RESEARCH ARTICLE

An empirical investigation of the relationships between nuclear energy, economic growth, trade openness, fossil fuels, and carbon emissions in France: fresh evidence using asymmetric cointegration

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Abstract

The intention behind the current analysis is to join the debate over the main factors to consider in the global fight against climate change. Thereby, the Non-linear Autoregressive Distributed Lag (NARDL) approach is applied to assess the impacts of nuclear energy, fossil fuels, income, and trade on carbon emissions in France from 1980 to 2020. In addition, the relevance of the Environmental Kuznets Curve (EKC) presumption is tested. The main results stipulate that nuclear energy lessens CO_2 emissions in France. However, fossil fuels and trade openness enhance these emissions. On the other hand, the current analysis confirms the presence of an inverted U-shaped curve relating economic growth to carbon emissions. Therefore, the EKC hypothesis is supported in our case. Indeed, by calculating the turning point, it is possible to extract the turning year corresponding to 2008. Furthermore, an asymmetric causality test is performed in order to identify the possible non-linear causal links between the potential drivers of carbon emissions. First, the causal linkage between CO_2 emissions and GDP is bidirectional. Furthermore, a unidirectional causal link between CO_2 emissions and non-renewable energies and a dual directional causal link between pollutant emissions and trade are identified. These empirical results are intended to guide the French government in the implementation of relevant energy and trade-related strategies in order to attain the ambitious targets of carbon emissions reduction. In fact, France should reduce imports of fossil fuels to curtail the positive effect of trade on carbon emissions. In addition, it is recommended to substitute fossil energies with renewable energies gradually by using adequate instruments and boosting research and innovation to mitigate the adverse influences of non-renewable energies on environmental quality. Finally, our findings confirm the positive role played by nuclear energy in the fight against climate change.

Keywords Carbon emissions · EKC hypothesis · Nuclear energy · Fossil fuels · Trade

Introduction

Climate change is manifested by several phenomena, including rising sea levels and global temperatures. Accordingly, the objective of the Paris Agreement is to maintain the increase in temperatures well under 2 °C by 2100. In fact, the climb in temperature is due to polluting emissions, in particular carbon emissions from the combustion and use of fossil fuels. Indeed, these emissions increased by 67% between 1990 and 2018 (Ministry of Ecological Transition 2021a). Hence, global anthropogenic greenhouse gas (GHG) emissions have maintained their upsurge and are perceived as the most important reason for global warming. The crucial share of the GHG emissions increment is constituted by carbon emissions [Intergovernmental Panel on Climate Change (IPCC) 2014]. Moreover, carbon emissions are considered a menacing matter facing not only the ecosystem but also economic development (Alola et al. 2019). In fact, since global warming is becoming more and more critical, the issue of environmental quality has received more consideration than ever from international organizations (IPCC 2014, 2021), politicians, and researchers in order to understand the main causes of environmental degradation and to predict its

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evolution over time. In spite of international agreements and the strong awareness toward mitigating carbon emissions by most countries, the global carbon dioxide emissions augmented by 1.4% between 2009 and 2019 [British Petroleum (BP) Statistical Review of World Energy 2021]. On the other hand, the consumption of fossil fuels is still prominent in industry, transport, building, and power in most countries according to the report of the Renewable Energy Policy Network for the 21st Century (REN 21) (2021).

With the increasing awareness about climate change and the spreading perception of the damages of the excessive use of fossil fuels (IPCC 2021), many countries, such as France, have been making efforts with the intention of enhancing the contribution of clean energies to the energy mix in order to reduce GHG emissions. In fact, France is among the top emitter countries in Europe with 251.1 million tons in 2020 (BP 2021). In addition, the law of "Energy Transition for Green Growth" has fixed the ambitious objective of alleviating GHG emissions by 40% between 1990 and 2030. Nevertheless, GHG emissions in France have decreased only by 19% between 1990 and 2018 which remains far from the ambitious objective of 40% during the period 1990–2030. Furthermore, to carry out its climate objectives, the French finance bill for the year 2021 allocated € 37 billion as climate-friendly spending (Ministry of Ecological Transition 2021a). Hence, analyzing the potential drivers of carbon emissions is a very interesting topic for the case of France since it allows the policymakers to direct the climate strategies in the right direction and hence attain the objectives in terms of carbon emissions reduction within the set deadlines.

Among the analyzed determinants, there are two energy-related drivers which are fossil fuels and nuclear energy. In fact, it is proven by many studies that fossil fuels contribute to the aggravation of climate change (Isiksal et al. 2019). Although France does not produce fossil fuels in big amounts, it is still a big consumer by importing fossil fuels from other countries such as Saudi Arabia and Kazakhstan. In addition, one of the main features of the energy system in France is the impressive progress made in nuclear energy generation since the oil crisis in 1973 (Millot et al. 2020). Furthermore, in 2019, public finance intended for research and development (R&D) in the energy sector attained almost € 1.2 billion. Nuclear energy accounts for 63% of this expenditure (Ministry of Ecological Transition 2021b). On the other hand, according to the International Energy Agency (IEA 2019), nuclear energy played a crucial role in global climate change engagement. In fact, nuclear power contributed to the avoidance of 63 gigatonnes of carbon emissions during 1971–2018. Moreover, the French nuclear sector is important not only for France but also for Europe, since France exports electricity mainly produced from nuclear energy to its neighbors in Europe. Therefore, the nuclear strategy in France has impacts also on the energy security of European countries. In this regard, multiple research works have analyzed the influence of nuclear power on environmental quality in general and CO_2 emissions in particular (Hassan et al. 2020; Mahmood et al. 2020; Pan and Zhang 2020; Nathaniel et al. 2021). Thus, France presents an interesting case to study as the country is a net importer of oil and has invested in nuclear energy since the 1970s in order to reduce its energy dependence and diversify its electricity mix.

In addition to the two aforementioned determinants, the effect of trade openness is analyzed too since France is the world's 6th largest exporter of goods and services (General direction of the treasury 2021). Subsequently, it will be very interesting to explore the impact of trade on CO_2 emissions in France. Finally, France has signed many agreements to mitigate its CO_2 emissions, which makes the topic of carbon emissions drivers very interesting and still relevant.

As outlined in the previous paragraphs, fossil fuels, nuclear energy, and trade openness are very important factors and driving forces to economic growth in the case of France. Therefore, France as a developed country wants to accelerate its economic growth while keeping the environmental quality standards. From this motivation, it is interesting in the French context to estimate the carbon dioxide emissions effects of fossil fuels, nuclear energy, and trade openness, along with testing the EKC hypothesis.

There are multiple studies that are concerned with the drivers of CO_2 emissions, even though only a few studies have explored this topic for the French case (Ang 2007; Iwata et al. 2010; Marques et al. 2016; Shahbaz et al. 2018; Pata and Samour 2022). In fact, the studies cited above have analyzed the effects of many crucial determinants such as energy consumption and output (Ang 2007), nuclear energy and renewable energies (Marques et al. 2016; Pata and Samour 2022), energy consumption, foreign direct investment (FDI), innovation, and financial development (Shahbaz et al. 2018), and finally nuclear energy, energy consumption, trade, and urbanization (Iwata et al. 2010). Although these studies are very interesting, no one of them has investigated the asymmetric effects of potential drivers of CO_2 emissions for the French case. Our study is in line with the research of Iwata et al. (2010). However, our research differs in many terms. First, they used the percentage of the total electricity produced by nuclear energy; however, in our study, the total nuclear energy production is adopted. Finally, they used the ARDL approach, but the NARDL approach along with the EKC hypothesis is adopted in our case in order to detect the asymmetric effects which present the novelty of our study. Hence, the main objective of our analysis is to fill this gap by using an asymmetric approach with the aim of investigating the asymmetric effects of CO_2 determinants for the French case.

In summing up, the foremost purpose of this research is to take part in the debate over the impact of nuclear power on environmental quality. Therefore, the NARDL approach is applied to detect the asymmetric effects of nuclear energy and income along with trade and fossil energy on CO_2 emissions in France from 1980 to 2020. In addition, the relationship between income and carbon emissions is carried out by checking the EKC assumption. The current research work presents two contributions to the actual literature. Firstly, it is the first study to use the NARDL approach in order to determine the impacts of nuclear energy, fossil fuels, and trade in France from the EKC hypothesis framework. Secondly, it represents the first study for the case of France that considers the asymmetric test suggested by Diks and Panchenko (2006) to explore the asymmetric causality among the potential drivers of carbon emissions.

To examine in depth this topic, this paper is structured into 5 interrelated sections. "The evolvement of the energy system in France: the prominence of nuclear power" section looks at both the past and current energy situations in France while emphasizing the predominance of nuclear energy. The "Literature review" section provides the data and the model specification. The main observations are embodied in the "Methodology" section. The "Results and interpretations" section presents results and finally, the "Conclusions and policy implications" presents the conclusions and offers preeminent policy suggestions.

## The evolvement of the energy system in France: the prominence of nuclear power

The energy system in France has been characterized by the preeminence of nuclear energy for many years and the steady progress of renewable energies. In addition, the primary national production represents a little more than half of France's energy supply (Ministry of Ecological Transition 2021b). According to Fig. 1, following the implementation of the French nuclear program, primary energy production increased from 514 tera-watt hour (TWh) in 1973 (including 9% nuclear) to 1423 TWh in 2020 (including 75% nuclear). However, primary energy production decreased by 8.7% in 2020 compared to 2019, which is explained by the decline in nuclear production (− 11.3%, 1072 TWh against 1209 TWh). This decline is mainly due to the pandemic context which led to delays in scheduled maintenance and the closure of the last two reactors at the Fessenheim Nuclear Power Plant on June 29, 2020. Nuclear production is thus falling to a level not seen since the early 1990s (1026 TWh in 1992 and 1091 TWh in 1994). Currently, France has 56 reactors in service that were commissioned between the end of the 1970s and the beginning of the 2000s (Ministry of Ecological Transition 2021b).

Concerning fossil fuels, their extraction has declined sharply. This situation is mainly due to the extraction of coal and natural gas, which has been almost zero since 2015. The decline in gas production has been remarkable since 1984. In fact, it fell from 61.38 TWh in 1984 to 17.5 TWh in 2000 to reach only 0.22 TWh in 2020. On the other hand, France has stopped coal mining since 2015 and plans to stop producing electricity from coal in 2022 (Ministry of Ecological Transition 2021b). Furthermore, the production of crude oil in France stands at 9.75 TWh in 2020 against 34.46 in 1970 and 44.56 in 1988, thus achieving a decrease of 72% compared to 1970. Production in 2020 represents only about 1% of national oil consumption. Since oil production in France is very limited, its supply of crude oil relies almost entirely on imports from Saudi Arabia and Kazakhstan.

At the same time, production from renewable sources (wind power, biofuels, biogas, etc.) has been growing steadily since the mid-2000s. In 2020, the primary production of renewable energy amounted to 340.76 TWh. The main sources remained biomass, hydro, and wind power. In fact,

Fig. 1 Primary energy production in France. Source: SDES (2021)
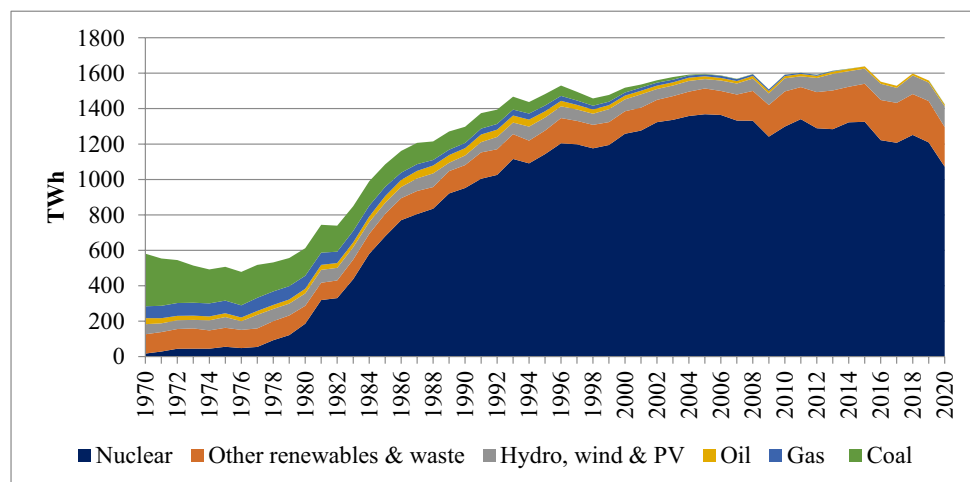
between 2019 and 2020, the primary production of renewable energies increased slightly, by 2.79 TWh (or +0.82%).

According to Fig. 2, energy consumption has tended to decrease slightly for several years. In fact, after steadily increasing until 2005 to reach a peak of 3155 TWh, primary energy consumption has declined slightly. The long-term trend is contrasted between energies: since 1990, the consumption of coal and oil has fallen by 72% and 27%, respectively. Conversely, during the same period, those of nuclear and natural gas increased by 14.5% and 44%, respectively, while that of renewable energies almost doubled. In 2020, the drop in primary energy consumption was historic (falling by 8.3%). This situation was mainly explained by the health crisis and the associated travel limitations. Furthermore, France's primary energy consumption stood at 2650.43 TWh in 2020. In fact, France's real primary energy mix consisted of 39.23% nuclear, 27.53% petroleum, 16.85% gas, 13.87% renewable energies and waste, and 2.52% coal (Fig. 2).

Concerning the French electricity mix, it was dominated by nuclear energy in 2020, as follows: 65.76% nuclear, 13.02% hydro, 10.45% conventional thermal, 7.98% wind, 2.67% PV, and 0.12% other sources. In 2020, net electricity production amounted to 510 TWh, down 6.8% from the previous year. This decrease was largely explained by the decline in nuclear production, which has been at its lowest level since the early 1990s. On the other hand, renewable electricity production increased compared to 2019. In fact, due to favorable weather conditions and the growth of the park, wind power production increased by 17.2% in particular. In addition, photovoltaic and hydraulic productions were also up, respectively, by 11.1% and 8.3% over 1 year (Ministry of Ecological Transition 2021b).

It should be noted that France is a net exporter of electricity to its European neighbors through the border interconnection lines, the most important part of its exports is satisfied by nuclear energy. In 2019, France imported 16 TWh and exported 73 TWh, i.e., an electricity export balance of 58 TWh, registering a decrease of 8% compared to 2018 due to the drop in nuclear and hydro production (Ministry of Ecological Transition 2019a).

Literature review

The links among nuclear power, income, and carbon emissions under the EKC hypothesis are well recognized in preceding research work (Dong et al. 2018; Mahmood et al. 2020; Syed et al. 2021). However, this study incorporates distinct control variables such as fossil fuel generation and trade openness from 1980 to 2020. In fact, fossil fuel generation is included in our model as a proxy for non-renewable energy. Actually, fossil fuel energy is perceived as the most ponderous component in the global energy mix (REN 21 2021). Concerning the empirical findings, a multitude of studies has demonstrated the negative effect of fossil fuels on the environmental quality through pollutant emissions (Lau et al. 2019; Bélaïd and Zrelli 2019; Ma et al. 2021; Haldar and Sethi 2022).

Moreover, the substantial role of trade openness as a determinant for CO_2 emissions is considered in our study. In fact, several studies have confirmed that the transfer of goods and services between trading partners of different countries in the world has a substantial effect on environmental quality (Cristea et al. 2013; Shahbaz et al. 2013; Kim et al. 2019; Fang et al. 2020; Aslam et al. 2021; Pata and Caglar 2021). In general, the influence of trade on the levels of pollution reveals several opposite findings.

Fig. 2 Primary energy consumption in France. Source: SDES (2021)
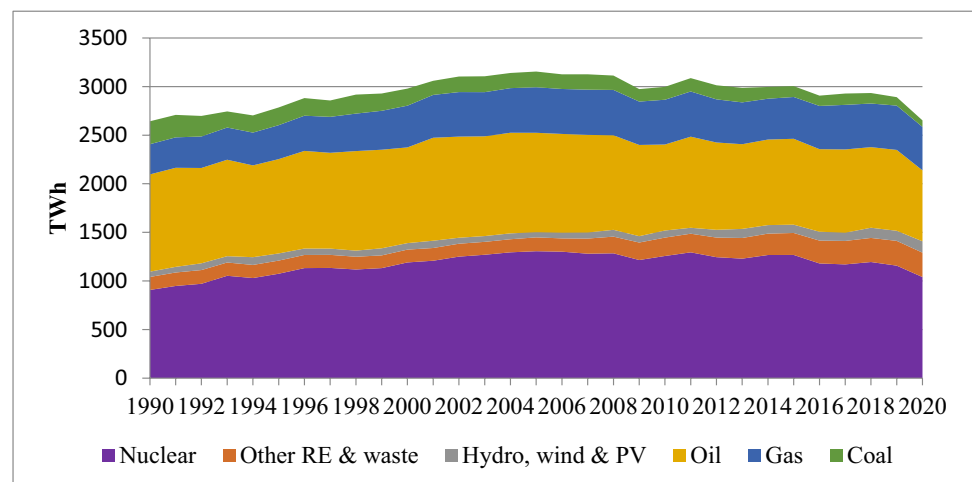
The nexus between economic growth and CO_2 emissions and the EKC hypothesis

The controversy of whether the liaison between per capita income and ecosystem deterioration follows an inverted U-shaped curve has been deeply analyzed by an impressive body of literature. In fact, following the research of Grossman and Krueger (1993, 1995) as well as Selden and Song (1994), many researchers have tried to discuss the presence of this relationship known as the EKC. Hence, since the 1990s, many researchers have tested the relevance of the EKC by applying different econometric methods. Many studies have presented a reviewing concerning the use of this hypothesis such as Dinda (2004), Stern (2004), Kijima et al. (2010), Kaika and Zervas (2013a, 2013b), and Sarkodie and Strezov (2019). In addition, the existing studies have used different indicators of environmental quality, but the majority of them have employed carbon dioxide emissions as an indicator of pollution.

Actually, the empirical findings concerning the EKC hypothesis are mixed, and there is a controversy about the validity of this assumption. In fact, the EKC hypothesis was validated widely (Apergis 2016; Li et al. 2016; Churchill et al. 2018; Acheampong et al. 2019; Ghazouani 2021; Salari et al. 2021; Zhang et al. 2021; Bouyghrissi et al. 2022; Hossain et al. 2022). However, the EKC assumptions were rejected by a considerable number of studies (Ben Jebli and Ben Youssef 2015; Kang et al. 2016; Antonakakis et al. 2017; Amri et al. 2019; Lawson et al. 2020). The research that rejected this hypothesis found different patterns of the EKC, such as the U-shaped form (Dinda et al. 2000; Pata and Caglar 2021), N-shaped form (Balsalobre-Lorente et al. 2018; Koc and Bulus 2020; Rej and Nag 2022), and inverted N-shaped form (López-Menéndez et al. 2014).

Multiple analyses were devoted to the case of a single country. For example, Ben Jebli and Ben Youssef (2015), as well as Amri (2018), found that the EKC assumption is not validated in Tunisia. However, for the same country, Ghazouani (2021) validated it. In addition, the results revealed that income had a negative influence on the environment and the presence of a bidirectional link between income and carbon emissions. Furthermore, Malik et al. (2020) and Zhang et al. (2021) validated the presence of the EKC in Pakistan and Ali et al. (2017) in Malaysia. In fact, Malik et al. (2020) demonstrated that economic growth increases CO_2 emissions.

China, as a great emitter of CO_2 emissions, has captivated the most attention (Jalil and Mahmud 2009; Dong et al. 2018; Wang and He 2019; Chen et al. 2020; Ahmad et al. 2021). The results for the case of China are also mitigated; for example, Pata and Caglar (2021) rejected the EKC hypothesis when Zhang and Zhang (2018) validated it.

The EKC in developed countries have also received great attention. For instance, Salari et al. (2021) validated this assumption in the case of the USA. However, Shahbaz et al. (2017a) confirmed the presence of the EKC; however, it is N-shaped in the presence of structural breaks and biomass.

Ben Youssef et al. (2016) analyzed the case of fifty-six countries divided into three panels according to their income level; they found that the causality between income and carbon emissions is bidirectional, and this relationship indicates an inverted U-shaped curve. Lawson et al. (2020) used a semi-parametric dynamic panel data model in order to concomitantly test the environmental convergence and EKC assumptions for the case of 106 countries, 21 are from the Organisation for Economic Co-operation and Development (OECD), and 85 are non-OECD from 1970 to 2015. Although the findings reject the validity of the EKC, they confirm the presence of the phenomenon of convergence of CO_2 emissions between countries with different income levels.

Concerning the case of France, the EKC hypothesis was validated by various studies (Ang 2007; Iwata et al. 2010; Can and Gozgor 2016; Shahbaz et al. 2018). For instance, Shahbaz et al. (2018) investigated the contributory factors to environmental degradation in the case of France from 1955 to 2016. They applied the bootstrapping ARDL approach in order to study the impacts of financial development, income, FDI, energy, and energy R&D on CO_2 emissions. The empirical results confirm that FDI and energy use boost carbon emissions, and the EKC hypothesis is confirmed. However, the other two variables improve the quality of the environment. Lastly, a comparison between France and Germany was carried out by Ma et al. (2021). The results attest the presence of the EKC.

The nexus between nuclear energy and CO_2 emissions

Varied analyses were concerned with the impact of nuclear power on the mitigation of pollution. A review of literature was given by van der Zwaan (2013) and Sovacool (2008). The studies concerned with the relationship between nuclear power and carbon emissions are multiple and offer mixed findings. In fact, some studies confirmed the positive influence of nuclear power on air pollution (Ishida 2018; Sarkodie and Adams 2018; Mahmood et al. 2020; Pan and Zhang 2020), but other studies demonstrated that the use of nuclear energy mitigates pollution (Apergis et al. 2010; Menyah and Wolde-Rufael 2010; Baek 2015, 2016; Lee et al. 2017; Dong et al. 2018; Hassan et al. 2020; Saidi and Omri 2020; Nathaniel et al. 2021). Other studies suggested that nuclear energy consumption has no effect on the environment quality (Al-Mulali 2014; Jaforullah and King 2015).

The lion's share of the studies is dedicated to a panel of countries such as countries with different levels of development (Apergis et al. 2010; Alam 2013; Akhmat et al. 2014; Ben Mbarek et al. 2018) or OECD countries (Lau et al. 2019; Saidi and Omri 2020). For instance, Azam et al. (2021) studied the case of a panel of ten countries with the highest CO_2 emissions from 1990 to 2014. The results of the panel fully modified ordinary least squares (FMOLS) revealed that the expansion of nuclear energy consumption is an efficient way to fight climate change. In fact, a 1% augmentation in nuclear energy declines carbon emissions by 0.012%. In the same line of research, Vo et al. (2020) treated the case of a panel of nine countries by using dynamic ordinary least squares (DOLS) and FMOLS estimations and found that nuclear energy consumption mitigates pollution.

The expansion of nuclear power for electricity generation in many countries has prompted numerous researchers to explore the effect of such a transition on the environment quality in a country-specific case. In fact, this issue was treated in the case of China (Dong et al. 2018), Japan (Ishida 2018), Pakistan (Zaidi et al. 2018; Mahmood et al. 2020), Iran (Kargari and Mastouri 2011), Republic of Korea (Kim 2020), South Africa (Sarkodie and Adams 2018), United Arab of Emirates (AlFarra and Abu-Hijleh 2012), and Spain (Pilatowska et al. 2020).

Other countries such as India (Bandyopadhyay and Rej 2021; Danish et al. 2021; Syed et al. 2021) and the USA (Menyah and Wolde-Rufael 2010; Jaforullah and King 2015; Baek 2016; Pan and Zhang 2020) have attracted the most consideration from scholars.

For the case of India, Bandyopadhyay and Rej (2021), Danish et al. (2021), and Syed et al. (2021) used the ARDL, the dynamic ARDL, and the NARDL approaches, respectively, and found that nuclear energy is a contributor to the environment amelioration. Concerning the case of the USA, Pan and Zhang (2020) employed the extended "Stochastic Impacts by Regression on Population, Affluence, and Technology" (STIRPAT) model along with the ridge regression to study the effects of many factors, notably nuclear energy, on air pollution in the USA. The results showed that alternative and nuclear energy of total energy consumption positively affects CO_2 emissions. However, in the same case of the USA, Baek (2016) used the ARDL approach and confirmed that nuclear consumption decreases air pollution. On the other hand, Jaforullah and King (2015) found no interlinkage between nuclear energy and CO_2 emissions by deploying a vector error correction model (VECM).

France, as one of the major nuclear energy producers, was also treated by many scholars (Iwata et al. 2010; Poinssot et al. 2014; Marques et al. 2016; Cany et al. 2018). While the studies are multiple and the approaches used are different, the results remain quite similar. In fact, Iwata et al. (2010) and Marques et al. (2016) used the ARDL approach and

demonstrated that the use of nuclear energy is beneficial to environmental quality. In addition, using the pair-wise Granger causality test, Iwata et al. (2010) found a unidirectional causality linkage from nuclear power to air pollution. On the other hand, Poinssot et al. (2014) applied the process chain analysis (PCA) in order to analyze the impacts of the nuclear fuel cycle on many environmental indicators in France. The results confirmed that nuclear power is one of the least impacting energies.

Many other interesting studies deal with the case of France in the context of a comparison with other countries such as Sweden (Millot et al. 2020) or Sweden and Spain (Pilatowska and Geise 2021). For instance, Pilatowska and Geise (2021) studied the impacts of nuclear energy along with fossil energies and renewable energies on carbon emissions and growth in three European countries by using the vector autoregression (VAR) model. The observations from the causality test showed that, in the formative phase, there is not any causal link among nuclear energy and air pollution in three countries. Concerning the expansion phase, there is one-way causality from nuclear to air pollution in Spain, bidirectional causality in France, and no significant causality in Sweden.

The studies that are interested in the case of France are not numerous compared to those that study France as part of a panel such as major nuclear-generating countries (Al-Mulali 2014; Baek and Pride 2014; Baek 2015), the group of seven (Nathaniel et al. 2021), and BRICS countries (Hassan et al. 2020). For instance, Baek (2015) used the FMOLS and DOLS approaches for estimation in the case of 12 principal nuclear-generating nations. The results revealed that the use of nuclear energy serves in the abatement of carbon emissions. In fact, a 1% increase in electricity produced from nuclear power abates carbon emissions by 0.12%.

The nexus between non-renewable energies and CO_2 emissions

Empirical studies have extensively investigated the influence of total energy on environmental deterioration which is designed via the CO_2 emissions or carbon footprint as well as other polluting emissions. In fact, fossil fuels (natural gas, oil, and coal) dominate the world's energy mix and are considered the most polluting sources.

In this context, several articles have examined this relation, either by focusing on the total energy or the substitution between fossil and renewable energy. For instance, Payne (2009) tested the causal link among energy and environmental degradation in the case of six Central American countries deploying the VECM model for the period 1971–2004. The findings confirm the positive linkage between energy and CO_2 emissions, which shows that energy causes environmental degradation in this set of countries. Moreover, many

studies have analyzed this linkage for India (Mahalik et al. 2021; Villanthenkodath and Mahalik 2022a; Villanthenkodath et al. 2022). In the same way, other similar works used different case studies, for example, Bangladesh (Islam et al. 2021); Pakistan (Khan et al. 2019); Gulf Cooperation Council (Kahouli and Chaaben 2022), and Qatar (Abulibdeh 2022).

On the other hand, the majority of studies in the recent empirical literature have explored the influence of renewable energies and fossil fuel consumption or production on environmental quality (Habeşoğlu et al. 2022). For instance, Bélaïd and Zrelli (2019) validated the negative impact of non-renewable electricity on environmental quality based on the case of the nations of the Middle East and North Africa (MENA) zone. Likewise, Bekun et al. (2019) examined this link and added the role of resource rents for a sample of 16 European countries. The author confirmed the significant involvement of growth and fossil fuel consumption in environmental deterioration.

Abumunshar et al. (2020) investigated the influence of renewable and conventional energies on CO_2 emissions, they also included the price of oil, and economic growth, in the case of Turkey. Their findings point out that oil, natural gas, and coal cause increased CO_2 emissions. Nevertheless, renewable energies reduce pollution. In addition, Anwar et al. (2021) investigated the case of a sample of the Association of Southeast Asian Nations (ASEAN) countries deploying the quantile regression model. The findings show that fossil fuels increase environmental pollution for the entire quantile.

Moreover, Adekoya et al (2022) studied the effect of renewable and non-renewable energies for both importing and exporting oil countries on environmental quality. For both groups of countries, fossil energy contributes significantly to the deterioration of environmental quality, with the impact being greater for oil exporting countries. On the other hand, Chien (2022) reported that the most important source of environmental degradation in N-11 economies is fossil fuel consumption. This result is based on the quantile regression method from 1990 to 2020. In the same way, this result is proved by Shafiei and Salim (2014), Bélaïd and Youssef (2017), Pata (2021), Adebayo and Rjoub (2022), Djellouli et al. (2022), Karaaslan and Çamkaya (2022), Mujtaba et al. (2022), Rahman and Alam (2022), and Zhao et al. (2022).

Saleem et al (2022), in another sense, projected their empirical work on the effect of fossil fuel energy production on CO_2 emissions by testing the effect of health expenditures for a sample of OECD countries between 2008 and 2018. They underlined the presence of a unidirectional causal linkage among fossil fuel production and carbon emissions. Villanthenkodath et al. (2021) explored the influence of fossil fuel share on CO_2 emissions in India using the ARDL model; they argued that the increase in fossil fuel share contributes to raising the level of CO_2 emissions. For the same case study, Rej et al. (2022) showed, by using a cointegration method, that in the long term the increase in liquefied petroleum gas can help in neutralizing the carbon level in India.

Moreover, concerning the case of France, Can and Gozgor (2016) used the error correction model (ECM) and the DOLS estimation techniques from 1964 to 2011 in order to assess the relationships among output, economic complexity, energy, and air pollution. The outcomes proved the existence of a positive impact of energy use on air pollution and a negative influence of economic complexity on polluting emissions in the long term.

On the other hand, Ang (2007) studied the links between carbon emissions, energy, and income during 1960–2000 period using a multivariate VECM. The outputs of the cointegration analysis highlight the existence of a strong long-term link between all variables. The results of the causality test suggest that output causes carbon emissions and energy in the long term; however, in the short term, there is a one-way causal link from energy consumption to output.

The nexus between trade openness and CO_2 emissions

The topic of a possible association between trade and the deterioration of the environment is well analyzed in the literature (Rauf et al. 2018; Fang et al. 2020; Ike et al. 2020; Muhammad et al. 2020; Su et al. 2020). However, the results are not conclusive about this relationship and depend on many factors such as the degree of development of the analyzed country and the methodology adopted. For instance, Appiah et al. (2022) investigated the impacts of imports and exports on pollution for the case of a panel of emerging countries by deploying "Driscoll-Kraay error's regression" in pooled ordinary least squares (OLS) from 1971 to 2013. The main results proved that a 1% increase in imports causes an upsurge of carbon emissions by 0.471%. Nevertheless, the effect of exports is not significant. In the case of the USA, Dogan and Turkekul (2016) found that trade enhances the quality of the environment. Moreover, Jalil and Mahmud (2009) used time series from 1975 to 2005 for the case of China and found that the influence of trade on environmental pollution is positive but statistically insignificant. For the same case of China, Michieka et al. (2013) used a VAR model to explore the linkages among exports, trade openness, coal consumption, and CO_2 emissions from 1970 to 2010. In addition, the study uses a Granger causality test established by Toda and Yamamoto and demonstrated a causal link from exports to air pollution.

On the other hand, Huang et al. (2022) used the NARDL model in the case of Pakistan and found that a negative variation in trade increases carbon emissions for the period

1990–2019. Furthermore, Villanthenkodath and Arakkal (2020) investigated the case of New Zealand by exploring the impacts of financial development, growth, FDI, and trade. They used the ARDL model and found that trade openness decreases carbon emissions. Additionally, an analysis elaborated by Jiang et al. (2022) explored the drivers of CO_2 emissions in countries of the Group of Seven (G7). The main results confirm that an increase in exports alleviates the ratio of consumption-based CO_2 emissions. However, a rise in imports boosts this ratio.

Meanwhile, other studies used a more general indicator such as the material footprint. For example, Sahoo et al. (2021) explored the impacts of urbanization, natural resources, along with other drivers on the material footprint for the case of BRICS countries. The principal findings suggested that foreign trade enhances environmental quality. Other recent studies deployed the indicator of ecological footprint such as Liu et al. (2022) for Pakistan and Dada et al. (2022) for Nigeria.

In the case of France, Mutascu (2018) explored the effect of trade on carbon emissions by deploying the wavelet tool. The results indicated that in the short term, there is no impact between the two variables. However, in the long term, trade openness enhances carbon emissions. Balsalobre-Lorente et al. (2018) investigated the case of 5 European countries which are Spain, the UK, Italy, Germany, and France. The results indicated that trade openness positively affects carbon emissions. Lastly, Dogan and Seker (2016) found that, in the European Union, trade alleviates air pollution.

Methodology

Data and descriptive analysis

The data concerning the generations of nuclear and fossil fuel energies measured by kilotonne of oil equivalent (Ktoe) are collected from the IEA. Moreover, the data of carbon emissions in million tonnes (MT) of CO_2 are also extracted from the previous source. The economic income corresponding to the real GDP per capita and the ratio of trade in a percentage of GDP are both obtained on the basis of the World Development Indicators (WDI). The data concerns the duration 1980–2020. The detailed definition of these components is illustrated in Table 1.

Moreover, a detailed description of the statistics is presented in Table 2. It is clear from Table 2 that non-renewable energies have the lowest volatility, while nuclear energy generation is the most volatile. The statistic of the skewness shows that CO_2 emissions (CO_2), nuclear energy (NUC), and the real GDP per capita (GDP) are negatively skewed, which means that they present longer left tails in comparison to a

Table 1 Definition of series

Variable	Definition	Measure	Source
CO_2	Carbon emissions	MT of CO_2	IEA (2022)
NUC	Total nuclear generation	Ktoe	IEA (2022)
GDP	Real GDP per capita	US$ constant 2010	WDI (2021)
TR	Trade openness	Percentage of GDP	WDI (2021)
NRE	Total fossil fuel generation	Ktoe	IEA (2022)

Table 2 Statistics

	$\ln CO_2$	lnGDP	lnNRE	lnNUC	lnTR
Mean	5.893	10.489	11.749	11.357	3.921
Maximum	6.182	10.695	11.989	11.675	4.167
Minimum	5.553	10.199	11.533	9.677	3.686
Std. dev	0.111	0.159	0.081	0.452	0.149
Skewness	−0.547	−0.474	0.008	−2.168	0.038
Kurtosis	4.561	1.841	4.330	7.206	1.658
Jarque–Bera	6.214 (0.044)	3.83 (0.147)	3.023 (0.220)	62.348 (0.000)	3.083 (0.214)

Note: the *p* values are presented between parentheses

normal distribution. In contrast, fossil fuel energies (NRE) and trade openness (TR) are positively skewed. In addition, the kurtosis coefficient exceeds 3 for CO_2, NRE, and NUC distributions which means that they are leptokurtic and have heavier tails compared with a normal distribution. Lastly, the Jarque–Bera statistic attests that NUC and CO_2 are not pursuing a normal distribution, unlike all other variables.

Moreover, Fig. 3 depicts the dynamics of the series and shows that all explicative variables have an increasing trend except NRE. Concerning the dependent variable, it shows a strong decrease in carbon emissions, mainly, during the period 1980–1986.

To assess the validity of the EKC, the GDP and the GDP squared term (GDP^2) are added. Accordingly, the specific role of the EKC is to specify the impact of economic income on environmental quality. Therefore, the following model specification will be adopted:

$$lnCO2_t = \alpha_0 + \alpha_1 lnGDP_t + \alpha_2 (lnGDP)_t^2 + \alpha_3 lnNUC_t + \alpha_4 lnNRE_t + \alpha_5 lnTR_t + \mu_t \tag{1}$$

where $lnCO_2$, lnGDP, $(lnGDP)^2$, lnNUC, lnNRE, and lnTR depict carbon emissions, GDP per capita, the square term of GDP per capita, nuclear power generation, fossil fuel energy generation, and trade openness, in logarithm form, respectively. The year is represented by the subscript "t", μ_t represents the error term, and α_0 illustrates the constant.

Fig. 3 Series trends
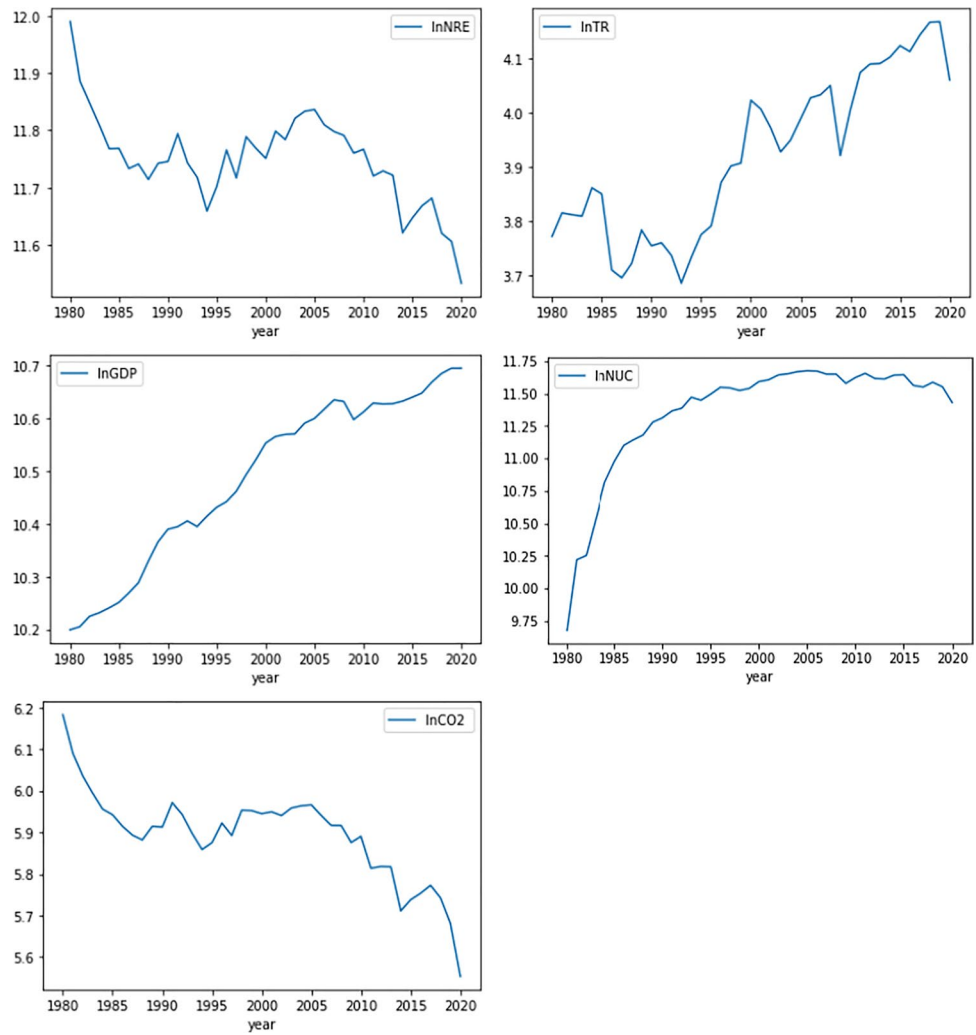
The factors (α_1, α_2, α_3, α_4, and α_5) present the elasticities corresponding to exogenous variables.

The NARDL approach

Recent studies consider that the reaction process of the determinants of CO_2 emissions is non-stable and non-linear (see, e.g., Lahiani 2020; Shahbaz et al. 2021). In this case, the standard linear cointegration (ARDL) becomes inadequate in terms of detecting the potential asymmetric effects (Villanthenkodath and Mahalik 2021; Saadaoui and Chtourou 2022). For this reason, it is necessary to adopt another approach that is able to capture the non-linearity characterizing the trends of the variables. Thus, the non-linear procedure specified by Shin et al. (2014) is adopted, which allows considering the asymmetric links between the variables (Villanthenkodath and Mahalik 2022b).

In fact, the NARDL model presents an extended form of the ARDL advocated by Pesaran et al. (2001). First, the linear form is presented in the following equation:

$$\Delta lnCO2_t = \alpha_0 + \rho_{CO2}lnCO2_{t-1} + \gamma_{GDP}GDP_{t-1}$$
$$+ \gamma_{GDP2}(lnGDP)^2_{t-1} + \gamma_{NUC}lnNUC_{t-1}$$
$$+ \gamma_{NRE}lnNRE_{t-1} + \gamma_{TR}lnTR_{t-1} + \sum_{i=1}^{p-1}\beta_i\Delta lnCO2_{t-i}$$
$$+ \sum_{i=0}^{q-1}\delta_i\Delta lnGDP_{t-i} + \sum_{i=0}^{q-1}\theta_i\Delta(lnGDP)^2_{t-i} + \sum_{i=0}^{q-1}\sigma_i\Delta lnNUC_{t-i}$$
$$+ \sum_{i=0}^{q-1}\varphi_i\Delta lnNRE_{t-i} + \sum_{i=0}^{q-1}\omega_i\Delta lnTR_{t-i} + \tau ECT_{t-1} + \mu_t$$

(2)

In order to highlight the asymmetric links between nuclear energy, fossil fuel energy, trade, and carbon emissions by taking into account the EKC model, the NARDL model presented in Eq. (3) is used:

$$\Delta lnCO2_t = \alpha_0 + \rho_{CO2}lnCO2_{t-1} + \rho_{GDP}lnGDP_{t-1} + \rho_{GDP2}(lnGDP)^2_{t-1}$$
$$+ \gamma^+_{NUC}lnNUC^+_{t-1} + \gamma^-_{NUC}lnNUC^-_{t-1} + \gamma^+_{NRE}lnNRE^+_{t-1}$$
$$+ \gamma^-_{NRE}lnNRE^-_{t-1} + \gamma^+_{TR}lnTR^+_{t-1} + \gamma^-_{TR}lnTR^-_{t-1} + \sum_{i=1}^{p-1}\beta_i\Delta lnCO2_{t-i}$$
$$+ \sum_{i=0}^{q-1}\delta_i\Delta lnGDP_{t-i} + \sum_{i=0}^{q-1}\theta_i\Delta(lnGDP)^2_{t-i}$$
$$+ \sum_{i=0}^{q-1}(\sigma^+_i\Delta lnNUC^+_{t-i} + \sigma^-_i\Delta lnNUC^-_{t-i})$$
$$+ \sum_{i=0}^{q-1}(\varphi^+_i\Delta lnNRE^+_{t-i} + \varphi^-_i\Delta lnNRE^-_{t-i})$$
$$+ \sum_{i=0}^{q-1}(\omega^+_i\Delta lnTR^+_{t-i} + \omega^-_i\Delta lnTR^-_{t-i}) + \mu_t$$

(3)

where ρ_{GDP} and ρ_{GDP2} are the long-term parameters linked to the GDP and the GDP^2. The EKC hypothesis check is based on the verification of the positive sign of ρ_{GDP} and the negative sign of ρ_{GDP2}. This relationship implies that economic growth increases polluting emissions, in the first phase, and brings them down when the economy is mature.

$\gamma_{NUC}^+, \gamma_{NRE}^+$, and $\gamma_{TR}^+ (\gamma_{NUC}^-, \gamma_{NRE}^-$, and $\gamma_{TR}^-)$ designate the long-run parameters attributed to positive alterations (negative alterations), respectively. σ_i^+, φ_i^+, and $\omega_i^+ (\sigma_i^-, \varphi_i^-, \omega_i^-)$ are the short-run parameters attributed to the positive alterations (negative alterations), respectively. In addition, positive $(lnNUC_t^+, lnNRE_t^+, lnTR_t^+)$ and negative $(lnNUC_t^-, lnNRE_t^-, lnTR_t^-)$ partial sums relative to nuclear energy, non-renewable energy, and trade, respectively, are presented in the following lines:

$$lnNUC_t^+ = \sum_{i=1}^{t} \Delta lnNUC_i^+ = \sum_{i=1}^{t} \max(\Delta lnNUC_i, 0)$$

$$lnNUC_t^- = \sum_{i=1}^{t} \Delta lnNUC_i^- = \sum_{i=1}^{t} \min(\Delta lnNUC_i, 0)$$

$$lnNRE_t^+ = \sum_{i=1}^{t} \Delta lnNRE_i^+ = \sum_{i=1}^{t} \max(\Delta lnNRE_i, 0)$$

$$lnNRE_t^- = \sum_{i=1}^{t} \Delta lnNRE_i^- = \sum_{i=1}^{t} \min(\Delta lnNRE_i, 0)$$

$$lnTR_t^+ = \sum_{i=1}^{t} \Delta lnTR_i^+ = \sum_{i=1}^{t} \max(\Delta lnTR_i, 0)$$

$$lnTR_t^- = \sum_{i=1}^{t} \Delta lnTR_i^- = \sum_{i=1}^{t} \min(\Delta lnTR_i, 0)$$

Then, the negative and positive long-term coefficients for each CO_2 emission determinant in the NARDL model framework are extracted. The following formulas provide the coefficients for the variables NUC, NRE, and TR, respectively:

$$\rho_{NUC}^+ = -\frac{\gamma_{NUC}^+}{\rho_{CO2}} \text{and} \rho_{NUC}^- = -\frac{\gamma_{NUC}^-}{\rho_{CO2}};$$

$$\rho_{NRE}^+ = -\frac{\gamma_{NRE}^+}{\rho_{CO2}} \text{and} \rho_{NRE}^- = -\frac{\gamma_{NRE}^-}{\rho_{CO2}};$$

$$\rho_{TR}^+ = -\frac{\gamma_{TR}^+}{\rho_{CO2}} \text{and} \rho_{TR}^- = -\frac{\gamma_{TR}^-}{\rho_{CO2}}.$$

The last step in the NARDL model involves a presentation of the dynamic multipliers related to favorable and unfavorable fluctuations, as follows:

$$m_{h,NUC}^+ = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial NUC_t^+}; m_{h,NUC}^- = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial NUC_t^-}$$

$$m_{h,NRE}^+ = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial NRE_t^+}; m_{h,NRE}^- = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial NRE_t^-}$$

$$m_{h,TR}^+ = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial TR_t^+}; m_{h,TR}^- = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial TR_t^-}$$

where $h \to \infty$; $m_{h,NUC}^+ \to \rho_{NUC}^+$; $m_{h,NUC}^- \to \rho_{NUC}^-$ (Shin et al. 2014).

Results and interpretations

Non-linearity and stationarity tests

First, the "Brock-Dechert-Scheinkman" (BDS) test elaborated by Broock et al. (1996) is adopted in order to check the nonlinearity in the data series. The null hypothesis considers that the data are independently and identically distributed. The conclusions from the non-linearity BDS test are mentioned in Table 3. The outcomes attest that the null hypothesis is rejected, in the sense that all variables are not identically and independently distributed which proves the presence of asymmetries. For this reason, it is necessary to use an asymmetric integration model to analyze the non-linear interactions.

Then, "the Augmented Dickey-Fuller" (Dickey and Fuller 1979) and "Zivot-Andrews" (Zivot and Andrews 1992) tests are applied for the unit root analysis. The null assumption of the two aforementioned tests is the occurrence of the unit root which designates the non-stationarity of the series.

Table 3 Results of BDS nonlinearity test

Variables	BDS statistic at different dimensions				
	m = 2	m = 3	m = 4	m = 5	m = 6
lnCO₂	0.130*	0.205*	0.258*	0.300*	0.303*
lnGDP	0.197*	0.332*	0.424*	0.493*	0.547*
lnGDP²	0.196*	0.331*	0.424*	0.492*	0.545*
lnNUC	0.129*	0.243*	0.341*	0.425*	0.496*
lnNRE	0.104*	0.159*	0.181*	0.221*	0.231*
lnTR	0.151*	0.240*	0.290*	0.316*	0.320*

Notes: * points up the rejection of the null assumption at 1% level of significance and "m" designs the embedding dimension

Table 4 Unit root analysis

Variables	Augmented Dickey-Fuller		Zivot-Andrews			
	Level	First difference	Level	Break year	First difference	Break year
lnCO$_2$	− 2.442**	− 4.560*	− 2.971	1996	− 5.780 *	1989
lnNUC	− 9.721*	− 4.049*	− 6.566*	1995	− 7.348*	1988
lnGDP	− 1.95	− 4.078*	− 3.307	2008	− 4.727***	2001
lnNRE	− 1.779***	− 6.758*	− 4.194	1998	− 7.887*	1995
lnTR	0.8321	− 5.640*	− 4.047	1986	− 6.087*	1994

Note: ***, **, and * represent the rejection of the null assumption at the significance level of 10%, 5%, and 1%, accordingly. The critical values of the Zivot-Andrews test are − 5.34, − 4.80, and − 4.58 for the levels of significance 1%, 5%, and 10%, respectively

Table 4 reports the outcomes of the two tests for all series. In fact, the augmented Dickey-Fuller test reveals that the null assumption is dismissed for CO$_2$, NUC, and NRE in level. However, the null assumption is dismissed, at the first difference, for all variables, which means that nuclear energy, fossil fuel energy, and CO$_2$ emissions are I(0), while the economic income and the trade openness are I(1).

Furthermore, previous studies have highlighted that classic unit root tests notably the "augmented Dickey-Fuller" are unable to detect the structural changes in the series which can lead to a misspecification of the variables' integration order (Perron 1989). Therefore, following Lahiani et al. (2019) and Syed et al. (2021), the Zivot-Andrews test is adopted, which is considered appropriate in the presence of nonlinearity in the time series. The Zivot-Andrews test shows that all series are stationary in I(1) except for lnNUC which is I(0). In fact, from the outcomes proved by this test, a break variable is created which designates the structural change for the endogenous variable of this model. This step allows us to check the solidity of our initial model.

The results of the precedent tests showed that all the variables are integrated in the order I(0) and I(1), and no variables are I(2). This finding leads us to apply the non-linear ARDL model since the conditions of the order of stationarity and linearity are valid.

Results of the NARDL approach

Bounds test results

Table 5 shows the outcomes of cointegration for the initial model and also for the model with the integration of the Break variable. The F-statistic (F_{PSS}) and the t-statistic (T_{BDM}) suggested by Pesaran et al. (2001) and Banerjee et al. (1998), respectively, validate the presence of asymmetric long-run cointegration between the selected variables at a 1% significance level. The asymmetric cointegration is detected as well when the Break component is added but at a significance level of 5%.

NARDL estimation results

The outcomes of the NARDL estimation are described in Table 6. In fact, the results express that the speed of adjustment (− 1.636) is negatively significant at the 1% level, meaning that the estimated NARDL model is stable. In addition, the R^2 value indicates that 98.74% of the data fit the regression model. In other terms, it indicates that 98.74% of the variance in CO$_2$ is collectively explained by the independent variables. Furthermore, the specificity of our investigation is that nuclear energy, nonrenewable energy, and trade are decomposed into positive and negative

Table 5 NARDL cointegration test

Bound Testing for Asymmetric cointegration				
Statistic	**NARDL**		**NARDL with Break point**	
F$_{PSS}$	4.1206*		3.9819**	
T$_{BDM}$	− 5.0776 *		− 4.1972**	
Pesaran et al. (2001)			Banerjee et al. (1998)	
Significance level	I (0)	I(1)	Significance level	Critical values
10%	2.26	3.35	10%	− 3.86
5%	2.62	3.79	5%	− 4.19
1%	3.41	4.68	1%	− 4.79

Note: * and ** indicate the thresholds levels at 1% and 5%, respectively

Table 6 NARDL long- and short-term estimations

	NARDL model			NARDL with break point		
Long-term analysis						
Variables	Coefficients	t-statistics	*P* value	Coefficients	t-statistics	*P* value
$lnCO2_{t-1}$	− 1.636 *	− 4.50	0.001	− 1.565*	− 3.77	0.004
$lnGDP_{t-1}$	54.763*	3.59	0.004	65.948**	2.87	0.019
$(lnGDP)^2_{t-1}$	− 2.597*	− 3.57	0.004	− 3.130**	− 2.85	0.019
Break	-		-	− 0.052	− 1.12	0.292
$lnNUC^+_{t-1}$	− 0.182**	− 2.74	0.018	− 0.193**	− 2.82	0.020
$lnNUC^-_{t-1}$	− 0.165	− 0.85	0.413	− 0.227	− 1.04	0.327
$lnNRE^+_{t-1}$	1.393*	3.62	0.004	1.476**	2.86	0.019
$lnNRE^-_{t-1}$	1.396*	4.47	0.001	1.442*	3.66	0.005
$lnTR^+_{t-1}$	− 0.085	− 0.67	0.513	0.056	0.32	0.753
$lnTR^-_{t-1}$	0.357*	3.04	0.0100	0.481**	3.04	0.013
Short-term analysis						
$\Delta lnGDP_t$	64.338 **	2.45	0.030	86.573***	2.13	0.062
$\Delta lnGDP_{t-1}$	− 109.257*	− 2.70	0.003	− 119.427*	− 3.53	0.006
$\Delta(lnGDP)^2_t$	− 3.044**	− 2.45	0.031	− 4.086***	− 2.13	0.062
$\Delta(lnGDP)^2_{t-1}$	5.171*	3.63	0.003	5.651*	3.51	0.007
$\Delta Break_t$	-	-	-	− 0.0403	− 1.09	0.305
$\Delta Break_{t-1}$	-	-	-	0.039	1.50	0.168
$\Delta lnNUC^+_t$	− 0.004	-0.04	0.969	0.029	0.21	0.838
$\Delta lnNUC^+_{t-1}$	− 0.097	− 1.65	0.125	− 0.108	− 1.62	0.140
$\Delta lnNUC^-_t$	0.369**	2.23	0.046	0.344***	1.83	0.100
$\Delta lnNUC^-_{t-1}$	0.122	0.63	0.543	0.251	1.16	0.277
$\Delta lnNRE^+_t$	0.122	0.63	0.543	0.617**	2.72	0.024
$\Delta lnNRE^+_{t-1}$	− 0.457	− 1.64	0.126	− 0.716***	− 1.93	0.086
$\Delta lnNRE^-_t$	1.162*	7.92	0.000	1.290*	7.46	0.000
$\Delta lnNRE^-_{t-1}$	− 0.424	− 1.75	0.105	− 0.369	− 1.14	0.284
$\Delta lnTR^+_t$	0.108	0.74	0.474	0.144	0.79	0.450
$\Delta lnTR^+_{t-1}$	0.181	1.18	0.261	0.138	0.79	0.449
$\Delta lnTR^-_t$	− 0.039	− 0.33	0.749	− 0.058	− 0.47	0.650
$\Delta lnTR^-_{t-1}$	− 0.284***	− 2.09	0.059	− 0.376***	− 2.12	0.063
constant	10.220	4.53	0.001	9.787*	3.81	0.004
R^2	0.9874			0.9953		
Wald statistics						
	F-statistics		*P* value	F-statistics		*P* value
$W_{LRlnNUC}$	0.005		0.941	0.019		0.893
$W_{SRlnNUC}$	3.025*		0.100	2.756		0.131
$W_{LRlnNRE}$	0.0001		0.992	0.015		0.903
$W_{SRlnNRE}$	1.377		0.263	2.361		0.159
W_{LRlnTR}	13.85*		0.003	11.65*		0.008
W_{SRlnTR}	3.874***		0.073	5.045**		0.051
Long-run parameters						
	Coefficient	F-statistics	*P* value	Coefficient	F-statistics	*P* value
ρ_{lnGDP}	33.463*	22.35	0.000	42.132**	9.524	0.013
$\rho_{(lnGDP)^2}$	− 1.587*	21.86	0.001	− 2.000**	9.373	0.014
ρ_{Break}	-	-	-	− 0.034	1.05	0.332
$\rho_{lnNUC^+_t}$	− 0.111*	12.31	0.004	− 0.123**	8.881	0.015
$\rho_{lnNUC^-_t}$	− 0.101	.7066	0.417	− 0.145	1.123	0.317
$\rho_{lnNRE^+_t}$	0.852*	58.19	0.000	0.943*	25.28	0.001

Table 6 (continued)

	NARDL model			NARDL with break point		
Long-term analysis						
Variables	Coefficients	t-statistics	*P* value	Coefficients	t-statistics	*P* value
$\rho_{lnNRE_t^-}$	0.853*	50.34	0.000	0.922*	39.65	0.000
$\rho_{lnTR_t^+}$	-0.052	.5425	0.476	0.036	.09499	0.765
$\rho_{lnTR_t^-}$	0.218 *	9.706	0.009	0.307**	8.285	0.018

Note: The asterisks (*), (**), and (***) refer to 1%, 5%, and 10% significance levels, sequentially

alterations, whereas the income and the square of GDP are non-decomposed in order to test the EKC model.

The first long-term result to be retained from this model is the following: the influence of income on carbon emissions is positive (54.763). This implies that a 1% upsurge in the level of income enhances CO_2 emissions by 54.763%. Concerning the squared real GDP per capita, it decreases the level of pollution by about 2.597%. Hence, the significant positive and negative signs of the coefficients of lnGDP and $(lnGDP)^2$, respectively, confirm the occurrence of an inverted U-shaped curve relating income with CO_2 emissions. Accordingly, the EKC hypothesis is supported in our case, which means that over the earliest phases of development, an increase in economic growth is coupled with a boost in pollutant emissions till a specific threshold level of GDP is reached when an increase of growth is followed by a decrease of pollutant emissions.

These results are consistent with diverse research dealing with the case of France and confirming the EKC hypothesis, such as Ang (2007), Iwata et al. (2010), Can and Gozgor (2016), Shahbaz et al. (2017b), Shahbaz et al. (2018), and Ma et al. (2021). Concerning other countries, the EKC is validated by Malik et al. (2020) in the case of Pakistan, and Salari et al. (2021) in the USA. However, our results are inconsistent with those of Ben Jebli and Ben Youssef (2015) and Amri et al. (2019) who rejected the EKC assumption in Tunisia and Pata and Caglar (2021) in the case of China.

Based on the coefficients related to the variable GDP and its square, the turning point of the EKC curve and the turning year are determined. The calculated turning point value is of the order of 37 930.53518 (US constant 2010) which corresponds to the logarithm value equal to 10.543. This value is lower than the highest real value over the sample period which means that this value is included in our sample. In fact, Ang (2007) and Iwata et al. (2010) have supported this result in the case of France. In addition, by calculating the turning point, it is possible to extract the turning year corresponding to 2008. Practically these results are not surprising since France is a developed country and its growth is mature. This outcome is inconsistent with the analysis of Dong et al. (2018) who consider that after the year 2028, which corresponds to the turning point, China will realize its mature economic growth.

On the other hand, the potential role of nuclear power on environmental deterioration is also analyzed. The results reveal that a favorable variation in generated nuclear power has a negative influence on carbon emissions. Notably, a 1% upturn in nuclear energy lessens CO_2 emissions by 0.182%. In contrast, a 1% decline in nuclear energy has a negative but non-significant influence on air pollution. Hence, our outcomes endorse the statement that nuclear energy could help in reducing CO_2 emissions, confirming the findings of the IEA (2019) which points out that nuclear energy makes a substantial contribution in enhancing the global fight against climate change. Our outcomes are in harmony with the conclusions of Iwata et al. (2010) and Marques et al. (2016) who stipulated the positive involvement of nuclear power in reducing pollutant emissions in the case of France. Our results are also consistent with Nathaniel et al. (2021) for the group of seven and Hassan et al. (2020) for the BRICS nations, and Syed et al. (2021) for the case of India. However, the results are in contradiction with those of Mahmood et al. (2020) in the case of Pakistan, Pan and Zhang (2020) in the case of the USA, and Sarkodie and Adams (2018) in the case of South Africa.

Furthermore, the estimated coefficients related to fossil fuel energy appear positive and significant. Specifically, a 1% increase in fossil fuel production culminates in an intensification of the CO_2 emissions by 1.393%, similarly, a decrease of 1% of this variable increases CO_2 emissions by 1.396%. Consequently, our results support the fact that CO_2 emissions are driven by fossil fuel production in France. These results are in accordance with the reported results of Ma et al. (2021) comparing France and Germany and Martins et al. (2021) in the case of the G7. Likewise, Kartal (2022) in the case of the top 5 carbon emitting countries and Lawson (2020) for 41 Sub-Saharan African countries confirm these results.

The negative impact of fossil fuels on environmental quality is expected. Therefore, France should reduce fossil fuel imports and consumption. This reduction can be compensated by increasing the investment and the use of clean technologies by substituting fossil fuels with renewable energies since their costs have slumped heavily during the last decades in conformity with the statement of the International Renewable Energy Agency (IRENA) (2020).

Lastly, the results attest that the estimated coefficients for trade openness are positive in the long term. More specifically, the results reveal that the downside variations in trade openness exert a positive effect (0.357), while the positive variations in the trade exert a negative but no significant influence on controlling CO_2 emissions in France. Consequently, there is a positive effect of the flows of international trade in France for both exports and imports on CO_2 emissions. In this regard, policymakers in France should enhance the use of clean technologies, by implementing incentive policies toward environmentally friendly industries and they should also penalize polluting industries by involving taxes and norms.

Hence, this outcome confirms that trade is a driver of carbon emissions in France. Theoretically, the type of influence of trade on environmental quality could be specified by scale, composition, and technique effects (Antweiler et al. 2001). The prevalence of one of these effects over the others will define whether trade boosts carbon emissions or declines them. In fact, the scale effect points out that trade increases the level of CO_2 emissions by improving economic growth. However, the technique effect indicates that trade enhances environmental quality as a result of the application of non-polluting technologies in the industry. Furthermore, the composition effect affects the implication of trade for CO_2 emissions depending on whether the clean or dirty technologies are dominant in the industry. Consequently, the pre-cited results are explained by the existence of scale and composition effects for the case of France.

This finding is analogous to Mutascu (2018) in the case of France, and Aslam et al. (2021) in the case of Malaysia. However, it is inconsistent with the results of Iwata et al. (2010) in the case of France, who found that trade has an insignificant influence on carbon emissions.

Concerning the short-term estimation in Table 6, it also confirms the EKC hypothesis. In fact, the income per capita increases the CO_2 emissions by 64.338% at a 5% significance level, and its squared curtails the level of CO_2 by 3.044% at a 5% significance level. Regarding nuclear energy, its positive change has no significant impact on CO_2 emissions in the short-run; in contrast, the negative change has a positive effect. In addition, the positive change in fossil fuels has positive but non-significant repercussions on CO_2 emissions, although the negative change reveals the existence of a significant and positive effect. Lastly, negative changes as well as positive ones in trade have no significant impacts, in the short-term.

Furthermore, the estimation of the NARDL model provides us with Wald statistics that describes the asymmetry of the variables after estimation. In fact, the results in Table 6 show that only the variable NUC is asymmetric in the short-term, and the variable TR is asymmetric in both the short and long run.

The next step is the analysis of the long-term asymmetric responses of CO_2 emissions to positive and negative variations in nuclear, fossil fuel, and trade openness, while the GDP per capita and its squared followed a symmetrical approach. Table 6 also details these asymmetric long-term parameters. It should be noted that these findings are identical to the variations proven by NARDL in the long term. Thereafter, a 1% upsurge in nuclear energy generates a decrease in CO_2 emissions by 0.111%. However, a 1% decrease in nuclear energy has no significant long-run reaction from CO_2 emissions. Moreover, a 1% increase in non-renewable energy generates a considerable upsurge in carbon emissions by 0.852%. Likewise, a 1% decrease in this variable has the same impact on environmental quality (0.853%). Finally, trade openness has a negative non-significant effect on CO_2 emission in the case of positive shock. However, it results in a raise in carbon emissions by 0.218% in the case of a negative shock.

In addition to the aforementioned findings, the results of a model that includes a break variable is presented for robustness purposes. This variable is extracted from the Zivot-Andrews integration test. It is obvious that the impacts are similar in this model in the long term. The same remark is for the short term, except for the lnNRE component that has revealed a significant effect following a positive shock.

Figure 4 presents the results of the dynamic asymmetric multipliers which characterize the dynamic adjustment process between the variables in the model, except for the case of real GDP per capita, and its square which are selected to have a linear reaction during the whole period in order to test the EKC hypothesis. Clearly, they design the asymmetric adjustment path of CO_2 emissions following one unit change of nuclear energy, nonrenewable energy, and trade openness. The analysis of this step allows French policymakers to integrate and design effective strategies to accomplish their objectives concerning the protection of the environment through the control of CO_2 emissions.

It can be observed from Fig. 4 that negative shocks on both nuclear energy and trade openness have a deeper influence on carbon emissions than positive ones in the long-term. Controversially, the effect of non-renewable energy on carbon emissions is equivalent in the case of positive and negative changes.

The sensitivity analysis

With the intention of checking the relevance of our model, Table 7 details the main sensitivity analyzing of the initial model, and the NARDL with break point. Concerning the sensitivity assessment of the NARDL model, the Durbin-Watson (D-W) statistic (2.535) specifies the non-presence of autocorrelation. In addition, the Breusch-Godfrey serial correlation test (0.2004) confirms the null hypothesis of
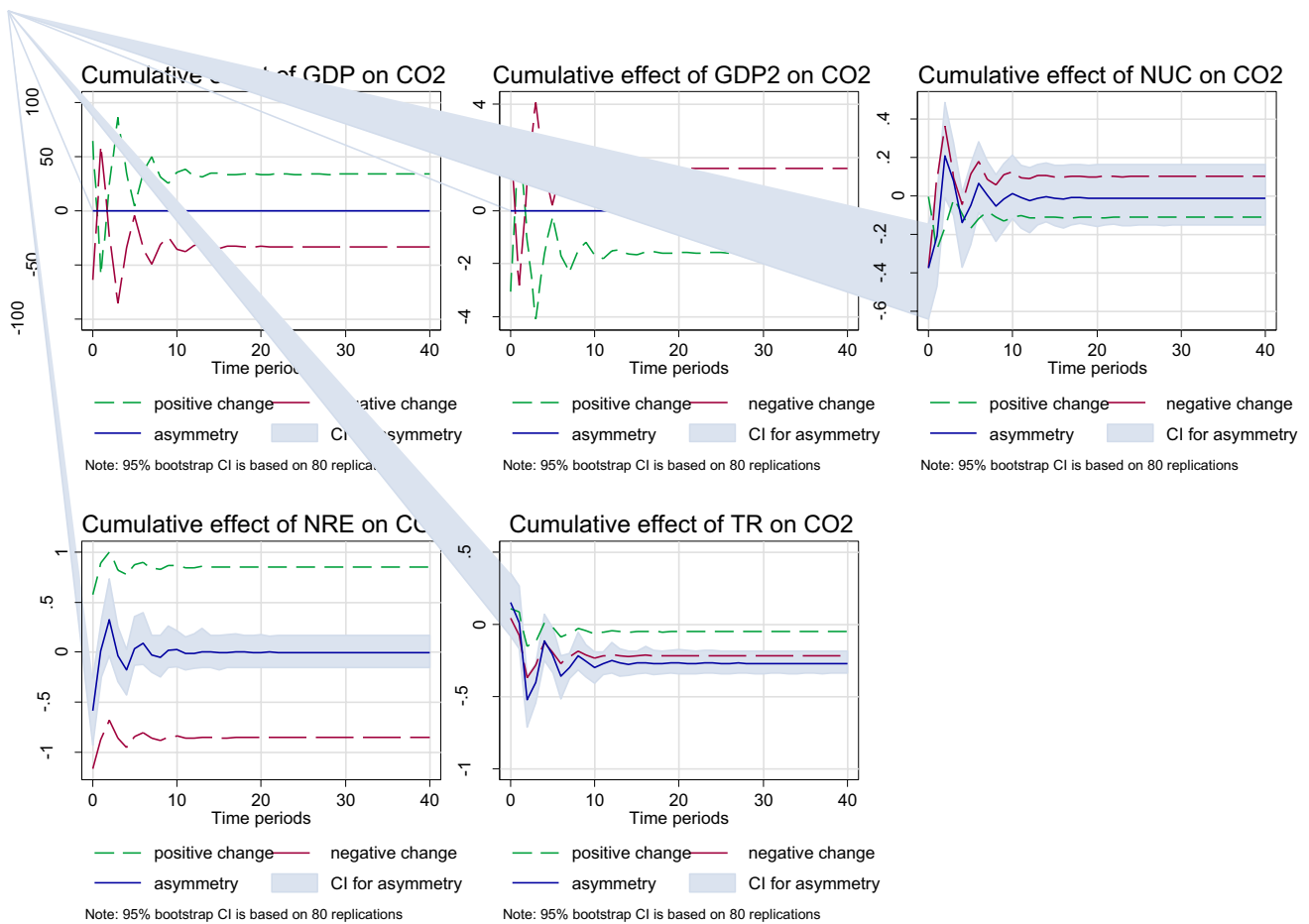
Fig. 4 Multipliers of accumulative effects of NUC, GDP, GDP.^{2}, NRE, and TR on CO2

Table 7 Sensitivity analysis of the NARDL model

	NARDL	NARDL with break point
D-W	2.535	2.279
SERIAL	0.2004 (0.6544)	1.623 (0.2027)
ARCH	1.842 (0.1748)	0.961 (0.3270)
J-B	1.258 (0.5331)	3.407 (0.1821)
CUSUM	Stable	Stable
CUSUMQ	Stable	stable

Note: *p* value are featured in ()

the non-existence of serial correlation of error terms, since the *p* value of the serial correlation test is insignificant at the different levels of significance. On the other hand, the autoregressive conditional heteroskedasticity (ARCH) test denies the existence of any conditional heteroskedasticity. Furthermore, the Jarque–Bera (J-B) test rejects the existence of normality in the model, at the different levels of significance. These results are also validated for

the non-linear model with a break variable. Finally, the CUSUM and CUSUMSQ tests are performed in order to check the model stability. Figures 5 and 6 present the CUSUM and CUSUMSQ tests for both models and indicate that the estimated lines are between the critical bounds at the 5% threshold. This means that the estimated parameters are stable during the interval 1980–2020.

Nonlinear causality test

In order to identify possible non-linear causal links between nuclear, GDP, fossil fuel energy, trade, and CO_2 emissions, the test of Diks and Panchenko (2006) is performed. Therefore, Table 8 includes the causal links from the explanatory variables to carbon emissions and also the opposite direction. First, the causal liaison between carbon emissions and GDP is bidirectional at 5% significance. The previous result means that income causes the degradation of the environment and vice versa. This outcome is similar to the finding of Bélaïd and Zrelli (2019) who found a feedback hypothesis between CO_2 emissions
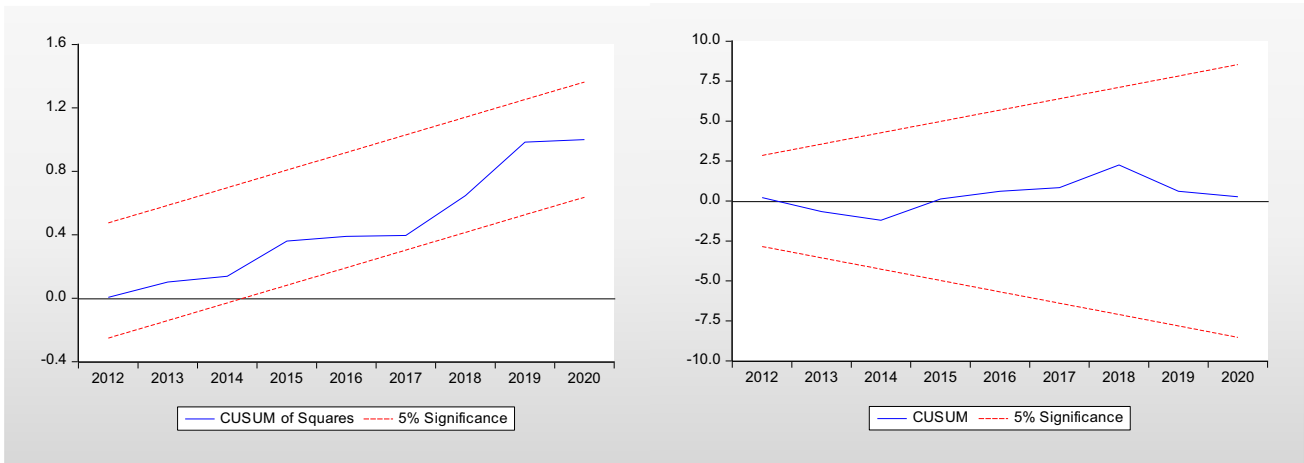
Fig. 5 Plots of CUSUM and CUSUMQ for NARDL model

Fig. 6 Plots of CUSUM and CUSUMQ for NARDL model with Break point

Table 8 Nonlinear Granger causality test

Dimension	1	2	3
lnCO2 = > lnGDP	0.784	2.001**	1.113
lnGDP = > lnCO2	1.391***	0.435	1.640**
lnCO2 = > lnNUC	− 0.666	0.775	0.769
lnNUC = > lnCO2	− 0.956	− 0.574	− 0.142
lnCO2 = > lnNRE	2.349*	1.720**	1.782**
lnNRE = > lnCO2	0.391	− 1.24	− 1.310
lnCO2 = > lnTR	− 0.206	1.568**	0.145
lnTR = > lnCO2	1.627**	0.975	1.372***

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

and income in the case of 9 Mediterranean countries from 1980 to 2014. This outcome is also congruent with Sinha et al. (2018) for 11 countries during the period 1990 and 2016. On the other hand, it is inconsistent with the finding of Tiba and Bélaïd (2020) who demonstrated a causal link from carbon emissions to GDP in the short term for a panel of 27 countries from 1990 to 2013. Moreover, there is a neutral causality between nuclear power and carbon emissions. This outcome is inconsistent with Menyah and Wolde-Rufael (2010) who found that nuclear power causes CO_2 emissions in the USA from 1960 to 2007. In addition, the outcomes of the non-linear test display a one-way causal link between carbon emissions and non-renewable energies. In this vein, Saleem et al. (2022) found a unidirectional causality between fossil fuel production and emissions for 38 OECD countries. Finally, the causal

link is bidirectional between carbon emissions and trade. This outcome is different from Appiah et al. (2022) who found a unidirectional causal link from exports to carbon emissions and a one-way causal link from imports to carbon emissions in the case of emerging economies. In addition, Michieka et al. (2013) demonstrated a causal link from exports to carbon emissions in the case of China. Finally, for Dogan and Turkekul (2016) no evidence was found among emissions and foreign trade in the USA.

Conclusions and policy implications

This research has analyzed the relations between CO_2 emissions, nuclear energy, and economic growth, considering the role of fossil fuels and trade openness from 1980 to 2020, in the case of France. First, in this framework, the relevance of the EKC assumption in France was evaluated. In addition, the asymmetric ARDL approach suggested by Shin et al. (2014) and the asymmetric test of causality of Diks and Panchenko (2006) were adopted to analyze the asymmetric cointegration and the non-linear causality in our model. The main outcomes of the current analysis will be synthesized in what follows.

First, the liaison between income and carbon emissions designs an inverted U-shaped relationship. More specifically, the upsurge in GDP generates a rise in CO_2 emissions while the squared GDP per capita decreases these pollutant emissions. Accordingly, our results disclosed the verification of the EKC assumption. In addition, the turning point related to income and CO_2 emissions was reached in 2008, which means that since this year, the increase in GDP per capita has been coupled with a decrease in CO_2 emissions in France. Consequently, France has been following a "green growth" path since 2008.

Second, the asymmetric influence of nuclear energy on CO_2 emissions shows that the overall impact is negative. In fact, it was highlighted that a 1% upturn in nuclear energy decreases carbon emissions by 0.182%, in the long term. Given that nuclear power is reducing CO_2 emissions in France, consequently, the dependence of the French electricity mix on nuclear power is not in contrast with its ambitious targets of mitigating CO_2 emissions and its fight against climate change. However, the management of nuclear plants encompasses many risks that are mentioned largely (Choi 2019; Carless et al. 2021) and proved by many disasters (for example, Chernobyl in 1986 and Fukushima in 2011). In addition, the perception of risks and acceptance of nuclear power by the population is a very important issue that should be taken into account (Ho et al. 2014; Lee and Gloaguen 2015; Perez et al. 2020). Moreover, Muellner et al. (2021) demonstrated that nuclear energy obviates only between 2 and 3% of

GHG emissions and the tendency will decrease by 2040. Hence, France should diversify its energy mix by introducing many types of renewable energy in order to mitigate its GHG emissions in the future.

Third, non-renewable energy negatively influences CO_2 emissions in France. In particular, positive and negative shocks to non-renewable energy are drivers of environmental pollution in the long term, which confirms the fact that fossil fuels are among the main trigger factors of climate change. Hence, in addition to the deployment of nuclear power in electricity generation, France should diversify the electricity mix by substituting fossil fuels with renewable energies which will enhance the environmental quality in France. Even though France has applied for challenging programs in the field of renewable energies, their share is still modest compared with nuclear energy. In fact, in 2020, nuclear energy represented 65.76%, against only 13.02% of hydro, 7.98% of wind, and 2.67% of PV (Ministry of Ecological Transition 2021b). To enhance the substitution of fossil fuels with renewable energies, the government should mobilize several tools and mechanisms such as feed-in tariffs, and support for R&D. In fact, boosting R&D budgets intended for renewable energies should be taken seriously by policymakers since 63% of this public funding was intended for nuclear power in 2019 (Ministry of Ecological Transition 2019b).

Fourth, trade openness is qualified as a driver of CO_2 emissions, more specifically only the downturn in this variable raises the level of CO_2 emissions, while the upturn action has no significant effect on environmental sustainability. In this case, the French government should adopt a strategy based on encouraging the use of clean industry. For example, it can impose taxes and standards on polluting industries, which can positively impact alternative industries based on clean technologies. In addition, the major part of fossil fuels consumed in France is imported, since fossil fuel production is very limited. Hence, decoupling imports from carbon emissions needs, firstly, the diminution of these polluting imports by reducing the consumption of fossil fuels in electricity, transport, and industry and substituting them with clean energies which are produced locally.

On the other hand, the test of Diks and Panchenko (2006) was performed in order to identify the possible non-linear causal relationships between nuclear energy, GDP, fossil fuel energy, trade, and CO_2 emissions. First, the causality between carbon emissions and GDP is bidirectional at 5% significance. This result means that income causes the degradation of environmental quality and vice versa. Moreover, a neutral non-linear causality between nuclear power and carbon emissions was found. Furthermore, the results of the non-linear test display a one-way causal link between carbon emissions and non-renewable energies. Finally, the causal link is two-way between carbon emissions and trade.

Future research can contribute to the existing literature by analyzing the substitution possibility between nuclear power and renewable energies in the case of France to put out useful policy suggestions. It will be interesting also to use a more general indicator as a proxy for environmental pollution such as the ecological footprint which has been recently used by scholars such as Altintas and Kassouri (2020), Ansari and Villanthenkodath (2021), Sahoo et al. (2021), Ansari et al. (2022), and Bandyopadhyay et al. (2022).

Author contributions Emna Omri: Conceptualization; methodology; writing, review and editing.

Haifa Saadaoui: Conceptualization; methodology; data collection; software; writing.

Availability of data and materials The links to the data sources are indicated in the sub-section "Data and descriptive analysis."

Declarations

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