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***UK's net-zero carbon emissions target:
Investigating the potential role of economic growth, financial development,
and R&D expenditures based on historical data (1870 - 2017)***

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Abstract: The 4th industrial revolution and global decarbonisation are frequently referred to as two, interrelated megatrends. In particular, the former, technological revolution is expected to fundamentally change the economy, society, and financial systems, and may also create opportunities towards a zero-carbon future. Therefore, in the presence of the UK's legally binding commitment to achieve a net-zero emissions target by 2050, we analyse the role of economic growth, R&D expenditures, financial development, and energy consumption in causing carbon dioxide (CO₂) emissions. Our analysis is based on historical annual data from 1870 to 2017, thereby employing the bootstrapping bounds testing approach to examine short- and long-run relationships. The results suggest the existence of cointegration between CO₂ emissions and its determinants. Financial development and energy consumption lead to environmental degradation, but R&D expenditures help reducing CO₂ emissions. The estimated environmental effects of economic growth support the EKC hypothesis. While a U-shaped relationship is depicted between financial development and CO₂ emissions, the nexus between R&D expenditures and CO₂ emissions is analogous to the EKC. In the context of the efforts to tackle climate change, our findings suggest policy prescriptions by using financial development and R&D expenditures as key tools to meet the emissions target.

Keywords: CO₂ Emissions, Economic Growth, Financial Development, R&D Expenditures, Net-zero Emissions

JEL Classifications: C22, O44, Q54, Q55

1. Introduction

The 4th industrial revolution and climate change are often seen as two, interconnected megatrends (BlackRock, 2020). On the one hand, the 4th industrial revolution is expected to deeply transform the way that the economy, society, and financial systems work. That is, through disruptive technological advances, such as artificial intelligence, the Internet of Things, and machine learning, people's lives will fundamentally change. At the moment, the direction of this transformation is unclear, but if steered effectively, it may benefit people and environment (Herweijer et al. 2018). For instance, in his recent descriptive analysis, Corfe (2020) lists several opportunities how the 4th industrial revolution may help to clean the environment. To decarbonize the industry, his list includes ideas such as green commercial vehicle fleets, 3D printing, and cloud-based computing. Nonetheless, there is also an increasing realisation that the technological revolution could exacerbate problems, for example in the form of unemployment or reduced wages (Acemoglu and Restrepo, 2018).

On the other hand, mainly due to growing anthropogenic greenhouse gas emissions, the increased possibility of a catastrophic climate change has recently been reported (Committee on Climate Change, 2019). That is, the climate is rapidly changing and planet Earth is warming, potentially more than the desired increase of 2⁰C above pre-industrial levels. Climate change is not only an existential threat to humankind in the developing world but also an important challenge for advanced countries, such as the UK.¹ Already today, the UK economy is suffering from climate change, manifested in a rising number of extreme weather events, warmer winters and hotter summers, rising sea levels of around 3mm a year, and changing rainfall patterns (Gov.uk, 2017). The health consequence of extreme weather events is comparatively large in the UK. The heatwave in 2003 has taken the life of two thousand people. Similarly, the 2007 flooding is regarded as a sign of climate change, which not only adversely affected 55,000 homes and killed 13 people but also amounted for economic losses of about £3.2 billion. Subsequently, the UK government has covered the average flooding loss of about £1.5 billion per year in the last two decades. These extreme events are economically and socially detrimental, and pose multifaceted challenges to the UK. Given the amount of damages caused to the UK economy, a climate emergency with a set of serious actions is required to lower the rising carbon emissions that will help the UK economy to protect environmental quality (Committee on Climate Change, 2019).

The Climate Change Act of 2008 has provided a legally binding framework for the UK government to regularly assess the risk for the UK arising from climate change, mitigate national greenhouse gas emissions, and prepare a climate change adaptation strategy (Gov.uk, 2019a). This important legislation established the world's first climate change target that is binding by law. Specifically, the UK's economy and households were expected to reduce carbon emissions by 80% until 2050 as compared to 1990 baseline (Gov.uk, 2015).² In addition, the UK has joined hands with the other 194 parties ratifying the Paris Agreement of 2015. The Paris Agreement was drafted in line with the United Nations Framework

¹ In their recent study, Chaudhry et al. (2020) find that climate change increases sovereign risk for G7 countries.

² Prior to this legislation, the UK had a climate policy stringency that was comparable to other Western European countries. For instance, between 1995 and 2009, on average the UK had the 11th strictest climate regulation out of 28 OECD countries, placing after countries like Denmark, Sweden, and Germany, but ahead of Finland, France, and Greece (Althammer and Hille, 2016).

Convention on Climate Change (UNFCCC), which calls upon the international community to tackle rising carbon emissions through greater regulatory efforts and financial capacities. It is quite likely that, if the UK among the other international partners fails to achieve its nationally determined reduction targets, then it has to face more flooding, greater pressure on scarce water resources, damage to natural or wildlife habitats, and occupational health risks from heatwaves (Committee on Climate Change, 2019). Considering the expected severity of climate change and the UK Climate Change and Risk Assessment, stating that the right time is now for the UK government to act on these challenges (Gov.uk, 2017), the UK government decided to speed up their efforts. Hence, instead of the 80% reduction goal, the UK became the first major country to pass a net-zero emissions law, targeting a 100% reduction of carbon dioxide (CO₂) emissions by 2050 (Gov.uk, 2019b). However, without appropriate actions, based on thorough empirical evidence about the factors causing CO₂ emissions in the long run, the facts on the ground will not change.

Economic activity is often considered as the main driver of CO₂ emissions. Indeed, it is essential to improve the lives of the people of the UK in the long run, so that people with better income and environmental education will demand better environmental quality. A better environmental quality is beneficial both for higher economic growth as well as for sustainable quality of human beings and other inhabitants. This is the key environmental protection mechanism of the Environmental Kuznets Curve (EKC) hypothesis. The evidence on the EKC hypothesis can be best described as mixed (Onafowora and Owoye, 2014; Apergis, 2016; Özokcu and Özdemir, 2017; Nasir et al., 2019). This contrast suggests that we shall see the growth-emissions nexus in a broader context and account for the country-level differences as well as other factors. Putting this together with the environmental ambitions of the UK government, it is important to see how the economic growth-emissions nexus prevails in the UK.

In addition to economic growth, financial development is considered to play a vital role in the dynamics of greenhouse gas emissions (Charfeddine and Ben Khediri, 2016; Bekhet et al., 2017; Nasir et al., 2019; Shahbaz et al., 2013a, b, 2016a, 2018a). Resource allocation by financial sector has the potential to influence emission levels (Tamazian and Rao, 2010; Jalil and Feridun, 2011; Zhang, 2011; Shahbaz et al., 2013a, 2016). For instance, financial development can help firms in developed countries to adopt better technologies, which can enable them to realize economies of scale in the production process, creating lower pollution levels. The financial sector is of particular importance for the UK, which has one of the largest and well-developed financial sectors in the world. By its size, the UK is the 5th largest economy in the world, whereas its financial sector tops the list of the Global Financial Centre Index (Yeandle and Wardle, 2019). This raises the question how financial development in the UK impacts the quality of the natural environment. Last but not least, innovation and technological improvements through research and development (R&D) expenditures are not only an important driver of economic growth (Freimane and Bāliņa, 2016; Minniti and Venturini, 2017), but also considered as another important determinant of carbon emissions for developed and developing countries (Churchill et al., 2019). For instance, it may be argued that developed countries, such as the UK, with their higher income levels can expect greater technological progress resulting from higher investments on R&D. These expenditures may enable them to adopt energy-saving and carbon reducing efficient

technologies (Churchill et al., 2019). The adoption of efficient technologies may help the UK economy to reduce the usage of earth's natural resources and reduce environmental pollution (Dinda, 2004) through proper waste management and the internalization of pollution (Arora and Cason, 1996). Therefore, R&D expenditures are crucial to meet ecological challenges, such as biodiversity loss, frequent flooding, and temperature increases.

In this context, this study contributes to expand the literature in four aspects: (i) It empirically examines the effects of economic growth, financial development, R&D expenditures, and energy consumption on environmental quality in a carbon emissions modelling framework for the UK, covering historical time series data from 1870-2017. (ii) The single unknown structural break unit root test is applied to decide on the order of integration of variables. (iii) The bootstrapped auto-regressive distributive lag model (BARDL) is applied to examine the long-run relationship between the variables. As robustness tests, we use ARDL bounds testing and Johansen and Juselius (1990) cointegration approaches. (iv) Both variance decomposition analysis and impulse response function as part of the innovative accounting approach are utilized to gauge the direction of causality in the carbon emissions model. In doing this, our study extends the current literature and is also different from existing studies (e.g. Charfeddine and Ben Khediri, 2016; Bekhet et al., 2017; Nasir et al., 2019; Shahbaz et al., 2013a, b; 2016a, 2018a) in terms of using long-run historical data for modelling the carbon emissions function for the UK. The use of historical data is equally important for research scholars and policy-makers, because it captures the lag effect of past information on environmental quality.³

Our empirical results confirm the presence of cointegration between carbon emissions and its determinants for the UK economy. Further, financial development and energy consumption impede the environmental quality by increasing carbon emissions, whereas R&D expenditures enhance the environmental quality. The inverted U-shaped EKC hypothesis between carbon emissions and economic growth is validated for the UK. Inverted U-shaped relationships are also detected between carbon emissions and the other determinants. These results help to infer policy recommendation on how the UK may achieve its commitment of net-zero emissions.

The remaining sections of the study include the following: Section 2 critically discusses prior research. In Section 3, both empirical modelling and data sources are highlighted. In Section 4, the empirical results are presented and discussed. Section 5 provides robustness tests. Section 6 concludes with policy implications.

2. Literature Review

2.1 Economic Growth & Carbon Emissions Nexus

Economic growth often measured in the form of gross domestic product (GDP) and being the sign of economic strength has been used as one of the core economic policy objectives. The capacity of a nation is often judged based on economic growth. Undoubtedly, higher growth

³ Nonetheless, our study is not the first one examining the determinants of CO₂ emissions for the UK. The recent study by Churchill et al. (2019) used panel data for G7 countries and also highlighted the importance of considering long-run historical data. Despite of this, our study is different from Churchill et al. (2019) in terms of methodology, i.e. we use the bootstrapping ARDL bounds testing approach within a time series framework to examine both the short-run and long-run effects, and regarding the additional considered determinants of CO₂ emissions, i.e. financial development and energy consumption.

is essential for countries in the mitigation of poverty and infrastructure enhancement in the long-run. Almost every single country in the 21st century wishes to continuously grow at a higher speed and often there is an element of comparison among economies based on their rate of growth. Yet, the higher growth resulting from greater economic activities requires a higher usage of energy. Greater use or larger burning of non-renewable energy mix such as coal, crude oil and natural gas than renewable energy (i.e. wind, solar and biomass) required in economic activities may result in environmental degradation via increasing carbon emissions. In this context, the question is: at what cost of ecological or environmental health, higher economic growth is desirable? This has become a matter of concern for policymakers, governments and ecologists with ever-increasing globalization, rapid climate change and global warming. Therefore, this has motivated the researchers to make an empirical understanding of the linkage between economic growth and carbon emissions.

Rooted in the EKC hypothesis, many researchers including economists and ecologists investigated the role of economic growth not only in the EKC modelling framework but also its wider consideration in the policymaking for climate change and sustainability. The studies based on the EKC hypothesis have produced inconclusive findings. For instance, the inconclusive results are reported by the study of Apergis (2016) for a panel sample of 15 countries. Onafowora and Owoye's (2014) using time series technique for 8 countries (China, Brazil, Japan, Egypt, Nigeria, Mexico, South Africa and South Korea) found mixed results. The inverted U-shaped EKC was found in the case of South Korea and Japan, whereas N-shaped EKC was reported for the remaining six countries. Such mixed findings may be associated with the differences in the development level as well as the differences in the energy mix (renewable vs non-renewable) in each country. In another study on 43 developing economies, Narayan and Narayan (2010) reported that improved environmental quality is only found in the Middle Eastern and South Asian countries. A study by Shahbaz et al. (2015) using time series framework for India, explores the effect of economic growth on environmental quality in India. They find the promoting role of economic growth in environmental quality in an emerging economy. In contrast, Shahbaz et al. (2018b) also find that economic growth deteriorates environmental quality in Japan.

Similarly, in a study on 27 developed economies, Al-Mulali and Ozturk (2016) found that environmental quality is improved with high levels of economic growth in only in the long term, not in the short term. By using comprehensive panel dataset for 26 OECD and 52 emerging economies, Özokcu and Özdemir (2017) found an evidence of N-shaped (an inverted N-shaped) relationship between growth and environmental degradation for OECD (emerging countries). These findings led them to argue that since the EKC hypothesis is not supported, economic growth alone may not be a sufficient parameter of enhancing environmental quality. Given the heterogeneity of EKC modelling results for panel studies, it is also important to explore the country-specific studies conducted within a time series framework. Drawing on the Spanish data, Esteve and Tamarit (2012) revealed that the income elasticity between carbon emissions and income is less than one, which indicates a decreasing path in their relationship. Fosten et al. (2012) found that economic growth benefits the UK economy while improving environmental quality in the long-run. Both Baek and Kim (2013) for Korea and Tiwari et al. (2013) for India supported the EKC hypothesis, while the studies of Song et al. (2013) on Chinese provinces, Apergis et al. (2017) and Atasoy (2017) on the

US economy revealed mixed results.⁴ A recent study by Pal and Mitra (2017) on Indian and Chinese economies deviated from the Kuznets' inverted U-shaped hypothesis. However, the study by Ang (2007) on France found that growth is not beneficial for long-run environmental quality due to its harmful carbon effect on the atmosphere. Nasir et al (2019) on ASEAN reported very weak evidence of EKC hypothesis, whereas the study by Pham et al (2020) on the European economies reported strong evidence of EKC hypothesis suggesting crucial differences among countries.

2.2 Financial Development & Carbon Emissions Nexus

The financial sector plays an essential role in economic growth and development. Finance coming from financial and non-financial institutions enables countries to grow, eradicate poverty and utilize limited financial resources. Similarly, energy financing is important for a country to engage in promoting environmental sustainability. The issue of climate change becomes difficult to handle by the governments if energy financing is not utilized efficiently or not considered by the policymakers in the formulation of climate policy. Given the growth and ecological implications of financial development, most of the studies in the field of energy economics argue that increased growth due to financial depth and development is the key driver of rising energy consumption (Sadorsky, 2010, 2011; Islam et al., 2013; Shahbaz et al., 2012, 2013b, 2016c; 2017). From a theoretical stand, financial development has dual effects on the pollution level. On the positive side, finance possessing wealth effect may degrade environmental quality (Frankel and Romer, 1999; Dasgupta et al., 2001; Sadorsky, 2010, 2011; Shahbaz et al., 2015). For instance, the increased finance with low cost of capital motivates business firms to produce more which leads to rising energy consumption (Mahalik et al., 2017). The higher consumption of energy pollutes atmosphere (Dasgupta et al., 2001; Sadorsky, 2011). In addition, the less costly banking loans emit more CO₂ emissions into the atmosphere by enabling consumers in excessive use of energy consumption in their households-built environment (Sadorsky, 2010; Zhang, 2011; Mahalik et al., 2017). In contrast, financing helps economies to improve environmental quality by using the imported pollution abatement technology (Claessens and Feijen, 2007; Tamazian et al., 2009; Tamazian and Rao, 2010). The developing countries with easy access to the financial loan are better able to import environmental-friendly technology from other countries (Frankel and Rose, 2002). Furthermore, business enterprises with easy access to banking loans import green technology and reduce CO₂ emissions by internalizing the negative externality (e.g. pollution level). In so doing, the business enterprises not only protect environmental quality by implementing the better pollution control mechanism but also enable economies to have green economy also by advancing low-carbon business activity (Tamazian et al., 2009; Claessens and Feijen, 2007).

Three strands of literature on the linkage between finance and pollution exist. The first strand shows a negative effect of increased finance on the pollution level. For instance, Tamazian et al. (2009) found the beneficial effect of increased finance on the environment in *BRICS* countries via reducing the pollution level. Jalil and Feridun (2011) found the pollution level reducing effect of increased finance in China. Shahbaz et al. (2013a, b) in their studies,

⁴The study by Ghosh (2010) for India reports no causality while linking the relationship between growth and pollution.

found the pollution level dampening effect of increased finance for both the Malaysian and South African economies. Abbasi and Riaz (2016) cited the beneficial effect of increased finance on environment in Pakistan. Dogan and Seker (2016) using panel data for a sample of top countries listed in the renewable attractiveness index, found that increased finance brings improved environmental quality by reducing the level of pollution discharged into the atmosphere. Katircioğlu and Taşpinar (2017) using the annual data of 1960-2010 for Turkey, found that development in financial sector improves environmental quality via reducing the level of pollution. Xiong and Qi (2018) using the panel data of 1997-2011 for 30 provinces in China, found that development in banking sector and stock market is effective in curbing the pollution level and thereby it improves the quality of natural environment. They further argued that the Chinese government should strengthen the green finance policy by developing inter-provincial coordination and interaction. The recent study of Shahbaz et al. (2018a) suggests the government of France economy to improve financial system activity for better quality of natural environment.

The second strand of studies links the positive relationship between a developed financial system and pollution level. For instance, Zhang (2011) for the Chinese economy indicated the beneficial effect of a developed financial system on natural environment. Shahbaz et al. (2016a, b) using the comprehensive financial index for Pakistan and Portugal, found that development in banking sector matters more for environmental degradation. Subsequently, the recent studies of Javid and Sharif (2016) for Pakistan and Salahuddin et al. (2018) for Kuwait found that development in financial system is harmful to natural environment. Nasir et al. (2019) further reported that development in financial sector weighs on environmental quality in ASEAN region.

The third strand of studies draws an insignificant relationship between development in financial sector and pollution level. For instance, Ozturk and Acaravci (2013) for Turkey and Omri et al. (2015) for 12 MENA countries found the long-run insignificant effect of financial system development on the pollution level. The mixed results for six GCC countries are reported by Bekhet et al. (2017) reveal that development in financial sector impedes environmental quality for Saudi Arabia, Oman, Kuwait and Bahrain, but improves it for UAE and Qatar. In another study for UAE, Charfeddine and Khediri (2016) reported the beneficial impact of development in financial sector on natural environment. In evidence from 27 European countries, the neutral effect is noted between development in financial sector and pollution by Coban and Topcu (2013).

2.3 Research & Development (R&D) Expenditures & Carbon Emissions Nexus

Schumpeter (1942) described ‘change in technology’ entering the production process in the forms of inventions and innovations. The research & development (R&D) expenditures are required to make the innovations process possible and successful. Furthermore, the diffusion process is likely to happen when both invention and innovation are adopted by individuals, business firms, and governments. Subsequently, Romer (1990) in his endogenous growth theory argued that the role of technological change is also essential in the process of economic growth. Using technological change as an endogenous technology entering in the production process to grow at a larger scale and helping the market function to operate smoothly. In light of this, Weitzman (1997) argued that technological change also plays a vital role in curbing

environmental pollution. Environmental quality improvement is possible if the producers use energy-efficient technology in production activity (Bruyn and Sander, 1997). While dealing with climate change and global warming not only requires an environmental policy on economic growth and financial development but also suggests policymakers and governments to consider energy innovation in the production process as both energy usage reducing and pollution curbing strategies (Jordaan et al., 2017). The simple reason is that the role of financial investment required in energy innovation has been increasingly important because of its capacity in the reduction of carbon emissions. The low carbon economy supported by energy innovations will also lead to a green sustainable future (Anadon et al., 2011; Gallagher et al., 2012). Fernández et al. (2018) also identified the role of energy innovation as ‘pollution internalizing strategy’ in combating climate change, global warming and promoting sustainable development in the long-run.

Moreover, energy innovation not only decreases the usage of energy required for economic activity but also reduces the intensity of pollution level (Garrone and Grilli, 2010; Ellabban et al., 2014). The subsidy from the government enables corporate firms to focus on energy innovation, which is beneficial for promoting sustainable quality of natural environment (Ockwell et al., 2010; Chen and Xu, 2010). For instance, the increased renewable energy helps corporate firms to increase their business activity without hampering the quality of natural environment (Hall and Bain, 2008; Luo et al., 2015). By looking into environmental issues, many researchers have used technological innovations as one of the control parameters in environmental degradation modelling with the usage of different econometric methods. For instance, Yeh et al. (2011) linked the nexus between climate change and rates of technological change. Jones (2002) argued that R&D investments in energy innovation can bring a reduction in carbon emissions. It was also argued that climate change challenge will be easy to handle if energy-saving technology is utilized in economic activities at a lower cost (Newell and Pizer, 2008). Sohag et al. (2015) also indicated that technological innovations reduce energy consumption by improving energy efficiency that helps in the reduction of carbon emissions. In contrast, Parry (2003) also argued that environmental quality gain from optimal pollution control is better than the role of technology adopted in economic activities. A study by Smulders and Nooij (2003) also indicated energy-saving technology as one of the effective instruments in reducing pollution level.

Jordaan et al. (2017) present a systematic review for the Canadian economy while looking at the role of energy innovation as pollution-reducing strategy. To mitigate the international greenhouse gas emissions targets, they suggested that government and industry need to advance clean energy through fiscal investment in energy innovations. By using energy sector data for the period 1995-2012, Jin et al. (2017) explored the relationship between energy technology innovation and environmental pollution in China and found that energy innovation improves environmental quality by reducing pollution level. Furthermore, technological progress in the energy sector is beneficial in reducing carbon emissions. On the policy side, they viewed that the Chinese government should invest more in innovations of the energy industry to bring energy efficiency as well as will reduce the burden on the usage of natural resources. Ganda (2019) using the panel data of 2000-2014 for the OECD countries, reported that renewable energy consumption and spending on research & development (R&D) significantly add in a healthy and cleaner environment, whereas other R&D variables, such as

triadic patent families and the number of researchers positively influence it. In a study on G-6 countries using a firm-level data of 2004-2016, Alam et al. (2019) found that R&D investment helps business firms to protect the quality of natural environment. Their findings also support the fundamental argument of natural resource-based view, indicating that the employment of firm's resources and capabilities on environmental activities enables a firm to achieve sustainable competitiveness by improving energy efficiency and reducing carbon intensities. In a contemporary study, Koçak and Ulucak (2019) found that fossil fuel energy R&D investment contributes to pollution level, whereas renewable energy R&D investment does not have any effect on it for a sample of 19 high-income OECD countries. On the policy side, Álvarez-Herránz et al. (2017) argue that energy innovation should be given a priority in sustainable environmental policymaking.

3. Theoretical Construction, Methodology and Data

3.1 Theoretical Construction and Data

Numerous studies have investigated the EKC framework and reported inconclusive empirical results (Shahbaz and Sinha, 2019). Besides economic growth, factors influencing the pollution level include, among others, institutional quality and democracy (Tamazain and Rao, 2010; You et al., 2015), financial development (Nasir et al., 2019), trade measures such as trade openness and FDI (Hille and Shahbaz, 2019; Hille et al., 2019), urbanization (Pham et al., 2020), transportation (Nassani et al., 2017), general as well as energy innovations (Shahbaz et al., 2018a; Yang et al., 2014), and government environmental expenditures (Hille and Lambernd, 2020). Although existing studies also treated financial development as an important determinant in the pollution modelling with employing data for country-level and panel-level empirical analysis, ambiguous results are reported (Zaidi et al., 2019). In search of the potential determinant of environmental quality, Churchill et al. (2019) added R&D intensity into the carbon emissions function and found the uncertain effect of R&D intensity on carbon emissions.⁵ This further warrants for empirical investigation of the EKC hypothesis by considering development in the financial system, R&D expenditures, economic growth and energy consumption as determinants of emissions while employing the time-series approaches on country-specific dataset.

This study employs an EKC framework to empirically analyze the environmental quality consequences of economic growth, development in the financial system, and R&D expenditures for the UK. There are environmental health consequences of development in the financial system (Shahbaz et al., 2016a). The development in financial markets may affect pollution level by not only reducing financial cost but also allocating financial resources to fund projects for purchasing clean and energy-efficient technology, which in result, may benefit economies in protecting the quality of natural environment (Tamazian et al., 2009). The development in the financial system with strong institutional quality enables the government of an economy to direct local and foreign investors for using clean and energy-saving technology. This is the sign of stringent environmental regulation, which not only increases productivity in production process but also adds in the sustainability of natural

⁵ Churchill et al. (2019) used panel data for G7 economies while examining the linkage between R&D intensity and pollution level. Their empirical evidence is less helpful to policymakers while designing environmental policy to R&D expenditures as key tool to improve environmental quality especially at [the](#) country-level.

environment. Further, growth in financial system stimulates business opportunities by providing cheaper loans for productive ventures that also stimulates economic activity and increases energy demand which degrades the quality of natural environment. The growth in the financial system via financial intermediation encourages the people for buying household items such as diesel or motorbikes, cars, air-conditioners, refrigerators, and washing machines etc. This is another source of energy demand that increases carbon emissions via financial development (Sadorsky, 2010; Zhang, 2011). Last but not least, financial development also contributes to carbon emissions by assisting public companies for lessening financial and operational cost (risk), spreading financial linkages and allocating financial resources to new and productive ventures that stimulate energy demand and hence, increase environmental degradation by rising CO₂ emissions.

Frankel and Romer (1999) cited that growth in financial system encourages firms for advancing R&D expenditures for introducing energy-efficient and environmental-friendly technologies. Similarly, endogenous growth theory also indicates the pivotal role of technological advancement as a result of which firm's investments in R&D not only bring efficiency in the production process but also enhance better usage of natural resources. This reveals that growth in income is accompanied with the affordability of investments in R&D and better adoption of efficient technologies, which, as a result, may improve environmental quality as well (Komen et al., 1997; Dinda, 2004). Further, Arora and Cason (1996) unveiled that investments in R&D improve environmental quality if the environmental management system is strong enough that ensures proper waste management. An increase in R&D expenditures stimulate economic activity, entailing increased domestic output, and hence trade that may increase carbon emissions via a scale effect. It is noted that adoption of new technology, has potential to improve efficiency, increases domestic output which may require more usage of energy resources (or natural resources) and may have a negative effect on environmental quality (Churchill et al., 2019). Moreover, energy consumption can be detrimental to the health of natural environment if massive use of energy resources pollute environment via discharging emissions into the atmosphere (Shahbaz et al., 2015). On other hand, energy consumption can contribute towards betterment of natural environment if clean energy is used extensively in economic activities.

Based on theoretical and empirical discussions, we model general carbon emissions function considering economic growth, financial development, energy consumption, and R&D expenditures as determinants of environmental quality using long history data for the UK economy spanning well over 147 years from 1870 to 2017. The general form of extended pollution function is modelled as follows:

$$C_t = f(Y_t, Y_t^2, R_t, F_t, E_t) \quad (1)$$

The logarithmic transformation is performed on all variables by taking the natural-log. However, we converted the data into per capita units. The empirical equation of extended carbon emissions function can be specified as:

$$\ln C_t = \beta_0 + \beta_1 \ln Y_t + \beta_2 \ln Y_t^2 + \beta_3 \ln R_t + \beta_4 \ln F_t + \beta_5 \ln E_t + \mu_i \quad (2)$$

where, \ln , C_t , Y_t , Y_t^2 , R_t , F_t , E_t and μ_t are natural log of carbon emissions, real GDP, squared of real GDP, research & development expenditures, broad money as proxy for financial development, energy consumption and residual term with the assumption of normality. Relationship between economic growth and pollution level is supposed to be inverted U-shaped in case $\beta_1 > 0, \beta_2 < 0$ otherwise U-shaped. R&D expenditures are environmentally friendly if $\beta_3 < 0$ otherwise it will increase carbon emissions. Financial development improves environmental quality if $\beta_4 < 0$ otherwise $\beta_4 > 0$. We further extend carbon emissions function by considering square terms of financial development and R&D expenditures for examining whether relationships between development in financial system, R&D expenditures and pollution level is inverted U-shaped or not. It may be noted that pollution level is positively associated with development in financial system and beyond a threshold level, it is also negatively linked with development in financial system. This shows improved quality of natural environment due to better financial system in long-run. When the countries wish to grow, they need to use the services of financial institutions but at the cost of environmental health in short-run. When the countries further wish to grow, they need to take care of environmental health in the long run with increased finance. The increased finance makes possible to have better environmental health by helping economies to use more of imported energy-saving technology in production.

We further extend carbon emissions function by considering square terms of financial development and R&D expenditures for examining whether the relationship between these variables and emission of carbon follows an inverted U-shaped. It is argued that carbon emissions are accompanied by financial development and after reaching a threshold level of financial development, further development improves environmental quality and lowers emissions of carbon. This implies that initially, the focus of financial sector remains on the allocation of resources to investment projects to boost economic activity (is termed as scale effect) which in resulting, increases energy demand and hence, environmental degradation is increased. After reaching the threshold level of income per capita, financial sector starts distributing resources to firms who adopt energy-efficient technology (is referred as technique effect) for domestic production following environmental regulations implemented by government (on public demand) for improving environmental quality. This in result raises energy efficiency, which improves environmental quality by reducing emissions of carbon. Similarly, with regard to R&D expenditures, it is crucial to account for the non-linearity in its association with carbon emissions. Intuitively, we would postulate that R&D expenditures involve economic activity which in resulting, lead-carbon emissions to increase initially. This would imply that in the short run, there would be a positive impact of R&D expenditures on carbon emissions. However, with the investment in R&D, there would long terms net gains as it would lead to innovation and development of sustainable solutions for increasing domestic production. Concomitantly, we would expect that in the long run, there would be a negative impact of R&D expenditures on carbon emissions leading to improvement in environmental quality. Therefore, we would expect a quadratic relationship between R&D expenditures and carbon emissions is inverted U-shaped. This suggests that carbon emissions function can also

be extended by including square terms of financial development (F_t) and R&D expenditures (R_t) in equation-2 and, equation-3 is modelled as follows:

$$\ln C_t = \alpha_0 + \alpha_1 \ln Y_t + \alpha_2 \ln Y_t^2 + \alpha_3 \ln F_t + \alpha_4 \ln F_t^2 + \alpha_5 \ln R_t + \alpha_6 \ln R_t^2 + \alpha_7 \ln E_t + \mu_t \quad (3)$$

Association between emissions and financial development is supposed to be inverted U-shape if $\alpha_3 > 0, \alpha_4 < 0$ otherwise U-shaped. Similarly, $\alpha_5 > 0, \alpha_6 < 0$ would imply an inverted U-shape relationship between emissions and R&D otherwise $\alpha_5 < 0, \alpha_6 > 0$ would confirm the presence of U-shaped association.

This study drew on a very long historical data set on United Kingdom, spanning over 147 years from 1870-2017. The data on R&D expenditures are obtained from Madsen and Ang (2016). The GDP data is collected from Maddison (2007). The data on emissions is collected from the Carbon Dioxide Information and Analysis Center (CDIAC) database (Marland et al. 2006). For the energy consumption, the data is obtained from Paul (2007). Broad money (M2) is used as measure of financial development and data is collected from the Global Financial Data database. All the data series are converted into per capita units by dividing population for which the data is obtained from Maddison (2007).⁶

3.2 Bootstrapping-ARDL Approach

For the analysis of cointegration, this study draws on the seminal work by McNown et al. (2018) and employs a bootstrapping ARDL cointegration framework. The novelty of this framework is that it accounts for the limitations, such as weak size and power properties for which the traditional ARDL approach suggested by Pesaran et al. (1996, 2001) ignores. Furthermore, capitalizing on traditional ARDL bounds testing framework, the bootstrapping ADRL incorporates advance testing of F-test with to increased power. Specially, we go a lot further than the conventional ARDL bounds testing approach (Pesaran et al., 2001) and in so doing, we employ three tests to determine cointegration between the variables. In a traditional ARDL, conditions of statistical significance of the error correction term and lagged variables help to conclude on the presence or absence of cointegration (Pesaran et al., 2001). In case the lagged dependent variable is statistically significant in error correction term, we conclude that the first condition holds. Whereas, if the lagged explanatory variables are shown to be significant, it suggests that the second condition holds. The critical (upper and lower) bounds testing devised by Pesaran et al. (2001) is only applicable in the second case, whereas in the first case scenario. Under the first case condition where we have statistically significant error correction term coefficient, we can proceed with the estimation of both the response and explanatory variables have the order of integration $I(1)$. However, an important factor at this juncture, we shall take into account is that the conventional approach to unit root testing might not be the appropriate methods of testing for the order of integration as they have low power and explanatory properties (Goh et al. 2017). Bootstrapping ARDL framework proposed by the McNown et al. (2018) can address this issue as their Monte Carlo simulations

⁶ We have updated data using world development indicators (CD-ROM- 2019) for all the variables from 1870-2017.

of the test statistics show that the critical values through bootstrapping critical yield greater power and size properties. There are numerous benefits of this approach, it is particularly effective even when we have a small sample size and dynamic time-series models. Nonetheless, the order of integration of variables does not cast doubts on the applicability of approach (Goh et al., 2017). Concomitantly, with these advantages, bootstrapping ARDL approach can easily address several issues which may arise in traditional ADRL bound testing framework, for instance, the problem of inconclusive cases (area) in the results (McNown et al. 2018)⁷. To reiterate, the conventional ARDL approach focuses on the bounds based on the data generating process where the order of integration of the underlying series is either I(0) or I(1). This led Narayan (2005) to argue that critical bounds, which were put forward by Pesaran et al. (2001), can lead to inconclusive results and are suitable only for long-span data samples. However, the bootstrapping approach eliminates the likelihood of indecisiveness, which may happen in the traditional approach to cointegration. Another novel feature of bootstrapping ARDL bounds testing approach is its effectiveness for the dynamic models where we have multiple independent variables. It may appear unimportant issue but is crucial to account for as there requires a strict exogeneity of explanatory variables for the critical values bounds proposed by Pesaran et al. (2001). However, in reality, the relationship among macroeconomic time series does not often support the assumption of strict exogeneity condition. The traditional, as well as bootstrapping can be expressed in mathematical terms. Let's consider an ADRL with three variables (p, q, r) , following Goh et al. (2017), it can be specified as:

$$y_t = \sum_{i=1}^p \alpha_i' y_{t-i} + \sum_{j=0}^q \beta_j' x_{t-j} + \sum_{k=0}^r \gamma_k' z_{t-k} + \sum_{l=0}^s \tau_{t,l}' D_{t,l} + \mu_t \quad (4)$$

whereas in equation-3, l, k, j and i are lag order ($l = 0, 1, 2, \dots, s; k = 0, 1, 2, \dots, r; j = 0, 1, 2, \dots, q$; and $i = 1, 2, \dots, p$); t denotes time, y_t is independent, x_t and z_t are independent and $D_{t,l}$ represents dummy variable and τ is its coefficient. The β 's and γ 's are the coefficients of the lagged independent variables. Lastly, μ_t represents the error-term with the finite variance and zero means. Equation-4 can also be specified in an error correction form as follows:

$$\Delta y_t = \phi y_{t-1} + \gamma x_{t-1} + \psi z_{t-1} + \sum_{i=1}^{p-1} \lambda_i' \Delta y_{t-i} + \sum_{j=1}^{q-1} \delta_j' \Delta x_{t-j} + \sum_{k=1}^{r-1} \pi_k' \Delta z_{t-k} + \sum_{l=1}^{s-1} \omega_l' \Delta D_{t,l} + \varepsilon_t \quad (5)$$

whereas $\phi = \sum_{i=1}^p \alpha_i$, $\gamma = \sum_{j=0}^q \beta_j$ and $\psi = \sum_{k=0}^r \gamma_k$ in equation-4. The related functions in equation-3 are captured by λ_i , δ_j , π_k and ω_l . By transforming a vector auto-regression (at levels) specified in error correction form, we can drive equation-5 from equation-4 along with a constant term (\tilde{c}) equation-5 can be estimated and then conditional model can be specified as:

⁷ Traditional ARDL approach to cointegration is applicable if we have mixed order of integration among variables.

$$\Delta y_t = \tilde{c} + \tilde{\phi}y_{t-1} + \tilde{\gamma}x_{t-1} + \tilde{\psi}z_{t-1} + \sum_{i=1}^{p-1} \lambda'_i \Delta y_{t-1} + \sum_{j=1}^{q-1} \lambda'_j \Delta x_{t-1} + \sum_{k=1}^{r-1} \lambda'_k \Delta z_{t-1} + \sum_{l=1}^s \tilde{\omega}'_l D_{t,l} + \varepsilon_t \quad (6)$$

It will require us to unanimously reject all three null hypotheses to conclude on the presence of cointegration among y_t , x_t and z_t . These can be stated as:

- i) The F_1 test is employed based on associated error-correction terms where null hypothesis is $H_0: \phi = \gamma = \psi = 0$ against alternative H_1 : any of ϕ, γ, ψ are different from 0.
- ii) Based on explanatory variables, The F_2 test that is employed, where null hypothesis is $H_0: \gamma = \psi = 0$ against alternative H_1 : either γ or ψ is different from 0.
- iii) T-test is constructed on the lagged values of the response variable where the null is $H_0: \phi = 0$ against the alternative that $H_1: \phi$ is different from 0.

The approach proposed by Pesaran et al (2001) has been often used to generate the critical values for the F_1 and t-tests, however, it does not account for the test statistic for F_2 test on the lagged explanatory variable. This limitation is, however, addressed by a more recent study by McNown et al. (2018) which employing the bootstrapping approach provides critical values for all three set of tests. Considering these benefits, we follow the approach and critical values by McNown et al. (2018) which without any doubt, provides us with empirical robust estimates.

4. Analysis Findings

4.1 Correlation Analysis

The descriptive statistics reported in Table-A1 (in Appendix) report the presence of high volatility in R&D expenditures compared to economic growth. Energy consumption is less volatile compared to carbon emissions. Volatility in economic growth is higher than volatility stems in financial development. The normality test based on Jarque-Bera stats shows that the underlying variables are normally distributed. The correlation analysis shows the existence of a positive correlation of growth, financial development and energy consumption with emissions. However, R&D expenditures show a negative correlation with carbon emissions. All other variables show a positive correlation with each other, except the R&D expenditures and energy consumption, which are found to be negatively correlated.

4.2 Unit Root Analysis

The ADF unit root test is applied to examine the stationarity properties underlying containing intercept and trend. The results presented in Table-A2 suggest that all the variables were found have unit root at the level, however at the first difference they were found to be stationary. In other words, our variables integrated or order I (1). Considering that the traditional ADF (Dickey and Fuller, 1979) unit root test does not account for the structural breaks in the data series, we compliment the unit root testing with approach proposed by Kim

and Perron (2009). The results in Table-A2 show presence of a structural break in the series, which were non-stationary at level with intercept and trend. The breaks are 2008, 1916, 1985, 1918, and 1887 in the series of carbon emissions, economic growth, financial development, energy consumption and, R&D expenditures. These correspond to major events, such as the Global Financial Crisis of 2008-09, which led to a significant reduction in carbon emissions, due to sharp decrease in economic activity. Similarly, the year of 1916 corresponds to the severity of WWI and its implications for the economy and per capita income. The break in financial development as measured by the monetary aggregates in 1985 reflects the impact of the suspension of the policy of targeting broad money in 1985⁸. The break in energy consumption around 1918 corresponds to the end of WWI which led to sudden changes in energy usage. We find carbon emissions, economic growth, financial development, energy consumption and, R&D expenditures are stationary at first difference containing information of single unknown structural break in each series. This confirms that all the variables are found stationary at first difference i.e. I(1).

4.3 ARDL Bounds Testing Analysis

The unique integration among our underlying variables implies that we can proceed with the application of bounds testing approach and finding long-run association among variables. We can only apply cointegration test if we have variables integrated of I(0), I(1) or I(0) / I(1). To start with, we also need an information criterion for appropriate lag length selection. The ARDL-F statistic is also affected by the number of lags. The Akaike Information Criteria (AIC) is used to decide on the optimal lag length and the results are presented in Table-A3 (second column 2) and with the ARDL F-stats. It shows that as the ARDL F-Stats are greater than upper critical bounds, hence the null of no cointegration has been rejected while carbon emissions, financial development, energy consumption and, R&D expenditures are treated as dependent variables. We accept the null hypothesis of no cointegration as ARDL F-statistic is less than lower critical bound when we used economic growth as dependent variable. Overall results show the existence of four cointegrating vectors. We may conclude that the emissions of CO₂, growth of the economy, financial development, energy consumption and, R&D expenditures have cointegration in the case of the UK from 1870 to 2017.

4.4 Bootstrap ARDL Cointegration Analysis

The bootstrapping ARDL bounds testing approach to cointegration is applied and the results are presented in Table-A4. We notice the rejection of the null hypothesis of no cointegration while treating carbon emissions as dependent and all other variables as explanatory variables. The alternative hypothesis was also accepted in the light of t-test on lagged explanatory variables. At the 1% and 5% levels of statistical significance, all three testes indicate four cointegrating vectors.

The evidence of cointegration in carbon emissions function was further strengthened by the existence of four cointegrating vectors. It implies that there is a long-run association between growth, financial development, energy consumption, R&D expenditures, and carbon

⁸Then the Chancellor of Exchequer Nigel Lawson suspended targeting broad money in 1985 giving the reason that the monetary aggregates were being distorted by financial liberalisation to justify.

emissions in the UK between 1870 and 2017. This confirms the established cointegration by ARDL bounds testing approach between carbon emissions and its determinants for the UK economy. Diagnostic testing results reported in the 9th column of Table-A4, suggest that there is no issue of serial correlation. The Jarque-Bera test statistics show the normal distribution of all the variables, whereas the difference between $Q-stat$ is the studentized range distribution statistic which fails to reject the null hypothesis confirming the normal distribution of data and residual(s).

Table-1: Long-Run Analysis

	Coeff.	T-Stat.	Coeff.	T-Stat.
Constant	-21.9627	-12.206	-15.3684*	-7.3762
$\ln Y_t$	6.1789*	17.7008	4.9426*	8.1725
$\ln Y_t^2$	-0.3289*	-18.114	-0.2818*	-8.3648
$\ln E_t$	0.4534***	1.8023	1.9525*	5.9478
$\ln F_t$	0.0428***	1.7397	-1.3815*	-3.8725
$\ln F_t^2$	....	....	0.1868*	4.1678
$\ln R_t$	-0.0545*	-3.4083	0.4079*	2.7505
$\ln R_t^2$	....	....	-0.0721*	-3.4294
D_{2008}	-0.1990*	-6.2538	-0.3191*	-12.3424
R^2	0.7780		0.9239	
$Adj-R^2$	0.7684		0.9195	
Durbin-Watson	1.8863		1.5793	
Stability Analysis				
	F-stat.	Sig.	F-stat.	Sig.
χ^2_{NORMAL}	0.4052	0.2314	0.4512	0.2204
χ^2_{SERIAL}	0.1854	0.8765	0.2052	0.8675
χ^2_{ARCH}	0.4885	0.2409	0.4808	0.2429
χ^2_{Hetero}	0.1951	0.8705	0.3053	0.8665
χ^2_{RESET}	1.0987	0.1234	1.9080	0.1114
CUSUM	Stable		Stable	
CUSUMsq	Stable		Stable	
Note: *, ** and *** show significance at 1%, 5% and 10% levels respectively.				

4.5 Long & Short-Run Analysis

The results of long-run analysis of carbon emissions function is reported in Table-1 suggests that there is a positive impact of GDP growth per capita in linear terms whereas the squared terms suggest negative impact at 1% level of statistical significance. Specifically, a 1% increase in real GDP per capita is supposed to increase the emissions of carbon by about 6.1789% (4.9426%). The negative coefficient for real GDP squared term shows its decarbonising effects at a higher income level in United Kingdom. It also confirmed the EKC for the British economy, as the relationship between income (real GDP per capita) and emissions is found to be an inverted U-shaped. In the light of the EKC hypothesis, it implies

that in the beginning, the growth of income (GDP) per capita will lead to increased emissions, however after reaching a threshold, further growth will lead to a reduction in carbon emissions. In a policy context, this would employ that the growth policies in Britain are cautious of environmental consequences which are evident in the British signing up to the Paris-Agreement, legally binding itself with zero-emissions by 2050 and most recently emphasis on other countries to raise climate ambitions in G-20 summit on June 2019 in Osaka, Japan. These findings are in line with Sephton and Mann (2016) and Shahbaz et al. (2017) as they also found that between economic growth and carbon emissions there is an inverted-U association in the UK, contrary to Balciyar et al. (2018) who argued that EKC hypothesis is not valid in the UK. Intuitively, increasing consumption of energy, significantly adds to emissions. Specifically, a 1% increase leads to increasing emissions by about 0.4534-1.9525%. Financial development also shows a positive relationship with carbon emissions, which is statistically significant as well at 1% level. It implies that financial development is not environment-friendly i.e. financial activity leads to increased emissions, impeding environment. This would suggest that the policy of curbing net emissions to zero needs to focus on financial development and its environmental consequences. Keeping other things constant, carbon emissions are expected to increase by 0.0428% as a result of 1% increase in financial development. This finding is similar to the study by Zhang (2011) on China and Sehrawat et al. (2015) study on as both of these studies reported a positive impact of financial development on carbon emissions.

On contrary, the results the oppose the findings by Tamazian et al. (2009) on BRIC countries, Jalil and Feridun (2011) and Zaidi et al. (2019) on China, Shahbaz et al. (2013a) on Malaysia, Álvarez-Herránz et al. (2017) on OECD countries, Shahbaz et al. (2018a) on French economy which reported that financial development lowers the emission and improves the quality of the environment. The results on the impact of R&D expenditures were more promising as it shows a negative impact on emissions. Specifically, *ceteris paribus*, a 1% increase in the expenditure on R&D was to a -0.0454% impact on the emissions. The negative impact of R&D on emission is in line with the existing evidence, for instance, the studies by Tamazian et al. (2009) on BRIC countries, Lee and Min (2015) for Japan, Xiong and Qi (2018) for China, Álvarez-Herránz et al. (2017) for OECD countries, Balsalobre-Lorente et al. (2018) for EU-5 countries, Cho and Sohn (2018) and Shahbaz et al. (2018a) for the French economy, and Fernández et al. (2018) for the United States also show that R&D expenditures lower carbon emissions and the resulting environmental quality is improved. Surprisingly, Koçak and Ulucak (2019) reported that the emissions are positively affected by the R&D expenditures in the OECD countries. On the contrary, Churchill et al. (2019) noted that the intensity of R&D has an uncertain impact on carbon emissions. In specific to the UK, the role of R&D in meeting climate challenges and policy objectives is benign. However, as advised by the Committee on Climate Change (CCC), Britain must invest more in low-carbon innovations, to hit the 2050 net-zero emissions target. Our empirical findings provide support to this notion. The dummy variable also improves environmental quality by lowering carbon emissions. This relates to financial crisis i.e. 2007-08 and UK manufacturing industry increased her efficiency and economy shifted from heavy industry towards advance industry and services which reduced energy usage in the industrial sector. Similarly, the UK Department for Business, Energy and Industrial Strategy (2018) reported that the financial

crisis is one of the factors that pushed business and industrial sectors for energy efficiency and switching economy to lower carbon fuels, which reduced carbon emissions. The changes in the quantity of aggregate demand due to the financial crisis as well as its composition are prima facie evident in the negative impact of crisis on carbon emissions. Conceivably, there is a positive side to it and should be seen in junction with the increasing importance and awareness of climate change.

In order to account for the non-linear effects of financial development as well as R&D, their squared terms have been included in carbon emissions function. The empirical results presented in Table-1 show that the linear term of financial development has positive while the quadratic term has a negative impact on carbon emissions. This suggests that the relationship between financial development and emissions is also U-shaped. The result is in line with the study by Shahbaz et al. (2013a) on Malaysia but it is insignificant statistically. On contrary, in a study on France, Shahbaz et al. (2018a) reported that between financial development and carbon emissions there is inverted U-shaped relationship which made them argue that financial development initially increases emission, but after a threshold, it contributes to reducing CO₂ emissions. In policy setting this finding has profound implications for the UK as it implies that the increasing financialization would hamper the environment by increased CO₂ emissions. Hence, the financial policy should focus on the allocation of finance to more efficient and environmentally friendly sectors of the economy. Green monetary and financial policies are very much required.

The results on R&D expenditure show that the linear term has a positive while the squared term has a negative impact on the emissions suggesting inverted U-shaped relationship between R&D expenditure and carbon emissions at 1% level of statistical significance. We may conclude that the EKC hypothesis is validated between R&D expenditures and carbon emissions. Empirical results are in line with Mensah et al. (2018) for OECD countries who reported the validation of R&D EKC in OECD countries. In specific to the UK it implies that R&D investment in innovation can help to cut emission to the net-zero target in the long term. Furthermore, the results do not evidence the autocorrelation between carbon emissions and the error term, whereas it also reveals that the errors follow a normal distribution. Empirical results also indicate no issue of autocorrelation, white heteroscedasticity and auto-conditional heteroscedasticity. In terms of specification, the Ramsey RESET test confirmed the correctness of specification. Finally, model stability at 5% level of significance is confirmed by the CUSUM and the CUSUMsq tests (see Figure-1).

The results of the short-run analysis reported in Table-2 show that the relationship between economic growth and emissions is inverted U-shaped, validating the EKC. Carbon emissions positively associated with energy consumption, which also turned out to be the dominant factor to impede environment by increasing emissions. The relationship between financial development and emissions is also positive and significant at 5% level, suggesting that financial sector development is not environment-friendly. The expenditures on R&D also show positive while dummy variable show negative and statistically significant (10% level) impact on emissions in short run. In the case of financial development, both linear and squared terms show a positive impact, though results were only significant for the former. However, both linear and squared terms of R&D expenditures show a positive but statistically insignificant impact on emissions. It shows that in the short run, we do not have U-shaped or

inverted U-shaped association between R&D expenditures and financial development and emissions.

Table-2: Short Run Analysis

	Coef.	T-Stat.	Coef.	T-Stat.
Constant	-0.0030	-0.9088	-0.0035	-1.0499
$\Delta \ln Y_t$	3.5741***	1.9256	3.9343*	2.9299
$\Delta \ln Y_t^2$	-0.1996***	-1.9646	-0.2174*	-2.9502
$\Delta \ln E_t$	2.6062*	7.9433	2.5640*	22.8381
$\Delta \ln F_t$	0.0860**	2.0634	0.0993*	2.9172
$\Delta \ln F_t^2$	....	....	0.0403	0.4262
$\Delta \ln R_t$	0.0403***	1.6937	0.0236	0.7267
$\Delta \ln R_t^2$	....	....	0.0569	0.5839
D_{2008}	-0.0374*	-2.9422	-0.0411*	-4.1954
ECM_{t-1}	-0.3820*	-4.0580	-0.5605*	-7.7816
R^2	0.8748		0.8913	
$Adj-R^2$	0.8685		0.8873	
Durbin-Watson	2.1421		2.0725	
Stability Analysis				
	F-statistic	P. value	F-statistic	P. value
χ^2_{NORMAL}	0.2207	0.2020	0.2007	0.1970
χ^2_{SERIAL}	0.8287	0.4338	0.8080	0.4408
χ^2_{ARCH}	2.1515	0.1123	2.1010	0.1129
χ^2_{ARCH}	0.1045	0.9817	1.1141	0.8107
χ^2_{RESET}	1.3596	0.1762	1.3060	0.1802
Note: CUSUM and CUSUMsq suggested parameter stability.				

The error correction term ECM_{t-1} show a negative coefficient (-0.3820) which is also statically significant at 1% level indicating validity of long-run relationship as well the speed of adjustment. The coefficients of ECM_{t-1} are -0.3820 and -0.5605 for linear and nonlinear models, indicating that the correction from short-run disequilibrium to a long-run equilibrium is about 38.20% and 56.05% respectively. The overall value of R^2 i.e. 0.8748 shows that the dynamics of carbon emissions are explained by the underlying explanatory variables to the extent of 87.48% out of 100% and the remaining variance of dependent variable is done by the residual term. There was no issue of serial correlation, white heteroscedasticity and auto-conditional heteroscedasticity in the estimation of carbon emissions function. The Ramsey RESET test suggested that the model was well specified. The model stability at 5% level of significance is also validated by CUSUM and CUSUMsq tests in short-run and long-run estimated (see Figure-1).

Figure-1: CUSUM and CUSUMsq



4.6 Results of the Variance Decomposition Analysis and Impulse Response Functions

The VECM Granger causality is one of the most widely used approaches to examine the direction of a causal relationship, but this approach does not provide the sign of relation, i.e. whether it is negative or positive. In this context, Shan (2005) proposed an innovative accounting approach (IAA) which report the sign of causal relationship between the variables. To account for the magnitude of the causal impact of innovation from the explanatory variables, this approach entails impulse response functions and variance decomposition and can go beyond the time horizon of response variables data series (see Pesaran and Shin (1999), Engle and Granger (1987), and Ibrahim (2005) for discussion on generalized forecast error variance decomposition and vector auto-regression (VAR) system). The results of variance decomposition analysis presented in Table-3 suggest that the emissions are significantly affected i.e. 75.97% by their own innovations. Among other factors, growth of the economy (5.20%), financial sector (9.48%), energy consumption (71.3%) and R&D expenditures (2.18%) also play their role. R&D expenditures contribute to economic growth by 22.33%. The contribution by innovative shocks stemming in carbon emissions, financial development and energy consumption is minimal. A 73.58% of economic growth is contributed by its own innovations in carbon emissions contribute to financial development by 18.66%. A 9.87%, 2.13% and 0.61% is contributed to financial development by economic

growth, energy consumption and R&D expenditures. There is about 68.70% variance is contributed by its own innovation in financial development.

There is some contribution of economic growth and financial development in the consumption of energy i.e. 8.89% and 5.35% respectively. The contribution of emissions to about is 39.14%. R&D expenditures contribute to energy consumption by 4.27%. A 42.33% of contribution to energy consumption is by innovative shocks stem in energy consumption. The innovations in emissions contribute to R&D expenditures by about 3.33%, whereas the contribution by financial development and energy consumption to R&D expenditures is about 14.34% and 15.42%. The contribution of economic growth to R&D expenditures is minimal i.e. 2.93%. A 63.96% is contributed to R&D expenditures by its own innovative shocks. Overall, we find that carbon emissions and economic growth are independent i.e. neutral effect. There was a unidirectional association from R&D expenditures to growth of the economy. Financial development is also caused by but similar is not true from the opposite side. No causal relationship exists between economic growth and energy consumption. Energy consumption is cause of carbon emissions. Financial development causes R&D expenditures, and R&D expenditures also cause energy consumption.

Table-3: Variance Decomposition (VDC) Analysis

VDC $\ln C_t$					
Period	$\ln C_t$	$\ln Y_t$	$\ln F_t$	$\ln E_t$	$\ln R_t$
1	100.0000	0.0000	0.0000	0.0000	0.0000
2	95.7645	1.5313	0.0001	0.1224	2.5814
3	94.5986	2.3302	0.1608	0.1449	2.7653
4	93.6059	2.6688	0.5840	0.2517	2.8894
5	92.8157	2.6080	1.2630	0.5275	2.7855
6	91.8202	2.4889	2.0987	0.9262	2.6658
7	90.5233	2.4619	3.0105	1.4460	2.5581
8	88.9473	2.5784	3.9418	2.0544	2.4777
9	87.1664	2.8247	4.8592	2.7291	2.4205
10	85.2678	3.1637	5.7446	3.4458	2.3779
11	83.3256	3.5574	6.5887	4.1858	2.3423
12	81.3952	3.9755	7.3867	4.9344	2.3079
13	79.5134	4.3975	8.1365	5.6808	2.2715
14	77.7021	4.8111	8.8374	6.4176	2.2316
15	75.9727	5.2098	9.4897	7.1399	2.1877
VDC $\ln Y_t$					
	$\ln C_t$	$\ln Y_t$	$\ln F_t$	$\ln E_t$	$\ln R_t$
1	14.724	85.2753	0.0000	0.0000	0.0000
2	8.3712	91.3994	0.0317	0.1349	0.0626
3	7.0209	92.6236	0.0620	0.2263	0.0669
4	6.2338	93.0802	0.0652	0.3062	0.3144
5	5.7509	92.8571	0.0582	0.3479	0.9857
6	5.3492	92.1021	0.0517	0.3590	2.1377
7	4.9953	90.8484	0.0472	0.3485	3.7604
8	4.6781	89.1794	0.0441	0.3284	5.7698

9	4.3986	87.1960	0.0444	0.3084	8.0524
10	4.1549	85.0058	0.0541	0.2947	10.4902
11	3.9419	82.7044	0.0806	0.2901	12.9828
12	3.7528	80.3670	0.1302	0.2952	15.4545
13	3.5813	78.0472	0.2070	0.3092	17.8550
14	3.4224	75.7790	0.3125	0.3312	20.1545
15	3.2732	73.5817	0.4461	0.3603	22.3384
VDC $\ln F_t$					
	$\ln C_t$	$\ln Y_t$	$\ln F_t$	$\ln E_t$	$\ln R_t$
1	5.4696	2.3627	92.1676	0.0000	0.0000
2	5.4825	1.7967	91.6808	0.6828	0.3569
3	7.7609	1.2939	89.0298	1.3596	0.5556
4	10.1273	0.9604	86.3235	1.9649	0.6237
5	12.4001	0.8830	83.7351	2.3874	0.5943
6	14.2889	1.1322	81.4176	2.6271	0.5339
7	15.7431	1.7154	79.3459	2.7107	0.4846
8	16.7836	2.5779	77.4887	2.6851	0.4644
9	17.4875	3.6297	75.8135	2.5964	0.4727
10	17.9417	4.7750	74.3015	2.4822	0.4994
11	18.2258	5.9332	72.9391	2.3685	0.5330
12	18.4024	7.0474	71.7141	2.2711	0.5647
13	18.5165	8.0842	70.6120	2.1979	0.5891
14	18.5986	9.0284	69.6162	2.1522	0.6043
15	18.6678	9.8777	68.7095	2.1343	0.6105
VDC $\ln E_t$					
	$\ln C_t$	$\ln Y_t$	$\ln F_t$	$\ln E_t$	$\ln R_t$
1	77.5497	0.5351	1.3637	20.5512	0.0000
2	61.7152	5.7454	2.0280	26.5448	3.9663
3	55.3572	8.6381	2.8727	28.7774	4.3544
4	50.6951	10.1110	3.6143	31.0922	4.4871
5	47.9399	10.4718	4.2012	33.0762	4.3106
6	45.9827	10.3625	4.6254	34.9171	4.1121
7	44.5276	10.0942	4.9189	36.5011	3.9579
8	43.3593	9.8245	5.1154	37.8265	3.8741
9	42.3923	9.6037	5.2435	38.9041	3.8563
10	41.5815	9.4337	5.3236	39.7732	3.8876
11	40.9021	9.3000	5.3698	40.4777	3.9502
12	40.3350	9.1869	5.3910	41.0581	4.0288
13	39.8628	9.0839	5.3932	41.5470	4.1128
14	39.4696	8.9856	5.3807	41.9681	4.1957
15	39.1409	8.8905	5.3569	42.3377	4.2739
VDC of $\ln R_t$					
	$\ln C_t$	$\ln Y_t$	$\ln F_t$	$\ln E_t$	$\ln R_t$
1	0.420	3.3084	0.0283	2.3916	93.8512
2	0.2040	5.8388	0.0916	6.8716	86.9938
3	0.2903	6.5823	0.5374	8.7221	83.8676
4	0.2716	6.2375	1.4066	10.2778	81.8063

5	0.2265	5.4893	2.6324	11.4909	80.1607
6	0.2020	4.7283	4.0817	12.4428	78.5451
7	0.2513	4.1233	5.6111	13.1638	76.8502
8	0.4036	3.7067	7.1078	13.7011	75.0806
9	0.6607	3.4467	8.5027	14.1014	73.2882
10	1.0074	3.2929	9.7661	14.4072	71.5261
11	1.4208	3.1994	10.8946	14.6524	69.8326
12	1.8773	3.1328	11.8998	14.8619	68.2280
13	2.3571	3.0723	12.7988	15.0532	66.7184
14	2.8453	3.0071	13.6097	15.2376	65.3001
15	3.3319	2.9325	14.3487	15.4220	63.9646

5. Robustness Checks

Results of conventional ADF unit root testing has shown that all the series were first differenced stationary. However, it is vital to test for the robustness of these results using Kim and Perron (2009) approach, which accounts for structural break. The results of ADF test with structural breaks supported the findings of conventional ADF test. All the series were found to be first differenced stationary in the presence of structural break (see Table-A2) suggesting robustness of our estimates. We also employed the Johansen and Juselius (1990) cointegration approach (see Table-4) which provided further support to findings on cointegration. Specifically, Max-Eigen statistic and Trace test statistic suggest rejection of the null hypothesis of no cointegration 1% and 5% levels of statistical significance. This reveals that carbon function entails two cointegrating vectors. It can be argued that the confirmation of cointegration vectors in carbon emissions function shows the possibility of long run association. There is an argument that when there is long-run equilibrium, there must be a short-run disequilibrium, is important to check whether the cointegrating vectors are present in carbon emissions function. In such a case, the findings reveal that our cointegration analysis is robust and is reliable.

Table-4: Johansen Cointegration Analysis

Hypothesized No. of CE(s)	Trace Stat.	Sig.	Max-Eigen Stat.	Sig.
$R \leq 0$	127.1424*	0.0013	47.6519**	0.0164
$R \leq 1$	79.4904**	0.0487	30.3477	0.2459
$R \leq 2$	49.1427	0.1546	24.6089	0.2371
$R \leq 3$	24.5332	0.4116	12.9728	0.6805
$R \leq 4$	11.5605	0.3428	10.9365	0.3167
$R \leq 5$	0.6244	0.4294	0.6244	0.4294

Notes: * and ** depict statistical significance at 1%, and 5% levels. MacKinnon et al. (1999) p-values are employed.

Table-5: Long-Run Analysis Robustness Check

Response Variable: $\ln C_t$								
Variables	FMOLS		CCR		OLS (1870-2008)		OLS (2009-2017)	
	Coef.	T-Stat.	Coef.	T-Stat.	Coef.	T-Stat.	Coef.	T-Stat.
Constant	-24.3260*	-12.1321	-24.2741*	-12.2479	-23.6571*	-15.6840	2.3459	0.0158
$\ln Y_t$	6.3621*	15.5431	6.3661*	15.7871	6.1345*	19.8561	-3.5441***	-1.9221
$\ln Y_t^2$	-0.3531*	-15.9852	-0.3531*	-16.1821	-0.3427*	-20.5874	0.1833***	1.7980
$\ln E_t$	1.5143*	9.6224	1.4745*	8.5460	1.7476*	14.7322	8.0505*	9.0845
$\ln F_t$	0.1133*	4.7078	0.1124*	4.7021	0.1176*	6.4546	1.7905*	12.2351
$\ln R_t$	-0.0999*	-2.9016	-0.0105**	-1.9598	-0.0387**	-2.4609	-0.7495*	-5.2601
D_{2008}	-0.2124*	-8.7142	-0.2139*	-8.4627	....	....	....	....
R^2	0.8843		0.8833		0.8739		0.9985	
$Adj-R^2$	0.8793		0.8783		0.8691		0.9970	

Notes: *, ** and *** depict statistical significance at 1%, 5% and 10% levels

We have divided our sample into two sub-samples following Kim and Perron (2009) empirical results, which indicated the presence of structural break for the year of 2008. This break in carbon emissions series relates to financial crisis occurred in the US economy who hit the UK economy as well. It is argued by Shahbaz et al. (2018a) that existence of structural breaks in the data may affect empirical results, we should re-estimate empirical results by dividing the whole sample into sub-samples based on the indication of structural break(s) to test the robustness of empirical findings. Due to financial crisis i.e. 2007-08, UK manufacturing industry efficiency and productivity have been affected and the economy shifted from heavy industry towards advance industry and services, which reduced electricity usage in industrial sector. Similarly, Business, Energy and Industrial Strategy (2018) reported that financial crisis is one of factors pushed business and industrial sectors for energy efficiency and switching economy to lower carbon fuels which reduced carbon emissions. The empirical results of FMOLS, CCR and OLS with sub-samples are reported in Table-5. We find that empirical results provided by FMOLS and CCR are similar to long-run empirical analysis. This validates the robustness of long-run empirical results. The empirical analysis of sub-samples also shows presence of EKC for the period of 1870-2008. On the contrary, over the period of 2009-2017, we find no significant evidence of inverted U-shaped relationship between growth of economy and emissions. The empirical analysis confirms the presence of U-shaped relationship between economic growth and carbon emissions i.e. economic growth is negatively linked with carbon emissions initially, but economic growth increases carbon emissions are the higher level of GDP per capita. This is a crucial finding, which implies that in contemporary Britain, the notion of long-term negative impact of economic growth on emissions does not prevail in the Post-global crisis period. Concomitantly, it requires more emphasis and being more cautious about the implication of economic growth for the environment. Consumption of energy seems to have a dominant positive impact on emission in pre (1870-2008) and post (2009-2017) break periods. The empirical results are also statistically very significant suggesting that an increase in energy consumption leads to higher consumption regardless of the period. Similarly, financial development also showed a very

significant positive impact on emissions in both periods. The coefficients are positive and statistically significant suggesting that financial development in the UK has severe ecological implications which as important in the post and pre-global financial crisis periods. Lastly, R&D expenditures have a negative and statistically very significant effect on carbon emissions. The empirical results are consistent with the earlier estimations using FMOLS and CCR approaches, which reflects the robustness of our results but is most importantly the prima facie evidence of the importance of R&D in tackling emissions.

6. Conclusion and Policy Implications

In the light of the 4th industrial revolution and global decarbonisation, this study uses historical data from 1870 to 2017 on the United Kingdom to re-examine the determinants of CO_2 emissions. Thereby, the focus is on the potential role of economic growth, R&D expenditures, financial development, and energy consumption. This analysis is important because, on one hand, the 4th industrial revolution may, through its disruptive technological advances, not only fundamentally change society as well as the economic and financial systems, but also create opportunities towards a zero-carbon future. On other hand, as a signatory of the Paris Agreement, the United Kingdom is the first member of the industrialized nations of the G7 group with a target to achieve a ‘carbon-free economy’ by 2050.

We use the unit root test of Kim and Perron (2009) due to its implication of covering the single structural break present in the data. In the presence of an unknown structural break, the long-run relationship between the series is empirically observed by utilizing the bootstrapping ARDL bounds testing. The robustness of the long-run analysis is also investigated by the application of ARDL bounds testing and Johansen-Juselious cointegration approaches. An innovative accounting approach is utilized to check the causal direction between the series.

The empirical results lead us to conclude on the presence of long-run association among the underlying variables. Specifically, the EKC hypothesis is validated for the UK, which implies that in short run economic growth of a country degrades the environment; however, it improves environmental quality beyond the threshold level. The post-global financial crisis period, however, showed less support to this notion, which imply that in the current climate the ecological consequences of economic growth should be given an utmost priority in the policy-making to achieve a sustainable natural environment. Economic growth in the United Kingdom has been buoyant after the Brexit referendum, although the rate of growth has been modest by historical averages. Considering the future events and British membership of the European Union, as well as the resulting effects on its economic growth and probable policy response, pose a whole set of economic and ecological challenges. In the policy setting, it implies that to achieve the target of carbon-free economy by 2050, Britain needs to develop the right attitude of building clean environment in the mind of people when they engaged in economic activities. Concomitantly, emphasis should be given on investment in projects, which are more sustainable, as well as facilitation of sustainable consumption. Our empirical results clearly suggest that excessive energy consumption is hitting hard the climate condition of the United Kingdom. This reflects the significance of energy usage no merely in the facilitation of economic activity but its ecological consequences. It is quite

alarming in policy setting, that there is a climate urgency for the government of UK to revisit its energy policy. There is prima facie evidence of the fact that the type of energy consumption and energy mix adopted so far has been leading to significant environmental degradation. Therefore, in policy setting, it is important that energy mix is revisited, and more emphasis should be given on renewable energy usage, if the target of carbon-free economy is to be met by 2050.

The British financial sector is one of the largest financial sectors in the world and it is multiple folds larger than other sectors of the economy. This size and significance are also evident in its environmental footprint, as our finding leads us to conclude the greater role of development in financial system for increased environmental pollution. In a policy setting, it implies that where financial sector is important for real economy, it has crucial implications for environmental stability. Therefore, financial activities and development should be focused on improving environmental quality and such form of financialization should be encouraged which are more sustainable. Green and sustainable finance are to be the focus of public and macroeconomic policymaking. Allocation of financial resources to environmentally less efficient sectors should be discouraged, while at the same time resources should be allocated to more sustainable sectors. Our empirical results on R&D expenditures lead us to conclude that R&D expenditures are beneficial for natural environment. The statistics showed very strong and empirically robust results, which give us strong confidence to infer that R&D is a key to tackling environmental challenges. Therefore, in policy setting and particularly to curb carbon emissions, it is vital to focus the public policy and allocation of resources to research and development. This will facilitate the efforts to cut carbon emissions to net of zero.

The nonlinear association between development in financial system and environmental pollution was found to be U-shaped. This is a quite alarming finding, implying that the increase in financial development causes environmental degradation, which does not diminish with the increasing financialization. Given the fact that the British financial sector is developed and still growing with its gigantic size and global significance, it is vital to take into account its environmental consequences. In a policy setting, the allocation of financial resources should be channelled to environmentally friendly and sustainable sectors. The policy of facilitation of financial development without its environmental consequences could have a drastic impact on environment. The results on linear and squared terms of R&D expenditures are having both positive and negative effects on environmental pollution, respectively, i.e. an inverted U-shaped relationship. This suggests that increasing innovation expenditures add to the improvement of environmental health, and hence in policy setting, more expenditures on innovation in production may result in better growth of natural environment. Thus, R&D expenditures are worth every penny and will further enable the UK economy to not be part of 'unchartered environmental territory'. Our findings have profound implication for tackling the environmental challenges and the ambitions of the British government to meet its Paris Agreement commitments, as it has committed to cut net emissions to zero by 2050.

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Appendix

Table-A1: Correlation Analysis and Descriptive Statistics

	$\ln C_t$	$\ln Y_t$	$\ln F_t$	$\ln E_t$	$\ln R_t$
Mean	7.8710	8.9570	4.0059	2.1577	2.2166
Median	7.9040	8.8389	3.8738	2.1698	2.0613
Maximum	8.0647	10.189	5.1839	2.2390	6.2353
Minimum	7.3667	8.0681	3.4557	1.9513	-1.5315
Std. Dev.	0.1365	0.6393	0.4167	0.0501	2.5898
Skewness	-1.3195	0.4647	1.3761	-0.9298	0.1511
Kurtosis	4.8544	1.9278	4.0860	4.2909	1.5582
Jarque-Bera	0.6415	0.1240	0.5398	0.3160	0.1338
Probability	0.5050	0.8202	0.5243	0.7989	0.8120
Sum	1164.90	1325.64	592.88	319.33	328.07
Sum Sq. Dev.	2.7394	60.0905	25.5341	0.3702	986.0106
$\ln C_t$	1				
$\ln Y_t$	0.1174	1			
$\ln F_t$	0.5989	0.6166	1		
$\ln E_t$	0.1976	0.6497	0.2104	1	
$\ln R_t$	-0.0576	0.9764	0.5474	-0.5583	1

Table-A2: Unit-Root Test

	ADF Test		ADF Test with Break		
	T-Stat.	Sig.	T-Stat.	Sig.	Date of Break
$\ln C_t$	0.8370	0.9989	-1.7585	0.9919	2008
$\ln Y_t$	-2.1360	0.5211	-4.0296	0.3537	1916
$\ln F_t$	-2.0019	0.5951	-4.0234	0.3547	1985
$\ln E_t$	-1.5544	0.6253	-1.7006	0.9928	1918
$\ln R_t$	-2.2469	0.4598	-3.0686	0.8904	1887
$\Delta \ln C_t$	-11.5919*	0.0000	-13.2126*	0.0001	1921
$\Delta \ln Y_t$	-8.7985*	0.0000	-9.4611*	0.0001	1919
$\Delta \ln F_t$	-8.0542*	0.0000	-9.0763*	0.0001	1987
$\Delta \ln E_t$	-10.3711*	0.0000	-10.8070*	0.0000	1933
$\Delta \ln R_t$	-9.1651*	0.0000	-10.7298*	0.0000	1920

Note: * shows significance at 1%.

Table-A3: The Bounds Cointegration Analysis

Bounds Testing Approach to Cointegration				Diagnostics					
Model	Lags	Break Year	F-statistic	χ^2_{NORMAL}	χ^2_{ARCH}	χ^2_{RESET}	χ^2_{SERIAL}	CUSUM	CUSUM _{SQ}
$C_t = f(Y_t, Y_t^2, E_t, F_t, R_t)$	6, 6, 5, 6, 5, 6	2008	13.349*	0.1822	1.7477	2.3562	0.0244	Stable	Stable
$Y_t = f(C_t, Y_t^2, E_t, F_t, R_t)$	6, 6, 6, 5, 6, 6	1916	2.1612	0.4013	2.1012	0.1305	1.0017	Unstable	Stable
$Y_t^2 = f(C_t, Y_t, E_t, F_t, R_t)$	6, 6, 6, 5, 6, 6	1916	2.6102	0.1191	1.0102	1.1003	2.0052	Unstable	Unstable
$E_t = f(C_t, Y_t, Y_t^2, F_t, R_t)$	6, 5, 5, 5, 5, 6	1918	11.7128*	2.0302	2.1001	0.30705	0.1500	Stable	Stable
$F_t = f(C_t, Y_t, Y_t^2, E_t, R_t)$	6, 6, 6, 5, 5, 5	1985	21.1722*	1.3003	2.1021	2.1005	0.3035	Stable	Stable
$R_t = f(C_t, Y_t, Y_t^2, E_t, F_t)$	6, 6, 5, 6, 5, 6	1887	14.8301*	1.2208	2.2021	2.1153	0.3112	Stable	Stable
Statistical Significance	Critical values (T = 52)								
	L.B I(0)	U.B I(1)							
1 %	7.317	8.70							
5 %	5.360	6.373							
10 %	4.437	5.377							

Note: * represents 1% statistical significance level. The AIC is used for optimal lag length section.

Table-A4: Bootstrapped ARDL Analysis

Bootstrapped ARDL Estimation						Diagnostic testing			
Models	Lags	Break date	F _{PSS}	T _{DV}	T _{IV}	\bar{R}^2	Q-stat	LM(2)	JB
$C_t = f(Y_t, Y_t^2, E_t, F_t, R_t)$	6, 6, 5, 6, 5, 6	2008	10.105*	-3.2209**	-4.2704***	0.7609	5.8088	2.7050	0.9015
$Y_t = f(C_t, Y_t^2, E_t, F_t, R_t)$	6, 6, 6, 5, 6, 6	1916	2.908	-1.8058	0.8065	0.6316	6.1607	0.4060	0.7777
$Y_t^2 = f(C_t, Y_t, E_t, F_t, R_t)$	6, 6, 6, 5, 6, 6	1916	3.161	-1.8290	1.0505	0.7592	5.6043	1.2005	0.7002
$E_t = f(C_t, Y_t, Y_t^2, F_t, R_t)$	6, 5, 5, 5, 5, 6	1918	12.615*	-7.1511*	-5.6191***	0.6038	4.2702	0.3050	0.8202
$F_t = f(C_t, Y_t, Y_t^2, E_t, R_t)$	6, 6, 6, 5, 5, 5	1985	13.159*	-7.9809*	-4.0901*	0.7154	5.8020	2.1035	0.6657
$R_t = f(C_t, Y_t, Y_t^2, E_t, F_t)$	6, 6, 5, 6, 5, 6	1887	12.206*	-8.4945*	-4.8065*	0.2222	6.2002	2.1051	0.9205

Note: *, ** and *** are 1%, 5% and 10% levels of statistical significance. For optimal lag length selection, Akaike Information Criterion (AIC) is used. Using asymptotic critical bounds generated by bootstrapping, F-statistic F_{PSS} (Pesaran et al. 2001) is calculated. T_{DV} and T_{IV} are t-statistic for dependent and independent variables, JB is Jarque-Bera and LM is the Langrage Multiplier test.