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The influencing factors of CO₂ emissions and the adoption of eco-innovation across G-7 economies: A novel hybrid mathematical and statistical approach

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The present study empirically analyzes the role of eco-innovation in plummeting carbon dioxide (CO₂) emissions in conjunction with renewable energy usage, foreign direct investment, and trade openness for the states in G-7 from 1990 to 2019 in a mathematical and statistical context. Under the dynamical framework, the estimates of mathematical grey relational analyses indicate that eco-innovation holds a stronger degree of association with CO₂ emissions. Further, the estimates demonstrate that, compared to the other G-7 states, Japan is the country where eco-innovation is a more striking variable. However, renewable energy utilization seems weaker in Japan, which necessitates adopting renewable energy to curb carbon emissions in the region. Statistically, the odds ratio illustrates a similar pattern, demonstrating that the odds of occurrence for eco-innovation are much stronger in reducing the rising levels of carbon emissions within the G-7 states. Moreover, trade openness and foreign direct investment were revealed to be the leading contributors to carbon emissions in Germany and Canada, respectively, whilst appearing to be significant variables in lowering emissions in the United States and the United Kingdom. The outcomes of this investigation offer significant perspectives for policymakers in formulating holistic and environmentally friendly policies by embracing eco-innovation as a potentially significant component for sustainable economic expansion and environmental health.

KEYWORDS

eco-innovation, CO₂, renewable energy, foreign direct investment, trade openness, grey mathematical modeling

Introduction

There is a growing consensus among countries worldwide that global warming poses a severe environmental threat (E. Rehman & Rehman, 2022). Most people think that anthropogenic emissions of dangerous gases like carbon dioxide (CO₂) are the main cause of the increase in global temperatures that are harming both environment and public health (Mumtaz et al., 2022). Therefore, it is important to pinpoint the elements that might assist reduce Carbon emissions and associated damaging environmental consequences. Governments started looking for a unified strategy as the negative impacts of environmental degradation, such as global warming and climate change, became increasingly obvious on a global level (Shazia et al., 2022). As a result, various conferences on environmental sustainability were convened domestically and internationally. Global temperatures have increased by 1.9°F since 1880 due to increased pollution; sea levels have increased by 178 mm in the past century; and CO₂ emissions have reached 413 parts per million, the highest level in 650,000 years (Kraaijenbrink et al., 2017). As a result, the world is currently confronting one of its greatest challenges due to the ongoing and accelerating degradation of the environment and climate. The 21st Conference (COP21) of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC), often known as the UNFCCC, is a significant milestone in the global community's response to these climatic variations. The Paris Agreement from the COP21 was a crucial milestone in improving global understanding and diplomacy over climate-related concerns. Due to the heavy utilization of energy, which releases Carbon dioxide into the atmosphere and eventually raises the global average temperature, COP21 was essential in the international community comprehending the negative impact that ongoing economic growth has had on climatic changes (United Nations Climate Change, 2021). The fast expansion in global output has also resulted in a larger contribution to global warming due to resource depletion and power consumption and then accelerated global warming (Fan et al., 2019). Additionally, as the population grows, the need for energy grows geometrically, increasing the destruction of the environment owing to the discharge of residues into the atmosphere. Today's global ecology faces substantial difficulties from concerns like climate change and global warming, which have negative impacts on the well-being, of animals, and species of plants (International Energy Agency, 2015).

Referring to this, the G7 countries, the United Kingdom, the united states, Canada, France, Germany, Italy, and Japan are committed to reducing Carbon dioxide emissions through

energy portfolio diversification, especially by incorporating green energy sources into their traditional energy portfolios (Murshed, 2020). Accordingly, these nations are responsible for around 30 and 25 percent of the world's energy intensity and these emissions (Ahmad et al., 2021). The G7 nations are also significantly reliant on imported and domestic non-renewable sources. It is interesting to note that most G7 countries import non-renewable energy to fulfill their energy demands. Around 96 percent, 84%, and 64 percent, respective of Japan, Italy, and Germany's supply are imported. These statistics underline the concern of the G7 countries' reliance on polluting fuels. These statistics help to illustrate why, despite their economic success, these nations have mostly failed to stop the deterioration of their environmental protection (Li & Haneklaus, 2022; Murshed et al., 2022; Xu et al., 2022). Due to these environmental harms, initiatives like the Paris Agreement (UNFCCC, 2016) require all nations to decrease emissions to some level while also thinking about ways to help mankind adapt to climatic changes. Reduced environmental deterioration, a critical worldwide issue that affects human development and wellbeing, has been addressed. Targets for carbon emissions are now desired as a result. Contrarily, limiting economic activity is not sustainable in the long run. The question of whether policymakers can integrate growth strategies with low-carbon plans to ensure that society's growth is optimum, efficient, and sustainable is therefore raised (E. Rehman et al., 2020) Shahzad et al., 2021).

Economic growth cannot be achieved over the long run without an unbroken flow of inputs like energy. As a result, the energy demand has dramatically expanded globally (Kirikkaleli & Adebayo, 2021). To combat the rising energy demand, the majority of nations throughout the world heavily rely on renewable resources including coal, crude oil, and natural gas. Indeed, the strong reliance on fossil fuels has exacerbated environmental challenges even worst (Adebayo et al., 2021; Fahad et al., 2022). Since the preindustrial era, anthropogenic greenhouse gas (GHGs) emissions have increased and are now at their greatest level (Arif et al., 2022). According to BP 2020 report, carbon pollution in this context increased by 43.66% during the previous 35 years, from 19,249.9 million tonnes in 1985 to about 34,169.0 million tonnes in 2019 (BP, 2020). In addition, if governments put up significant steps to decrease these emissions in the next years, carbon emissions are predicted to elevate around 2050. The global average temperature rose by 0.85°C between 1980 and 2012. Additionally, the manufacture of conventional energy-intensive goods necessitates greater energy use, worsening the atmosphere. Nevertheless, producing smart and complicated items could need minimal energy, which might promote ecological sustainability (Razzaq et al., 2021). The COP21 also

emphasizes the importance of supporting green and sustainable growth to slow down ecological destruction. It is necessary to implement structural changes in the manufacturing activity by using cleaner resources of energy to reach the objectives of transitioning to green growth along with a low-carbon economy. The techniques used by nations throughout the world to produce energy urgently need to alter. As opposed to utilizing fossil fuels, which are not sustainable, this promotes the use of cleaner, renewable energy. The fast development and use of renewables are being driven by a wide range of factors, including the need to reduce greenhouse gas emissions, increase energy access, boost the economy, provide energy security, and mitigate environmental changes (UNFCCC, 2016).

Trade openness is essential for increasing the flow of goods and services and increasing economic productivity, but the relevance of viable options for Pollutant emissions is still up for dispute (Destek & Sinha, 2020). Even though some studies have suggested that trade openness is environmentally unfriendly, others contend that it improves it. Still, others contend that there is no connection between trade openness and ecological sustainability (Ali et al., 2020). Trade is a substantial contributor to Carbon emissions from industry in the G7 nations, and the amount of carbon dioxide is a component of the ultimate domestic demand for imported products (Adebayo et al., 2022). Even though countries are shifting their reserves to concentrate on project efficiency and use a broad range of environmental innovations to stabilize trade and Carbon dioxide, achieving greener and more efficient performance remains a significant issue in this world, with global trade and development being the key determinants (Y. Liu et al., 2022; H. Khan et al., 2022). Chen et al. (2019) used the error correction (ER) model and the autoregressive distributed lag (ARDL) technique to examine the connection between GDP, trade openness, RE, and CO₂ emissions from 1980 to 2014 for the case of China. The findings show that trade and renewable energy have the worst ecological consequences than economic production, which has an inverted U-shaped association with these emissions. Furthermore, the Granger causality research verified a bidirectional causality between carbon emissions, trade, and renewables. But there is also proof that rapidly increasing foreign trade and FDI cause environmental destruction (Ren et al., 2014). FDI is the main engine driving industrial growth and economic expansion. FDI is a clear choice related to technical transition, productivity improvements, and employment creation. However, the presence of FDI in a nation is not necessarily trouble-free. For instance, FDI will likely lead to the development of new industries which might harm the ecology (Usman et al., 2022). Khan et al., 2020, 2020b) examined how environmental variables interacted in 190 different nations. They employed stationary and non-stationary models and discovered that the independent variables in this study had a big impact on one another. They also discovered that FDI has a favorable level of carbon emission

whereas renewable energy has a negative impact. Similarly, Zameer et al. (2020) study the impact of natural resources, renewables, and foreign direct investment on CO₂ emissions for OECD nations. According to them, renewable energy has a good positive impact on environmental performance and also shows that abundance of natural resources, and foreign investment raises carbon dioxide emissions. Furthermore, Manta et al. (2020) investigate the connection between financial development, carbon dioxide emissions, and energy usage in European nations. They employed FMOLS and VECM metrics, and the statistics revealed that CO₂ emissions and energy have no long-term influence on economic prosperity. They have discovered, however, a bidirectional association between financial progress and development. They also show that financial growth does not lessen pollution, that energy usage accelerates financial advancement, and that financial expansion increases pollution in the short run.

Eco-Innovation is another recent aspect of the growth-environment nexus that has been deemed to have a substantial impact on ecological quality. For instance, according to research by Hodson et al. (2018). Eco-innovation lowers carbon emissions because it offers decent usage of resources and offers affordable solutions to minimize carbon dioxide emissions. Similar research was undertaken by Cagno et al. (2015), who revealed how eco-innovation improves energy efficiency and consequently lessens the utilization of non-renewable resources that aid to lower pollution. The link between economic development, eco-innovation, and carbon dioxide emissions was researched by Álvarez-Herránz et al. (2017). According to them, Eco-innovation promotes the use of cleaner energy and production in the economy. Mushta et al. (2020) looked at how innovation affected economic development, income inequality, and CO₂ emissions in China at the local and national levels. Throughout this period, from 1995 to 2015, they collected data using panel data econometric approaches and discovered that the relationship between income inequality, CO₂ emissions, and economic growth in China is moderated by environmental innovation. Between the years 1995–2015, Bilan et al. (2019) explored the role of Renewable Energy and GDP Per Capita on Carbon dioxide emission in the European Union countries. The authors demonstrate that the adoption of RE results in an improvement in ecosystems using cointegration and other methodologies like VECM. The role of RE in emission Reduction is examined by Dong et al. (2018) in the setting of EKC in China from 1993 to 2016. The use of renewable energy reduces environmental damage over the long and short term. On the other hand, using fossil fuels intensifies harmful emissions. Largest economies over the period 1990–2015. Using hierarchy, the authors show that GDP and population increase CO₂ emissions, while RE decreases CO₂ emissions. Moreover, the causes of CO₂ emissions in the 50 industrialized nations between 1990 and 2015 are evaluated by de Souza Mendonça et al. (2020). The findings demonstrated employing hierarchy that Renewables reduce CO₂ emissions, while Gross

Domestic Product and the population gradually increase emissions. By employing the global panel data to examine the link between Economic output, Renewables, and Carbon dioxide emission, [Fatima et al. \(2021\)](#) add to the body of existing literature. The paper demonstrates that Gross domestic product modifies the link between Renewables and Carbon intensity using several analytical techniques. Economic growth also affects non-renewables, which in consequence drives up Carbon dioxide emissions. [Awosusi et al. \(2022\)](#) investigate the connection between globalization, renewables, rental costs, and Carbon intensity in Colombia from 1970 to 2017. The authors demonstrate how globalization and renewables aid in the mitigation of climate change using FMOLS, DOLS, and ARDL. In 73 nations between 1990 and 2019, [Dou & Li \(2022\)](#) look into the connections between eco-innovation, natural gas, and Carbon intensity. The EKC hypothesis is present, according to the regression results, and innovation lowers CO₂ levels.

In this article, we consider making the specific instance that before designing effective policies for reducing carbon dioxide (CO₂) emissions, it is crucial to thoroughly examine the part played by ecological innovation in the perspective of growing trade openness and foreign direct investment in the overarching cycle of carbon emissions. The proposed article examines the connection between renewable energy consumption, trade openness, foreign direct investment (FDI), and carbon emission based on the continuing discussion regarding eco-innovation and environmental quality. Employing mathematical and statistical methods in comparison, we aimed to investigate the relationship stated. In the beginning, we applied an integrated mathematical grey relational analysis (GRA) model of grey system theory (GST), which comprised the Deng degree of GRA, absolute degree of GRA, and second synthetic degree of GRA. When compared to traditional statistical models, the GRA models offer several benefits. For example, they show improved precision and could produce accurate results even with small samples. In addition, we used a statistical technique called odds ratio estimation (OR) to quantify the strength of the relationship between the dependent and independent factors. When equated to other methods, the mentioned grey methodology is more suitable for producing results that are convincing and help to prevent endogeneity problems. By concentrating on the worst variables in the G-7 regions, the proposed model offers policymakers and decision-makers a valuable tool and a source of extra practical insights to make more effective decisions to minimize air pollution.

Methods

Data sources

The interaction between CO₂ emissions, eco-innovation (technical innovation), trade openness, foreign direct investment, and the use of renewable energy for G7 economies was empirically

examined in the present work. The carbon emissions (CO₂), measured in metric tonnes, were used as the response variable in this investigation. Renewable energy use has been estimated as a % of total final energy consumption, while environmentally friendly technical innovation has been quantified as a % of all technologies. Except for the variable eco-innovation, which was taken from the OECD data repository, the World Bank Indicators website provided data on foreign direct investment, CO₂ emissions, trade openness, and the utilization of renewable energy sources. In this analysis, statistics from 1990 to 2019 were analyzed. [Table 1](#) provides adequate information regarding the measurement unit and source of data for the observed variables. To proceed with the analysis, a mathematical and statistical comparison has been conducted. Grey relational analysis was used for a mathematical investigation, integrating with absolute GRA and Deng GRA. In addition, we assessed the ODDS ratios for a conventional statistical analysis to investigate the interactions between the response and explanatory variables. As the subjected methodologies were intended to investigate a one-to-one relationship, there was no need to test for homogeneity, normality, or multicollinearity, whereas the first step in the grey methodology was to normalize the data before moving on to the subsequent analysis.

Grey modeling

Grey relational analyses

GRA methods are one of the fundamental aspects of grey system theory (GST), which was presented in 1982 by Chinese scholar Deng Julong to deal with ambiguous processes with partial information ([Ng & Deng, 1995](#)). The basic principle behind grey modeling is that the measure of closeness (or correlation) of the multilateral pattern of a given dataset representing the structural properties, could be used to foresee the closeness of a linkage among system variables. A detailed description of the GRA method can be found in ([S. Liu et al., 2011](#)). The incorporation and effective application of grey approaches have been demonstrated in the literature in several scientific disciplines ([S. Rehman et al., 2022](#)) ([Javed & Liu, 2018](#)) ([Mahmoudi et al., 2019](#)) ([Javed et al., 2018](#)) ([E. Rehman & Rehman, 2022](#)) ([Mumtaz et al., 2022](#)). The present investigation is carried out by engaging GRA methodologies. The data series are investigated by engaging GRA methodologies. The GRA models are designed using SPSS ([IPCC, 2019](#)). [Figure 1](#) depicts the conceptualized GRA paradigm. The accompanying section summarizes the computing algorithms for grey relational models.

Deng's grey relational analysis model

Let \mathbb{Y}_i be the reference series of the given data set denoting a dependent parameter and \mathbb{Y}_j be the comparative sequences of the given data set denoting an independent parameter, then, at that point grey relational gradient (GRG), the real number degree

TABLE 1 Description of variables utilized in the study.

Variable	Unit	Source
Dependent variable		
Carbon emissions	Metric tons per capita	WDI, (2019a)
Independent variable		
Renewable energy consumption	Renewable energy per capita consumption (KWH)	WDI, (2019c)
Eco-innovation	% Of total technologies	OECD, (2019)
Trade openness	% Of GDP	WDI, (2019d)
Foreign direct investment	BoP, Current US\$)	WDI, (2019b)

WDI, World development indicators; OECD, the Organization for Economic Cooperation and Development.

addressing the output of the GRA model is depicted as γ_{ij} or $\gamma(\mathbb{Y}_i, \mathbb{Y}_j)$ and can be accompanied by (Yamaguchi et al., 2007):

$$\gamma(\mathbb{Y}_i, \mathbb{Y}_j) = \frac{1}{h} \sum_{\ell=1}^h \gamma(\mathcal{Y}_{i(\ell)}, \mathcal{Y}_{j(\ell)})$$

Where,

$$\gamma(\mathcal{Y}_{i(\ell)}, \mathcal{Y}_{j(\ell)}) = \frac{\min_k \min_{\ell} |\mathcal{Y}_{i(\ell)} - \mathcal{Y}_{j(\ell)}| + \zeta \max_k \max_{\ell} |\mathcal{Y}_{i(\ell)} - \mathcal{Y}_{j(\ell)}|}{|\mathcal{Y}_{i(\ell)} - \mathcal{Y}_{j(\ell)}| + \zeta \max_k \max_{\ell} |\mathcal{Y}_{i(\ell)} - \mathcal{Y}_{j(\ell)}|}$$

In this case, $\zeta \in (0, 1)$ represents a distinguishing coefficient, and is generally assumed to be at 0.5.

Absolute grey relational analysis model

If \mathbb{Y}_i (dependent) and \mathbb{Y}_j (independent) are two distinct data series connected within a system, the algorithm for computing the absolute GRA is shown below (S. Liu et al., 2011) (Wu et al., 2014).

$$\epsilon_{ij} = \frac{1 + |\mathbf{r}_i| + |\mathbf{r}_j|}{1 + |\mathbf{r}_i| + |\mathbf{r}_j| + |\mathbf{r}_i - \mathbf{r}_j|}$$

Where,

$$\mathbf{r}_i = \int_1^h \mathbb{Y}_i^0 dt, \mathbf{r}_j = \int_1^h \mathbb{Y}_j^0 dt, \mathbf{r}_i - \mathbf{r}_j = \int_1^h (\mathbb{Y}_i^0 - \mathbb{Y}_j^0) dt$$

Second synthetic grey relational analysis model

The SSGRA model can be produced by incorporating the given equation.

$$\mathcal{P} = \vartheta \epsilon_{ij} + (1 - \vartheta) \gamma_{ij} \quad \vartheta \in [0, 1]$$

where \mathcal{P} indicates the SSGRA model, ϵ_{ij} indicates the absolute GRA model whereas γ indicates the Deng GRA model outcomes across the two grey data series i.e., \mathbb{Y}_i and \mathbb{Y}_j . Whenever a decision-maker seeks an inclusive evaluation that combines the pros of both ϵ and γ without endorsing one over another and so sets ϑ at 0.5. We assumed ϑ at 0.5 for our analysis. The detailed literature on grey modeling can be obtained from (S. Liu et al., 2011) (Kalyon et al., 2018). A graphical roadmap for the

grey framework employed in our research is displayed in Figure 1.

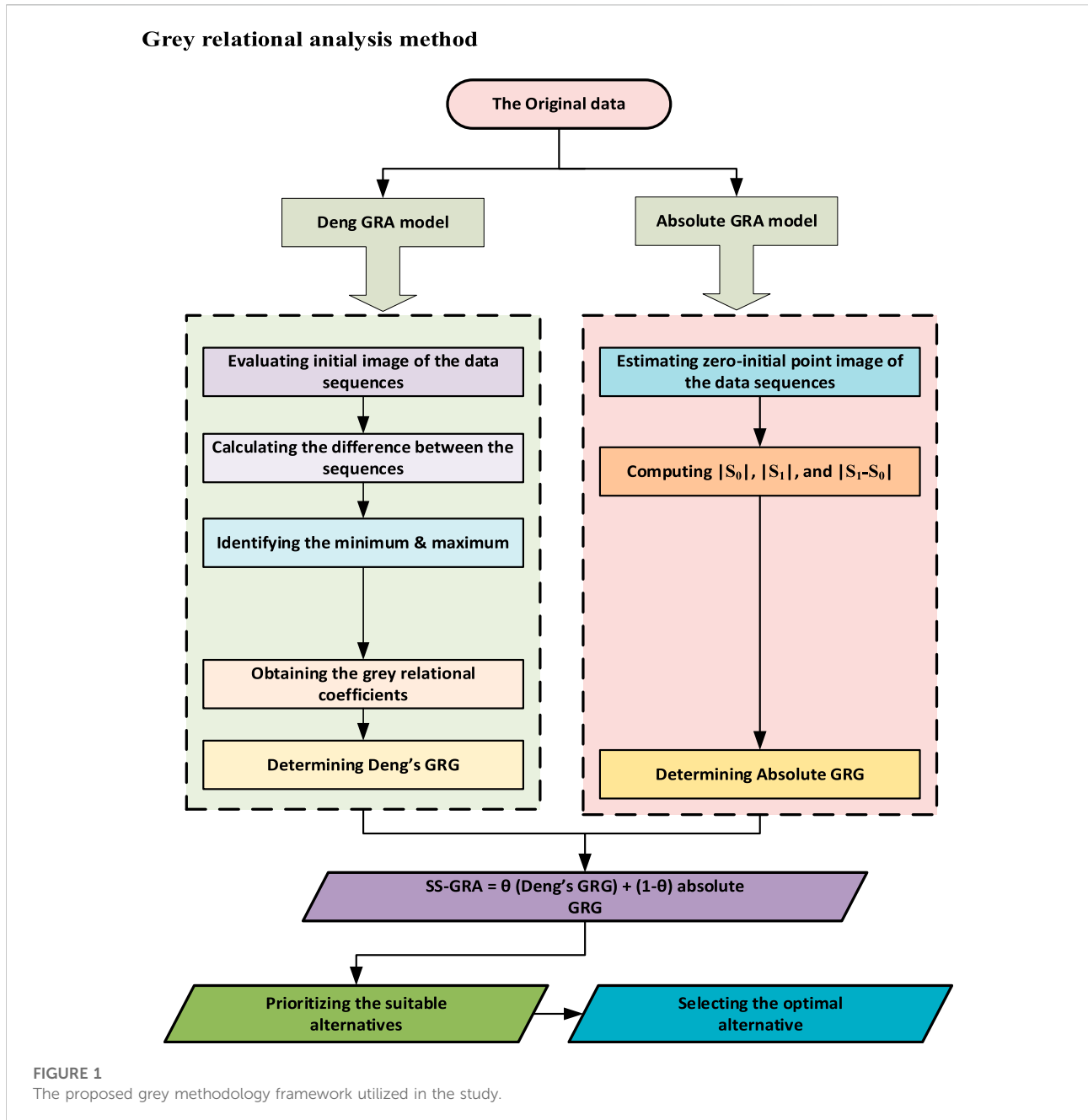
Results and discussion

Renewable energy consumption

In this investigation, as per Deng-GRA results, Italy (0.8457) has the most elevated influence between renewable energy use and carbon emissions, whilst the most fragile influence is observed for Japan (0.6672) (Table 2). Likewise, the same sequence is generated among the G-7 nations based on the absolute-GRA model findings. Italy (0.8547) acquired the greater measure of association trailed by Canada and Germany based on the results by absolute-GRA. The weakest associations were found in the United States and Japan, with grey relational weights of 0.6988 and 0.6734, respectively. Bodily, the assessment from the SS-GRA model demonstrated that across all G-7 economies, Italy (0.8502) appeared to be the leading country in terms of reducing CO₂ emissions through renewable energy consumption, swiftly followed by Canada (0.8031) and Germany (0.7878). The statistical investigation also revealed a similar pattern of sequence, implying that Italy (OR: 17.05 (11.67-27.48)) has a higher odd of minimizing carbon emissions through renewable energy use, while Japan (OR: 1.98 (0.24-2.54)) has the lowest odds ratio with significant p values.

Eco-innovation

An intriguing and insightful ranking gained importance when considering the role of eco-innovation on carbon emissions among the G-7 economies. The adoption of eco-innovation appeared to be more dramatic in the Japanese region (Deng-GRA: 0.9708, absolute-GRA:0.9802, SS-GRA:0.9755), and it was placed foremost in light of the outcomes of all three grey relational models, with comparatively higher strength of correlation. The findings in Table 3 demonstrated that the adoption of eco-innovation



is a key predictor of reducing carbon emissions in the Japanese region followed by the UK (Deng-GRA:0.8576, absolute-GRA:0.8504, SS-GRA:0.8540) and France (Deng-GRA:0.8002, absolute-GRA:0.8000, SS-GRA:0.8001). Under all grey models, the US placed seventh and the UK ranked sixth, implying that these countries have the lowest impact among the G-7 nations due to their adoption of eco-innovation and reduction of carbon emissions. On comparing these results with statistical analysis, Japan (OR: 21.32 (16.73-28.91)) sustained its ranking pattern,

with higher odds of emissions reduction owing to eco-innovation adoption, followed by the UK (OR: 16.09 (10.25-19.37)) and France (OR: 11.72 (7.65-14.44)). Our findings corroborated some earlier investigations that likewise showed a substantial linkage between adopting eco-innovation and lowering carbon emissions.

Trade openness

Table 4 displays a review of the interactions between carbon emissions and trade openness among G-7 nations using GRA

TABLE 2 Mathematical and statistical assessment between CO₂ emissions and renewable energy.

G-7 economies	Deng-GRA	Absolute-GRA	SS-GRA	OR (95%CI)	p-value
Germany	0.7977	0.7779	0.7878	10.90 (9.06-13.54)	0.000
France	0.7521	0.7447	0.7484	6.39 (3.25-9.11)	0.003
Canada	0.8064	0.7998	0.8031	12.07 (9.33-14.58)	0.000
Japan	0.6672	0.6734	0.6703	1.98 (0.24-2.54)	0.002
Italy	0.8457	0.8547	0.8502	17.05 (11.67-27.48)	0.000
United Kingdom	0.7446	0.7300	0.7373	5.21 (3.64-8.21)	0.002
United States	0.7026	0.6988	0.7007	4.31 (2.97-6.04)	0.001
Grey rank	Italy > Canada > Germany > France > United Kingdom > United States > Japan				
OR rank	Italy > Canada > Germany > France > United Kingdom > United States > Japan				

Note: GRA, grey relational analysis; OR, odds ratio; G-7, group of seven; SS, second synthetic; CI, confidence interval. $p < 0.01$ is considered as statistically significant.

TABLE 3 Mathematical and statistical assessment between carbon emissions and eco-innovation.

G-7 economies	Deng-GRA	Absolute-GRA	SS-GRA	OR (95%CI)	p-value
Germany	0.8107	0.7877	0.7992	5.55 (1.11-7.23)	0.001
France	0.8002	0.8000	0.8001	11.72 (7.65-14.44)	0.000
Canada	0.6549	0.6603	0.6576	0.96 (0.05-2.07)	0.003
Japan	0.9708	0.9802	0.9755	21.32 (16.73-28.91)	0.000
Italy	0.7256	0.7090	0.7173	3.34 (0.78-6.05)	0.001
United Kingdom	0.8576	0.8504	0.8540	16.09 (10.25-19.37)	0.000
United States	0.7627	0.7771	0.7699	4.86 (2.06-7.49)	0.002
GRA rank	Japan > United Kingdom > France > Germany > United States > Italy > Canada				
OR rank	Japan > United Kingdom > France > Germany > United States > Italy > Canada				

Note: GRA, grey relational analysis; OR, odds ratio; G-7, group of seven; SS, second synthetic; CI, confidence interval. $p < 0.01$ is considered as statistically significant.

models. As per Deng-GRA estimates, Germany has the maximum impact, with an expected strength of 0.9557, attributable to trade openness being a substantial contribution to minimizing carbon emissions, preceded by Canada (0.8852) and France (0.8796). Considering the estimates determined for absolute-GRA, although the equivalent sequence emerged, the measure of the relationship was showed considerably higher for Germany (0.9645) on comparing with the rest of the G-7 economies. Meanwhile, in a grey relational assessment of trade openness on lowering CO₂ emissions among G-7 economies, the US and UK are identified as the less significant nations. Predominantly, the strength of the relationship is considerably more grounded for Germany (SS-GRA:0.9601), suggesting that trade openness has a considerable influence on lowering carbon emissions within this region, led by the US (SS-GRA:0.7328) and UK (SS-GRA:0.8606). On comparing these results with odds ratios, a slightly distinct pattern is ascertained for the economies under investigation. With a slight change in estimations, France and the UK switched their positions. The United Kingdom (OR:5.75, 95% CI (1.99-

7.07)) has higher odds of lowering carbon emissions attributable to trade openness, however, France (OR:5.66; 95% CI (2.21-8.03)) has lower odds when compared with the rest of the economies.

Moreover, in accordance with the Deng-GRA model result, the Canadian nation (0.9342) has a better measure of influence between foreign direct investment and carbon emissions, whilst the United Kingdom (0.5822) has the most fragile level of influence. The stronger impact estimate of foreign direct investment on reducing carbon dioxide emissions in Canada demonstrates that the two are intrinsically connected. A relatively similar sequence appeared again in the findings of the absolute-GRA model, albeit with more intensity. The level of interaction for decreasing carbon emissions against FDI is substantially higher in the case of Canada, with an approximated grey significance of 0.9406. At a broader level, FDI is viewed as the primary contributor to reducing emissions in the Canadian region, based on the findings estimated from the SS-GRA model. The higher the degree of association between FDI and carbon emissions, the more

TABLE 4 Mathematical and statistical assessment between carbon emissions and trade openness.

G-7 economies	Deng-GRA	Absolute-GRA	SS-GRA	OR (95%CI)	p-value
Germany	0.9557	0.9645	0.9601	8.43 (6.41-10.01)	0.000
France	0.8796	0.8708	0.8752	5.66 (2.21-8.03)	0.000
Canada	0.8852	0.9154	0.9003	7.07 (4.55-9.32)	0.000
Japan	0.7575	0.7707	0.7641	2.09 (0.21-4.70)	0.001
Italy	0.8189	0.8069	0.8129	3.33 (1.07-5.31)	0.001
United Kingdom	0.8557	0.8655	0.8606	5.75 (1.99-7.07)	0.000
United States	0.7367	0.7289	0.7328	0.23 (0.06-2.53)	0.002
GRA rank	Germany > Canada > France > United Kingdom > Italy > Japan > United States				
OR rank	Germany > Canada > United Kingdom > France > Italy > Japan > United States				

Note: GRA, grey relational analysis; OR, odds ratio; G-7, group of seven; SS, second synthetic; CI, confidence interval. $p < 0.01$ is considered as statistically significant.

TABLE 5 Mathematical and statistical assessment between carbon emissions and FDI.

G-7 economies	Deng-GRA	Absolute-GRA	SS-GRA	OR (95%CI)	p-value
Germany	0.8113	0.8311	0.8212	10.91 (7.07-13.44)	0.000
France	0.9326	0.9406	0.9366	23.68 (18.05-29.11)	0.000
Canada	0.9580	0.9376	0.9478	22.90 (18.27-28.56)	0.000
Japan	0.7808	0.8008	0.7908	3.29 (1.37-6.21)	0.001
Italy	0.8642	0.8664	0.8653	13.01 (7.34-15.04)	0.002
United Kingdom	0.5822	0.6202	0.6212	1.16 (0.54-3.09)	0.001
United States	0.8019	0.7999	0.8009	6.57 (3.66-9.32)	0.000
Grey rank	Canada > France > Italy > Germany > United States > Japan > United Kingdom				
OR rank	France > Canada > Italy > Germany > United States > Japan > United Kingdom				

Note: GRA, grey relational analysis; OR, odds ratio; G-7, group of seven; SS, second synthetic; CI, confidence interval. $p < 0.01$ is considered as statistically significant.

closely those variables are related (Table 5). After Canada, France (0.9366) appeared to be more significant in reducing its carbon emission due to FDI with an approximated grey score of 0.9366 and placed 2nd, pursued by Italy (0.8653) and Germany (0.8212) with moderately less strength. A slightly different sequence appeared when we computed odds ratios for the selected variables to examine the associations. France and Canada altered their ranking order with only a smidgeon difference of 0.78. France appeared with a slightly higher odds of decreasing CO₂ emissions attributable to FDI (OR:8.27, $p < 0.000$) when compared with Canada (OR:22.90, $p < 0.000$).

FDI has a considerable impact on carbon emissions, implying that FDI in France and Canada is more ecologically beneficial than in the rest of the G-7 economies. In this case, previous research contradicts each other, with some claiming that FDI has a favorable impact on environmental quality and others claiming that it has a negative impact.

We also compared our outcomes to those of the SS-GRA model using odd ratios. It can be noticed that the patterns

achieved by the two methods are relatively identical. Their respective strengths, however, are the fundamental point of distinction. Despite the range of GRA models and odd ratios are not the same, their judgments can be contrasted as both ranges allow the decision-maker to assess whether the interaction is frail, significant, or extremely significant. Table 6 shows the ranking sequences of G-7 economies based on mathematical and statistical analyses for better interpretation of the results.

Discussion and concluding remarks

For the period 1990-2019, this research preliminary examines the impacts of renewable energy usage, eco-innovation, trade openness, and FDI on CO₂ emissions in G-7 economies. The relationship between the determinants listed above is thoroughly documented in the environmental literature, however, evidence on the individual and

TABLE 6 Ranking sequence based on mathematical and statistical analysis.

CO₂ emissions (response variable)

Renewable energy consumption	
Mathematical	Italy > Canada > Germany > France > United Kingdom > United States > Japan
Statistical	Italy > Canada > Germany > France > United Kingdom > United States > Japan
Eco-innovation	
Mathematical	Japan > United Kingdom > France > Germany > United States > Italy > Canada
Statistical	Japan > United Kingdom > France > Germany > United States > Italy > Canada
Trade openness	
Mathematical	Germany > Canada > France > United Kingdom > Italy > Japan > United States
Statistical	Germany > Canada > United Kingdom > France > Italy > Japan > United States
Foreign direct investment	
Mathematical	Canada > France > Italy > Germany > United States > Japan > United Kingdom
Statistical	France > Canada > Italy > Germany > United States > Japan > United Kingdom

comparative effects of countries is scarce. To examine the individual impacts and their relative intensities among the studied nations, a multicriteria decision-making approach is implemented. To achieve the aforementioned objectives, we adopted two ways to investigate the interactions within variables across the studied economies: an advanced mathematical grey relational methodology and a statistical technique named Odds ratios. According to GRA outcomes, Japan claimed to be a prospective nation among G-7 economies in minimizing its carbon dioxide emissions due to eco-innovation, whereas renewable energy utilization is considered to be more striking in decreasing carbon emissions in Italy. Furthermore, Germany was revealed to be more potent as a result of trade openness while Canada appeared to be influential due to the FDI variable. In the current investigation, we implemented three grey relational models (Deng GRA, absolute GRA, and SS-GRA models), which might potentially replace conventional data analysis techniques. The estimated statistics confirmed the suitability and effectiveness of the grey relational model technique.

Renewable energy use plays a crucial role in abating CO₂ emissions and improving environmental quality (Fareed et al., 2016). The linkage between renewable energy consumption and CO₂ emissions emerged to be stronger in Italy than in other G-7 economies, implying that G-7

governments must adopt the use of renewables for a sustainable future. These figures are consistent with earlier research that found significant inverse relationships between the use of green energy and carbon emissions (S. Rehman et al., 2022) (Dong et al., 2020) (E. Rehman et al., 2020).

Eco-innovation has a significant influence on reducing carbon emissions in Japan, according to the current figures. This evidence speculated that eco-innovation may benefit Japan more than the other G-7 economies by significantly reducing pollution emissions or curbing the strain on natural resources. Eco-innovation is a key indicator of ecologically sustainable growth, energy efficiency, and climate variability, as evidenced by the growth of the industry for eco-services and eco-goods related to the environment over the last few decades (M. Li et al., 2021) (Shahzad et al., 2021). However, our findings are in accordance with prior empirical studies that found a significant negative linkage between eco-innovation and total carbon dioxide emissions (consumption and production-based). Among such investigations are BRICS (Razzaq et al., 2021), OECD (Puertas & Marti, 2021), China (Wang et al., 2020), the United States (Sun et al., 2021), France (Ding et al., 2021), and India (Tao et al., 2021). Therefore, rather than focusing on economic determinants, liable and innovative conduct towards ecological parameters

could be more advantageous in strengthening environmental sustainability.

Trade openness is found strongly and significantly associated with carbon emissions in Germany as compared to other regions of G-7 economies which reveals that trade openness is an environmentally friendly indicator. This empirical finding is consistent with a range of investigations in the existing literature (Ibrahim & Ajide, 2021), (Shahbaz et al., 2019), (Mutascu, 2018), and (Hdom & Fuinhas, 2020). The argument that trade openness enhances environmental quality can be substantiated by the fact that the technique effect outweighs the scale effect (Shahbaz et al., 2013) (Ferrantino, 1997) (M. Li et al., 2021). We could make the argument that the scale effect arises when an economy moves from a developing to a developed phase, implying trade liberalization, which enhances exports and, by extension, economic expansion. Alternatively, trade liberalization alters an economy's industrial hierarchy, while the technique effect encourages economies to adopt more efficacious and cleaner technologies (Ahmad et al., 2021). Therefore, the availability of comparative advancements in ecologically clean sectors and breakthroughs in fuel efficiency can validate the net impact of abating CO₂ emissions (Lorente & Álvarez-Herranz, 2016) (Shahbaz et al., 2013) (D B Lorente & Alvarez-Herranz, 2016). Lately, Shahbaz et al. assessed the impact of trade openness on environmental quality over the 1980-2014 period employing data from low, middle, and high-income nations. They determined that trade openness is first positively correlated with carbon emissions and that at a certain level, this association inevitably falls, a phenomenon known as the EKC effect (Shahbaz et al., 2017) (Hashmi et al., 2021).

FDI tended to be more remarkable in Canada than in the other G-7 economies, as per the empirical findings. In most environmental literature, the elasticity of carbon emissions to FDI is found positive in the region of Canada. Existing empirical studies on the impact of FDI on the environment are contradictory. FDI has two main effects on the environment. It may cause substantial environmental damage in host countries, worsening their environment. On the contrary, it may incorporate more environmentally friendly technologies and management procedures to help host nations enhance their environmental quality. The G-7 economies should stimulate FDI inflows, specifically in technology-intensive and environmentally friendly businesses, and capture the possible negative impact of pollution-intensive FDI inflows on the environment, in order to improve environmental quality (Hashmi et al., 2021) (Hashmi et al., 2021).

Henceforth, it is reasonable to conclude that the factor of eco-innovation contributes more to the transition of the economies to sustainable energy resources, thus abating CO₂

emissions. The country-specific findings demonstrate that renewable energy use, ecological innovation, trade openness, and FDI are key drivers of environmental quality improvement in G-7 economies. Among the parameters investigated, the coefficient of eco-innovation has a strong and considerable influence in Japan when compared to the other G-7 economies. This signifies that by implementing economic modalities that promote green innovation in economic processes, CO₂ emissions can indeed be lowered and environmental quality can be improved. These findings suggest that ecological innovation is the optimum determinant in making significant advancements in sustainable development, whether by limiting the ecologic impacts of production modes, improving nature's resilience to environmental stressors, or attaining a more productive and liable use of natural resources. These facts are in agreement with those published previously by Doğan et al. (2022) (Doğan et al., 2022) and X. Ji. et al. (Ji et al., 2021).

Policy recommendation

The empirical facts offer a few compelling policy implications. Initially, the study discovered eco-innovation as a key abating component of environmental degradation among others. Therefore, it is imperative to spend on green technologies to minimize environmental deterioration and to explore innovative ways of energy usage to enhance environmental quality. Policy-makers must concentrate on various legislative proposals, in particular, to be rational in their endeavors in adopting renewable energy resources. Multiple streams of renewable energy should be encouraged by the G-7 governments in both the residence and business sectors. They should also concentrate on public-private cooperation to raise citizens' knowledge of environmentally friendly activities. This goal can be achieved through the use of social and mass media.

Furthermore, the G-7 governments must develop policies to encourage households and businesses to embrace eco-innovation by lowering interest rates on energy-efficient purchases, which will serve to enhance the positive impact of FDI on renewable energy consumption. Residential, commercial, and industrial users should be able to get financing for solar energy installation at a cheaper interest rate from the G-7 economies and the financial sector, as this will speed up the transition from NRE to RE consumption. The G-7 economies should also minimize non-renewable energy subsidies while providing tax relief for renewable energy to help expedite the transition from NREC to REC.

Future research should dig into the combined effects of all renewable energy sources to identify which one contributes the most to improving environmental quality. For comparison purposes, the impact of each fossil fuel should be investigated,

separately. In this instance, multicriteria decision analysis can particularly be advantageous.

Data availability statement

The data used to support the findings of this study are included within the article.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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