



Convergence analysis of ammonia emissions by sector and fuel source in OECD countries from 1750 to 2019 using a new Fourier-centric wavelet approach

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Abstract

Although ammonia emissions are not as huge as carbon and methane emissions, they pose significant threats to ensuring environmental sustainability and productivity. However, the existing literature has paid less attention to the underlying characteristics of ammonia emissions. The chief target of this study is to investigate the stochastic convergence of ammonia emissions at the aggregate level, by sector, and by fuel source in 37 Organization for Economic Cooperation and Development countries for more than two centuries of data. Using a newly proposed Fourier-augmented wavelet unit root test, the empirical findings reveal that the relative ammonia emissions series in most Organization for Economic Cooperation and Development countries follow the unit root process in the aggregate, sectoral, and fuel-specific analyses. Therefore, these findings refer to the existence of divergence, while stochastic convergence does not exist in most cases. Having a divergent pattern of ammonia emissions has several policy implications for policymakers in the context of environmental sustainability. (i) Relative ammonia emission cannot revert to its steady-state path without policy intervention, (ii) policymakers have a chance of affecting the dynamics of ammonia emissions in Organization for Economic Cooperation and Development countries. (iii) As a policy response, the study recommends the pursuit of national environmental policies with consideration to the unique characteristics of the individual countries as the non-existence of convergence of environmental series could result in a diverse level of consciousness of environmental degradation among countries with divergent patterns on emissions levels.

Keywords Ammonia emissions · Convergence · Sectoral analysis · Fuel-specific analysis · Wavelet · Environmental policy

Introduction

The study of pollutant convergence has several major ramifications. The incidence of convergence in pollutant emissions is critical for planners of environmental policies in both advanced and emerging economies to launch appropriate policy designs for the environment. The manifestation or otherwise of pollutant convergence can have an impact on various climate agreements reached internationally. When there is no convergence of pollutants, for example, the allocation of emissions rights may result in a significant migration of emission-intensive companies (Payne 2020). Pollutant convergence is a crucial characteristic of many frameworks of climate change. If pollutants are not predicted to be converging in the future, environmental designs that are equitable may not be successful. This, according to Churchill et al. (2018), occurs as a result of countries with relatively low levels of emissions being more probable to support egalitarian agreements, as these types of

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agreements would imply that countries with more levels of pollution would shoulder much of the pollution mitigation burden. Furthermore, understanding the stochastic behavior of relevant pollutants is a critical element for conducting cointegration analysis as well as generating reliable long-run estimates of the relative pollution series (Solarin et al. 2019).

Ammonia emissions are the main alkaline gases in the atmosphere that add to the formation of secondary particles. Several economic activities have been recognized as responsible for ammonia emissions. These activities include fertilizer manufacturing, combustion of fossil fuel, coke manufacturing, and livestock management. Fertilizer production and livestock waste management are the major ammonia-emitting activities. Although ammonia emissions are not part of greenhouse gases, they indirectly add to greenhouse gas emissions. This occurs when ammonia emissions volatilize from the soil, trajected through the air, and are re-located somewhere else. This re-located ammonia emissions can subsequently act as a substrate for a pollutant, nitrous oxide, which is a potent greenhouse gas. Ammonia emissions add to the deposition of acid and eutrophication, which eventually can lead to water and soil quality changes. The consequent effects of acid deposition can be substantial, including adverse impacts on aquatic ecosystems in lakes and rivers, and impairment of crops, forests, and other vegetation. Such ecosystems include important ecological sites including those recognized under the European network of Natura 2000 (Bastian 2013).

Eutrophication can cause acute decreases in the quality of water with consequent effects including the decline in biodiversity, changes in species composition, and toxicity impacts (Ti et al. 2019). Ammonia emissions are irritating to the throat, nose, and eyes, if inhaled in lesser amounts and are poisonous if inhaled in huge amounts (U.S. Environmental Protection Agency 1995). Ammonia emissions add to secondary particulate aerosol formation, a vital air pollutant as a result of its harmful effects on human health. When mixed with air in specific magnitudes, it is explosive and is even more explosive when mixed with oxygen. Considering the adverse effects of ammonia on both environmental degradation and human health, it could be said that having insights into how ammonia emissions move in the long run is vital for establishing efficient policies.

The implications of testing for convergence in pollutant emissions coupled with the negative consequences of degradation of the environment (including ammonia emissions) have attracted the interest of academics, resulting in a slew of papers on the subject. We are not aware of any paper on the convergence of ammonia emissions. Most of the existing studies have concentrated on the convergence of primary greenhouse gases, particularly CO₂ emissions (Payne 2020; Churchill et al. 2018; Barassi et al. 2018; de Oliveira and Bourscheidt 2017; and Strazicich and List

2003). The convergence of sulfur oxide emissions (SO₂) has received relatively little attention in the extant literature (Solarin and Tiwari 2020; Payne et al. 2014; List 1999). Papers on ecological footprints' convergence are also available (Ulucak and Apergis 2018; Solarin et al. 2019; Ulucak et al. 2020).

The goal of this research is to add at least three new findings to the existing body of knowledge on the convergence of pollutant emissions. To begin, we look into the hypothesis of ammonia emissions convergence in OECD nations from 1750 to 2019. For a variety of reasons, we have focused on OECD countries. First, in 2019, according to the United Nations Division of Statistics (2021), the OECD countries' cumulative gross domestic product (in 2015 prices) was US\$51 trillion, accounting for 61% of the world's total GDP. Second, in the majority of the years studied, ammonia emissions increased in OECD countries. In OECD countries, for example, ammonia emissions increased from 4610 kilotons in 1900 to 7360 kilotons, 13,346 kilotons, and 13,620 kilotons in 1950, 2000, and 2019. (Feng et al. 2020). Third, in 2019, countries in OECD contributed about 22% of global ammonia emissions (Feng et al. 2020). Finally, ammonia emission reduction technologies in OECD countries are frequently more effective than those accessible in most of the less developed nations. As a result, many emerging economies frequently solicit expert advice from their counterparts in OECD countries when formulating policies to reduce ammonia emissions.

We are focusing on a pollutant emission that has relatively not received enough consideration in the extant literature while employing a considerable long data period to maximize the robustness of a large sample size. Second, our investigation of convergence of ammonia emissions covers six different sectors across the selected OECD countries including waste, transportation, residential, commercial and others, industry, and energy production. Thirdly, we have also examined the convergence of ammonia emissions across eight sources of ammonia emissions (biomass, natural gas, brown coal, hard coal, heavy oil, light oil, diesel oil, and process) in these countries. The bulk of ammonia emissions come from processes among the sources of ammonia emissions and from agriculture among the sectors. It has previously been demonstrated in the literature that larger relative series are more likely to be divergent (Solarin 2019). The pattern and volume of ammonia oxide emissions vary by sector and source (Feng et al. 2020), and failing to account for these variations could lead to incorrect policy conclusions for the respective sector and source. As a result, taking into account convergence across sectors and sources provides more information that policymakers may find useful.

Fourthly, we used a newly developed wavelet-based unit root method with a Fourier function proposed by Aydin and Pata (2020). The Fourier-enhanced wavelet-based unit root

data allows us to consider structural changes, frequently observed in economic data, which prevents biased hypothesis tests (Erdogan and Okumus 2021). Moreover, traditional unit root strategies with structural changes assume a sharp occurrence of structural changes in economic series. However, emphasized that smooth changes in economic data might be more frequently seen than sharp ones (Enders and Lee 2012). The use of the Fourier-augmented wavelet-based unit root method allows us to capture long-term signals of the structural change in greenhouse gas emissions. The results of this study are likely to provide clues on whether each of the OECD countries needs to focus more on using individual (or country-specific) policies or common (or regional) policies in addressing environmental degradation. The empirical results provided evidence for divergent ammonia emissions in most of the OECD countries. The general implication of these results is that in the event of any major structural change in the distribution of ammonia emissions across these countries, the gaps in their relative ammonia emissions would not traject back to their initial equilibrium over a certain time period. Hence, it is recommended that the unique characteristics of the individual countries should play a central role when the authorities in these countries are designing national environmental policies aimed at addressing environmental degradation.

Review of extant literature

Beginning from the pioneering works of Grossman and Krueger (1991, 1995) on the relationships between income per capita and environmental degradation, and Dietz and Rosa (1994, 1997) who developed the Stochastic Impact by Regression on Population, Affluence, and Technology (STIRPAT) framework to explain the driving forces of the environment, research into the dynamics of the environment has become quite robust. The latest advances in this strand of literature include Bello et al. (2018) on the impact of electricity consumption on the environment in an emerging economy; Razzaq et al. (2021a) on the role of tourism and technological innovation on the environment; Razzaq et al. (2021b) on the interrelationships between waste, economic growth, and the environment. Others have also incorporated the dynamics of COVID-19 and its effect on the environment (Razzaq et al. 2020) as well as of fiscal decentralization and green innovation (Sun and Razzaq 2022).

However, research on the nature of convergence of pollutant emissions dates back to more than 20 years ago and the primary focus has been on CO₂ emissions. Furthermore, a large part of the extant papers has examined the convergence of pollutants at national and international levels while limited consideration at the level of sectors in the economy. Because of differences in the chosen sample space,

techniques of analysis, and time-period, empirical results of CO₂ emissions convergence studies most times vary. The study of Strazicich and List (2003), which used the first-generation test of panel stationarity to investigate the relative stochastic convergence of CO₂ emissions in 21 developed countries, was among the earliest set of work on the stochastic convergence of pollutant emissions. The empirical findings point to the stochastic convergence of the series. Yu et al. (2018) investigated the convergence of carbon emissions intensity in 24 industries in China during 1995–2015. The outputs provide evidence of strong convergence of carbon intensity in 20 industries, while there is weak support for convergence in the remaining four industries.

Barassi et al. (2018) considered the relative CO₂ emissions convergence for 28 member countries of OECD between 1950 and 2013. Using a fractional integration that provides for breakpoints, the findings provide support for weak convergence as less than half of the countries display convergence. The relative per capita CO₂ emissions convergence in 44 OECD and non-OECD countries during the period 1900 to 2014 was examined by Churchill et al. (2018). Employing a residual augmented least squares (RALS) approach, their empirical results show evidence of stochastic convergence. Karakaya et al. (2019) used a unit root test to demonstrate that there is weak support for CO₂ emissions in advanced nations. Tiwari et al. (2021) examined the convergence of CO₂ emissions across states in the U.S from 1976 to 2014. Using the pair-wise and Fourier approach, the results largely support the presence of divergence in the series.

Other papers address the convergence of other pollution indicators, such as sulfur oxide and nitrogen oxide emissions, as well as various components of the ecological footprints. List (1999) investigated the stochastic convergence of sulfur oxide and nitrogen oxide in ten U.S. regions from 1929 to 1994 using a traditional unit root test. The empirical findings point to a convergence of the series. Employing a residual augmented least squares approach, Payne et al. (2014) examined the convergence of sulfur oxide emissions in U.S. states and observed that stochastic convergence exists. Solarin and Tiwari (2020) also observe the convergence of sulfur oxide emissions in OECD nations. Lee and List (2004) used conventional unit root tests to test the convergence hypothesis in nitrogen oxide emissions in the USA from 1900 to 1994 and reached the conclusion of convergence of nitrogen oxide emissions.

For the period 1961–2013, Ulucak and Apergis (2018) focused on the ecological footprint convergence in several European economies. The results show the existence of a few convergence clubs using a club clustering technique. For the period 1961–2016, Erdogan and Okumus (2021) focused on the club and stochastic convergence of ecological footprint in 89 countries that cut across different socioeconomic

groups. The empirical findings demonstrate a disparity in ecological footprint among these countries using a panel stationarity test that allows for smooth transitions. There are various convergent clubs among the nations, according to the club convergence analysis. Investigating the stochastic convergence of the six components of ecological footprints including the grazing land, built up, fishing ground, carbon, forest land, and cropland for 92 countries using a data span that covers the period 1961 to 2014, Solarin et al. (2019) validated the existence of diverse convergence patterns in the series. Ulucak et al. (2020) examined the convergence of ecological footprint and its components in 23 sub-African countries during 1961–2014. The empirical findings suggest that that ecological footprint, as well as its types, do diverge as a whole. However, except for built-up-land footprint and forest-land footprint, several clubs are found for the components.

Data and methodology

In order to carry convergence tests out on ammonia emissions in 37 OECD countries, we retrieved the ammonia data (in kilotons) from Feng et al. (2020). Stochastics convergence can be estimated by testing the unit root properties

of the relative series of the ammonia emission as defined as follows:

$$Relative\ Ammonia\ emission_{it} = \ln(Ammonia\ emission_{it}) - \ln(Ammonia\ emission_t) \tag{1}$$

where \ln capture converted logarithmic values. i captures each OECD member included in the sample and t is the time period. In Eq. (1), there is evidence for convergence if the relative ammonia emission is stationary. We presented the historical evolution of the relative ammonia emissions in Fig. 1. It could be inferred from Fig. 1 that the nature of ammonia emissions began to change at the beginning of the 1900s. It may be related to the cumulative effect of the Industrial Revolution, which is called Industry 1.0, and the increase of the use of electric power in the production process, which is known as Industry 2.0 as well. In addition, the cycles in the nature of the data have increased after the 1950s. It could be related to an increase in economic activities by using information and communication technologies in the production process, which is called Industry 3.0. In addition, it must be noted that the post-1950s is the period when environmental concerns rose due to the increase in ecological effects of pollutants. Many significant environmental events occurred during this period, such as the Stockholm Conference (Ozcan and Ozturk 2019). It could be said

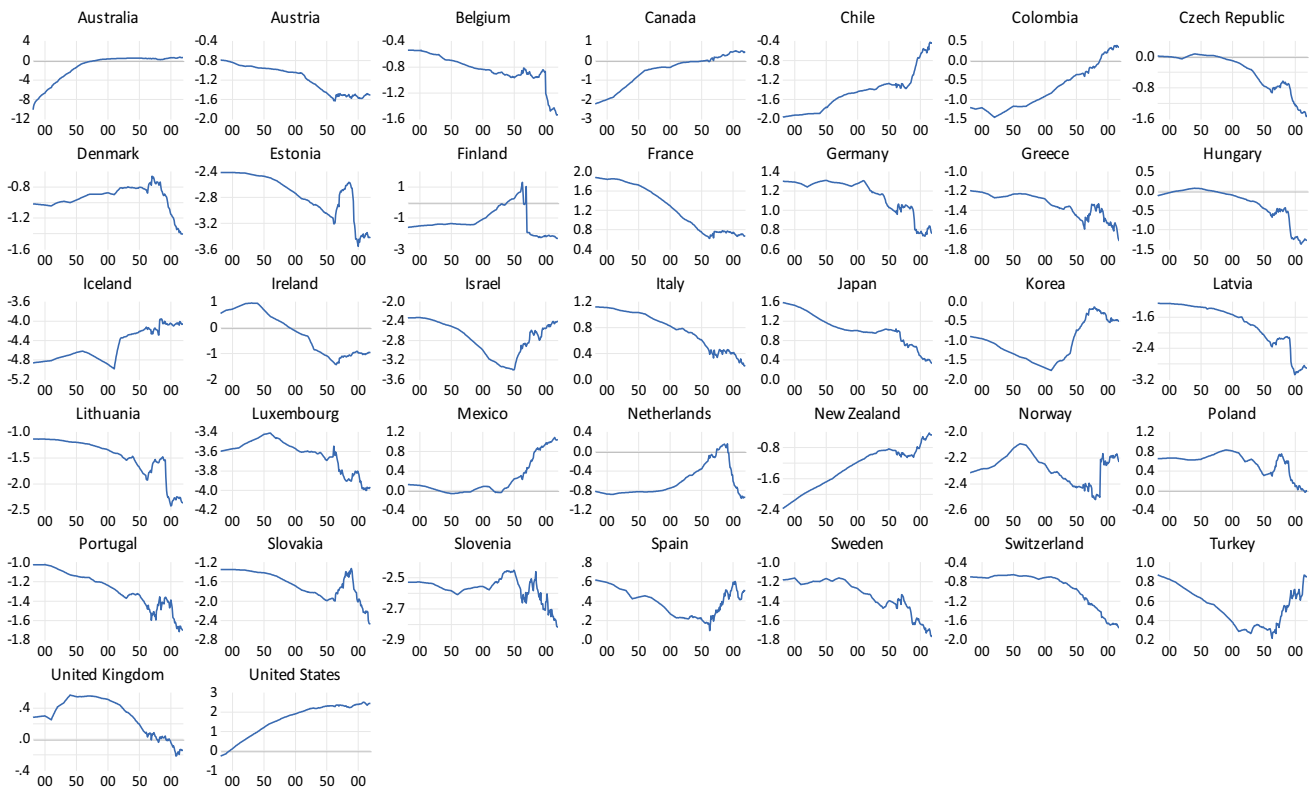


Fig. 1 Relative aggregate ammonia emissions of the OECD countries (1781–2019). Note: The sector-specific graphs can be provided upon request

that the historical evolution of ammonia emissions is highly consistent with environmental economics literature.

Afterward estimating relative ammonia emissions, we employed a newly proposed FWADF (Aydin and Pata 2020). It is widely known that the nature of the economic data may be vulnerable to structural shifts because of socioeconomic events such as economic crises, natural disasters, and international treaties. Conventional unit root/stationarity methods could fail to capture the changes in the nature of the data, and such a modeling strategy could lead to biased hypothesis tests, empirical inferences, and policy implications (Adedoyin et al. 2020; Perron 1989; Shahbaz et al. 2020). To address this issue, we employed the newly developed FWADF method in empirical estimations. Unlike conventional unit root/stationarity methods, FWADF allows us to model and consider possible structural changes in smooth form because of the numerosness of smooth shifts rather than sharp ones (Enders and Lee 2012; Erdogan et al. 2020). Moreover, most unit root/stationarity methods decide the validity of the Fourier functions exogenously. Such an assumption could be hard to satisfy. FWADF method allows us to preliminarily test the statistical significance of using the Fourier function. Such a strategy may help us to avoid biased empirical estimations, and the theoretical background of the FWADF could be explained as follows. Traditional time-domain methods do not take the frequency factor into account, in this respect, all features of the data might not be employed. Nonetheless, the low-frequency factor of the data enables us to obtain extensive insights into the features of the series. To estimate that characteristics of the series establish the simple idea of the wavelet methods. Fan and Gençay (2010) suggested a unit root method based on the wavelet approach that uses the variance ratio method. Continuous wavelet transform and discrete wavelet transform are two wavelet transforms that can be used in the wavelet approach (DWT). According to the work of Gençay et al. (2001), the utilization of DWT in economic series is sensible; therefore, Aydin and Pata (2020) used the DWT approach in conjunction with the Haar filtering strategy. The following wavelet and scaling parameters can be calculated (Aydin and Pata, 2020; Erdogan and Solarin, 2021):

$$w_{1,t} = \sum_{l=0}^{L-1} h_l x_{2t+1-l \bmod N}, \quad (2)$$

$$v_{1,t} = \sum_{l=0}^{L-1} g_l x_{2t+1-l \bmod N}, \quad (3)$$

where $l = 1, \dots, L-1, t = 1, \dots, T/2$. The $w_{1,t}$ and $v_{1,t}$ are wavelet parameter and scaling parameter, while h and g are scaling filter and wavelet filter, respectively. The L denotes wavelet filter length and \bmod indicates mode operator used in

the filtering process. Eroğlu and Soybilgen (2018) expanded the basic method by using the following specification:

$$\Delta V_{1,t} = \sum_{j=1}^p \rho_j \Delta V_{1,t-j} + \delta V_{1,t-1} + \varepsilon_t, \quad (4)$$

where $j = 1, \dots, J$, V is the scaling parameter computed through the wavelet filtering approach. δ is the coefficient, which signifies the presence or otherwise of stationarity, ρ is the coefficient associated with ΔV . Similar to the augmented Dickey Fuller (ADF) method, the wavelet ADF (WADF) uses the null hypothesis of the “ $H_0 : \delta = 0$.” The WADF method does not account for the possibility of structural shifts in the series. Aydin and Pata (2020) expanded the WADF method by enhancing the model specification with structural change as follows:

$$y_t = \mu(t) + \varepsilon_t, \quad (5)$$

where y_t is related time series evolved by following the process shown in Eq. 5 and $\mu(t)$ includes the structural changes of y_t at unknown dates. Yazgan and Özkan (2015) utilize Eq. 6 to estimate the unknown deterministic factor:

$$\mu(t) \cong \alpha \sum_{i=1}^n \{(2i-1)^{-1} \sin [2\pi(2i-1)kt/T]\}, \quad (6)$$

where $i = 0, 1, \dots, n+1$, and n, k , is the occurrence of the deterministic factor, frequency of the Fourier, respectively, and term α indicate their size (amplitude). Moreover, T is the time period. Aydin and Pata (2020) presume $n = 1$ and use Eq. 6 to obtain FWADF estimation:

$$\Delta V_{1,t} = \sum_{j=1}^p \rho_j \Delta V_{1,t-j} + \delta V_{1,t-1} + \beta \sin(2\pi kt/T) + \varepsilon_t. \quad (7)$$

The V is related to the scaling parameter computed through the wavelet filtering approach, β is the coefficient associated with the Fourier function, respectively. Aydin and Pata (2020) utilize the FWADF approach of Enders and Lee (2012), and the method contains a two-stage estimation strategy: First, Eq. (7) is estimated for $1 \leq k \leq 5$, and the model, having minimum residual squares, is chosen. Second, validity of nonlinearity is decided using traditional t -test. Provided that k is statistically significant, FWADF could be employed. Aydin and Pata (2020) suggested the employment of WADF estimation when the t -statistic is not statistically significant.

Empirical results

First, we conducted the convergence analysis for the aggregate series of ammonia emissions in OECD countries and reported the results in Table 1. Due to the unavailability of data, we excluded Australia in the convergence analysis

Table 1 Convergence of ammonia emissions results for OECD countries

OECD member	FWADF [†]	t-stat. [†]	k [†]	WADF [†]	FWADF*	t-stat.*	k*	WADF*
Australia	-	-	-	-	-5.964	4.13	1	-4.643
Austria	-2.130	2.43	1	-1.678	-2.798	2.89	1	-1.813
Belgium	-1.780	-2.13	1	-	-2.865	-2.44	1	-
Canada	-0.477	-4.50	2	-	-1.783	-2.16	3	-
Chile	0.530	-2.01	2	-	-1.699	2.10	1	-0.977
Colombia	-2.383	-1.58	1	-2.178	-2.854	2.88	5	-2.554
Czech Republic	-0.059	2.62	4	-0.164	-1.227	1.17	4	-1.171
Denmark	-0.840	-1.31	1	1.799	1.866	-1.41	5	1.482
Estonia	-3.579	1.45	4	-3.483	-3.788	1.88	4	-3.421
Finland	-2.295	1.84	2	-1.863	-3.034	-1.94	3	-
France	-3.101	-2.75	2	-	-3.552	3.09	1	-1.809
Germany	-1.396	1.46	4	-1.270	-1.492	-0.44	5	-1.617
Greece	-0.814	1.54	5	-0.583	-1.238	1.61	4	-1.185
Hungary	-1.440	0.92	4	-1.377	-1.915	0.78	4	-1.182
Iceland	-1.960	1.77	5	-1.709	-2.296	1.52	2	-2.407
Ireland	-4.60	4.01	1	-2.167	-4.083	3.71	1	-1.614
Israel	0.520	1.72	3	-0.018	1.072	-1.64	1	-
Italy	-1.192	1.66	5	-1.357	-2.330	-2.70	3	-
Japan	-3.054	-3.15	1	-	-4.177	-3.99	1	-
Korea	-0.817	-2.59	2	-	-1.857	-3.16	1	-
Latvia	-1.960	0.90	4	-1.912	-2.249	1.20	4	-2.111
Lithuania	-2.207	1.15	4	-2.139	-2.613	1.44	4	-2.405
Luxembourg	-1.585	0.50	1	-1.682	-1.772	-1.32	3	-1.817
Mexico	-0.800	1.32	3	-1.260	-1.490	0.20	4	-1.517
Netherlands	-3.296	-2.23	1	-	-2.526	-2.45	1	-
New Zealand	-1.871	-3.27	4	-	-1.085	2.40	1	-1.735
Norway	-3.198	3.06	1	-1.651	-4.363	3.88	1	-1.196
Poland	-1.409	1.60	4	-1.211	-1.851	1.78	3	-1.934
Portugal	-1.437	1.78	5	-1.795	-1.541	3.59	5	-2.363
Slovakia	-0.937	2.12	4	-1.135	-2.182	-1.14	2	-1.865
Slovenia	-0.146	2.38	5	0.029	-1.424	-1.95	1	-
Spain	-0.554	1.69	5	-0.771	-0.045	2.19	4	-0.677
Sweden	-0.965	2.08	3	-0.679	-1.007	-1.27	5	-1.157
Switzerland	2.224	2.93	1	1.110	0.307	1.35	3	-0.402
Turkey	3.347	2.86	5	1.548	1.663	1.72	5	1.594
United Kingdom	-0.369	3.43	1	-0.665	-1.829	2.27	1	-1.498
United States	1.546	3.27	1	0.461	-1.103	2.02	1	-1.254

[†]Denotes the data covering 1750–2019, while * denotes the data covering 1781–2019. *k* is frequency of Fourier terms. Bold statistics is significance at least 10% level. -3,690, -3,050, and -2,75 are critical values at 1%, 5%, and 10% for WADF statistics, 1%, 5%, and 10% are critical values at 1%, 5%, and 10% for t-statistics, respectively. FWADF critical values test are in Appendix Table 10

conducted for the period from 1750 to 2019. According to the empirical results, the Fourier term (FT) is significant at least a 10% significance level in the eight of 36 OECD countries; therefore, we employed the FWADF test, and the H_0 hypothesis (unit root) is accepted in Belgium, Canada, Chile, Estonia, France, Japan, Korea, and New Zealand, whereas H_1 hypothesis (stationarity) is accepted for the Netherlands. Moreover, the WADF test shows that the H_0 hypothesis is accepted in 27 OECD countries, while the H_1 hypothesis is

accepted for Estonia. It can be said that convergence exists in the Netherlands and Estonia, while divergence is accepted remainder. Moreover, we examined the convergence properties of OECD countries by including Australia in the convergence analysis conducted for the period from 1781 to 2019. The results suggest a statistical significance of the FT in nine of 37 OECD nations; therefore, we employed the FWADF test for those countries, and the findings show that the H_0 hypothesis is accepted in Belgium, Canada,

Israel, Italy, Korea, the Netherlands, and Slovenia, while H_1 hypothesis is accepted in Finland and Japan. Moreover, WADF test results show that the H_0 hypothesis is accepted in 24 OECD countries, while the H_1 hypothesis is accepted in Australia and Estonia. Thus, convergence exists in Australia, Estonia, Finland, and Japan, while divergence is accepted in the remainder.

Furthermore, we investigated the convergence properties of sectoral ammonia emissions for OECD countries

(Table 2). The Fourier term is significant in 10 of 37 OECD nations, and FWADF empirical results indicate that H_0 hypothesis is accepted for Australia, Czech Republic, Greece, Israel, Lithuania, and the USA, while the H_1 hypothesis is accepted for Canada, France, Japan, New Zealand, and the USA in the industrial sector. The WADF test results show that the H_0 hypothesis is accepted in 17 OECD nations, while the H_1 hypothesis is accepted in 10 OECD nations. Thus, convergence is valid on the industrial ammonia emissions of

Table 2 Sectoral convergence of ammonia emissions results (industry and energy)

OECD member	Industry			Energy				
	FWADF	<i>t</i> -stat	<i>k</i>	WADF	FWADF	<i>t</i> -stat	<i>k</i>	WADF
Australia	-1.948	-1.93	4	-	-4.737	2.15	4	-4.152
Austria	-4.481	2.89	1	-2.843	-4.124	2.07	1	-2.879
Belgium	-3.603	2.48	1	-2.415	-3.161	-1.77	3	-
Canada	-5.405	-4.43	1	-	-2.649	0.78	3	-2.760
Chile	-4.346	-1.45	3	-4.057	-2.089	2.20	2	-2.011
Colombia	-3.825	2.95	2	-2.350	-2.027	-1.00	5	-2.142
Czech Republic	-2.462	-2.17	3	-	-2.364	1.21	1	-2.462
Denmark	-2.750	1.61	5	-3.088	-1.675	-1.63	1	-
Estonia	-1.774	-1.23	2	-2.102	-2.897	-1.65	4	-
Finland	-2.106	-0.65	4	-2.269	-1.336	-1.80	5	-
France	-3.487	-2.23	3	-	0.546	-1.16	1	-0.055
Germany	-4.837	3.60	1	-2.716	-4.780	-1.89	3	-
Greece	-1.369	-2.27	2	-	-2.989	1.91	1	-2.217
Hungary	-3.091	2.55	1	-2.303	-4.794	-2.33	3	-
Iceland	-1.671	0.83	3	-1.786	-	-	-	-
Ireland	-2.575	0.84	1	-2.476	-2.780	-1.43	1	-1.808
Israel	-1.710	-1.78	3	-	-3.062	-3.24	1	-
Italy	-4.466	2.37	1	-3.603	-2.063	4.23	2	-2.016
Japan	-3.598	-2.43	3	-	-3.310	-2.17	3	-
Korea	-2.905	-1.97	1	-2.526	-2.408	1.41	5	-2.300
Latvia	-1.297	2.24	5	-1.868	-3.482	2.43	1	-2.603
Lithuania	-1.761	-2.46	2	-	-3.714	3.35	1	-1.700
Luxembourg	-3.243	1.44	1	-2.860	-2.965	3.58	1	-1.124
Mexico	-1.859	-0.85	3	-1.915	-2.310	2.08	2	-1.165
Netherlands	-1.562	1.43	2	-1.451	-3.790	3.18	1	-2.244
New Zealand	-3.598	-2.49	1	-	-1.058	-1.02	5	-1.148
Norway	-4.075	1.85	1	-3.451	-4.384	2.85	2	-3.063
Poland	-1.713	-1.20	3	-1.877	-3.526	2.22	1	-2.576
Portugal	-5.353	-3.95	1	-3.103	-2.466	-2.41	4	-
Slovakia	-0.982	2.15	1	-1.560	-4.655	3.75	1	-2.423
Slovenia	-1.609	1.03	5	-1.764	-2.720	2.54	2	-1.702
Spain	-3.716	1.06	1	-3.677	-0.996	0.97	1	0.768
Sweden	-4.419	2.80	1	-2.870	-4.588	1.33	1	-4.354
Switzerland	-4.518	3.17	1	-2.852	-2.972	-1.50	2	-2.552
Turkey	-0.895	1.59	5	-0.903	-1.159	1.34	4	-0.944
United Kingdom	-2.462	-1.13	1	-2.350	0.376	-1.37	1	-0.864
United States	-4.558	-2.60	1	-	-0.881	-3.01	2	-

Due to data availability, convergence of ammonia emissions analysis in industrial sector is conducted for 37 countries from 1950 to 2019, while convergence of ammonia emissions analysis in energy production sector is conducted for 36 countries from 1946 to 2019. See the note of Table 1 for other explanations

Austria, Canada, Chile, Denmark, France, Italy, Luxembourg, Japan, Norway, New Zealand, Portugal, Sweden, Spain, Switzerland, and the USA. Furthermore, convergence analysis for energy-related ammonia emissions shows that the FT is significant for 10 OECD nations, and FWADF test findings confirm that the H_0 hypothesis is accepted for Denmark, Finland, Israel, Portugal, and the USA, while the H_1 hypothesis is accepted for Belgium, Estonia, Germany, Hungary, and

Japan. The WADF estimations confirm that the H_0 hypothesis is accepted for 21 countries, while the H_1 hypothesis is accepted for Australia, Austria, Canada, Norway, and Sweden. Thus, convergence is valid for energy-related energy ammonia emissions of Austria, Australia, Canada, Belgium, Estonia, Germany, Hungary, Norway, Japan, and Sweden.

The convergence analysis conducted for ammonia emissions of the transportation sector (Table 3) reveals that the

Table 3 Sectoral convergence of ammonia emissions results (transportation and waste)

OECD member	Transportation			Waste				
	FWADF	<i>t</i> -stat	<i>k</i>	WADF	FWADF	<i>t</i> -stat	<i>k</i>	WADF
Australia	-1.865	1.76	3	-2.031	-5.566	3.74	1	-4.200
Austria	-3.762	-2.47	1	-	-2.419	2.22	1	-2.813
Belgium	-1.809	2.91	2	-1.637	-1.958	-2.42	3	-
Canada	-4.275	3.06	1	-2.623	-1.043	-3.17	3	-
Chile	-0.906	1.33	3	-1.326	-4.727	-3.39	1	-
Colombia	-1.075	-1.59	2	-0.755	-2.998	-2.31	1	-
Czech Republic	-2.260	0.79	5	-2.320	-1.647	2.86	1	-1.682
Denmark	-2.212	-2.14	1	-	-2.641	2.12	1	-2.217
Estonia	-4.447	3.24	1	-2.087	-1.760	2.49	1	-1.545
Finland	-2.720	-2.76	1	-	-2.512	2.19	1	-2.061
France	-3.645	-1.79	4	-	-2.191	2.99	1	-1.891
Germany	-2.622	-1.78	1	-	-2.117	-2.51	3	-
Greece	-3.298	-2.30	2	-	-1.121	1.70	1	-1.562
Hungary	-0.360	-2.55	1	-	-2.335	-1.69	1	-2.316
Iceland	-1.976	2.75	3	-1.651	-2.383	-2.34	3	-
Ireland	-0.958	-1.49	1	-2.330	-2.533	2.13	1	-2.171
Israel	-1.595	-1.43	4	-1.680	-1.930	-2.06	1	-
Italy	-3.545	-2.13	4	-	-2.710	2.08	1	-2.387
Japan	-3.902	-1.62	2	-	-2.956	-1.96	1	-
Korea	-1.717	2.04	4	-1.425	-3.163	-3.27	1	-
Latvia	-1.465	1.38	3	-2.225	-2.787	2.41	1	-2.178
Lithuania	-2.159	-1.80	2	-	-2.754	2.36	1	-2.141
Luxembourg	-1.532	3.26	2	-1.493	-2.068	-1.27	4	-2.155
Mexico	-1.905	3.54	3	-1.719	-1.532	-2.17	1	-
Netherlands	-2.545	0.96	3	-2.827	-1.345	1.74	1	-2.002
New Zealand	-1.601	-1.08	4	-1.719	-2.730	-0.71	1	-2.602
Norway	-2.663	-3.19	1	-	-2.678	-1.93	3	-
Poland	-1.012	1.47	2	-1.887	0.109	2.20	4	-0.304
Portugal	-2.357	-2.85	1	-	-2.531	-1.92	1	-
Slovakia	-2.004	-2.24	4	-	0.565	1.90	4	0.342
Slovenia	-1.649	-3.35	1	-	-9.931	-2.52	1	-
Spain	-1.650	-3.06	1	-	3.648	1.81	4	3.483
Sweden	-3.002	-3.51	1	-	-2.622	-2.11	3	-
Switzerland	-4.151	-3.24	1	-	-1.846	-1.31	4	-2.260
Turkey	-2.769	-2.08	5	-	-1.143	-2.20	1	-
United Kingdom	-2.745	-2.29	1	-	-2.205	2.91	1	-1.754
United States	-0.554	1.16	1	-2.452	0.627	-0.54	3	0.589

Due to data availability, convergence of ammonia emissions analysis in waste sector is conducted for 37 countries from 1781 to 2019, while convergence of ammonia emissions analysis in transportation sector is conducted for 37 countries from 1951 to 2019. See the note of Table 1 for other explanations

FT is significant in 19 of 37 OECD countries, and FWADF test results suggest that the H_0 hypothesis is accepted in 13 countries, while the H_1 hypothesis is accepted in Austria, France, Greece, Italy, Japan, and Switzerland. The WADF test results show that the H_0 hypothesis is accepted in 18 countries while the H_1 hypothesis is accepted for the Netherlands. Thus, convergence exists in Austria, France, Greece, Italy, Japan, the Netherlands, and Switzerland. Moreover, the convergence analysis conducted for waste sector originated

ammonia emissions exhibits that the FT is significant in 15 of 37 OECD nations, and FWADF estimations show that the H_0 hypothesis is accepted in 13 countries, while the H_1 hypothesis is accepted for Chile and Slovenia. The WADF test results suggest that the H_0 hypothesis is accepted in 20 countries, while the H_1 hypothesis is accepted for Australia and Austria; therefore, convergence exists in the waste-originated ammonia emissions in Australia, Austria Chile, and Slovenia.

Table 4 Sectoral convergence of ammonia emissions results (agriculture and residential, commercial, and other)

OECD member	Agriculture				Residential, commercial, and other				
	FWADF	<i>t</i> -stat	<i>k</i>	WADF	FWADF	<i>t</i> -stat	<i>k</i>	WADF	
Australia	-5.736	3.80	1	-4.583	-3.631	-1.16	3	-3.495	
Austria	-2.028	1.58	1	-2.249	-2.290	1.56	5	-2.252	
Belgium	-2.788	-2.86	1	-	0.385	2.32	2	-0.106	
Canada	-1.579	-2.56	3	-	-0.361	-4.00	3	-	
Chile	-1.131	2.03	1	-0.224	-3.064	-2.32	1	-	
Colombia	-1.962	-0.90	2	-1.983	-3.314	-3.14	1	-	
Czech Republic	-0.543	1.31	4	-0.517	-3.639	3.00	1	-2.182	
Denmark	1.603	1.30	2	1.556	-1.132	-1.65	5	-	
Estonia	-3.325	1.84	4	-2.939	-3.769	3.31	2	-1.993	
Finland	-2.963	-1.91	1	-	-2.671	1.64	1	-2.113	
France	-3.001	-2.31	2	-	-3.032	1.77	5	-2.703	
Germany	-0.783	-0.35	5	-0.880	-2.752	-1.92	2	-	
Greece	2.121	1.42	4	2.437	-1.827	1.15	5	-1.779	
Hungary	-1.671	0.84	4	-1.583	-2.720	3.55	1	-1.104	
Iceland	-2.168	1.62	2	-2.320	-1.205	0.87	1	-0.950	
Ireland	-4.237	3.87	1	-1.634	-3.035	2.18	1	-2.364	
Israel	0.694	-1.77	1	-	-4.265	-2.80	2	-	
Italy	-0.631	2.60	5	-0.523	-1.613	2.64	1	-0.276	
Japan	-3.717	-3.69	1	-	-2.023	1.17	5	-2.162	
Korea	-0.925	-3.53	1	-	-2.776	2.55	2	-2.074	
Latvia	-2.315	1.36	4	-2.100	-0.081	-1.28	2	-0.779	
Lithuania	-2.564	1.46	4	-2.335	-1.991	-1.41	3	-1.853	
Luxembourg	-1.110	1.33	2	-1.295	-0.072	1.85	3	-0.409	
Mexico	-1.519	-0.71	2	-1.404	-4.025	-3.27	1	-	
Netherlands	-2.522	-2.56	1	-	-2.282	1.60	4	-2.379	
New Zealand	-1.610	-2.75	3	-	-0.049	-2.43	2	-	
Norway	-4.306	2.59	1	-3.364	-2.703	-2.00	3	-	
Poland	-1.661	1.92	3	-1.642	-2.846	2.69	1	-1.240	
Portugal	-3.197	-1.75	1	-	-3.056	1.75	5	-3.271	
Slovakia	-1.094	-1.98	1	-	-1.952	1.68	1	-1.101	
Slovenia	-1.034	-1.89	1	-	-2.133	-1.51	4	-1.978	
Spain	0.130	2.13	4	-0.527	0.602	2.43	2	-0.170	
Sweden	0.044	-1.03	5	-0.128	-3.463	2.33	4	-2.866	
Switzerland	-0.146	0.93	1	-0.637	-5.135	1.78	4	-4.879	
Turkey	2.883	1.83	5	1.768	-2.782	-3.07	1	-	
United Kingdom	-0.757	0.99	1	-1.064	-2.000	-1.59	5	-2.313	
United States	-2.270	2.97	1	-1.849	-4.786	4.16	1	-2.276	

Due to data availability, convergence of ammonia emissions analysis in agricultural and residential-commercial-other sector are conducted for 37 countries from 1781 to 2019. See the note of Table 1 for other explanations

The convergence analysis conducted for the agricultural sector is reported in Table 4. The findings reveal that the FT is significant in 12 of 37 OECD nations, and FWADF results validate that nine OECD countries follow the unit root process, while Japan follows the stationary process. The WADF test outputs validate that 22 countries follow the unit root process while, Australia, Estonia, and Norway follow the stationary process. Thus, convergence exists in agriculture-related ammonia emissions in Australia, Estonia, Japan, and Norway. Besides, the FWADF test conducted for residential, commercial, and other activities-related ammonia emissions suggests that the FT is significant in the 10 OECD countries, and ammonia emissions of seven countries follow the unit root process, whereas Colombia, Israel, and Mexico's ammonia emissions' follows the stationary process. The WADF test shows that 23 countries follow the unit root process, while Australia, Portugal, Sweden, and Switzerland follow the stationary process. Therefore, the convergence of residential, commercial, and other activities-related ammonia emissions is valid in Australia, Colombia, Israel, Mexico, Portugal, Sweden, and Switzerland.

Besides, we analyzed whether convergence exists in the input using the production and consumption process in the economy. We reported the FWADF test results in Table 5, and the results validate that the FT is significant in 11 of 37 OECD countries. The FWADF test results indicate that eight of 11 countries' biomass-originated ammonia emissions follow the unit root process, while Colombia, Mexico, and Portugal follow the stationary process. The WADF test results suggest that 21 of 37 OECD countries follow the unit root process, whereas Australia, Belgium, France, Japan, and Korea follow the stationarity process. Therefore, Australia, Belgium, Colombia, France, Japan, Korea, Mexico, and Portugal have a convergent pattern in biomass-originated ammonia emissions. The FWADF test for natural gas suggests that the FT is significant in 11 of 36 OECD nations, and eight of 11 countries' ammonia emissions follow the unit root process, while natural gas originated ammonia emissions of Chile, Greece, and Lithuania follow the stationary process. Moreover, the WADF test results validate that natural gas-based ammonia emissions of 18 of the 25 OECD countries follow the unit root process, while natural gas-based ammonia emissions of Austria, Belgium, Colombia, Finland, Ireland, Luxembourg, and Portugal follow the stationary process. Thus, Austria, Lithuania, Colombia, Chile, Finland, Belgium, Greece, Ireland, Luxembourg, and Portugal have a convergent pattern of ammonia emissions.

The FWADF findings for ammonia emissions of brown coal (Table 6) suggest that the FT is significant in eight of 20 OECD nations, and five of eight OECD countries have a divergent pattern on brown coal-based ammonia emissions, and Australia, Canada, and New Zealand has a convergent pattern on brown coal-based ammonia emissions. The

WADF test findings suggest that nine of 12 OECD countries exhibit a divergent pattern, while France, Poland, and Slovenia have a convergent pattern. Thus, the convergence hypothesis is valid for brown coal-based ammonia emissions of Australia, Canada, France, New Zealand, Poland, and Slovenia. Moreover, the FWADF test for hard coal-based ammonia emissions proved that the FT is significant in eight of 36 OECD nations and four of eight countries follow the unit root process, while Canada, Denmark, Korea, and Slovakia follow the stationary process. The WADF findings evidenced that 23 of 28 OECD countries have a divergent pattern on hard coal-based ammonia emissions, while the Czech Republic, Greece, Israel, Lithuania, and the Netherlands have a convergent pattern. Hence, the convergence hypothesis is valid on hard coal-based ammonia emissions of Canada, the Czech Republic, Denmark, Greece, Korea, Israel, Lithuania, the Netherlands, and Slovakia.

The FWADF test for heavy oil (Table 7) suggests that the FT is significant in 11 of 37 OECD nations, and heavy oil-originated ammonia emissions of five of 11 OECD countries exhibit unit root process, while heavy oil-based ammonia emissions of Colombia, Estonia, France, Ireland, Japan, and Luxembourg exhibit stationary process. The WADF test results show that 21 of 26 OECD countries have a divergent pattern, while Austria, Germany, Iceland, the Netherlands, and Turkey have a convergent pattern. Hence, the convergence hypothesis is valid in Austria, Colombia, Estonia, France, Germany, Iceland, Ireland, Japan, Luxembourg, the Netherlands, and Turkey. Moreover, the FWADF test for light oil evidence that the FT is significant in 17 of 37 OECD nations, and light oil-based ammonia emissions of 12 of 17 countries exhibit unit root process, while light oil-based ammonia emissions of Australia, Austria, France, Luxembourg, and Switzerland follow the stationary process. In addition, the WADF test proves that 19 of 20 OECD countries follow the unit root process, while the Netherlands follows the stationary process. Therefore, light oil-based ammonia emissions of Australia, Austria, France, Luxembourg, and Switzerland have a convergent pattern.

The FWADF test for diesel oil-based ammonia emissions of OECD countries proves that the FT is significant in 10 of 37 OECD nations and seven of 10 OECD countries follow unit root process, while the Czech Republic, Germany, and Poland follow the stationary process (Table 8). The WADF test results provide that 24 of 27 OECD countries follow the unit root process, while Belgium, Denmark, and Switzerland follow the stationary process. Therefore, the convergence hypothesis is valid for diesel oil-based ammonia emissions of Belgium, the Czech Republic, Denmark, Germany, Poland, and Switzerland. The FWADF test for process-based ammonia emissions of OECD countries shows that the FT is significant in six of 37 OECD nations and five of six

Table 5 Fuel-specific convergence of ammonia emissions results (biomass and natural gas)

OECD member	Biomass				Natural gas				
	FWADF	<i>t</i> -stat	<i>k</i>	WADF	FWADF	<i>t</i> -stat	<i>k</i>	WADF	
Australia	-3.958	1.94	1	-3.643	-1.719	2.29	1	-1.968	
Austria	0.213	1.44	5	0.053	-3.683	2.30	2	-2.844	
Belgium	-3.376	1.33	1	-3.232	-3.662	2.46	2	-3.320	
Canada	-4.471	0.95	4	-0.470	-1.816	-1.84	3	-	
Chile	-2.374	-2.15	3	-	-3.546	-1.69	1	-	
Colombia	-3.822	-4.08	1	-	1.714	5.26	2	-2.963	
Czech Republic	-3.178	3.53	1	-1.080	-0.217	1.87	1	-1.223	
Denmark	-3.059	2.83	1	-1.353	-1.461	1.18	4	-1.398	
Estonia	-4.252	3.22	2	-1.858	-2.740	1.75	1	-2.500	
Finland	-3.025	-1.95	2	-	-2.851	2.59	2	-4.823	
France	-3.639	0.62	5	-3.602	-2.462	-1.02	4	-2.492	
Germany	-3.610	3.73	1	0.009	0.099	3.16	1	-2.280	
Greece	-2.178	-1.38	3	-2.184	-4.310	-2.00	1	-	
Hungary	-2.404	3.53	1	-1.123	-1.009	1.02	5	-1.002	
Iceland	-0.132	1.77	1	1.476	-	-	-	-	
Ireland	-2.230	3.08	1	-1.285	-8.448	3.15	2	-6.302	
Israel	-3.315	2.92	1	-1.824	-1.712	0.90	3	-2.085	
Italy	-1751	2.34	1	-1.347	-2.509	1.59	3	-2.468	
Japan	-3.487	-1.29	4	-3.300	-2.632	-1.80	3	-	
Korea	-4.075	1.90	2	-3.647	0.106	1.55	1	-1.816	
Latvia	-0.866	1.54	1	-1.492	-2.330	2.42	1	-2.496	
Lithuania	-1.462	1.77	1	-1.891	-4.484	-2.94	2	-	
Luxembourg	-1.965	3.02	1	0.697	-6.036	4.02	1	-3.467	
Mexico	-4.654	-4.71	1	-	-2.430	-2.21	4	-	
Netherlands	-1.344	2.54	1	-1.843	-2.976	-3.47	2	-	
New Zealand	-1.423	-3.33	2	-	1.423	4.01	1	-2.438	
Norway	-2.615	-2.57	2	-	-1.137	1.46	2	-1.369	
Poland	-2.184	2.68	1	-0.182	-2.255	0.94	2	-2.065	
Portugal	-3.762	-1.99	3	-	-2.830	-0.78	1	-2.889	
Slovakia	0.122	-1.76	5	-	-2.645	1.70	3	-2.079	
Slovenia	-2.013	-1.77	4	-	-3.027	1.71	1	-2.453	
Spain	-1.465	-0.84	5	-0.968	-2.629	1.87	2	-1.812	
Sweden	-2.349	-2.60	2	-	-0.151	-2.91	2	-	
Switzerland	-1.066	1.98	1	0.532	0.022	2.69	1	-2.136	
Turkey	-2.027	-2.80	1	-	-2.927	-2.32	1	-	
United Kingdom	-2.020	2.25	1	-1.482	-0.906	-3.20	3	-	
United States	-3.908	2.89	1	-2.543	-0.906	-2.59	1	-	

Due to data availability, convergence of ammonia emissions analysis in biomass is conducted for 37 countries from 1781 to 2019, while convergence of ammonia emissions analysis in natural gas is conducted for 36 countries from 1971 to 2019. See the note of Table 1 for other explanations

countries follow the unit root process, while Japan follows the stationary process. The WADF test proposes that 29 of 31 OECD countries follow the unit root process, while Australia and Estonia follow the stationary process. Therefore, convergence is valid for Australia, Estonia, and Japan. In addition, to see empirical outcomes at a glance, we provided a summary of the empirical results in Table 9.

Discussion of the results

The environmental effect of economic development has been rising since the Industrial Revolution, and greenhouse gases have unprecedentedly grown. Most of the researchers and policymakers focused on the question of whether greenhouse gas emissions exhibit a convergent pattern. Within this context, knowing the dynamic pattern of greenhouse gases enabled researchers to have a deep understanding of

Table 6 Fuel-specific convergence of ammonia emissions results (brown coal and hard coal)

OECD member	Brown coal			Hard coal				
	FWADF	<i>t</i> -stat	<i>k</i>	WADF	FWADF	<i>t</i> -stat	<i>k</i>	WADF
Australia	−3.839	−2.13	1	-	−0.406	1.43	1	1.609
Austria	−1.770	−1.43	2	−1.710	−3.589	2.27	2	−2.711
Belgium	-	-	-	-	−3.227	3.22	1	−2.101
Canada	−3.423	−2.69	1	-	−4.006	−3.37	1	-
Chile	-	-	-	-	−1.839	−1.63	3	-
Colombia	-	-	-	-	−2.585	1.10	1	−2.601
Czech Republic	−2.637	3.14	1	−2.312	−4.040	3.26	4	−3.156
Denmark	-	-	-	-	−3.029	−1.66	3	-
Estonia	−1.337	2.76	1	−1.602	−1.549	3.10	1	−1.747
Finland	−1.815	−2.38	4	-	−2.384	1.70	1	−2.447
France	−4.294	0.80	2	−4.343	−3.769	4.16	1	−0.634
Germany	−2.262	−2.46	4	-	−1.691	−1.73	3	-
Greece	0.396	0.96	2	0.298	−3.927	−1.03	5	−3.875
Hungary	−2.803	2.38	1	−2.058	−2.581	1.46	1	−2.513
Iceland	-	-	-	-	-	-	-	-
Ireland	−0.639	−1.65	3	-	−2.978	2.35	2	−1.702
Israel	-	-	-	-	−4.469	1.86	3	−4.006
Italy	−4.051	−1.52	2	−1.458	−1.681	1.54	4	−2.024
Japan	-	-	-	-	−0.623	1.71	3	−1.670
Korea	-	-	-	-	−3.632	−2.56	4	-
Latvia	−1.455	−1.74	4	-	−2.404	−0.92	5	−2.655
Lithuania	−0.008	1.38	5	−0.179	−5.473	4.25	1	−3.391
Luxembourg	-	-	-	-	−1.392	2.22	4	−1.830
Mexico	-	-	-	-	−1.662	2.20	4	−2.059
Netherlands	-	-	-	-	−5.091	2.56	3	−2.756
New Zealand	−3.315	−1.64	2	-	−0.349	2.10	1	−1.392
Norway	-	-	-	-	−2.215	−0.91	4	−1.257
Poland	−3.919	−1.27	2	−3.752	−2.248	1.17	1	−2.446
Portugal	-	-	-	-	−2.193	2.27	1	−2.314
Slovakia	−0.262	2.44	1	−1.102	−3.964	−2.97	1	-
Slovenia	−3.575	1.16	3	−3.372	−1.572	−0.93	3	−1.703
Spain	-	-	-	-	−3.410	2.17	1	−2.485
Sweden	-	-	-	-	−4.904	3.67	2	−2.709
Switzerland	-	-	-	-	−1.051	1.29	2	−1.812
Turkey	0.487	1.52	1	−0.412	0.529	2.01	4	−1.015
United Kingdom	-	-	-	-	−2.268	−2.21	3	-
United States	−3.078	−2.75	1	-	−3.041	−2.02	1	-

Due to data availability, convergence of ammonia emissions analysis in brown coal is conducted for 20 countries from 1950 to 2019, while convergence of ammonia emissions analysis in hard coal is conducted for 36 countries from 1950 to 2019. See the note of Table 1 for other explanations

the current situation of environmental pollution, projection of climate change, and establishment of mitigation policies. A significant part of the research has been devoted to understanding the steady-state path of carbon emissions; however, other greenhouse gas emissions and environmental pollution indicators have been mostly ignored. Ammonia emissions are one of the neglected ecological burdens. Although it is not entirely considered a greenhouse gas emission, it has core importance because of economic activities such as

agriculture, husbandry, and feed manufacturing. Therefore, understanding the nature of ammonia emissions could be a key point for policymakers on internalizing the negative externality of anthropogenic activities on the environment. Therefore, the main research question of this paper was whether ammonia emissions of OECD countries exhibit a convergent pattern. To this end, we utilized a wavelet-based unit root approach extended with Fourier functions. Using the Fourier centric–wavelet unit root method allows

Table 7 Fuel-specific convergence of ammonia emissions results (heavy oil and light oil)

OECD member	Heavy oil				Light oil				
	FWADF	<i>t</i> -stat	<i>k</i>	WADF	FWADF	<i>t</i> -stat	<i>k</i>	WADF	
Australia	-4.571	3.92	1	-2.615	-2.901	-2.13	4	-	
Austria	-4.080	-1.40	3	-3.842	-3.367	-2.49	1	-	
Belgium	-1.564	-3.15	1	-	-2.305	2.77	2	-2.054	
Canada	-3.708	1.92	3	-2.741	-4.140	2.98	1	-2.566	
Chile	-1.354	2.92	5	-2.231	-1.951	-1.29	5	-1.822	
Colombia	-3.909	-2.83	1	-	-4.182	3.88	1	-1.436	
Czech Republic	-1.407	-1.50	3	-1.211	-2.537	0.86	5	-2.564	
Denmark	-3.479	2.88	1	-2.150	-1.412	2.20	2	-2.354	
Estonia	-2.893	-2.07	4	-	-1.022	2.50	3	-1.486	
Finland	-2.737	-1.22	2	-2.428	-2.572	-2.70	1	-	
France	-3.808	-3.72	2	-	-4.882	-1.95	4	-	
Germany	-5.078	2.48	1	-4.123	-2.897	-1.89	1	-	
Greece	-1.566	-3.61	2	-	-3.001	-3.02	2	-	
Hungary	-2.739	2.36	1	-1.519	-0.346	-2.10	1	-	
Iceland	-5.542	2.63	3	-4.444	-2.563	1.54	3	-2.530	
Ireland	-3.537	-2.58	2	-	-2.593	1.13	5	-2.624	
Israel	0.696	1.70	5	0.725	-1.247	-1.21	1	-2.047	
Italy	-2.930	-1.18	2	-2.749	-3.774	1.64	5	-2.249	
Japan	-5.689	-2.62	3	-	-2.535	0.49	4	-2.094	
Korea	-0.200	2.17	4	-0.161	-2.185	2.00	4	-1.776	
Latvia	-0.284	1.39	5	-0.109	-1.523	1.64	3	-2.26	
Lithuania	-0.698	1.70	1	-1.307	-3.317	2.46	1	-1.728	
Luxembourg	-3.125	-3.94	3	-	-3.708	-2.78	1	-	
Mexico	-2.254	-1.58	1	-1.846	-1.497	3.25	3	-1.789	
Netherlands	-5.760	3.73	5	-4.658	-2.527	0.95	3	-2.771	
New Zealand	-2.986	-2.19	2	-	-1.579	-1.18	4	-1.726	
Norway	-0.979	1.50	3	-1.120	-3.240	-2.40	1	-	
Poland	-1.228	-1.75	4	-	-1.151	-2.68	1	-	
Portugal	-0.868	0.73	3	-0.646	-2.727	-2.10	1	-	
Slovakia	-2.124	-2.21	5	-	-1.892	-1.39	4	-2.066	
Slovenia	-1.048	-1.13	4	-1.352	-2.491	-2.16	1	-	
Spain	-3.332	3.21	1	-1.092	-2.207	-1.78	1	-	
Sweden	-1.849	1.91	5	-1.972	-2.427	-3.23	1	-	
Switzerland	-2.951	2.25	4	-2.557	-3.463	-3.06	1	-	
Turkey	-3.145	-1.53	4	-3.448	-2.606	2.10	1	-2.154	
United Kingdom	-3.629	2.49	1	-2.026	-3.169	-2.03	1	-	
United States	-3.136	3.49	3	-2.237	-1.855	-2.34	3	-	

Due to data availability, convergence of ammonia emissions analysis in heavy oil and light oil are conducted for 37 countries from 1950 to 2019. See the note of Table 1 for other explanations

us to consider dynamic changes in the nature of the data ignored in the former literature. Such a strategy could help us to prevent possible biased hypothesis tests and policy inferences, determine whether the future of the ammonia emissions in the OECD countries could be projected, and fill the existing body of knowledge. The results provide us with deep insights into the nature of ammonia emissions in OECD countries.

The foregoing results indicate divergence of ammonia emissions among OECD countries as the series follows the unit root process at aggregate, sectoral, and source level for the majority of the countries. These findings are attributable to several factors. Such factors include the differences in the structure of economic activities and disparities in the economic growth rates of the countries that made up the OECD. As emissions, including ammonia emissions, are influenced by economic growth, these disparities also

Table 8 Fuel-specific convergence of ammonia emissions results (diesel oil and process)

OECD member	Diesel oil				Process				
	FWADF	<i>t</i> -stat	<i>k</i>	WADF	FWADF	<i>t</i> -stat	<i>k</i>	WADF	
Australia	-0.989	-1.78	4	-	-5.813	3.95	1	-4.594	
Austria	-3.052	-2.60	1	-	-2.865	2.96	1	-1.824	
Belgium	-3.029	2.16	2	-3.841	-0.881	1.22	3	-1.937	
Canada	-2.994	2.13	1	-2.067	-1.740	-2.47	3	-1.449	
Chile	-2.047	1.54	2	-1.481	-1.589	2.06	1	-0.685	
Colombia	-2.570	1.18	5	-2.569	-2.30	-2.49	5	-2.172	
Czech Republic	-3.628	-3.40	2	-	-0.946	1.32	5	-0.909	
Denmark	-3.790	1.75	1	-3.256	1.428	1.31	4	1.596	
Estonia	-0.417	2.86	3	-1.240	-3.752	1.84	4	-3.402	
Finland	-2.682	2.78	2	-1.772	-2.985	-1.90	1	-	
France	-2.218	-1.46	5	-2.166	-3.073	2.55	1	-1.898	
Germany	-5.617	-2.08	4	-	-1.775	-0.42	2	-1.778	
Greece	-1.437	1.23	3	-1.892	-1.639	-1.53	2	-0.982	
Hungary	-3.605	2.57	1	-2.355	-1.798	0.87	4	-1.698	
Iceland	-1.132	3.41	3	-1.828	-2.248	1.48	3	-2.387	
Ireland	-3.287	3.16	4	-2.439	-4.093	3.73	1	-1.600	
Israel	-1.545	-1.55	4	-1.755	0.873	-1.73	1	-	
Italy	-2.715	1.73	3	-2.231	-1.614	2.75	5	-1.712	
Japan	-1.450	-1.83	3	-	-4.114	-3.97	1	-	
Korea	-0.062	-2.39	2	-	-1.960	-3.26	1	-	
Latvia	-1.546	-1.28	5	-1.061	-2.521	1.37	4	-2.320	
Lithuania	-3.581	2.08	1	-2.746	-2.689	1.50	4	-2.467	
Luxembourg	-0.719	3.24	2	-1.942	-1.419	-1.363	3	-1.521	
Mexico	-2.034	-2.61	2	-	-1.350	1.46	5	-1.562	
Netherlands	-0.349	3.02	2	-1.990	-2.502	-2.48	1	-	
New Zealand	-1.412	-0.77	4	-1.464	-1.543	-2.58	3	-1.837	
Norway	-0.761	-4.69	1	-	-4.494	4.03	1	-1.943	
Poland	-4.670	-4.03	2	-	-1.784	1.81	3	-1.857	
Portugal	-2.083	0.99	4	-	-1.776	3.17	5	-1.905	
Slovakia	-1.701	-1.52	4	-2.072	-1.753	1.66	4	-1.841	
Slovenia	-2.766	3.16	2	-1.716	-1.089	-1.76	1	-	
Spain	-1.031	2.01	3	-0.643	-0.061	2.19	4	-0.707	
Sweden	-1.623	-2.01	4	-	-1.085	-1.16	5	-1.221	
Switzerland	-3.033	-1.47	1	-3.083	-0.623	-1.12	5	-0.731	
Turkey	-2.252	1.95	1	-1.925	1.799	1.74	5	1.707	
United Kingdom	-3.179	2.10	3	-2.312	-1.922	2.29	1	-1.583	
United States	-4.612	3.79	2	-2.523	-0.980	2.54	1	-1.274	

Due to data availability, convergence of ammonia emissions analysis in process is conducted for 37 countries from 1781 to 2019 while convergence of ammonia emissions analysis in diesel oil is conducted for 37 countries from 1950 to 2019. See the note of Table 1 for other explanations

contribute to the lack of convergence of ammonia emissions among the OECD countries. For several decades, countries in the OECD have experienced differences in economic growth paths with accelerated productivity in some of the most affluent economies and a substantial slowdown in others. For instance, in the 1990s, while the USA, which is arguably one of the most affluent member countries of the OECD, experienced accelerated growth driven primarily by advancement in information and communications

technology (ICT), some other member countries such as continental Europe and Japan experienced slowdowns (OECD 2003).

Apart from the differences in the structure of economic activities and disparities in the economic growth rates, differences in the fossil fuel endowments among OECD countries are also another possible reason for the reported divergence in their ammonia emissions. Though member countries in OECD share some economic characteristics,

Table 9 Summary of the results

	Aggre- gate		Sectoral convergence					Input								
	A'	A*	In	En	Tr	Wa	Ag	Re	Bm	Ng	Bc	Hc	Ho	Lo	Do	Pr
Australia	D	C	D	C	D	C	C	C	C	D	C	D	D	C	D	C
Austria	-	D	C	C	C	C	D	D	D	C	D	D	C	C	D	D
Belgium	D	D	D	C	D	D	D	D	C	C	-	D	D	D	C	D
Canada	D	D	C	C	D	D	D	D	D	D	C	C	D	D	D	D
Chile	D	D	C	D	D	C	D	D	D	C	-	D	D	D	D	D
Colombia	D	D	D	D	D	D	D	C	C	C	-	D	C	D	D	D
Czech Republic	D	D	D	D	D	D	D	D	D	D	D	C	D	D	C	D
Denmark	D	D	C	D	D	D	D	D	D	D	-	C	D	D	D	D
Estonia	C	C	D	C	D	D	C	D	D	D	D	D	C	D	C	C
Finland	D	C	D	D	D	D	D	D	D	C	D	D	D	D	D	D
France	D	D	C	D	C	D	D	D	C	D	C	D	C	C	D	D
Germany	D	D	D	C	D	D	D	D	D	D	D	D	C	D	C	D
Greece	D	D	D	D	C	D	D	D	D	C	D	C	D	D	D	D
Hungary	D	D	D	C	D	D	D	D	D	D	D	D	D	D	D	D
Iceland	D	D	D	-	D	D	D	D	D	-	-	-	C	D	D	D
Ireland	D	D	D	D	D	D	D	D	D	C	D	D	C	D	D	D
Israel	D	D	D	D	D	D	D	C	D	D	-	C	D	D	D	D
Italy	D	D	C	D	C	D	D	D	D	D	D	D	D	D	D	D
Japan	D	C	C	C	C	D	C	D	C	D	-	D	C	D	D	C
Korea	D	D	D	D	D	D	D	D	C	D	-	C	D	D	D	D
Latvia	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
Lithuania	D	D	D	D	D	D	D	D	D	C	D	C	D	D	D	D
Luxembourg	D	D	C	D	D	D	D	D	D	C	-	D	C	C	D	D
Mexico	D	D	D	D	D	D	D	C	C	D	-	D	D	D	D	D
Netherlands	C	D	D	D	C	D	D	D	D	D	-	C	C	C	D	D
New Zealand	D	D	C	D	D	D	D	D	D	D	C	D	D	D	D	D
Norway	D	D	C	C	D	D	C	D	D	D	-	D	D	D	D	D
Poland	D	D	D	D	D	D	D	D	D	D	C	D	D	D	C	D
Portugal	D	D	C	D	D	D	D	C	C	C	-	D	D	D	D	D
Slovakia	D	D	D	D	D	D	D	D	D	D	D	C	D	D	D	D
Slovenia	D	D	D	D	D	C	D	D	D	D	C	D	D	D	D	D
Spain	D	D	C	D	D	D	D	D	D	D	-	D	D	D	D	D
Sweden	D	D	C	C	D	D	D	C	D	D	-	D	D	D	D	D
Switzerland	D	D	C	D	C	D	D	C	D	D	-	D	D	C	C	D
Turkey	D	D	D	D	D	D	D	D	D	D	D	D	C	D	D	D
United Kingdom	D	D	D	D	D	D	D	D	D	D	-	D	D	D	D	D
United States	D	D	C	D	D	D	D	D	D	D	D	D	D	D	D	D

*Denotes the data covering 1750–2019, while * denotes the data covering 1781–2019. *In*, industry; *En*, energy; *Tr*, transport; *Wa*, waste; *Ag*, agriculture; *Re*, residential, commercial, and other; *Bm*, biomass; *Ng*, natural gas; *Bc*, brown coal; *Hc*, hard coal; *Ho*, heavy oil; *Lo*, light oil; *Do*, diesel oil; *Pr*, process

they differ markedly in terms of their fossil fuel endowments. For instance, while Canada's total proven oil reserves at the end of 2019 were 169,692 million barrels, the corresponding figure for Australia was only 2390 million barrels (British Petroleum 2020). The same scenario also plays out in terms of natural gas endowment where the United States has a total proven reserve of 12.9 trillion cubic meters as of the end of 2019 while Denmark, Italy, Germany, Norway,

the Netherlands, Poland, and the UK have a combined total natural gas proven reserves of 2 trillion cubic meters as at the end of 2019 (British Petroleum 2020).

Closely related to the differences in fossil fuel endowment is the differences in the composition of energy supplied and used as another probable reason for the lack of convergence in ammonia emissions in OECD countries. Carbon emissions, including ammonia emissions, are dependent on

the quantity of total energy supplied and usage. Central to this is the structure of the fuel mix of energy supply among the OECD countries which is related to differences in the contribution of alternative energy sources. McKibbin and Stegman (2005) have shown that there is little evidence in the convergence of the contribution of coal, gas, and other fuel sources to the total primary energy supply in the 1970s and early 2000s. As fuel combustion due to energy usage is one of the sources of ammonia emissions, divergence in the structure and composition of energy supply and usage will likely result in divergence in ammonia emissions.

It is also observed that the divergence of aggregate ammonia emissions is also reflected at the sectoral level. Matter of fact, the divergence reported in the industry, energy, transportation, waste, agriculture, residential, commercial, and other sectors contributed to the divergence in aggregate ammonia emission across the majority of the OECD countries investigated. This is also corroborated by the reported divergence based on the various energy inputs such as biomass, natural gas, brown coal, hard coal, heavy oil, light oil, diesel oil, and process. This is unsurprising as the behavior of a series at the aggregate level is always influenced by what is obtainable not only at the sectoral level but also on the nature of input as aggregate is the summation of several individual components.

It is noted that these seemingly different factors are in fact interrelated. Differences in the level and structure of economic activities can result in differences in energy supply and usage and therefore differences in emissions. In the same vein, differences in the usage of alternative energy sources are also linked to differences in fossil fuel endowment. It is therefore unsurprising that despite the existence of convergence evidence in carbon emissions (Emir et al. (2019); Erdogan and Acaravci (2019); Erdogan and Solarin (2021); Payne and Apergis (2021); Solarin (2019); the outcome of this study is consistent with empirical findings of studies such as Aldy (2006, 2007), Criado and Grether (2011), Herrerias (2013) Yamazaki et al. (2014), and Li et al. (2014) who have also provided evidence of divergence in carbon emissions.

Conclusion and policy implications

In recent times, more than ever before, environmental issues have become more prominent issues of deliberation among countries and world leaders. The overarching goal is to develop policies that will mitigate environmental degradation from worsening and guarantee a resilient and sustainable environment. In this regard, scientists have sought to unravel the stochastic behavior of a number of environmental indicators, the bulk of which are concerned with carbon dioxide emissions. Despite the fact that ammonia emissions

pose a serious threat to environmental sustainability and production, the stochastic character of ammonia emissions has received little attention. This research extends the present papers by investigating the stochastic convergence of ammonia emissions in 37 OECD nations over two centuries. The newly proposed Fourier-augmented wavelet unit root test was employed to analyze the data and the empirical results provided evidence for divergent ammonia emissions in most of the OECD countries. This finding is laced with several policy implications.

First, if there are empirical results of the convergence of some series across nations, then our capacity to forecast the future is boosted (McKibbin and Stegman 2005). Therefore, the lack of convergence in ammonia emissions among the majority of the OECD countries implies a limitation in our ability to predict the future as it will almost be impossible to predict the future trend in ammonia emissions gaps based on the previous movement. Secondly, the lack of convergence of ammonia emissions is an indication that the series is not reverting to its mean. As a result of this, shocks to ammonia emissions will have long-term permanent impacts on it in many OECD countries. The general implication of this is that in the event of any major structural change in the distribution of ammonia emissions across these countries, the gaps in their relative ammonia emissions would not traject back to their initial equilibrium over a certain time period. The few exceptions to this are Australia, Estonia, Finland, Japan, and the Netherlands with signs of convergence in their aggregate ammonia emissions.

Thirdly, while it is naturally more convenient for OECD member countries to use joint policies against environmental pollution, the existence of divergence in ammonia emissions implies that the pursuit of national environmental policies with consideration to the unique characteristics of the individual countries will be more appropriate. As pointed out by Ulucak and Apergis (2018), the non-existence of convergence of environmental series could result in a diverse level of consciousness of environmental degradation among countries with divergent patterns on emissions levels. Therefore, in the event of divergence, as has been reported in this study, the adoption of heterogeneous environmental policies by each country will likely guarantee a more stable and sustainable environment.

Furthermore, as sectoral level convergence and the nature of energy inputs have significant implications for the pattern of convergence in aggregate ammonia emissions, concerted efforts on environmental policies should be directed to focus on the various sectors of the economy. There should be synergy between environmental policymakers at the sectoral level and at the national level in order to achieve the best result. In the same vein, energy policymakers should also be in coordination with environmental policymakers since

the nature of various energy inputs also has implications for the pattern of convergence in ammonia emissions at the national level.

Conclusively, the OECD comprises countries with some of the biggest carbon emissions, including ammonia emissions, across the globe. As there is little evidence in support of the convergence of ammonia emissions across these nations, it is recommended that individual countries should design appropriate environmental protection policies that will take into consideration the unique nature of each country. As the series is non-reverting to their mean, caution should be taken to avoid a generalized environmental policy that will lump up all the countries together as any error of judgment of placing the countries on a wrong environmental trajectory might be very difficult to correct in the long run. In this instance, therefore, the designers of environmental policies in each OECD member country need to understand the stochastic properties of the environmental series as this will go a long way in guiding them to shape an effective policy to promote a sustainable environment.

This paper has some limitations. First, the employed sample of this paper is limited to 37 OECD countries. Future studies may consider investigating the existence of convergence in ammonia emissions in different samples and time spans. Second, due to having limited spaces in this paper, we could not conduct a comparative empirical estimation; hence, future studies may consider conducting

Table 10 FWADF model with constant and trend critical values

k	1%	5%	10%
1	-4.13	-3.58	-3.29
2	-4.07	-3.48	-3.17
3	-3.93	-3.37	-3.00
4	-3.83	-3.24	-2.89
5	-3.69	-3.10	-2.82

Source: Aydin and Pata (2020)

convergence analyses with conventional unit root/stationarity and unit root/stationarity methods with sharp structural changes and extend the existing body of the research.

Appendix

10

Author contribution Sakiru Adebola Solarin: Main idea conception. Wrote the introductory background and parts of the concluding section of the manuscript. Sinan Erdogan: Handled the methodology and

analysis parts of the manuscript. Mufutau Opeyemi Bello: Reviewed the extant literature. Wrote parts of the discussion and concluding section of the manuscript.

Data availability The datasets are available in <https://zenodo.org/record/4025316#.Ycqt2BBzIU>

Declarations

Competing interests The authors declare no competing interests.

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