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Renewable Energy Consumption and the Ecological Footprint in Denmark: Assessing the Influence of Financial Development and Agricultural Contribution

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Abstract: The aim of this study is to empirically examine the relationship between renewable energy consumption and the ecological footprint (EF), using Denmark as a case study, based on data covering the period from 1990 to 2020. In examining this relationship, the roles of agricultural, forestry, and fisheries value-added; economic growth; and financial development are also explored. The analysis, conducted using fractional frequency Fourier approaches, considers the presence of structural breaks. The results reveal a negative relationship between renewable energy consumption and EF, while a positive relationship is found between agricultural, forestry, and fisheries value-added; economic growth; and financial development with the EF. According to the causality analysis, a unidirectional causality is detected from renewable energy consumption to the EF. These findings highlight the potential impact of renewable energy on EF and emphasize the importance of integrating green energy investments and renewable fuel usage into strategies aimed at reducing the EF.

Keywords: agriculture; renewable energy; ecological footprint; financial development; Denmark

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1. Introduction

One of the greatest challenges the world faces today is environmental degradation (ED), manifested through global temperature rise, declining air quality, thinning of the ozone layer, the depletion of natural resources, and the reduction of biodiversity [1]. These indicators of ED have led to various extraordinary situations, including food scarcity, the extinction of many species, and extreme weather conditions [2]. It is an inevitable reality that such situations will occur more frequently and with greater severity in the future.

In earlier scientific studies, CO_2 emissions and other greenhouse gas emissions were used as indicators of ED. However, over time, it has been argued that these indicators cannot fully explain the multifaceted nature of ED, and the search for a more comprehensive concept to replace this notion was initiated. In this process, ref. [3] introduced the concept of the "ecological footprint" (EF) to encompass many aspects of ED [4]. EF is a concept that shows the human impact on CO_2 emissions, built-up areas, arable land, pastures, forests, and water bodies and has been quantified in recent years. The EF defines Earth's carrying capacity, and since this measure inherently has a futuristic element, it is also an indicator of sustainability [5]. The EF is a scientific accounting indicator addressing how much natural resources should be utilized within Earth's capacity to renew itself [6].

The EF reflects how human activities affect natural resources and serves as a key measure of environmental sustainability (ES). The agricultural sector (AS) is one of the significant determinants of the EF, as it involves the use of natural resources for food production and other agricultural products. Agricultural production directly affects environmental factors such as land use, water consumption, and energy use. Ref. [7] found that an increase in agricultural value-added in E7 countries leads to an increase in the EF, with this relationship further strengthened by natural resource rents. This suggests that the growth of the agricultural sector brings along environmental costs.

The impact of the AS on the EF is also closely related to the type of energy used and energy efficiency. Ref. [8] showed that in BRICS-T countries, while renewable energy (RE) consumption has a reducing effect on the EF, agriculture and fossil fuel consumption negatively impact this effect. This finding highlights the importance of RE use in reducing the environmental impacts of agricultural production. The sustainability of the energy sources used in agriculture is a key factor in influencing the environmental pressure exerted by this sector. Additionally, the efficiency of technologies used in agriculture is another important element with the potential to reduce environmental impacts. Ref. [9] argued that agriculture and international trade should be considered together, emphasizing that agriculture poses both direct and indirect environmental pressures. Agriculture is not limited to food production processes; it can also lead to long-term environmental problems such as soil erosion, depletion of water resources, and loss of biodiversity. In this context, understanding the relationship between the AS and EF requires considering not only the sustainability of agricultural practices but also the role of international trade, energy consumption, and financial development (FD). Within this theoretical framework, the increase in agricultural value-added, if not managed to enhance ES, may lead to an increase in the EF.

The relationship between the AS and the EF is directly linked to macroeconomic factors such as economic growth (EG) and FD. EG typically leads to increased agricultural production, which in turn results in greater consumption of environmental resources. Ref. [10], in examining the relationship between RE consumption and agriculture in BRIC countries, noted that EG is parallel to increased environmental pressure through agricultural production. However, the author emphasized that RE consumption can play a role in reducing the EF in this growth process. When RE replaces fossil fuels, it significantly reduces the environmental impact of energy use in agriculture. In this context, RE emerges as a critical factor in balancing the environmental impact of the AS.

FD is another important variable shaping the relationship between the agricultural sector and the EF. Ref. [11] demonstrated in their study on Somalia that FD supports increased efficiency in the AS, which plays a significant role in reducing environmental impacts. Access to financial resources can help the adoption of more efficient and environmentally friendly technologies in agriculture. Similarly, Ref. [12], in a study conducted on China, stated that FD in the AS, when integrated with forestry and RE use, reduces the EF. These findings show that FD has the potential to enhance not only agricultural productivity but also ES.

Lastly, RE is another key factor determining the relationship between the AS and the EF. Ref. [13] showed that RE consumption reduces the EF in emerging countries. This is directly related to the types of energy used in agriculture. Widespread use of RE sources in agriculture replaces fossil fuels, providing a cleaner production process and consequently reducing the EF. Refs. [10,14] similarly emphasized that RE is a crucial tool in reducing the environmental impact associated with agricultural production. Investments in RE can help reduce the negative environmental effects of agriculture and its EF.

The aim of this study is to empirically examine the relationship between RE consumption and the EF. In exploring this relationship, the roles of agricultural, forestry, and fisheries value-added; EG; and FD have also been highlighted. Denmark has been chosen as the sample country for the study. According to data from 2019, Denmark's EF per capita is 7.3 gha, and its biological capacity per capita is 4.3 gha, resulting in a biocapacity deficit of −3 gha (−71%) [15]. In 2017, the country adopted an Action Plan for the implementation and monitoring of the 2030 Agenda and the Sustainable Development Goals (SDGs). In this context, Denmark's environmental actions focus on SDGs 2, 3, 6, 7, 8, 9, 12, 13, 14, and 15, which include transitioning to a green economy (SDG 8), continuing to maintain a strong agricultural and food industry that focuses on sustainability and resource efficiency (SDG 2), preventing and limiting the spread of harmful pollutants to human health (SDG 3), and halting the decline of biodiversity (SDG 15), among other crucial issues [16].

It is thought that this study will contribute to the literature in several aspects. First, it examines the relationship between RE and the EF in the case of Denmark. Secondly, agriculture, forestry, and fisheries use added value, EG, and FD as complements to RE in influencing the EF. Thirdly, it uses a new method in econometric analysis, the Fractional Frequency Fourier approach.

In the study, empirical analyses were made with a multivariate model using the annual time series data of Denmark for the period 1990–2020. In the empirical analysis, in which agriculture, forestry, and fisheries value-added; EG; and FD were used as explanatory variables, along with RE consumption, the stationarity of the series was investigated with the ADF test and the fractional frequency Fourier (FFF) ADF test, which takes into account structural breaks, and FFF approaches were used in the examination of cointegration and causality relationships.

The parts of the study are organized as follows. In the second part, information is provided about the empirical literature examining the relationship between the EF and RE consumption, FD, EG, and agricultural value-added. Section 3 presents the data and model, Section 4 the method, and Section 5 the results and conclusions.

2. Literature Review

There are many studies in the literature on the determinants of environmental pollution, or ED, and its relationship with various macroeconomic magnitudes. In this study, the relationship between ED and renewable energy, FD, EG, and primary sector value-added is examined. In this context, the literature review of the study is presented under the following four subheadings:

2.1. EF and Renewable Energy Consumption

A review of studies addressing ED in the literature shows that, until recent years, carbon emissions were commonly used as an indicator of ED. In this context, non-renewable energy consumption has often been identified as one of the primary determinants of ED or carbon emissions [17–21]. However, especially in the last five years, it has been observed that the EF has increasingly been used as an indicator of ED, replacing carbon emissions in empirical studies. This shift stems from the growing belief in the literature that the EF more comprehensively represents ED than carbon emissions. While CO_2 and other greenhouse gas emissions are considered fundamental determinants of environmental pollution, it is argued that these indicators fail to capture the multifaceted nature of ED. Therefore, the concept of "EF" has been introduced to encompass multiple aspects of ED [4]. Similarly, in the literature, RE consumption is also used as one of the determinants of the EF.

In the literature, there are studies that examine the relationship between RE consumption and the EF across multiple countries or country groups, as well as studies that test this relationship using a single-country example. Among the studies focusing on countries and country groups, one of the first works is Ref. [22]. In the study, the Environmental Kuznets Curve (EKC) hypothesis was tested across 15 EU countries, using EF data for the period 1980–2013, alongside variables such as real GDP per capita, trade openness, and per capita renewable and non-renewable energy consumption, employing the second-generation panel data methodology. The results indicated that RE consumption reduces the EF. In the study Ref. [23] focusing on the BRICS countries, the relationship between RE and the EF was investigated. Using data from the period 1992–2016 and applying FMOLS and DOLS long-run estimators, it was found that RE consumption decreases the EF. Another study published in the same period [5] tested the EKC hypothesis using panel data analysis with data from 24 OECD countries over the period 1980–2014, focusing on variables such as renewable and non-renewable energy consumption, trade openness, EG, and the EF.

According to the results obtained using the second-generation panel data method, it was concluded that the increase in RE consumption reduced the EF. Another study, Ref. [24], using 1990–2005 period data on eight developing Asian countries and the cross-sectional augmented autoregressive distributed lag (CS-ARDL) approach, found that RE use in the region significantly reduced its EF [25] in the ten financially richest source countries, ref. [26] in E5 countries, ref. [27] in 130 countries, and [28] in OECD countries, similarly concluding that RE use reduces the EF.

Studies examining the relationship between RE consumption and the EF in the context of a single country have been conducted both for developed and developing countries. Among developed countries, especially the United States has been the subject of a relatively higher number of studies [10,29,30]. In these studies, it has generally been found that RE consumption reduces the EF. One of the significant studies on developing countries is Ref. [31], which focuses on Turkey. The study investigated the effect of RE consumption on the EF for the period from the first quarter of 1965 to the fourth quarter of 2017. Using the Quartile ARDL and Granger causality analysis, the study found that RE consumption had a negative impact on the EF for each quantile. Other studies on Turkey, Refs. [18,21,32], also found that RE consumption negatively affects the EF. From studies on individual countries—Ref. [33] on Saudi Arabia, Ref. [34] on Pakistan, Ref. [35] on Malaysia, Ref. [36] on India, and Ref. [37] on Malaysia—it was concluded that RE consumption reduces the EF. In contrast, Ref. [6], using quantile regression for China, found that RE had a positive effect on the EF at both low and high quantiles.

2.2. EF and FD

When the studies on the relationship between the EF and RE consumption are evaluated in general, it can be stated that the studies have intensified; especially in the last five years, individual countries as well as country groups have been selected as samples, and the effect of RE consumption on the EF has been found to be negative in the majority of the studies.

It is stated that FD can theoretically have both a positive and negative impact on environmental quality. Namely, it is assumed that FD, together with the wealth effect, will lead to an increase in economic output and increased energy consumption, and this increased energy consumption will increase ED. On the other hand, it is also stated that FD can lead to investment in more advanced technologies, thus more efficient energy use and thus reducing ED [38]. In the empirical studies conducted on this subject, results confirming both approaches have been obtained. In other words, in some studies examining the relationship between the EF and FD, it has been determined that FD reduces the EF, while in some studies, on the contrary, FD increases the EF.

One of the first studies to conclude that FD reduces the EF was conducted in Ref. [39]. In their study, the validity of the EKC for the EF was examined in 11 newly industrialized countries, and the role of FD was also investigated. Using data from the period 1977–2013 and employing the Augmented Mean Group (AMG) and heterogeneous panel causality methods, the analysis revealed that as FD increased in China and Malaysia, the EF decreased. Additionally, a one-way causality relationship from the EF to FD was identified.

Another study focusing on developed countries was conducted in Ref. [40] on the G7 countries. The study, which used data from the period 1980–2015 for these countries, investigated the long-term relationship between variables using the threshold cointegration test. The results indicated that, in Japan, FD reduced the EF in the long run. In other studies on developed countries, such as those in Ref. [41] with 27 countries and Ref. [42] on Singapore, it was concluded that FD increases the EF.

There is a substantial body of literature examining the relationship between FD and the EF in developing countries. One such study is Ref. [43], which focuses on western Asia and Middle Eastern countries. Using data from the period 1990–2017 and analyzing it with the STIRPAT model, the study concluded that a 1% increase in FD in the included countries led to a 0.0016% increase in the EF. The study also identified a one-way causality relationship from FD to the EF.

Ref. [31] found that FD increased the EF in 17 developing countries, while Ref. [44] showed that FD reduced the EF and boosted environmental protection in South Asia. In addition to studies on country groups, there are also individual country studies. In the work Ref. [45] on Malaysia and Ref. [46] on Pakistan, FD was found to increase the EF. In contrast, Ref. [47] on Brazil and Ref. [32] on Azerbaijan concluded that FD reduced the EF.

In studies where both developed and developing countries are used as a sample, similar divergent results have been obtained. For example, Ref. [48] analyzed the relationship between FD and the EF for 131 countries. Using data from the period 1971–2017, the study employed various methods. The findings indicate that all FD indicators for the 131 countries significantly contributed to reducing the environmental footprint, thus improving the environmental quality.

In the study Ref. [29] on APEC countries, similar results were found, where FD was observed to reduce the EF. On the other hand, the study Ref. [38] on 110 countries concluded that FD increased the EF.

2.3. EF and Economic Growth

Since the mid-2000s, numerous empirical studies have been conducted on the relationship between EG and ED. The theoretical foundation of these studies is based on the EKC hypothesis, inspired by Refs. [49,50], which suggests that there is an inverted U-shaped relationship between EG and ED. In these studies, carbon emissions have often been used as an indicator of ED, and varying empirical results have been obtained. However, although few in the early years, there have also been studies that used the EF as an indicator of ED [51–53]. In these studies, generally, no significant relationship was found between the variables, or in other words, the EKC was not supported. However, studies conducted in later years have demonstrated a relationship between the variables, providing evidence that the EKC hypothesis may not hold in some cases. Many studies have found a positive relationship between EG and the EF. One of the earliest of these studies is Ref. [54], which examined the effects of the GDP, energy consumption, FD, and urbanization on the EF. Using fixed effects and the generalized method of moments (GMM), the empirical findings revealed an inverted U-shaped relationship between the EF and GDP growth, confirming that the EKC hypothesis holds for middle-high- and high-income countries.

In another study, Ref. [55] investigated the relationship between the GDP and EF for 45 countries across low-, middle-, and high-income groups from 1961 to 2013. Using second-generation panel data techniques like CUP-FM and CUP-BC, the study found that the EKC hypothesis was validated for all income groups—low-, middle-, and high-income countries. Ref. [56] concluded that, similar to energy consumption, foreign direct investment, and urbanization, EG contributed to an increase in the EF, thereby worsening environmental pollution. Other studies that reached similar conclusions include those by Refs. [57–61].

In the literature, there are also studies where EG negatively impacts the EF, as seen in Refs. [5,62]. In Ref. [62], the relationship between EG, energy consumption, globalization, and the EF was analyzed for the Gulf Cooperation Council (GCC) countries. The study found a negative relationship between EG and the EF, suggesting a U-shaped relationship between the two variables.

In Ref. [5], the effects of renewable and non-RE consumption, EG, and trade openness on the EF were examined for 24 OECD countries over the period 1980–2013. Similarly, the study concluded that there is a U-shaped relationship between EG and the EF.

In some studies, mixed results have been found, with a positive relationship between the EF and EG in some countries of a given sample group and a negative relationship in others. Ref. [63] examined the EF–GDP link under the EKC hypothesis and found that the relationship differed across cases depending on the functional form applied.

Ref. [48] found a positive impact of EG on the EF in high-income countries, while middle- and low-income countries showed a negative effect. Similarly, in the study conducted in Ref. [64] for 20 countries, a positive relationship between EG and the EF was found in 10 countries, while no relationship was identified in the remaining 10 countries.

2.4. EF and Agricultural Added Value

The impact of agriculture on ED has become an increasingly debated topic in the literature, especially over the past five years. However, the number of studies in this field that use agricultural value-added as a variable is quite limited. In most studies examining the agriculture–ED relationship, CO2 emissions have been used as an indicator of ED. Examples of such studies include [33,65–68], where the effect of agriculture on CO_2 emissions is found to be positive in some studies while negative in others. In studies that use the EF instead of CO2 emissions, the impact of agriculture on the EF has generally been found to be positive. This is seen in Refs. [12,69,70].

When examining studies on the agriculture–ED relationship that use agricultural value-added as a representation of agricultural production, it can be stated that one of the earliest studies in this limited number of works is Ref. [71]. In the study, data from 53 countries for the period 1980–2010 were analyzed using three different panel data estimators. As a result of the analyses, it was determined that agricultural value-added reduces environmental pollution levels. Another study that reached the same conclusion was conducted in Ref. [72] on the Tunisian economy. Using the ARDL approach and VECM (Vector Error Correction Model), the study concluded that agricultural value-added reduces ED. In contrast, one of the most recent studies on the topic, Ref. [73], analyzed the data from E7 countries for the period 1990–2019. In the study, which examined the relationship between the EF and economic globalization, agricultural value-added was also included as one of the independent variables. Using three estimation methods—DOLS, FMOLS, and Panel-ARDL—the study concluded that agricultural activities increase the EF, i.e., they worsen the environmental quality of E7 countries. Similarly, in the study Ref. [74]

on Turkey, it was determined that agricultural value-added per capita increases the per capita EF.

3. Empirical Analysis

In this section, first of all, information is provided about the data set, model, and methods used in the study. Afterwards, the results of econometric analysis are evaluated.

3.1. Data and Empirical Methodology

In this study, the relationship between the EF (EF) and the factors influencing it for Denmark was analyzed using a multivariate model with annual time series data. The EF (EF) is the dependent variable in the analysis, while agricultural, forestry, and fishing value-added (AGR); gross domestic product (GDP); financial development (FD); and renewable energy consumption (RENEW) are the independent variables. The AGR variable was selected as an independent variable based on Refs. [8,10,35,70,71,75–79]. The GDP variable was chosen based on Refs. [22,40,41,44,54,63,80–83]. The selection of the FD variable was based on Refs. [37,40,43,48,56,84–90]. In this study, the economic value-added of the agriculture, forestry, and fishing sector is selected as an independent variable. The variable agriculture, forestry, and fishing value-added (% of GDP) used in this study includes livestock (animal husbandry) activities, as well, according to the World Bank's definition. The rationale behind this choice lies not only in the sector's contribution to economic development but also in its significant impact on ES. Agricultural activities exert direct pressure on the EF through factors such as land use changes, deforestation, loss of biodiversity, and intensive use of chemical inputs. In addition, greenhouse gas emissions—particularly, methane and nitrogen oxides—originating from this sector have lasting negative effects on the environment. Therefore, analyzing the impact of the economic value-added of the agriculture, forestry, and fishing sector on the EF enables a meaningful and comprehensive assessment within the context of ES. Finally, the RENEW variable was included as an independent variable in the model based on Refs. [5,10,23,25,28,34,57,91,92].

While CO_2 emissions represent only a fraction of overall pollution, the EF refers to broader ED [58]. The EF metric was introduced by Ref. [3]. Each variable used in the study is subjected to logarithmic transformation. Aggregate data on the relevant variables examined in the model cover the years 1990–2020. Details on the variables are presented in Table 1.

Table 1. Data sources.

Abbreviations for Variables	Variables	Data Source
EF	EF	Global Footprint Network
AGR	Agriculture, forestry, and fishing value-added (% of GDP)	WB
GDP	Gross domestic product (constant 2015 USD)	WB
FD	Domestic credit to private sector (% of GDP)	WB
RENEW	Renewable energy consumption (% of total final energy consumption)	WB

The natural logarithms of the variables were used for more consistent results, as the log-linear model outperforms the simple regression model. The model is as follows:

$$InEF_t = \beta_0 + \beta_1 InAGR + \beta_2 lnGDP + \beta_3 FD + \beta_4 lnRENEW + \varepsilon_t \quad (1)$$

In the model presented above, t = 1990, . . ., 2020 represents the time period; ε_t represents the error term; and In refers to the logarithmic transformation. In Equation (1), β_0 is the constant term, and β_1 is the coefficient of agricultural, forestry, and fishing value-added, which is expected to have a positive sign [40,63]. Despite some studies in the literature suggesting that agricultural production negatively impacts environmental quality [71], the sign of the coefficient is expected to be positive due to the widespread use of fossil fuels in agricultural activities [10]. β_2 is the coefficient for income growth, which is expected to have a positive sign. β_3 is the coefficient for financial development. There are two differing views in the literature regarding the impact of FD on the EF. According to the first view, FD negatively affects ED [93,94], while the second view suggests that FD positively affects ED [84,95]. Finally, β_4 represents the coefficient for renewable energy consumption, which is theoretically expected to have a negative sign [6,23].

3.2. FFF-ADF Unit Root Test

The traditional ADF unit root test does not account for structural breaks. This leads to biased results from the test. In other words, it causes the failure to reject the unit root hypothesis [96]. In this context, the Fourier ADF unit root test, developed in Ref. [97], takes these structural breaks into account. Moreover, the number, location, and form of structural changes do not reduce the power of the test [98]. To apply the Fourier ADF unit root test, the model estimation provided below is first conducted:

$$\Delta y_t = \beta_0 + \beta_1 \sin\left(\frac{2\pi kt}{T}\right) + \beta_2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_3 y_{t-1} + \sum_{i=1}^{p} \alpha_i \Delta y_{t-1} + e_t \quad (2)$$

In the model above, the terms T, t, k, and π represent the sample size, trend term, frequency value, and pi coefficient (3.1416), respectively. The value that minimizes the sum of squared residuals is determined as the optimal k. The significance of the trigonometric terms is tested as $\beta_1 = \beta_2 = 0$.

In the model estimation, the frequency value can take integer or fractional values. In Ref. [99], it is demonstrated that the frequency value can take fractional values. In Ref. [100], the value of k ranges between 0 and 2, while in Ref. [101], the value of k ranges between 0 and 5. Ref. [100] stated that the value of k can take a maximum of 2, with 0.1 increments. It was also noted that nonlinear trend problems and excessive filtering situations can be limited with 0.1 increments. In Ref. [101], the value of k was considered in the range [0.1, 0.2, . . ., 5], and critical values were tabulated. In testing the significance of the trigonometric terms, the critical values are derived from Ref. [97]. In the Fourier ADF unit root test developed with fractional frequency, the critical values are tabulated by Ref. [101]. Monte Carlo simulation was used in the tabulation of these critical values.

3.3. FFF Autoregressive Distributed Lag Cointegration Test

In detecting the long-term relationship between variables, some cointegration tests fail to capture structural breaks [1,102]. However, according to some tests, it is possible to detect structural changes in advance [103,104]. However, these tests require prior identification of the magnitude and type of structural changes. In the cointegration test proposed by Ref. [105], there is no need for prior assumptions regarding the number, form, or timing of the breaks. Therefore, the flexibility in this test facilitates easier estimation. Moreover, in the case of smooth-transition structural breaks, the potential loss of power caused by the dummy variable is prevented.

The Fourier ADL equation proposed by Ref. [105] can be estimated as follows:

$$\Delta\gamma_{1t} = d(t) + \delta_1 y_{1,t-1} + \gamma' y_{2,t-1} + \mu \Delta y_{2t} + e_t \quad (3)$$

In the equation above, δ_1 represents a scalar and γ_{1t} a dependent variable. In the model, Δ refers to the first difference. In their study, Ref. [106] estimated the equation proposed by Ref. [105]. The main objective here is to identify the optimal value for k. In their study, Ref. [106] modified the integer frequency values suggested by Ref. [105] to fractional values. Thus, as emphasized in the work Ref. [99], the frequency value changes within the range [0.1, 0.2, . . ., 5] instead of the range [1, 2, . . ., 5]

3.4. FFF Fourier Form Toda–Yamamoto Causality Test

Ref. [107] proposed a new causality approach by adding the Fourier function to the vector autoregressive (VAR) model. This approach takes structural changes into account. In causality analysis, Ref. [107] stated that the difference of unit root series should be taken. However, differencing variables leads to a loss of long-term information [106]. In this context, Ref. [108] proposed the Fourier Toda–Yamamoto (FTY) causality test, which allows for the presence of series of different integration orders and structural changes. In this test, the frequency value takes integer values between 1 and 5 ($1 \leq k \leq 5$). That is, the frequency value takes integer values. Ref. [99] showed that temporary breaks can be detected when the frequency value is an integer, and permanent breaks can be detected when the frequency value is fractional. The superiority of fractional frequency in detecting permanent breaks has played a significant role in the introduction of the fractional frequency flexible Fourier Toda–Yamamoto (FFFF-TY) causality approach into the literature. This approach was developed by Pata & Yılancı [40].

The two-variable FFFF-TY approach can be written as follows using the Fourier function:

$$Y_t = \beta_0 + \beta_1 \sin\left(\frac{2\pi kt}{T}\right) + \beta_2 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{i=1}^{I+dmax} \vartheta_i Y_{t-i} + \sum_{i=1}^{I+dmax} \phi_i X_{t-i} + u_t \quad (4)$$

$$X_t = \delta_0 + \delta_1 \sin\left(\frac{2\pi kt}{T}\right) + \delta_2 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{i=1}^{I+dmax} \phi_i Y_{t-i} + \sum_{i=1}^{I+dmax} \vartheta_i X_{t-i} + v_t \quad (5)$$

In the above model, d refers to the maximum degree of integration, while I = VAR refers to the optimal delay length. The terms t, t, and k refer to the sample size, trend term, and frequency value, respectively. The frequency value is between [0.1, 0.2, 0.3, . . ., 5]. The null hypothesis tests the absence of causality, while the alternative hypothesis tests the existence of causation. At this point, Wald statistics are used.

The FFFF-TY approach has two important advantages. The first of these allows for the examination of causality between integrated series to varying degrees. The latter allows for permanent refractions taking into account the fractional frequency [109].

In conclusion, this method has recently attracted considerable attention due to its success in modeling structural changes and complex nonlinear dynamics frequently observed in environmental- and energy-related time series. Studies such as Ref. [110] and Ref. [111] have shown that this approach offers greater flexibility and stronger results in capturing long-term trends and periodic behaviors compared to conventional methods. Furthermore, Ref. [112] examined the convergence of per capita EFs among BRICS-T countries using Fourier unit root tests, thereby supporting the applicability of this approach to environmental indicators. The relationship between renewable energy consumption and the EF is particularly influenced by gradual transitions in energy policies, technological developments, and sustainability practices, making the use of this method especially meaningful. Therefore, in line with the literature, the FFF approach is a suitable choice both methodologically and empirically to uncover the dynamics of this relationship.

4. Empirical Results

For econometric analysis, first of all, the stationarity of the variables was examined. ADF and FFF-ADF tests in Tables 2 and 3 were used for unit root examination of variables. As a result of the unit root examination, it was determined that the variables became stationary when the first difference was taken.

Table 2. Fourier ADF unit root test results.

Variables	Frequency	Minimum Sum of Squared Residuals	F Test	Optimal Lag	Fourier ADF Test Statistic
EF	0.9	9.06×10^{-5}	10.746 *	2	−3.298
ΔEF	1.2	0.0001	3.823	2	−4.826
AGR	0.7	0.656	3.958	1	−3.010
GDP	3.2	0.007	2.768	1	−1.919
FD	0.4	1.330	4.252	1	−2.875
RENEW	0.5	0.056	3.477	6	−1.264

Note: * indicates significance at 1%. The critical values of the F test for frequencies are 10.35, 7.58, and 6.35 for the 1%, 5%, and 10% levels, respectively. The critical values of the FADF test for all frequencies were obtained from Ref. [101].

Table 3. ADF unit root test results.

Variables	I(0)	I(1)
AGR	−1.811 (0.368)	−5.992 (0.000)
GDP	−1.910 (0.323)	−3.575 (0.012)
FD	−1.034 (0.727)	−5.089 (0.000)
RENEW	0.513 (0.984)	−6.297 (0.000)

After the first difference of the variables is taken, the prerequisite for examining the cointegration relationship is provided. The results of the FFF Fourier ADL test are presented in Table 4. According to the results in Table 4, there is a long-term relationship between the variables.

Table 4. FFF-ADL cointegration test results.

Model	$t^{F}_{ADL}\ (\hat{k})$	$\hat{k}$	1%	5%	10%	Cointegration Relationship
lnEF = f (lnAGR, lnGDP, InFD, lnRENEW)	−5.028 **	1	−5.383	−4.698	−4.333	✓

Note: ** indicates the significance of the values at the level of 5%. Ref. [106] were used for the table values.

The long-term coefficient estimation results are shown in Table 5. Model estimation was made by adding trigonometric terms. Accordingly, all variables in the model are statistically significant. Value-added, GDP, and FD positively affect the EF. On the other hand, renewable energy consumption leads to a decrease in the EF in the long run.

Table 5. Long-term coefficient estimations (FMOLS).

Intercept	2.126 (0.000) ***
LAGR	0.003 (0.019) **
LGDP	0.028 (0.007) ***
LFD	0.002 (0.012) **
LRENEW	−0.011 (0.002) ***
Sin	−0.0001 (0.883)
Cos	−0.001 (0.033) **

Note: **, and *** indicate the significance of the values at the level of 5%, and 1%, respectively.

Within the scope of the FFF Toda–Yamamoto causality test applied in the study, null (H_0) and alternative (H_1) hypotheses were established for each relationship. According to the test results, the null hypothesis, stating that RE consumption does not cause the EF, and the null hypothesis, stating that the EF does not cause FD, were statistically rejected. Thus, a unidirectional causality was identified between these pairs of variables. In contrast, no statistically significant causality was found from agriculture, EG, and FD to the EF, and the null hypotheses related to these variables could not be rejected (Table 6).

Table 6. FFF Toda–Yamamoto causality test results.

H_0 Hypothesis	Wald Test Statistic	Asymptotic Probability Value	Bootstrap Probability Value	Appropriate Delay Length	Appropriate Frequency Value
lnEF = f (lnAGR, lnGDP, InFD, lnRENEW)					
AGR/→EF	0.793	0.373	0.379	1	0.7
GDP/→EF	1.265	0.531	0.543	2	0.7
FD/→EF	0.002	0.957	0.958	1	0.6
RENEW/→EF	7.396	0.024 **	0.042 **	2	0.6
EF/→AGR	0.997	0.317	0.327	1	0.7
EF/→GDP	1.381	0.501	0.515	2	0.7
EF/→FD	4.053	0.044 **	0.058 *	1	0.6
EF/→RENEW	0.257	0.876	0.885	2	0.6

Note: *, ** indicate the significance of the values at the level of 10%, and 5% respectively. A total of 10,000 simulations were used in the analysis.

5. Conclusions and Discussion

5.1. Discussion

This study investigates the relationship between the EF; renewable energy; EG; FD; and agricultural, forestry, and fishing value-added in Denmark. The analysis, conducted using FFF approaches, took into account the presence of structural breaks. Considering the presence of structural breaks allowed for a more detailed interpretation of the analysis results. The empirical findings reveal a positive relationship between EG and the EF in

Denmark. This suggests that the country largely achieves EG through the use of fossil resources. Additionally, the study shows that FD increases ED. This result can be explained by the fact that the increase in FD reduces financing costs, which in turn boosts EG and consequently increases energy consumption.

Another important variable, the agricultural, forestry, and fishing value-added, is significant not only for its environmental importance but also as a component of the EF. The conversion of forests into agricultural land results in plant and tree shortages, which pose a serious environmental threat. Additionally, inorganic fertilizers or chemicals, by emitting nitrogen oxides, create an unhealthy environment [70]. Various studies in the literature investigate the impact of agricultural value-added on the environment (e.g., [12,35,75,78,79]), with most of these studies focusing on the effect of agricultural value-added on carbon emissions. In contrast to those studies, this research investigates the effect of a more comprehensive indicator, the agricultural, forestry, and fishing value-added, on the EF. According to the analysis results, a positive and significant relationship was found between the agricultural, forestry, and fishing sector and the EF in Denmark. In other words, it was determined that this sector negatively affects the environmental performance of Denmark. The analysis results support the findings of Refs. [70,75,78].

Many international studies have shown that the impact of agriculture on the EF is complex and highly dependent on country-specific conditions. Ref. [7] found that an increase in agricultural value-added in E7 countries leads to a higher EF, and this relationship is further intensified by natural resource rents. Similarly, Ref. [113] indicated that in the case of the Philippines, agriculture can increase environmental pressure once a certain threshold is exceeded. Ref. [8] demonstrated that while RE consumption reduces the EF in BRICS-T countries, agriculture and fossil fuel consumption have adverse effects. Likewise, Ref. [9] argued that agriculture and international trade should be evaluated together, emphasizing that agricultural activities pose both direct and indirect risks to ES. Ref. [74] (2024), as well as Ref. [14], also showed that agriculture is mostly positively associated with the EF in the context of Türkiye and BRICS countries. These findings are consistent with the results of our study focusing on Denmark. Despite being a country known for its strong environmental policies and leadership in RE investments, Denmark still faces challenges in managing the environmental pressures associated with agricultural activities.

According to Denmark's 2023 inventory report, the AS is the second-largest source of emissions in the country, following the energy sector. Furthermore, agriculture accounts for approximately 28% of Denmark's total greenhouse gas emissions, with more than 80% of these emissions coming from methane and nitrogen oxides [8]. At this point, with the right policies in place, the environmental pressure exerted by agriculture could be alleviated.

Finally, RE plays a significant role in reducing ED. In line with theoretical expectations, the analysis reveals a negative and significant relationship between RE and the EF. The results are consistent with Refs. [24,114]. Denmark has made significant strides in the development and use of renewable energy. Electricity generated from renewable sources accounts for 67% of the total electricity supply, with 46.8% coming from wind energy and 11.2% from biomass. In 2020, with the Danish Parliament's Climate Law, targets were set to reduce greenhouse gas emissions by 70% by 2030 (relative to 1990 levels) and achieve climate neutrality by 2050 [115].

The results of the causality analysis reveal a unidirectional causality from RE consumption to the EF. This finding highlights that RE can influence the EF and underscores the importance of incorporating green energy investments and the use of renewable fuels into strategies for reducing the EF.

5.2. Conclusions

The findings of this study offer meaningful insights for shaping effective environmental and energy policies. The negative relationship between RE consumption and the EF underlines the vital role that clean and sustainable energy sources play in mitigating ED. This outcome reinforces the idea that investing in RE infrastructure—such as wind, solar, and biomass—can significantly reduce the environmental burden. On the other hand, the positive association found between EG; FD; and agricultural, forestry, and fisheries value-added with the EF signals the need for a more cautious and sustainability-oriented approach in these sectors. Without intervention, the continued growth of these areas may lead to increased resource depletion and environmental stress.

The findings of this study reveal that renewable energy consumption plays a decisive role in achieving environmental sustainability. The result indicating that an increase in renewable energy use reduces the ecological footprint in the case of Denmark demonstrates that green energy transitions yield direct environmental benefits. In this context, investing in renewable energy is not only essential for diversifying energy supply but also for alleviating pressure on natural ecosystems. On the other hand, the positive impact of agriculture, forestry, and fisheries activities, along with economic growth and financial development, on the ecological footprint suggests that unchecked expansion in these areas can harm the environment. This implies that development processes, if not aligned with sustainability principles, may intensify environmental degradation. Therefore, unless economic and financial growth targets are supported by environmentally friendly policies, they may exceed the ecosystem's carrying capacity and lead to irreversible damage in the long term. These results highlight that, for policymakers, it is not only crucial to invest in renewable energy but also to implement comprehensive policies that drive transformation in environmentally harmful sectors. Ensuring sustainable development clearly requires an integrated management approach across energy, the economy, and natural resource use.

The findings of this study carry significant policy implications for promoting sustainable development in Denmark. In particular, the increasing global concerns over energy security and ED in recent times necessitate prioritizing policies that encourage the transition from non-renewable energy to cleaner and more sustainable energy sources. In this context, promoting energy technologies is a crucial issue for Denmark. The policies to be addressed should combine political regulations with market mechanisms. Specifically, environmental-friendly and reliable energy supply, along with future growth and competitiveness objectives, should be supported. Furthermore, carbon pricing mechanisms, the enhancement of agricultural performance, and investments in clean energy projects are among the practices that should be encouraged to ensure ES.

To tackle these challenges, Denmark needs to reinforce its commitment to RE and diversify its clean energy portfolio. At the same time, efforts should be made to enhance the environmental performance of the AS by promoting low-emission practices, minimizing chemical fertilizer use, and encouraging nature-friendly farming methods. In the financial sector, expanding green finance tools, such as green bonds and sustainability-linked loans, should be prioritized to foster environmental responsibility. Furthermore, implementing carbon pricing mechanisms and environmental taxes can reduce fossil fuel reliance and support investments in clean technologies. A comprehensive policy that aligns environmental goals with economic and sectoral development is crucial for Denmark's long-term sustainability.

However, simply investing in RE will not suffice to achieve Denmark's sustainable development objectives. It is equally important to support the agricultural and forestry sectors with technologies that minimize their environmental impact. Thus, alongside green energy investments, promoting sustainable agricultural practices and channeling financial resources toward these initiatives is necessary. Achieving Denmark's environmental goals in the long term requires a strategy that integrates the increased use of RE with improvements in agriculture, industry, and finance. This holistic approach will ensure more effective progress toward Denmark's sustainability targets.

This study also has several limitations. First, the analysis is limited to Denmark; therefore, the generalizability of the findings to other countries may be restricted. Additionally, the variables used in the model are represented by specific indicators, and other structural or institutional factors that may influence ES were not included. Lastly, although the FFF approach offers significant advantages in modeling structural breaks and nonlinear relationships, it also has certain limitations. In particular, the selection of parameters such as frequency and lag length can directly affect the applicability of the method, and the sensitivity to these parameters may limit the reliability and generalizability of the results. Future research could test the validity of the model through comparative studies across different countries and develop more comprehensive models by incorporating additional variables, such as institutional quality, the effectiveness of environmental policies, and the level of technological advancement. Moreover, the use of panel data instead of time series could allow for a more detailed analysis of long-term dynamic relationships.

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