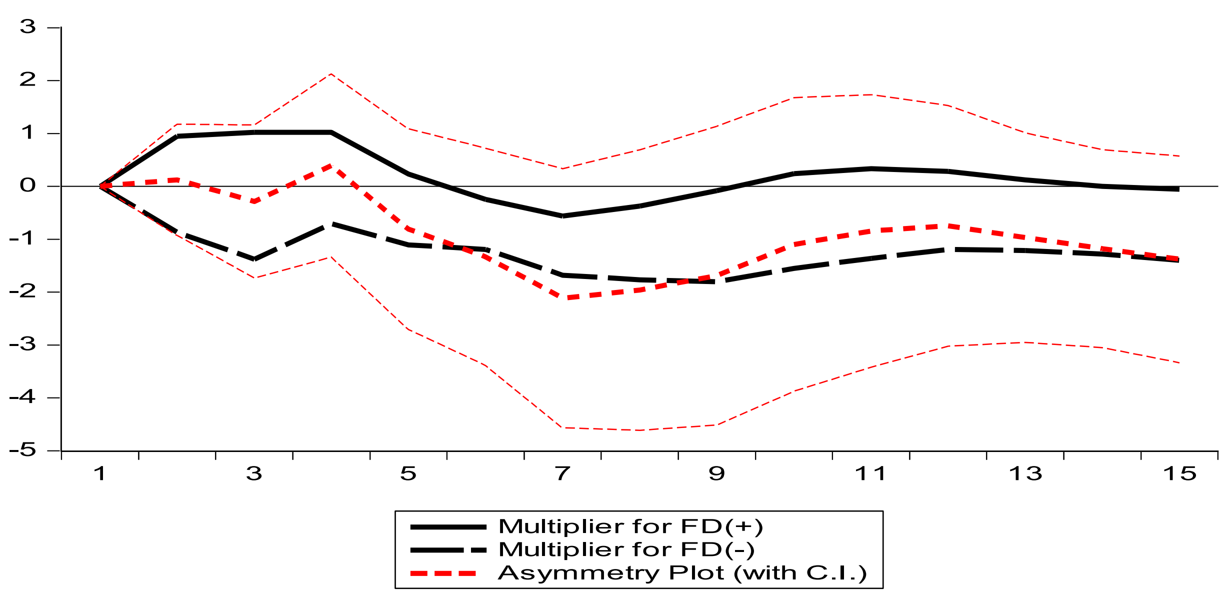

Fig. 14. The cumulative effect of FD on CO2.

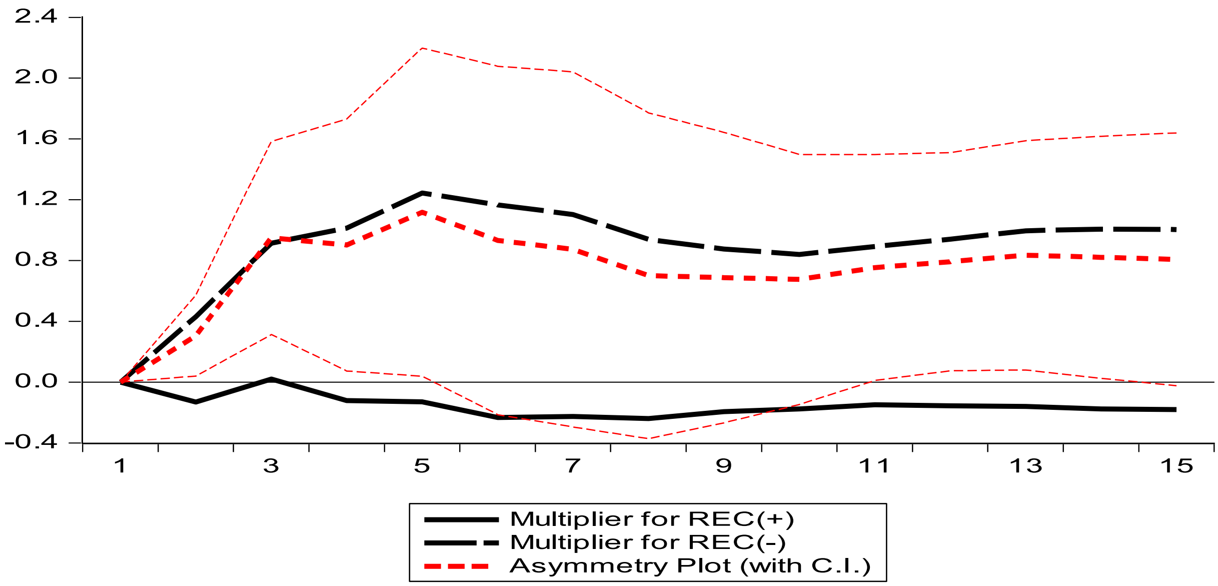

Fig. 15. The cumulative effect of REC on CO2.

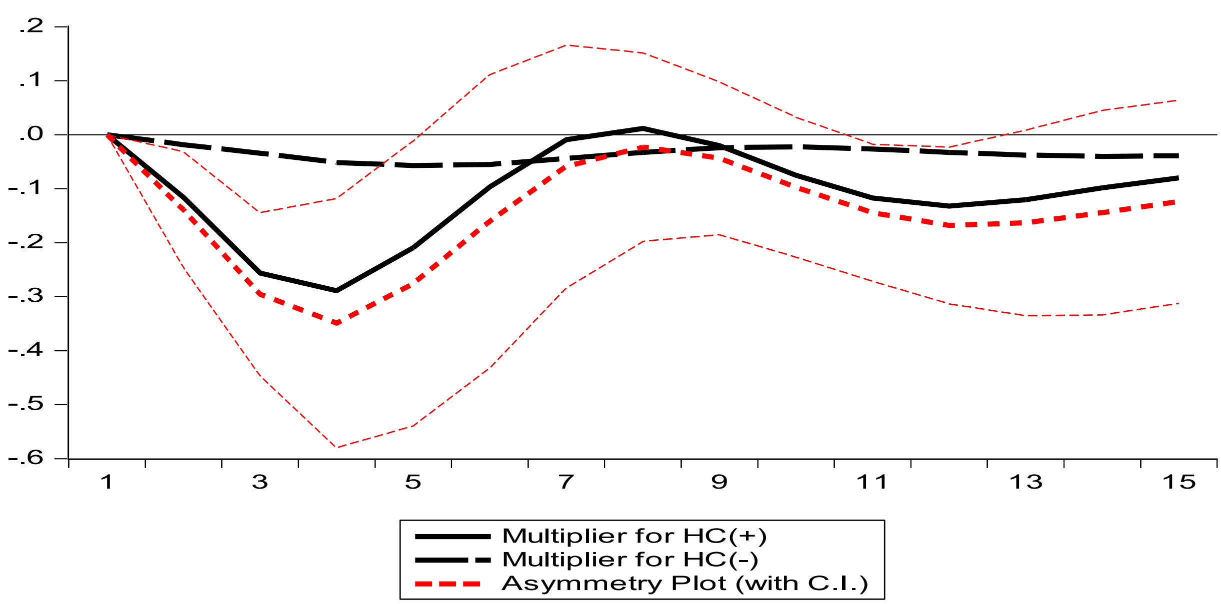

Fig. 16. The cumulative effect of HC on CO2.

UK

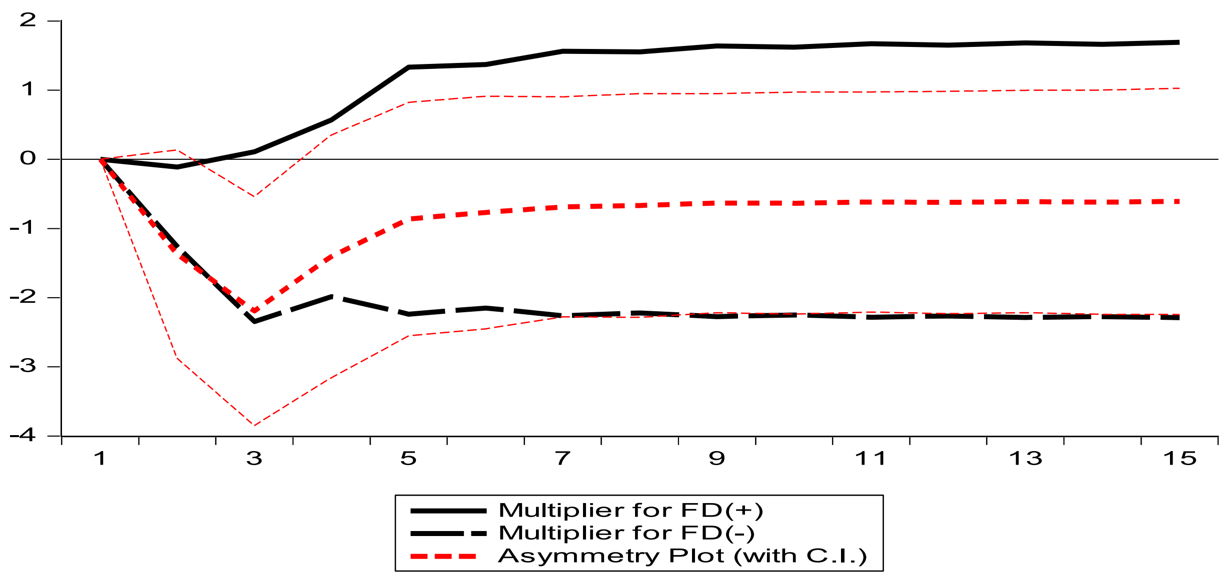

Fig. 17. The cumulative effect of FD on CO2.

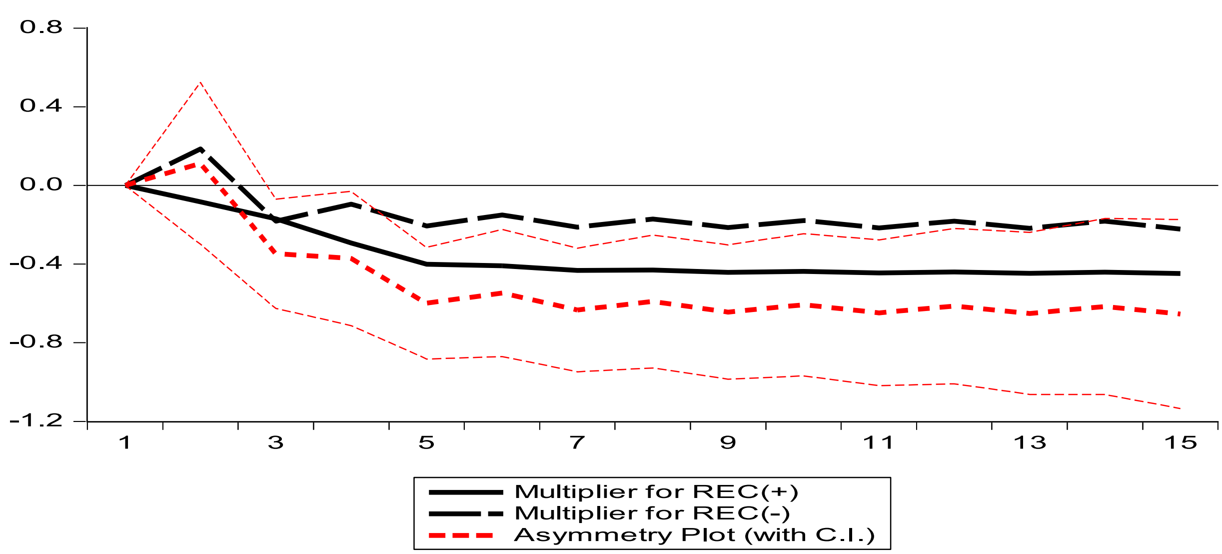

Fig. 18. The cumulative effect of REC on CO2.

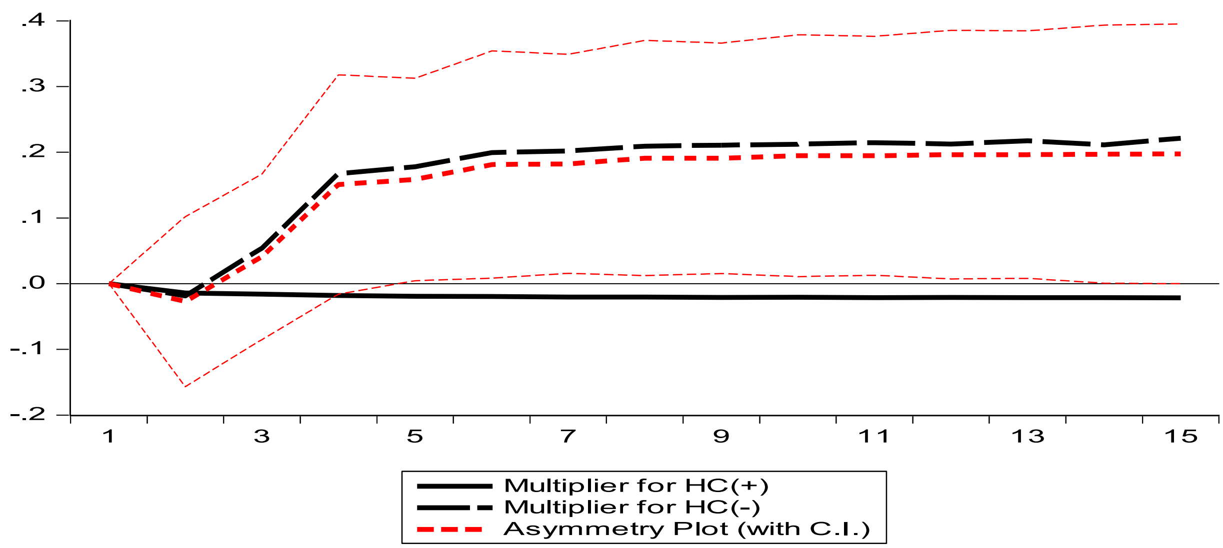

Fig. 19. The cumulative effect of HC on CO2.

USA

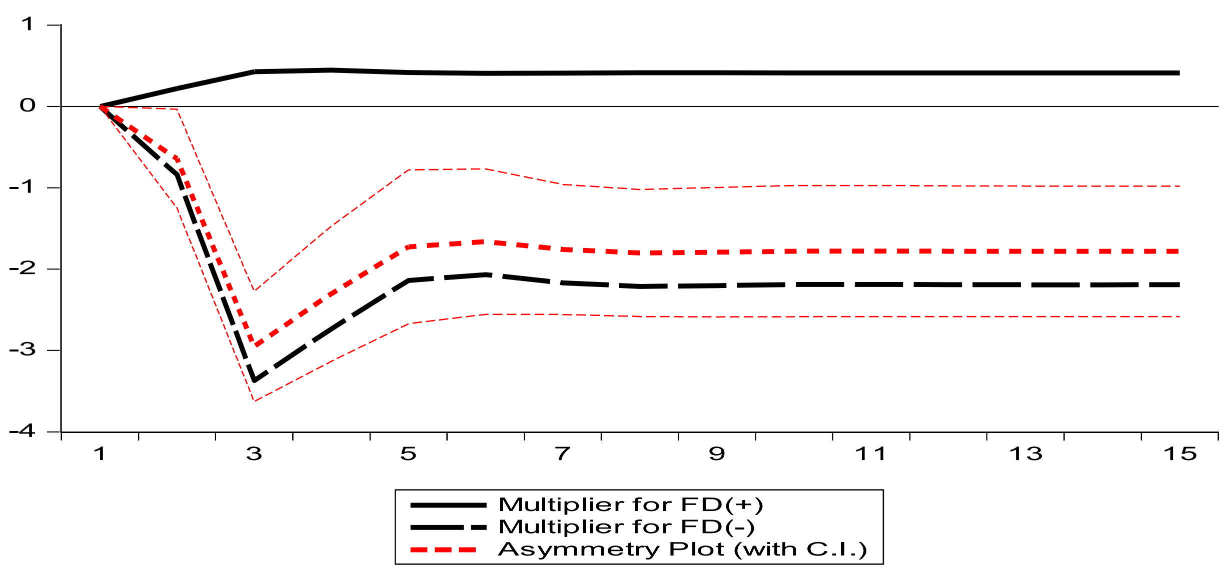

Fig. 20. The cumulative effect of FD on CO2.

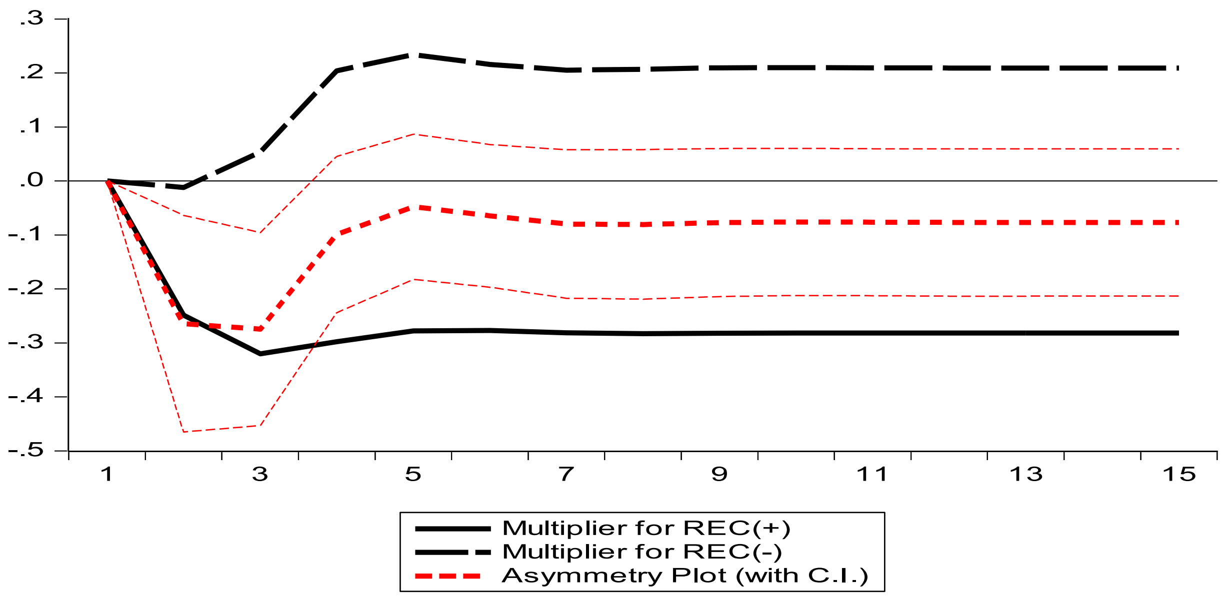

Fig. 21. The cumulative effect of REC on CO2.

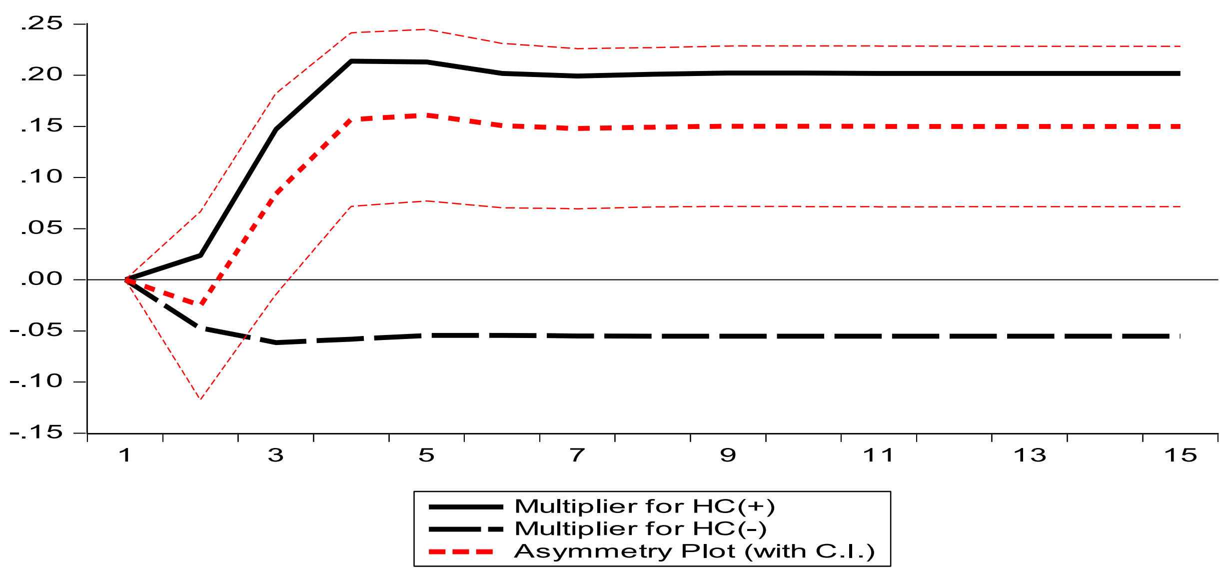

Fig. 22. The cumulative effect of HC on CO2.

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