Nuclear Energy Consumption and Economic Growth in the UK: Evidence from Wavelet Coherence Approach

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Abstract

The aim of this present study is to assess the causal link between nuclear energy consumption and economic growth in the UK using Toda Yamamoto causality and wavelet coherence tests with the objective of responding to the following questions: (i) Does consumption of nuclear energy lead to economic growth in the UK and/or does economic growth lead to the consumption of nuclear energy sources in the UK, and (ii) if so, why? The findings from wavelet coherence reveal that changes in economic growth lead to changes in nuclear energy consumption in the UK at different frequencies, especially in the long-run, and in different periods between 1998 and 2017. In addition, there is a positive correlation between nuclear energy consumption and economic growth between 2002 and 2006 in the short-run. In this study, we also checked the consistency of the findings from wavelet coherence which is confirmed by the outcomes of Toda Yamamoto causality test. Therefore, the present study is likely to attract great interest from the policy-makers and researchers in this field. At the same time, it is likely to start a new debate.

Keywords:

Nuclear Energy Consumption; Economic Growth; UK; Wavelet Coherence; Granger Causality

1. Introduction

The impact of energy consumption has been assessed in different contexts, across countries, and using several data structures and methodology. In fact, the reasons for the abundance of research on energy issues are not far-fetched. Apart from raising concerns about global emissions, the contribution of stable energy and electricity supply to achieving the growth prospects of nations has been at the forefront of many studies and the importance of such causality analysis cannot be overestimated (Lau et al., 2019). Moreover, consumption of and access to stable power supply from several energy sources is one of the focal points of developing as well as developed countries like the United Kingdom. This is because it can form a basis for sustainable economic and social development by enabling businesses prosper with consequent improvement in the standards of living. Thus, since energy consumption cannot be separated from the growth prospects of a country, many governments have sourced power from nuclear energy, which is a type of energy generated when atoms split, and this is generated by the construction of nuclear power plants.

[FIGURE 1 HERE]

Although, in comparison to other energy sources, nuclear energy may be full of controversies; it remains an important aspect of electricity consumption in many developed countries and for sustainable economic development (Toth and Rogner, 2006). For example, as shown in Figure 1, the amount of electricity produced by nuclear sources is significant across selected European countries with up to 79% in France. Also, in recent times, the UK has demonstrated an upward trend in its use of nuclear sources for generating energy. Thus, it is worth investigating whether the observed trend has the capacity to moderate the growth agenda and the corresponding direction of causality.

Interestingly, while some countries have decreased their use of nuclear energy sources as is the case in Sweden, others have increased their exploration of this energy source. In fact, Sweden's exploration of energy from nuclear sources declined from nearly 50% in 1999 to a little above 30% in 2015. This trend reinforces the need to examine fresh evidence for the motivation for and impact of this energy source. According to Wolde-Rufael and Menyah (2010), there is a one way causality that runs from growth of the economy to the consumption of nuclear energy for both Canada and Sweden. In the Netherlands, however, the contribution of energy generated from nuclear sources is between 2% to 4% (see Fig. 1). This is however low considering the relevance and benefits of energy from nuclear sources in comparison to others.

Albeit the consumption of energy from nuclear sources in the UK is non-negligible; for a developed country it has suffered a relatively lower contribution. Since 1999 it suffered a downward trend until the global financial crisis of 2007/2008. However, empirical evidence in the literature suggests two way causality between the consumption of nuclear energy and growth of the econmy in the UK and France (Wolde-Rufael and Menyah, 2010). The results of causality tests however defer, and research suggests that this may depend greatly on the method adopted or the country involved. A one-way causality may occur where nuclear energy consumption will depend on economic growth and vice-versa for some countries (unidirectional relationship), or there will be a two-way relationship between them where they will depend on one another (bidirectional), and sometimes no relationship is discovered (no causality). According to Omri et al. (2015), nuclear energy consumption has a one-way causal relationship to economic growth in Belgium; but this finding contradicts the one-way relationship which runs from economic growth to nuclear consumption for Bulgaria, Canada, Netherlands and Sweden. Additionally, nuclear energy consumption and economic growth depend on each other for the case of France, Argentina, Brazil and the USA. In fact, there is no relationship between nuclear energy consumption and economic growth for Finland, Hungary, India, Japan, Switzerland and the UK.

[FIGURE 2 HERE]

In the energy-growth nexus debate, there are studies on several sources of energy; wind, coal, oil, solar and nuclear sources. Thus, while it may seem like an option to dismiss the causality between growth and energy production and consumption from nuclear sources due to its relatively low contribution in many countries, research suggests otherwise as there is much evidence on the pattern of movement in the trend of both variables. As shown in Figure 2, apart from the divergence in the global financial crisis-era (between 2008 and 2010), the percentage of electricity production from nuclear sources and the growth rate of GDP per capita have shown a closely similar pattern. In fact, about a quarter of electricity generation in the UK comes from nuclear sources and is expected to rise to a third by 2035. Consequently, in an attempt to safeguard the relevance of nuclear energy consumption, the UK Atomic Energy Authority (UKAEA) was established in 1954 in order to oversee the development of nuclear energy in the UK.

However, the approval of energy from nuclear energy sources is divided amongst people who are concerned about climate change and high environmental value with less concern for nuclear energy (Corner et al., 2011). These concerns are related to issues regarding the disposal of radioactive waste, terrorism and nuclear material. Hence, there is less motivation for the use of energy from nuclear sources, thereby leading to limited nuclear power plants. Additionally, power from nuclear energy sources raises concerns with regard to global warming and climate change (Ozcan and Ari, 2015). In fact, nuclear energy production by the UK in 2006 was 19% with CO_2 emissions of 0.2% and the resultant GDP growth of 1.8%. In 2008, there was a 13% nuclear energy production of total energy in the UK and CO_2 emission of 0.2% but is related to a notable decline of -1.12% in the GDP per capita, although this does not denote any direction of causality as yet. As of 2009, nuclear energy consumption increased to 18.5% and 0.1% CO_2 emission and this records a more negative effect on the GDP per capita of -4.9%. In 2008 and 2009, nuclear energy consumption of total energy in the UK seemed to align with a negative effect on the economic growth (GDP per capita). However, there is no consensus on the direction of causality (if any).

According to Yoo and Ku (2009), there is a one-way causal relationship from nuclear energy consumption to economic growth. Recent evidence by Saidi and Ben Mbarek (2016) also showed that between nuclear energy and economic growth, a one-way causal relationship exists. Such findings suggest that there is a need for the UK to adopt government policies which will increase the nuclear energy production of the country, either by increasing the number of nuclear power plants or adopting other policies because of the fluctuating contribution of the nuclear energy production as a percentage of total energy and its resultant effect on economic growth.

Amongst several mediating factors, research also places importance on the quality of a country's political institution which helps increase its social, governmental and economic preparedness to tackle climate change and its effects, as a result of production of energy from nuclear energy sources (Sarkodie and Adams, 2018).

Albeit nuclear power plants have been found to have high construction costs, they have relatively low running costs and longevity which simply means they are cost-effective. However, authors argue against nuclear energy because of the acclaimed effect of CO_2 emissions; yet nuclear power stations only produce CO_2 emissions during construction and fuel processing, not when electricity is being generated. Hence, to reduce carbon intensity, there is a need to increase the number of nuclear power plants as a way of improving nuclear energy share (Peng et al., 2019). Uranium which is the raw material for producing nuclear fuel is highly available and lasts for a very long period of say 40-60 years; therefore nuclear power can be seen as a long-term low-carbon solution since there is no fear of scarcity of raw materials for its production. This strengthens the prominence of energy generation from nuclear sources.

Many studies on the causality between nuclear energy consumption and economic growth adopted the Granger causality test (Apergis et al., 2009; Menyah and Wolde-Rufael, 2010; Wolde-Rufael and Menyah, 2010; Yoo and Ku, 2009). Such an approach has known limitations as it basically shows cause-effect relationships. Thus, the present study seeks to complement and improve on this using the wavelet hypotheses, which is a novel approach in the energy-growth debate. The wavelet method in determining the causality of the variables is adopted to shed some light on the causal link between nuclear energy consumption and economic growth in the UK.

The significance of this is to fill the gap in previous studies and to determine if there is any causal relationship between nuclear energy consumption and economic growth as well as the direction of causality.

The rest of this investigation is composed as follows: The next segment exhibits the survey of related literature in a stylised format offered in section 2. Section 3 gives the data and methodological approach applied over the span of the study. Therefore, section 4 spotlights on the discusion of study outcomes. In conclusion, section 5 renders the finishing up comments.

2. Literature Review

2.1 Energy Consumption-Growth Nexus

There is a vast volume of literature on the energy-growth nexus (Saint Akadiri et al., 2019; Bekun et al.,2019a,b; Wesseh and Lin, 2018; Emir and Bekun,2019; Yoo and Ku, 2009; Naser, 2015; Cherni and Essaber Jouini, 2017; Apergis and Payne, 2010; Adedoyin et al., 2020a, 2020b; Apergis et al., 2010). There is however no consensus as to the causality between the energy consumption. While some depict unidirectional causality, others show a bidirectional relationship and others that there is no causality at all between them. Some studies show disparity in the unidirectional causality by showing that nuclear energy consumption depends on economic growth while others state otherwise. Surprisingly, studies on the causality between the two variables in different countries present different results[1].

Furthermore, determining the causal relationship between nuclear energy consumption and economic growth also involves investigating not only the direction of causality (i.e. if one

[1] See Appendix for details on the review of the related literature.

variable occurs as a result of the other) but also to find out if they simply depend on one another. This causality has been determined using different methods and different variables, and of course, they all had different results while determining the causality, which can be attributed to the variation in the methods adopted. A unidirectional causality simply means that there is a one-way dependency between the two variables. A bidirectional causality relationship means the two variables relatively depend on one another. However, while using panel vector error correction model, Apergis and Payne (2010) established that there is two way link between the consumption of nuclear energy and the growth of the economy in the long run, while only a one way relationship which runs from the consumption of nuclear energy to the growth of the economy holds in the in the short run. This means that in the long run, nuclear energy consumption and economic growth depends on one another; while in the short run, economic growth depends on nuclear energy consumption.

With more awareness of the consequences of exploring energy sources in terms of emissions, much progress has been made in the literature to capture emissions from energy sources. Advancing in energy literature, CO_2 emissions have been discovered to be the main cause of global warming; its reduction is therefore necessary. However, it is nearly impossible to stop global warming, since CO_2 emissions last between 50-100 years in the atmosphere. Nuclear energy consumption contributes to the reduction of CO_2 emissions. This can be done when electric power plants driven by fossil fuels are being replaced by nuclear power plants.

Also, CO_2 emissions have been discovered to result in environmental degradation. This might be the reason some researchers have decided to test the validity of the environmental Kuznets curve hypotheses, positing that in the early stages of economic development degradation will increase over time and then after a threshold more equal as per capita income increases. However, nuclear energy is known as a low-carbon technology (Corner et al., 2011). However, the positive and negative impacts of CO_2 emissions on renewable energy indicate that the major problem of CO_2 emissions stems from the industrial and not the energy sector (Luqman et al., 2019). Also, since nuclear energy provides energy without emitting carbon, there is a need for the government to increase the share of nuclear power portfolio of any country (Gokmenoglu and Kaakeh, 2018). According to Lau et al. (2019), the EKC hypotheses is valid for the Organization for Economic Cooperation and Development (OECD) countries, an intergovernmental organization with 36 member countries in which the United Kingdom (UK) also belong to while using the generalized system method and modified ordinary least square method. Because of the differences in government policies and climate conditions, it is possible to establish different causality relationships between nuclear energy consumption and economic growth.

[TABLE 1 HERE]

Furthermore, when the causality relationship between nuclear energy consumption and economic growth is determined using different methods, like the Granger causality tests, Vector error correction model, Bounds Test Approach etc. for the same country, similar or same results can be achieved. Yoo and Ku (2009) found that there is a unidirectional causality running from nuclear energy consumption to economic growth for Switzerland using Granger Causality, Co-integration, and Error correction model. They repeated the test in 2009, but using tests for unit roots co-integration and Granger-causality, and still discovered the same results for Switzerland.

Conversely, different results can also be achieved when different methods are used to determine the causality relationship between nuclear energy consumption and economic growth. (Tabi and Omri, 2017) found that no causality was found between nuclear energy consumption and economic growth for the same for Switzerland. What this means is that the method of analysis determines to a great extent the causality relationship to be discovered between nuclear energy consumption and economic growth. However, green economic growth is a path of economic growth which is concerned with natural resources in a sustainable manner. It is an alternative to typical industrial growth. The driving factors of green economic growth known as GEG are cleaner energy and technological innovations while militarization is detrimental to green energy growth (Sohag et al., 2019).

There are many other methods used in determining the causality between nuclear energy consumption and economic growth. Dumitrescu and Hurlin tests is one of the most recently used (Bekun et al., 2019; Piacentino et al., 2019; Rahman and Velayutham, 2020). Wolde-Rufael (2010) adopted the Bounds Test Approach in determining the relationship between nuclear energy consumption and economic growth for India, and discovered that a short- and long-term relationship exists between nuclear energy and economic growth. A different method known as the Translog causality-based model was adopted in 2018 by (Wesseh and Lin, 2018), and they also established that a two-way (bidirectional) causal relationship exists between all energy types (electricity, natural gas, petroleum) and economic growth. Also, in bootstrap corrected causality method was adopted by (Aslan and Çam, 2013). However, to the best of our knowledge, there are not many studies on the connection between economic growth and nuclear energy consumption for the UK. This paper not only attempts to establish a causal relationship between them, but it also attempts to do so using the wavelet coherence method.

2.2 Analyses of Wavelet Coherence in Energy Studies

There have been various studies determining the relationship between energy use and economic growth using the wavelet coherence approach, some of which are considered here. (Pal and Mitra (2019) revisited the renewable energy consumption and industrial production (IP) using the continuous wavelet approach for the US. They discovered that geothermal, wind, biofuels, wood and waste have a significant effect on the US. Their wavelet analyses, however, depict the impact of renewable on US economy at 1-3-year frequency and 3-8-year frequency for the time period from January 1989 to November 2016. (Boubaker and Ali, 2017) discovered that oil price and stock market price are directly affected by their own news and volatilities and indirectly affected by the volatilities of other prices and wavelet scale. Energy pairs, however, show strong dynamics in co-movement in time during various investment horizons. Therefore, there is a need to keep in mind the time-varying nature as well as the investment horizon of energy markets while considering its dependence, (Vacha and Barunik, 2012).

Progressing in the use of wavelet hypotheses, (Yang et al., 2017) contributed to the literature by concluding that the degree of co-movements between the crude oil price and exchange rates deviate overtime. There is also a negative relationship between the returns of the crude oil price and exchange rates for the oil-producing countries. (Sharif, Jammazi, Ali, Jawad, & Shahzad, 2017), while taking an insight on wavelet approach to determine the relationship between Electricity and growth in Singapore, discovered that there is a unidirectional causal relationship from electricity generation to economic growth. Furthermore, interdependence between oil and stock returns for East Asian countries is homogenous while China and Japan have a weaker correlation with oil prices compared to other East Asian countries. However, investors should be concerned with increased co-movements during the crisis period which suggests a high risk of contagion (Yang et al., 2017). While attempting to analyse possible co-movement between oil prices and automobile stock return using the wavelet coherence analyses, (Pal and Mitra, 2019) discovered that the co-movement between oil price and automobile stock return is strong during November 2000-December 2002 and March 2006- December 2009 in India. The relationship between oil prices and consumer price index for the period of January 1871- June 2018 in the US has changed, i.e. a decrease in the oil price - inflation pass through overtime. Also, based on the wavelet analyses, there is a significant correlation between crude oil prices and global economic activity at high frequencies in the short run and at low frequencies in the long run (Dong et al., 2019).

Including the abovementioned, a number of studies have analysed energy use and economic growth using the wavelet coherence hypotheses, yet none has attempted to examine the causal relationship which exists between nuclear energy consumption and economic growth using the wavelet approach for the case of the UK. The aim of this study, however, is not only to look at the relationship between nuclear energy consumption and economic growth for the UK but to do this using the wavelet coherence approach whilst providing fresh evidence and contributing to the ongoing debate.

3. Data and Methodology

This section of this study focuses on the data choice and econometrics procedure applied. The data used in this study are Real GDP and Nuclear Energy Consumption from the World Bank and UK Energy Statistics, respectively. The time series variables used in the empirical tests of this study consist of quarterly data for the period 1998Q1 to 2017Q4. While the natural logarithm of the real GDP is used as a proxy for economic growth in the estimated model, we used the seasonally adjusted Nuclear Energy Consumption. Table 2 reports the descriptive statistics and codes of the time series variables used in this study. The summary statistics show economic growth (GDP) has highest average over the sampled period relative to Nuclear Energy Consumption (NEC). Both series display light tail as reported by kurtosis with values less than 3, while economic growth is negatively skewed. NEC is positively skewed and normally distributed as reported by Jarque-Bera probability test statistics.

[TABLE 2 HERE]

To investigate the time-frequency dependence of GDP and NUC in the UK, the wavelet coherence approach which is firstly developed by Goupillaud, Grossmann, and Morlet (1984) is employed in the present study. The main novelty of wavelet coherence is that the approach combines time-domain causality and frequency domain causality. Therefore, this allows the present study to capture the long-run and short-run causal links between GDP and NEC in the UK. In other words, a multi-scale decomposition method brings out a natural framework to show frequency-dependent behaviour for exploring the relationship between GDP and NEC.

The present adopts the wavelet ψ based on the Morlet family of wavelet. The equation is rendered as $\psi(t) = \pi^{-\frac{1}{4}}e^{-i\omega_0 t}e^{-\frac{1}{2}t^2}$, p(t), t=1, 2, 3….., T.

Here, two wavelet parameters namely location (*k*) as well as and frequency (*f*) are essential. The core importance of the parameter *k* is to outline the precise location in time by a fluctuation of the wavelet. On the other hand, *f* controls the variations in the frequencies. $\psi_{k,f}$ is constructed initially by the transforming ψ. The transformation equation is presented as:

$$\psi_{k,f}(t) = \frac{1}{\sqrt{h}}\psi\left(\frac{t-k}{f}\right), \ k,f \in \mathbb{R}, f \neq 0 \quad (1)$$

Furthermore, the continuous wavelet can be constructed from ψ contingent on earlier mentioned wavelet parameter of *k* and *f* provided that the time series data set p(t) as follows:

$$W_p(k,f) = \int_{-\infty}^{\infty} p(t)\frac{1}{\sqrt{f}}\overline{\psi\left(\frac{t-k}{f}\right)}dt, \quad (2)$$

The aforementioned already generated time series p(t) with its corresponding coefficient ψ is presented in the equation below:

$$p(t) = \frac{1}{C_\psi}\int_0^{\infty}\left[\int_{-\infty}^{\infty}|W_p(a,b)|^2 da\right]\frac{db}{b^2}. \quad (3)$$

The adoption of the wavelet power spectrum (WPS) is pertinent as it characterised with more information and amplitude of the time variables. see equation below for details:

$$WPS_p(k,f) = |W_p(k,f)|^2. \quad (4)$$

The present study adopts the Wavelet coherence techniques. This is premised on the inherent traits of the coherence approach over conventional correlation. The coherence approach allows for a broader capture of both time domains of the time series p(t) and q(t) in combined time-frequency based causalities.

Furthermore, the cross wavelet transform of the times series takes the following form;

$$W_{pq}(k,f) = W_p(k,f)\overline{W_q(k,f)}, \tag{5}$$

where $W_p(k,f)$ and $W_q(k,f)$ denotes cross wavelet transform for p(t) and q(t), respectively as outlined by (Torrence and Compo 1998). In summary, Torrence and Compo (1998) mentioned that the square version of the wavelet coherence can be constructed as:

$$R^2(k,f) = \frac{\left|C\left(f^{-1}W_{pq}(k,f)\right)\right|^2}{C\left(f^{-1}|W_p(k,f)|^2\right)C\left(f^{-1}|W_q(k,f)|^2\right)} \tag{6}$$

From eq. (6) the time and smoothing process over time is captured by C, with values ranging from $0 \leq R^2(k,f) \leq 1$. It is worth mentioning here that when $R^2(k,f)$ gets close to unit (1), this denotes that between the time series there exists correlation at a particular scale, surrounded by a black line and represented by the colour red. While in the case of value of $R^2(k,f)$ close to Zero (0), it depicts the scenario of no correlation between the time series which is displayed by the colour blue.

In the computation of the values of $R^2(k,f)$, there is no clear distinction for a positive or negative correlation. Thus, the idea of Torrence and Compo (1998) comes handy, as it helps to detect the variance in wavelet coherence via the indications of deferrals in the wavering of two time-series (Pal and Mitra, 2017). The equation that provides the differentiation in the wavelet coherence phase is given as:

$$\phi_{pq}(k,f) = \tan^{-1}\left(\frac{\mathrm{L}\{C(f^{-1}W_{pq}(k,f))\}}{O\{C(f^{-1}W_{pq}(k,f))\}}\right), \quad (7)$$

From equation (7) the lag operators L and O represents both imaginary operator and real part operator respectively.

In the interpretation of the wavelet coherence graphical display, the horizontal axis represents the time dimensions and the frequency is rendered on the vertical axis. In addition, higher scale is denoted by lower frequency. In regions of time-frequency space, in cases where two series co-vary exist; they can be located by the wavelet coherence. Also, the colour red depicts significant association while the colour blue denotes lower interrelation among series. The cold areas away from the significant region tell about the time and frequency with no interrelation among the series. While in the scenario of an arrow in the wavelet graphical plots depicts the lag and lead phase relationship among the investigated variables. The zero phase difference depicts that there exists a co-movement between two variables at a precise scale. In addition, when the arrows point to right (left) it indicates the time series are in phase (anti-phase). However, when the two series are in phase, it represents that two variables move in similar direction while an opposite anti-phase denotes they move in reverse direction. Furthermore on wavelet coherence schematic graph, arrow pointing left-up or right-down depicts the first series is leading the other variable. Conversely, the second variables lead when the arrow points left-down.

In order to reinforce the direction of causality flow between the variables under review, the current study employed the use of the Toda and Yamamoto (T-Y, hereafter) Granger causality methodology as a robustness check. The Toda and Yamamoto (1995), a modified Wald test statistic (MWALD) known for its merits over the traditional Granger causality test. The T-Y techniques are constructed in the VAR setting. The MWALD is easy to estimate, as it does not require any pre-stationarity test. However, it does not work with variables integrated of order 2 as outlined by (Kirikkaleli and Gokmenoglu, 2019).

4. Empirical Findings

As an initial step, we used wavelet power spectrum to explore the vulnerability periods and identify the behaviour of the GDP and NEC variables, which are reported in Figure 3-4. In this study, a scale of 23 periods is selected since the dataset covers the period from 1998Q1 to 2017Q4. In Figures 3 and 4, the white cone-shaped curve shows the cone that dominating an edge below where the wavelet power exerts effects because of discontinuity. On the other hand, the thick black shape represents a 0.05 per cent level of significant derived by Monte Carlo simulations. Figure 3 reports the wavelet power spectrum for nuclear energy consumption in the UK. The results clearly show that there was a significant vulnerability in nuclear energy consumption between 2006 and 2012 at 6 and 8 quarter scales. In addition, we also observed that the variable is vulnerable between 2012 and 2016 but in the short-run. As seen in Figure 4, the GDP is significantly vulnerable in the UK between 2007 and 2010 at different frequencies, ranging from 3 periods (high frequency) to 16 periods of scale (low frequency) due to the recent global crisis.

[FIGURE 3 HERE]

[FIGURE 4 HERE]

To investigate the time-frequency dependency of GDP and NEC in the UK, we used the wavelet coherence approach, which allows the bi-dimensional time-frequency causality to be detected.

Hence, the long-term and short-term causal links between GDP and NEC in the UK are investigated in the present study. The wavelet coherence between GDP and NEC is presented in Figure 5, which undoubtedly shows that GDP has a strong effect in explaining NEC in the long-term since a right-up arrow can be observed within the thick black shape at the bottom of the white cone-shaped curve. This clearly reveals how the economic growth in the UK is important for predicting nuclear energy consumption. This is consistent with the proposition of the growth-induced energy hypothesis, where economic growth triggers consumption of energy source (Shahbaz *et al*., 2011; Shahbaz *et al*., 2014), in this study's case cleaner energy like nuclear energy.

Furthermore, this position aligns with the assertion of the United States Energy Information Administration that energy is a catalyst for economic growth as it spurs socio-economic activities (EIA, 2018). In addition, economic growth and nuclear energy consumption are in phase in the UK between 2002 and 2006, but only in the short term. As a robust causality test, we also employed TY Causality Test to capture the causal link between economic growth and nuclear energy consumption in the UK. As can be seen in Table 2, the growth led-nuclear hypothesis is empirically proved based on the outcomes of the TY causality technique. Therefore, it is worth to mention that the outcome of the wavelet coherence test is in line with the outcome of TY causality test. The outcomes also reveal that the null hypothesis that nuclear energy consumption does not cause economic growth in the UK cannot be rejected at 5% level, indicating that changes in nuclear energy consumption in the UK do not significantly lead to changes in economic growth. The present study did not find support for nuclear energy induced growth for the period under consideration. The plausible reason could be the fact that the UK is like other economies on the trajectory of a paradigm shift from fossil fuel-based energy sources to renewables like nuclear energy. This takes time given the infrastructure and adaptation to technologies of renewable energy sources. This probably explains why the UK is at a technical stage of her growth trajectory in accordance with the Kuznets Curve ideology (Balsalobre-Lorente et al., 2018; Shahbaz and Sinha, 2019).

[FIGURE 5 HERE]

[TABLE 3 HERE]

5. Conclusion

The pioneering study of Kraft and Kraft (1978) affirms the indispensable role of energy consumption as a driver for socio-economic growth of most economies. This is achievable on the fact that most production processes need the energy to thrive. Thus, energy consumption supports livelihood and wellbeing as outlined by Samu et al. (2019). However, there is a trade-off in the consumption of energy sources, as it is well documented in the energy literature that most economies rely on fossil-based energy sources which are characterized by pollutant emissions (CO_2) given they are readily available.

Although the nexus between energy consumption and economic growth has received considerable attention from scholars, there is no consensus on the effect of nuclear energy on economic growth in the world. To the best of our knowledge, there has been no comprehensive attempt so far to detect both the short and long term causal links between nuclear energy and economic growth. Therefore, the present study aims to fill this gap by investigating the link between nuclear energy and economic growth in the UK, over the period of 1998Q1 to 2017Q4 using the wavelet coherence approach. The approach allows the bi-dimensional time-frequency causality to be observed.

Findings of this study mirror that changes in economic growth lead to changes in nuclear energy consumption in the UK at different frequencies, especially in the long-run, and in different periods between 1998 and 2017. This implies how important economic growth in the UK is for predicting nuclear energy consumption. Moreover, we found that nuclear energy consumption and economic growth are in phase between 2002 and 2006 but in the short-run. It is worthy to mention that the outcome of the TY causality test underlines the growth-led nuclear hypothesis. Our study's finding of growth-induced energy consumption (nuclear) finds empirical support from the study of Lean and Smyth 2010) and Ameyaw et al. (2016). The current study joins the strands of studies that support the hypothesis that the bigger the economy the higher the demand for energy consumption. This is very insightful and informative for the government administrators in the UK, as caution should be in place for the blend of her energy consumed. As departure from renewables like nuclear, biomass and hydro among others will not only harm the economy but also the environment at large.

Additionally, it is crucial for the policymakers of the UK economy to structure development focused approaches and systems so as to grow the economy from environemntally friendly sources. For example, existing development goals can be structured and executed as an additional push to growing renewable sources that can advance and invigorate monetary development in turn. As the income level rises in the UK, there would be a switch towards ventures and administrations that can improved ecological mindfulness, implementation of stricter energy rules and reception of clean advances. Also, since power generation utilizing petroleum derivatives is considered destructive to the earth, policymakers in the UK should structure vitality strategies with the intention to dishearten the utilization of non-renewable energy sources in existing power plants.

In summary, based on the outcome of this study, the need for the UK government administrators to strengthen their commitment to renewable energy consumption in the long-run is paramount in times of global energy consciousness. This is to foster the attainment of sustainable development goals (SDG's) as it relates to energy for cleaner energy and a more eco-friendly environment. This is a call for more pragmatic steps on part of the government to reinforce commitment to renewable energy infrastructure and technologies. Although this study makes it possible to identify strong empirical findings, further studies should be conducted for other countries where there is nuclear energy consumption.

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Appendix

Table 1. Schematic Representation of existing literature

Author(s)	Period	Region	Methodology	Direction of Causality
Yoo & Jung (2005)	1977-2002	Korea	Granger causality, cointegration, error correction model	There is a unidirectional causality which runs from NEC to EG.
Apergis & Payne (2009)	1980-2005	16 Countries	Panel vector error correction model	Bidirectional causality exists between NEC and EC in the long run. Unidirectional causality also exists in the short run but runs from NEC to EG.
Yo & Ku (2009)	1986-2005	Argentina, France, Germany, Korea, Pakistan and Switzerland	Cointegration and Granger-causality	There is a bidirectional relationship between NEC and EG in Switzerland. For France and Pakistan, there is a unidirectional causality which runs from EG to NEC. Unidirectional causality also runs from NEC to EG for Korea.
Wolde-	1969-2006	India	Bounds test approach	There is a unidirectional causality which runs from

Author(s)	Period	Region	Methodology	Direction of Causality
Rufael (2010)			Toda and Yamamoto (1995 causality test	NEC to CO2 emissions without feedback.
Apergis et al. (2010)	1984-2007	19 countries	Granger causality tests	NEC causes a reduction of CO_2 emissions in the short run. REC does not contribute to reductions in emissions.
Lee & Chiu (2011)	1971-2006	Developed countries	Panel co-integration	There is a unidirectional causality which runs from oil prices and EG to NEC in the long run. However, there is no causality between NEC and EG in the short run.
Saban, Fuat , & Selim (2011)	1980-2007	OECD Countries	Panel granger causality approach; Toda-Yamamoto causality	There is no causality between NEC and EG in eleven out of fourteen cases. This supports neutrality hypotheses.
Chu & Tsangyao (2012)	1971-2010	G-6 countries	Bootstrap panel granger causality test	NEC granger causes economic growth in Japan, the UK and the US. Also, there is one-way causality from EG to oil consumption only in the US and that oil

Author(s)	Period	Region	Methodology	Direction of Causality
				consumption does not granger cause EG in G-6 countries except for Germany and Japan.
Akhmat & Zaman (2013)	1975-2010	South Asian countries	Bootstrap panel granger causality method	There is no causality between NEC and EG. This upholds the neutrality hypotheses in most of the countries.
Mounir et. al. (2015)	1990:1 to 2011:4	France	Vector error correction model	There is bidirectional causality between NEC and EG
Hanan Naser (2015)	1965-2010	Russia, China, South Korea and India	Johansen cointegration technique	There is a causal link which runs from energy consumption (Oil and nuclear energy) to EG
Anis, Nejah & Amel (2015)	1990–2011	17 countries	Dynamic simultaneous equation	There is unidirectional causality from EC to REC and bidirectional causality between NEC and EG.
Burcu & Ari (2015)	1980-2012	15 OECD Countries	Bootstrap causality test	There is no causal relationship between NEC and EG in 10 OECD countries. However, there is a significant

Author(s)	Period	Region	Methodology	Direction of Causality
				causality between EG and NEC in 5.
Saidi & Mbarek (2016)	1990-2013	9 developed countries	Dynamic panel	There is a unidirectional causality which runs from REC to EG in the short run, but none between NEC and EG. In the long run, there is bidirectional causality between REC and EG.
Cherni & Jouini (2017)	1990-2015	Tunisia	ARDL and Granger causality test	There is a bidirectional relationship between EG and CO_2 emissions as well as between REC and EG. There is no relationship between CO_2 Emissions and REC.
Ito (2017)	2002-2011	42 countries	Difference GMM	Non-REC has a negative impact on EG for developing countries. In the long run, REC contributes positively to EG.
Lau et al. (2019)	1995-2015	18 OECD countries	GMM and FMOLS	EKC hypotheses are valid in OECD countries
Gokmenoglu & Kaakeh	1968-2014	Spain	Johansen cointegration test,	There is a unidirectional Granger causality which runs from NEC to EG

Author(s)	Period	Region	Methodology	Direction of Causality
(2018)			VECM and Granger causality test	
Wesseh & Lin (2018)	1980–2016	Egypt	Translog causality-based model	There is bidirectional causality between all energy types (electricity, natural gas, petroleum) and EG
Dong et al. (2018)	1993-2016	China	ARDL, Bayer-hank cointegration, and the VECM; Granger causality test	There is evidence supporting the EKC hypotheses for CO_2 emissions. Fossil fuel consumption contributes to CO_2 emissions in China in the short and long run
Sohag, Dilvin & Malik (2019)	1980-2017	Turkey	ARDL	Cleaner energy and technological innovations are driving factors in promoting Green Economic growth in the long run. Also, militarization is detrimental to GEG
Luqman, Ahmad & Bakhsh	1990-2016	Pakistan	ARDL	There is a positive impact on economic growth due to shocks on REC.

Author(s)	Period	Region	Methodology	Direction of Causality
(2019)				

NB: NEC represents nuclear energy consumption; EG represents economic growth; REC represents renewable energy consumption; GMM represents the generalized method of moments; FMOLS represents fully modified ordinary least squares; VECM represents vector error correction model

Table 2. Descriptive Statistics

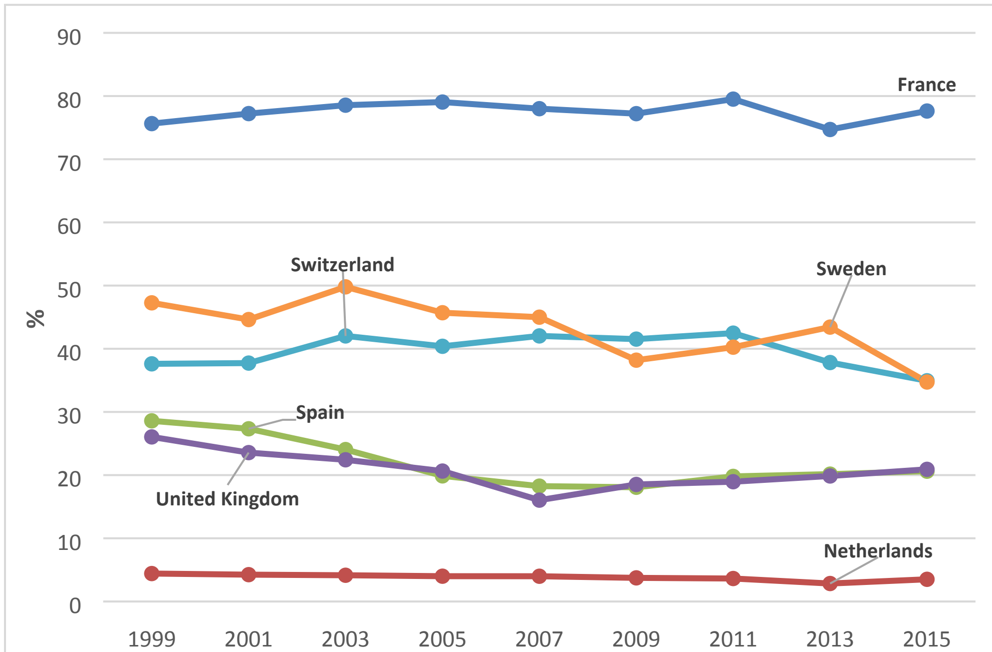
Code	GDP	NEC
Variable	Real GDP	Nuclear Energy Consumption
Source	World Bank	UK Energy Statistics
Mean	5.768	4.266
Median	5.798	4.066
Maximum	5.903	6.346
Minimum	5.599	2.738
Std. Dev.	0.096	0.843
Skewness	-0.634	0.471
Kurtosis	1.989	2.521
Jarque-Bera	8.771	3.723
Probability	0.012	0.155

Table 3. TY Causality Test

Direction of Causality	Lag	MWALT	Prob.
NEC → EG	3	0.802	0.848
EG → NEC	3	9.739	0.020**

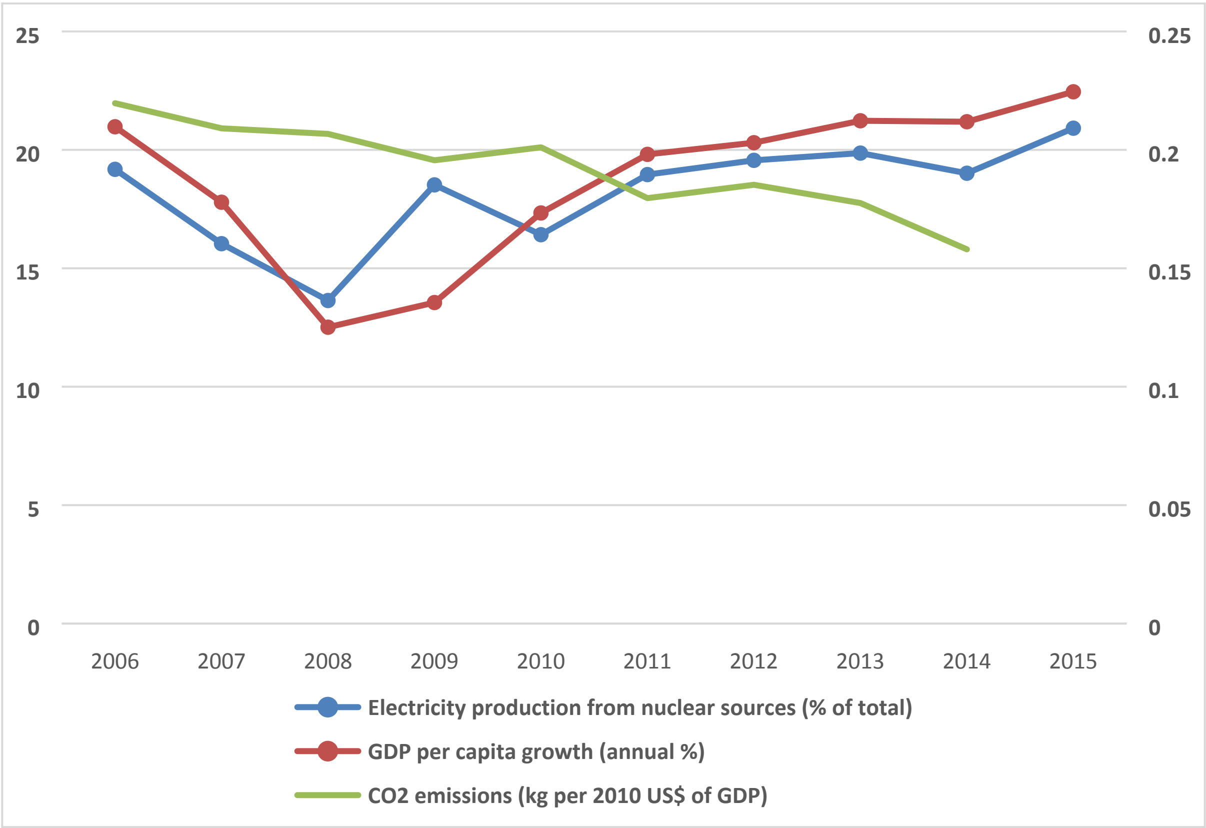
Note: → presents the direction of causality. ** indicates 5% signifcance level.

Figure 1. Energy from Nuclear Sources



Source: World Bank Development Indicators

Figure 2. Nuclear Energy Consumption, GDP Growth, and CO_2 Emissions of the UK



Source: World Bank Development Indicator

Figure 3. Wavelet Power Spectrum for Nuclear Energy Consumption

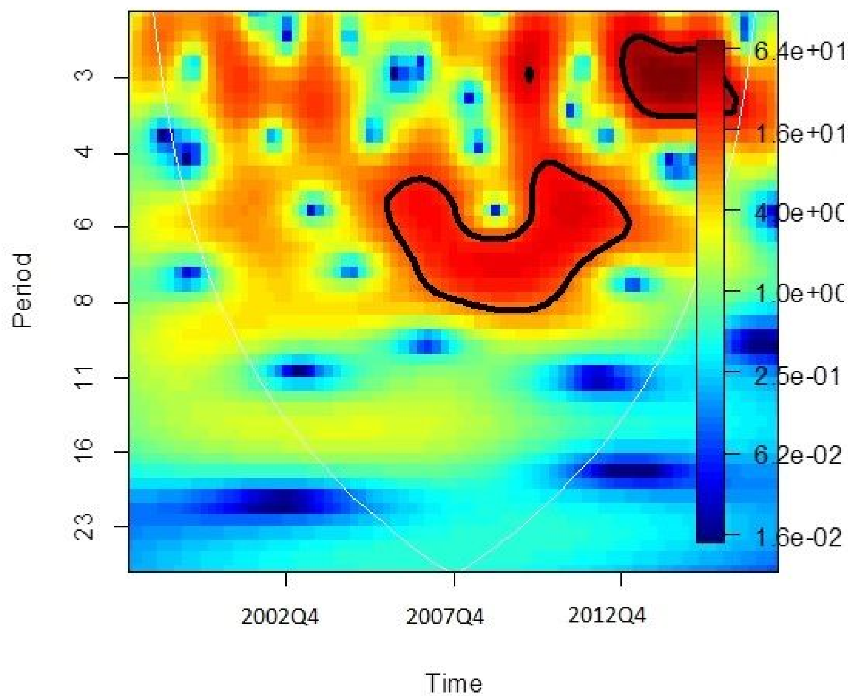


Figure 4. Wavelet Power Spectrum for Economic Growth

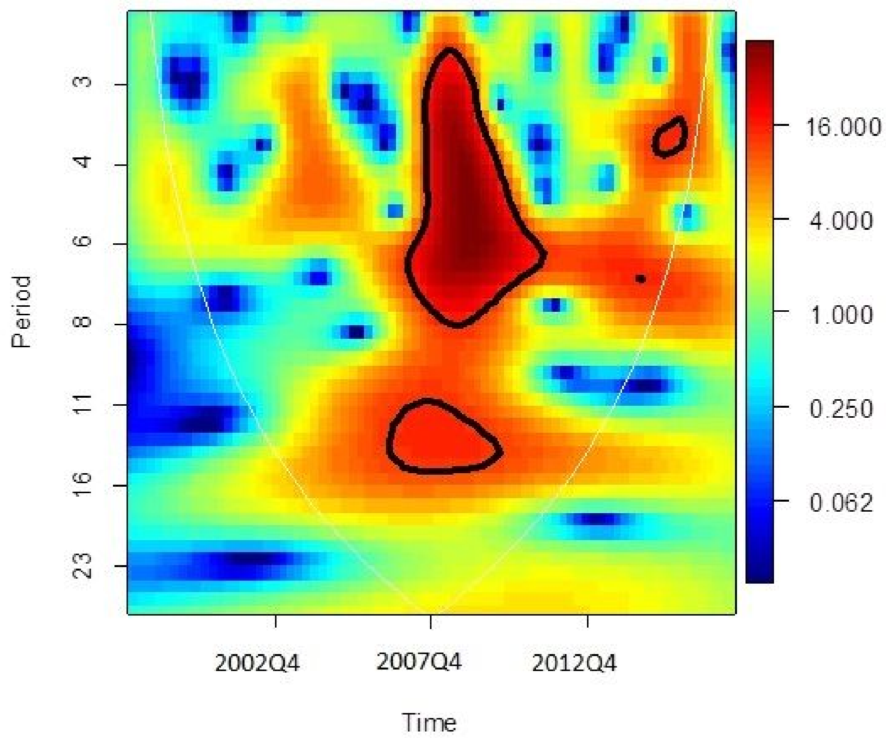


Figure 5. Wavelet Coherence Between Economic Growth and Nuclear Energy Consumption