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Research article

The long and winding road of energy transition: A club convergence analysis

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Abstract: Signed by 194 countries and legally binding since 2016, the 2015 Paris agreement stipulates a 45% reduction in carbon dioxide emissions by 2030 from 2010 levels, with net-zero performance in 2050. To this extent, an ambitious energy transition program has been agreed upon, according to which fossil fuel energy is gradually replaced by renewable energy. How prepared are the world economies to accommodate these requirements, and how conducive is the energy consumption status quo for their fulfilment? To answer this question, we applied a club convergence analysis to the energy usage patterns of 79 developed and developing countries for the time interval 2010–2019. Country clubs were identified for each energy source; the smaller the number of clubs and the more numerous the club membership, the better. According to our analysis, only solar energy showed relative club convergence, coupled with an increasing trend in the average consumption. All other energies showed club convergence. As an additional step, we divided our energy users into big and small consumers, relative to the panel consumption mean. Several patterns emerged. The big consumers of oil and gas converge by either increasing or maintaining their average consumption. The big consumers of coal converge by maintaining their average consumption. Only the biggest consumers of nuclear energy and biofuels and the big consumers of other renewables converge by increasing consumption. Considering the current global consumption level of fossil fuels (81.5% in 2023) and the energy consumption patterns observable during the period 2010–2019, gargantuan efforts are needed to accomplish the energy transition program.

Keywords: club convergence; energy transition; net-zero; energy consumption; renewable energy consumption

1. Introduction

1.1. The long- and short-term effects of carbonic acid on climate

As early as 1897, Arrhenius demonstrated that the carbonic acid (H_2CO_3) present in the atmosphere can influence the temperature on the ground [1]. He calculated that tripling the value of the carbonic acid in the atmosphere would have triggered an 8 to 9 °C increase in arctic ground temperatures, enough to recreate Tertiary conditions. Conversely, a 0.6 decrease would have lowered temperatures by 4 to 5 °C. He singled out volcanic activity as the sole source of significant climate imbalance.

Little over half a century later, Plass introduced the carbon dioxide (CO_2) theory of climate change [2]. According to this theory, variations in atmospheric carbon dioxide levels lead to changes in climate. He calculated that a doubling of the atmospheric carbon dioxide would have increased the ground temperature by 3.6 °C, while a halving would have decreased it by 3.8 °C. He noted that the carbon dioxide resulting from human economic activity was the biggest inorganic contributor to atmospheric carbon dioxide and was responsible for a 1.1 °C increase in temperature per century.

Only two years later, using historic data spanning close to 100 years (1865 to 1956), Callendar identified an increasing trend in the data that came from 20th century carbon dioxide atmospheric measurements [3]. In contradistinction, the data pertaining to the 19th century revealed no trend. Callendar set the baseline value at 290 parts per million (ppm), the 19th century average, and calculated a 12% increase on the baseline in 1956. He remarked that part of the increase was due to fossil fuel consumption.

In 1972, a group of researchers at MIT were commissioned by the Club of Rome to write a report on sustainable development [4]. The report entitled The Limits to Growth put climate change on the political agenda. Working within an exponential growth framework, the report endorsed an atmospheric concentration of 380 ppm for carbon dioxide emissions by the year 2000. This is a 32% increase from the 19th century average calculated by Callendar in 1958. The combustion of fossil fuels was singled out as the sole contributor to this increase.

Fast forward to the present day, and carbon dioxide atmospheric concentrations exceed 400 ppm, an increase of 38% from the 19th century value. Scientists calculated values of a maximum of 425 ppm of atmospheric carbon dioxide for the last Tertiary stage, the Pliocene [5]. It is believed that carbon dioxide was a contributory factor to the Pliocene climate, a climate characterized as a permanent El Nino-like state [6–8]. Similar concentrations of atmospheric carbon dioxide will be reached by the middle of the 21st century [9].

In the short term, more precisely in only 25 years, the increase in carbon dioxide atmospheric concentrations would lead to Pliocene-like climatic conditions [7,9]. Long term, a conservative 1.1 increase per century, as calculated by Plass in 1956, would create climatic conditions detrimental to human life on Earth. Near and far future aside, the adverse effects of climate change on peace and security are already felt in numerous regions of the globe. Repeatedly identified as a threat to global security, climate change is classed as a threat multiplier by the United Nations (UN). Starting in 2008, UN has been working on climate change and security and has produced a number of reports highlighting the link between the two. The most recent of these reports, The Climate Change and Security Partnership Project Final Report (2022), emphasized the link between climate change, peace, and security [10].

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established. Its objective is to provide policymakers worldwide with scientifically researched information about climate change. In their 1990 report, the IPCC designated fossil fuel combustion as one of the primary sources of atmospheric carbon dioxide, and recommended the production of energy from nuclear and renewable sources as a response strategy [11]. The 2023 report mentioned that during the time interval 1990–2019, the largest growth in carbon dioxide emissions was triggered by fossil fuels and industry [12]. Moreover, the emissions reductions that have already been achieved were not sufficient to reverse the growing trend. The report recommended a substantial reduction in fossil fuels, coupled with an increase in low-emission energy sources.

1.2. The link between fossil fuels and atmospheric carbon dioxide

The relationship between carbon dioxide and renewable and non-renewable energy consumption was explored by several researchers who provided mixed results. The majority of the studies recommended that carbon dioxide emissions reduction policies should focus on supporting renewable energy sources to the extent that these can take over a significant share from the non-renewable sources.

Apergis et al. (2010) found carbon dioxide emissions to be positively associated with renewable energy consumption and negatively associated with nuclear energy consumption [13]. They concluded that in the short run, nuclear energy contributed to a reduction in carbon dioxide emissions, while renewable energy did not. The lack of storage capacity associated with renewables was offered as a potential explanation. Data was collected from 19 developed and emerging economies during the time period 1984–2007. A similar conclusion was reached by Salim and Rafiq (2012), who identified a short run bidirectional causality between carbon dioxide emissions and renewable energy. The subsidized price of oil did not play a determinant role in the demand for renewable energy. Data was collected from 6 major developing economies during the time period 1980–2006.

Sebri and Ben-Salha (2014) offered support for the ecological modernization theory, according to which emissions can be curved with the aid of environmental and economic measures [14]. The following findings were obtained: A negative long run effect of renewable energy and a positive effect of non-renewable energy on carbon dioxide emissions, a unidirectional causality from carbon dioxide emissions to renewable energy and a bidirectional causality between carbon dioxide emissions and non-renewable energy, and a positive impact of carbon dioxide emissions on renewable energy and a negative impact of on non-renewable energy. The study concluded that increases in the use of renewables reduce carbon dioxide emissions in the long run. In turn, carbon dioxide emissions stimulate an increased use of renewable energy and a decreased use of non-renewable energy, even in the short term. Data was collected from 29 OECD countries during the time period 1980–2011.

Magazzino et al. (2021) investigated the relationship between carbon dioxide emissions, coal consumption, and solar and wind energy production among the three largest coal consumers (China, India and the US) [15]. They identified a bidirectional relationship between carbon dioxide emissions and coal consumption. Carbon dioxide emissions were not affected by solar and wind production. Moreover, they found that a decrease in coal consumption, coupled with an increase in solar and wind production, led to a decrease in carbon dioxide emissions, and they explained this result as dependent on policies aimed at the 2 types of energies. The time intervals 1983, 1986, and 1990 to 2017 were used.

1.3. The research question

As numerous studies have shown, human economic activity, as currently conducted, has a negative impact on the climate, mainly through fossil fuels. This is a particularly problematic conclusion, as large-scale economic activity is a precondition for economic growth and development. The giant leaps that have been made in the last two and a half centuries would have been impossible without the use of fossil fuels on a massive scale. In hindsight, fossil fuels are a double-edged sword, giving rise to unprecedented progress and previously unimaginable geopolitical and environmental threats. A fast-paced replacement of fossil fuels with renewables is seen today as the way forward for humanity. To this extent, an ambitious energy transition program was set up by the 2015 Paris Agreement. Although human economic activity must continue, it has to reimagine itself completely in order to comply with this program. However, it is uncertain how the replacement of fossil fuels with renewables will impact economic growth. This uncertainty will probably diminish the appeal of the transition for some economies. Research on the nexus of economic growth, energy consumption, fossil fuel consumption, and renewable energy consumption found effects that ranged from neutral to negative and positive, and from bidirectional to unidirectional, with results varying based on sample and methodology [16–18]. In contrast, the impact of fossil fuels and renewables on carbon dioxide emissions is unequivocally clear: Fossil fuels increase carbon emissions, while renewables decrease them [16–18].

To comply with the 2015 Paris Agreement, economic entities of all kinds must therefore gradually adapt their consumption. Within this context, the following questions regarding energy consumption by the world's economies arise: 1) Is there evidence that at least some of the world's economies decrease their fossil fuel consumption? 2) Is there evidence that at least some of the world's economies increase their renewables consumption? 3) Is there evidence that at least some economies have similar energy consumption patterns? 4) Is there evidence for a worldwide effort to mitigate the effects of climate change? One potential area of exploration may be the consumption of fossil fuels and renewables by the world's economies. An analysis of the long-term evolution of the energy portfolios belonging to economies worldwide might provide tentative answers. As we know, economies cannot operate in a vacuum, and therefore, it is safe to assume that at least some of the world's economies will show similarities in their energy use. Identifying such groups may prove useful for policy implementation and evaluation. The national energy portfolios can be delved into at the aggregate level for a bird's eye view, or at the individual energy type level for granularity. We believe the latter option is far more helpful for policy implementation and evaluation. Financially, geographically, and politically, national economies differ widely as to the types and amounts of energy that they can accommodate, hence the suitability of club convergence.

1.4. Convergence and energy convergence

Convergence is, in the words of Kerr Clark, the father of convergence theory, ‘the tendency of societies to grow more alike, to develop similarities in structures, processes and performance’ [19]. Convergence is important as ‘it points to the direction of change’ [19]. Economic analysis has been using three types of convergence: Absolute, conditional and club convergence. Absolute convergence suggests that countries that differ in their initial conditions converge to one another, irrespective of their fundamentals [20]. According to the conditional convergence hypothesis, countries that have similar basic characteristics converge to one another, irrespective of their initial conditions [20]. In contradistinction to conditional convergence, club convergence enables heterogeneity among countries and predicates that countries that have similar fundamentals converge to one another, based on the similarity of their initial conditions [20]. While absolute convergence has been rejected by some experimental studies, conditional and club convergence have received substantial empirical support [20]. A significant milestone in the development of convergence analysis was the paper published by Phillips and Sul in 2007 [21]. Within the framework of a novel data panel model for the representation of transitional behavior, Phillips and Sul (2007) introduced an econometric test of relative convergence and a clustering method for club convergence. To date, the Phillips and Sul (2007) method has been used across research areas, from economics to finance, ecology, energy, and health studies [22].

Within the field of energy convergence, only a handful of researchers looked at fossil fuels and renewable energy separately. Most of the researchers concentrated on energy as a whole, using variables such as per capita energy consumption, electricity intensity, efficiency, and productivity. We were unable to identify studies that entailed convergence in gas, nuclear, or renewable energy types. International convergence in fossil fuel consumption was investigated by Nazlioglu et al. (2022) and Cai et al. (2023) [23,24]. International convergence in renewable energy consumption was investigated by Reboredo (2015), Cai and Menegaki (2019), Berk et al. (2020), Butnaru et al. (2020), Presno and Landajo (2021), Bigerna et al. (2021), Saba and Ngepah (2022), and Helmi et al. (2023) [25–32]. As a general rule, the longer the time interval, the stronger the possibility of convergence.

Nazlioglu et al. (2022) analyzed convergence in oil consumption per capita in a sample of 16, mostly European countries that they considered representative from the point of view of oil consumption [23]. The data spanned 1890–2017 and was tested via sigma, beta, and relative convergence. Absolute convergence was identified in the overall data, while conditional convergence was found for the time intervals 1930–1969, 1970–1993, and 1994–2017. Relative convergence, with 4 convergence clubs, was identified in the data of the last interval. Cai et al. (2023) focused on the stochastic convergence of 39 countries in their coal consumption [24]. Relying on nonlinearities (unit root tests), Cai et al. (2023) deemed 34 of the 39 countries as convergent for the time period 1960–2017.

A variety of samples and techniques were used for the investigation of convergence in renewable energy. Reboredo (2015) and Cai and Menegaki (2019) concentrated on developed and emerging economies [25,26]. Berk et al. (2020), Butnaru et al. (2020) and Presno and Landajo (2021) focused on European Union (EU) economies, while Helmi et al. (2023) focused on the G-7 members [27–29]. Bigerna et al. (2021) and Saba and Ngepah (2022) worked with large samples of 176 and 183 countries, in an effort to address global convergence [30,31]. Cai and Menegaki (2019), Butnaru et al. (2020), and Helmi et al. (2023) worked with intervals of over 50 years starting from the early 1960s [26,28,32]. Reboredo (2015), Berk et al. (2020), Presno and Landajo (2021), Bigerna et al. (2021), and Saba and Ngepah (2022) used intervals of maximum 25 years beginning in the early 1990's and 2000's [25,27,29–31]. Reboredo (2015), Berk et al. (2020), Presno and Landajo (2021), Bigerna et al. (2021), and Saba and Ngepah (2022) focused on convergence in the contribution of renewable energy to the total energy supply [25,27,29–31]. Cai and Menegaki (2019), Butnaru et al. (2020), and Helmi et al. (2023) focused on renewable energy consumption [26,28,32]. Reboredo (2015), Presno and Landajo (2021), and Saba and Ngepah (2022) employed the concept of relative convergence (club convergence) [25,29,31]. Cai and Menegaki (2019) and Helmi et al. (2023) relied on nonlinearities (unit root tests) [26,32]. Berk et al. (2020), Butnaru et al. (2020), and Bigerna et al. (2021) used beta and sigma convergence [27,28,30].

Reboredo (2015) reported as convergent, only 8 of the 39 developed and emerging countries included in the study [25]. Cai and Menegaki (2019) reported convergence for 21 Organization for Economic Cooperation and Development (OECD) countries and 14 emerging economies when testing on the panel as a whole [26]. They also reported convergence for 22 countries when testing countries individually. Berk et al. (2020) found that 14 EU countries converged in their use of renewable energy, while Butnaru et al. (2020) concluded that all EU countries converged [27,28]. Presno and Landajo (2021) identified 2 convergence clubs among the EU members when considering the time interval 2004–2018 [29]. Shortening the time interval to only 4 years resulted in 3 convergence clubs and 1 divergent unit. Bigerna et al. (2021) concluded that 176 countries converged in their consumption of renewable energy [30]. Helmi et al. (2023) found evidence of convergence only for 4 of the G-7 countries [32]. Saba and Ngepah (2022) divided their 183 countries into 2 convergence clubs [31].

2. Materials and methods

2.1. Overall remarks

We concentrated on the following energy types: Coal, oil, gas, nuclear, hydro, biofuels, other renewables, solar, and wind. We used the share of each energy type in the individual economy energy portfolio as a unit of analysis. We sourced our data from the Our World In Data (OWID) database, where 79 economies are registered. This is an incomplete sample, as there are 194 countries recognized by the UN and 218 economies recognized by the World Bank. Based on the above numbers, our sample covers 40% of the UN-recognized countries and 36% of the world's economies.

According to the UN classification, we covered the overwhelming majority of the developed countries and 28% of the developing countries. Among the developing countries in our sample, there are 7 countries that are classed as in transition. Our sample includes only 1 least developed country and does not include heavily indebted countries. Asia Pacific and Eastern and Western Europe are very well represented. Latin America and the Caribbean have satisfactory coverage. Africa is very poorly represented. See Tables 1 and 2 for details.

According to the WB classification, we covered little over half of the High Income economies and 30% of the Middle Income economies. There are no Low Income economies in our sample. Europe and Central Asia, Middle East and North Africa, North America, and South Asia are very well represented. Latin America and the Caribbean has satisfactory coverage. Sub Saharan Africa is very poorly represented. See Tables 1 and 2 for details.

Table 1. Classification by development level.

UN Development	Total	Sample	%	WB Income	Total	Sample	%
Developed	36	34	94	High Income	83	46	55
Transition	17	7	41	Upper Middle Income	54	20	37
Developing	158	45	28	Lower Middle Income	54	12	22
Least Developed	45	1	<1	Low Income	26	0	
Heavily Indebted	39	0					

Table 2. Classification by geographical level.

UN Region	Total	Sample	%	WB Region	Total	Sample	%
Africa	54	4	7	East Asia Pacific	13	38	34
Asia Pacific	55	26	47	Europe and Central Asia	39	58	67
Eastern Europe	23	16	70	Latin America and the Caribbean	9	42	21
Latin America and the Caribbean	33	9	27	Middle East and North Africa	11	21	52
Western Europe and Other	29	23	79	North America	2	3	67
				South Asia	4	8	50
				Sub Saharan Africa	1	48	2

2.2. Sample and methodology

Although, in some cases, OWID data goes back to as early as 1960, we restricted our analysis to the time interval 2010–2019. This is the nearest to the present interval of a minimum acceptable length (10 years) that contains the largest number of consumers for each of the energy types reported. For example, for biofuels, the number of consumers was 1 in 1980, 3 in 1990, 8 in 2000, 53 in 2010, and 57 in 2019. We excluded the time period 2020–2022 from our analysis due to the 2020 Pandemic and the 2022 Ukrainian war. Data from IEA revealed a marked decline in the consumption of fossil fuels and a moderate, yet atypical increase in the consumption of renewables for the year 2020 (IEA, 2020), with the slow recovery initiated in 2021, severely disrupted by the 2022 global energy crisis (IEA, 2021, 2022) [33–35]. For the entire period 2020–2022, the energy consumption data shows anomalies that are difficult to evaluate.

We refer to the economies in our sample as consumers. We differentiate small and big consumers, based on the percentage share allocated to a particular energy type. The small consumers have a share that is smaller than the sample mean, while the big consumers have a share that is bigger than the sample mean.

We focused our analysis on convergence. For our analysis, we used the R package ConvergenceClubs developed by Sichera and Pisutto (2019) [36]. The package builds upon the work of Phillips and Sul (2007, 2009) [21,37]. The implementation is as follows: 1) log-t regression test (Stage 1), 2) clustering algorithm with log-t regression test (Stage 2), and 3) merging algorithm with log-t regression test (Stage 3). For brevity, we reported only the results of Stage 3. To put more meat on the bones, we attempted to briefly describe our clubs. We chose the yearly relative transition parameters as the units of measure. We first calculated country average relative transition parameters (country ARTPs) and 2019 country relative transition parameters (country RTPs). We applied the following descriptive statistics to the ARTPs: Maximum, mean, median, minimum, and growth rate. We included these measures, together with the 2019 RTPs, in Appendix 1 (Sample descriptive statistics). We then calculated club interval average relative transition parameters (club interval ARTPs) and 2019 club average relative transition parameters (club 2019 ARTPs), for which we compiled relative values (RVs) and orders of magnitude (OMs). We included these measures in Appendix 1. We divided our clubs into high (club interval ARTPs above the mean) and low consumption clubs (club interval ARTPs below the mean). We designated the clubs where the RTPs are closest to the panel mean as medium high (above the panel mean) and medium low (below the panel mean). We tabulated the number of small and large consumers per total and club. Finally, we calculated Gini and Lorenz Asymmetry indices based on club interval ARTPs for the total number of consumers and separately for big and small consumers, and for convergence clubs with at least 10 members. We included these measures in Appendix 2 (Club descriptive statistics).

3. Summary of results

3.1. Convergence statistics

For all sources of energy, except solar, the log t regression rejected the null hypothesis of convergence in the percentage of coal in the energy portfolio at a 5% confidence level.

3.1.1. Coal

74 economies were initially allocated to 10 convergence clubs, while 2 economies diverged. Subsequently, the number of clubs was reduced to 6, and the 2 units remained divergent.

3.1.2. Oil

74 economies were initially allocated to 4 convergence clubs, and 5 economies diverged. Subsequently, the number of divergent units was reduced to 3.

3.1.3. Gas

73 economies were initially allocated to 9 convergence clubs, and 3 countries diverged. Subsequently, the number of clubs was reduced to 7 and the number of divergent units to 1.

3.1.4. Nuclear

29 economies were allocated to 4 convergence clubs, and 1 economy diverged.

3.1.5. Hydro

67 economies were initially allocated to 9 convergence clubs. Subsequently, the number of clubs was reduced to 8, and the initial number of divergent units was reduced from 3 to 2.

3.1.6. Biofuels

55 economies were allocated to 4 convergence clubs, and 2 diverged.

3.1.7. Other Renewables

67 economies were allocated to 6 clubs, and 1 economy diverged. The number of clubs was reduced to 4.

3.1.8. Wind

70 economies were allocated to 5, and then to 3 convergence clubs.

3.1.9. Solar

78 economies converge in their share of solar within the energy portfolio. The small beta value indicates relative convergence.

3.2. Tables and figures for convergence statistics

3.2.1. Regression and club allocation results (log-t regression)

Following are the regression and club allocation results (Tables 3–11).

Table 3. Regression coal.

	Units	Beta	Std.err	T
All	76			
Club 1	11	−0.33	0.212	−1.556
Club 2	11	0.042	0.17	0.248
Club 3	11	0.111	0.189	0.587
Club 4	6	0.335	0.321	1.046
Club 5	30	−0.353	0.224	−1.581
Club 6	5	−0.435	0.273	−1.595

Table 4. Regression oil.

	Units	Beta	Std.err	T
All	79			
Club 1	7	0.185	0.163	1.134
Club 2	14	−0.062	0.133	−0.467
Club 3	37	−0.157	0.133	−1.174
Club 4	18	−0.007	0.126	−0.057

Table 5. Regression gas.

Clubs	Units	Beta	Std.err	T
All	76			
Club 1	4	−0.087	0.397	−0.129
Club 2	14	−0.189	0.117	−1.608
Club 3	5	0.213	0.229	0.93
Club 4	26	−0.103	0.116	−0.891
Club 5	13	0.202	0.271	0.746
Club 6	10	−0.3	0.191	−1.576
Club 7	3	−0.777	1.09	−0.713

Table 6. Regression nuclear.

	Units	Beta	Std.err	T
All	30			
Club 1	7	−0.656	0.451	−1.455
Club 2	2	−2.335	1.578	−1.48
Club 3	8	−0.714	0.519	−1.376
Club 4	12	0.218	0.24	0.906

Table 7. Regression hydro.

	Units	Beta	Std.err	T
All	70			
Club 1	7	−0.232	0.239	−0.971
Club 2	4	−0.853	1.267	−0.673
Club 3	19	−0.515	0.344	−1.496
Club 4	18	−0.323	0.392	−0.824
Club 5	12	−0.246	0.161	−1.534
Club 6	2	−3.878	3.298	−1.176
Club 7	3	−1.737	1.131	−1.536
Club 8	3	1.126	2.313	0.487

Table 8. Regression biofuels.

Clubs	Units	Beta	Std.err	T
All	57			
Club 1	2	−0.213	0.194	−1.095
Club 2	6	−1.082	0.658	−1.645
Club 3	39	−0.453	0.28	−1.617
Club 4	9	0.059	0.098	0.607

Table 9. Regression other renewables.

Clubs	Units	Beta	Std.err	T
All	68			
Club 1	7	0.096	0.084	1.146
Club 2	22	−0.063	0.134	−0.469
Club 3	15	0.462	0.441	1.048
Club 4	23	0.036	0.224	0.16

Table 10. Regression wind.

Clubs	Units	Beta	Std.err	T
All	70			
Club 1	2	−0.114	0.312	−0.366
Club 2	43	−0.035	0.056	−0.625
Club 3	25	−0.07	0.11	−0.638

Table 11. Regression solar.

	Units	Beta	Std.err	T	P
All	78	0.272	0.074	3.765	0.998

3.2.2. **Detailed club membership**

Following is the detailed club membership (Tables 12–20).

Table 12. Club membership coal.

Club Membership Coal
Club 1
South Africa, Estonia, Vietnam, China, India, Kazakhstan, Indonesia, Poland, North Macedonia, Philippines, Morocco
Club 2
Czechia, Taiwan, Pakistan, Australia, Bulgaria, South Korea, Turkey, Japan, Ukraine, Malaysia, Sri Lanka
Club 3
Hong Kong, Israel, Chile, Slovakia, Germany, Slovenia, Romania, Thailand, Finland, Russia, Bangladesh
Club 4
United States, Greece, Colombia, Austria, Netherlands, Mexico
Club 5
Hungary, New Zealand, Ireland, Denmark, Croatia, Brazil, Belarus, Portugal, Belgium, Italy, Canada, Uzbekistan, Spain, Sweden, Lithuania, United Kingdom, France, Peru, Egypt, Iceland, Norway, United Arab Emirates, Luxembourg, Latvia, Argentina, Algeria, Cyprus, Iran, Singapore, Kuwait
Club 6
Switzerland, Oman, Qatar, Ecuador, Saudi Arabia
Divergent
Venezuela, Azerbaijan
Not included
Iraq, Trinidad and Tobago, Turkmenistan

Table 13. Club membership oil.

Club Membership Oil
Club 1
Luxembourg, Sri Lanka, Hong Kong, Iraq, Ecuador, Saudi Arabia, Lithuania
Club 2
Morocco, Greece, Kuwait, Latvia, Belgium, Netherlands, Portugal, Ireland, Spain, Thailand, Denmark, South Korea, Croatia, North Macedonia

Continued on next page

Club Membership Oil
Club 3
Philippines, Chile, Mexico, Peru, Israel, United Arab Emirates, Japan, Taiwan, Italy, Colombia, United Kingdom, United States, New Zealand, Slovenia, Indonesia, Malaysia, Brazil, Switzerland, Egypt, Australia, Austria, Hungary, Germany, Argentina, Algeria, Finland, Oman, Belarus, France, Canada, Romania, Poland, Azerbaijan, Turkey, India, Bulgaria, Bangladesh
Club 4
Venezuela, Iran, Qatar, Vietnam, Pakistan, Slovakia, Sweden, Estonia, Czechia, Kazakhstan, Russia, Turkmenistan, South Africa, Norway, China, Iceland, Ukraine, Uzbekistan
Divergent
Cyprus, Singapore, Trinidad and Tobago

Table 14. Club membership gas.

Club Membership Gas
Club 1
Uzbekistan, Turkmenistan, Iran, Trinidad and Tobago
Club 2
Oman, Azerbaijan, Algeria, Bangladesh, Qatar, Belarus, Egypt, Venezuela, United Arab Emirates, Russia, Argentina, Kuwait, Israel, Iraq
Club 3
Pakistan, Mexico, Italy, Saudi Arabia, United Kingdom
Club 4
Malaysia, Netherlands, Hungary, Thailand, United States, Lithuania, Ukraine, Latvia, Croatia, Canada, Ireland, Kazakhstan, Portugal, Romania, Australia, Slovakia, Peru, Germany, Turkey, Belgium, Colombia, Spain, Japan, Austria, Greece, Taiwan
Club 5
Indonesia, New Zealand, Poland, Czechia, Luxembourg, South Korea, France, Denmark, Chile, Singapore, Bulgaria, Slovenia, North Macedonia
Club 6
Switzerland, Brazil, Hong Kong, Norway, Vietnam, China, Philippines, Estonia, India, South Africa
Club 7
Finland, Morocco, Ecuador
Divergent
Sweden
Not included
Cyprus, Iceland, Sri Lanka

Table 15. Club membership nuclear.

Club Membership Nuclear
Club 1
Sweden, Ukraine, Slovakia, Bulgaria, Switzerland, Finland, Slovenia
Club 2
Czechia, Hungary
Club 3
Belgium, South Korea, Spain, United States, Romania, United Kingdom, Russia, Canada
Club 4
Taiwan, Germany, Japan, Pakistan, Argentina, South Africa, China, Mexico, India, Brazil, Netherlands, Iran
Divergent
France
Not included
Algeria, Australia, Austria, Azerbaijan, Bangladesh, Belarus, Chile, Colombia, Croatia, Cyprus, Denmark, Ecuador, Egypt, Estonia, Greece, Hong Kong, Iceland, Indonesia, Iraq, Ireland, Israel, Italy, Kazakhstan, Kuwait, Latvia, Lithuania, Luxembourg, Malaysia, Morocco, New Zealand, North Macedonia, Norway, Oman, Peru, Philippines, Poland, Portugal, Qatar, Saudi Arabia, Singapore, Sri Lanka, Thailand, Trinidad and Tobago, Turkey, Turkmenistan, United Arab Emirates, Venezuela, Vietnam

Table 16. Club membership hydro.

Club Membership Hydro
Club 1
Iceland, Ecuador, Brazil, Switzerland, Venezuela, Colombia, Peru
Club 2
Sweden, New Zealand, Austria, Canada
Club 3
Croatia, Slovenia, Vietnam, Turkey, Latvia, Chile, Sri Lanka, Romania, Finland, North Macedonia, Pakistan, China, Portugal, Argentina, Italy, Slovakia, Russia, Malaysia, France
Club 4
India, Japan, Philippines, Spain, Bulgaria, Egypt, Greece, Kazakhstan, Uzbekistan, United States, Mexico, Iran, Indonesia, Azerbaijan, Ukraine, Australia, Iraq, Germany

Continued on next page

Club Membership Hydro
Club 5
Lithuania, Morocco, Ireland, Thailand, Czechia, Taiwan, United Kingdom, Luxembourg, Bangladesh, Poland, Belarus, South Korea
Club 6
Hungary, South Africa
Club 7
Belgium, Estonia, Algeria
Club 8
Denmark, Israel, Netherlands
Divergent
Norway, Turkmenistan
Not included
Cyprus, Hong Kong, Kuwait, Oman, Qatar, Saudi Arabia, Singapore, Trinidad and Tobago, United Arab Emirates

Table 17. Club membership biofuels.

Club Membership Biofuels
Club 1
Brazil, Luxembourg
Club 2
Sweden, Indonesia, Argentina, Thailand, Colombia, Lithuania
Club 3
Denmark, Peru, Slovenia, Austria, Finland, France, Spain, Ireland, Romania, Portugal, Philippines, Norway, Bulgaria, Poland, Slovakia, Latvia, Germany, United Kingdom, Hungary, Czechia, Netherlands, Croatia, Belgium, Greece, Switzerland, Canada, Malaysia, Italy, Estonia, Cyprus, Iceland, India, South Korea, Israel, Ecuador, Mexico, Japan, Ukraine, United States
Club 4
Turkey, Australia, China, Hong Kong, Belarus, South Africa, Russia, New Zealand, North Macedonia
Divergent
Taiwan
Not included
Algeria, Azerbaijan, Bangladesh, Chile, Egypt, Iran, Iraq, Kazakhstan, Kuwait, Morocco, Oman, Pakistan, Qatar, Saudi Arabia, Singapore, Sri Lanka, Trinidad and Tobago, Turkmenistan, United Arab Emirates, Uzbekistan, Venezuela, Vietnam

Table 18. Club membership other renewables.

Club Membership Other Renewables
Club 1
Finland, Denmark, New Zealand, Estonia, Latvia, United Kingdom, Croatia
Club 2
Sweden, Philippines, Chile, Brazil, Germany, Italy, Indonesia, Slovakia, Bulgaria, Thailand, Turkey, Austria, Czechia, Portugal, Luxembourg, Hungary, Lithuania, Belgium, Japan, Switzerland, Ireland, South Korea
Club 3
Poland, Netherlands, Colombia, Spain, India, France, Slovenia, China, United States, Mexico, Canada, Ecuador, Australia, North Macedonia, Pakistan
Club 4
Cyprus, Argentina, Taiwan, Peru, Romania, Greece, Sri Lanka, Malaysia, Singapore, Azerbaijan, Norway, Ukraine, Israel, Belarus, South Africa, Hong Kong, Qatar, Vietnam, Russia, Bangladesh, Kazakhstan, Iran, Venezuela
Divergent
Iceland
Not included
Algeria, Egypt, Iraq, Kuwait, Morocco, Oman, Saudi Arabia, Trinidad and Tobago, Turkmenistan, United Arab Emirates, Uzbekistan, Venezuela

Table 19. Club membership wind.

Club Membership Wind
Club 1
Denmark, Ireland
Club 2
Portugal, Germany, Spain, Sweden, United Kingdom, Greece, Lithuania, Finland, Morocco, Romania, Austria, Brazil, Croatia, Belgium, Poland, France, Turkey, Australia, United States, Netherlands, Italy, Estonia, Norway, Chile, China, New Zealand, Canada, Mexico, India, Luxembourg, Argentina, Peru, Egypt, South Africa, North Macedonia, Pakistan, Cyprus, Bulgaria, Philippines, Latvia, Sri Lanka, Thailand, Ukraine

Continued on next page

Club Membership Wind
Club 3
Hungary, Czechia, Taiwan, Japan, Kazakhstan, South Korea, Vietnam, Azerbaijan, Belarus, Switzerland, Ecuador, Iran, Indonesia, Israel, Colombia, Iceland, Venezuela, Slovenia, Russia, Slovakia, Algeria, Bangladesh, Kuwait, Hong Kong, Saudi Arabia
Not included
Algeria, Egypt, Iraq, Kuwait, Malaysia, Morocco, Oman, Qatar, Saudi Arabia, Singapore, Trinidad and Tobago, Turkmenistan, United Arab Emirates, Uzbekistan, Venezuela

Table 20. Club membership solar.

Club Membership Solar
Convergence (1 Club)
Greece, Chile, Japan, Italy, Germany, Australia, Israel, Spain, Cyprus, Bulgaria, Switzerland, Morocco, Belgium, United Kingdom, China, Hungary, Netherlands, Turkey, Denmark, India, Czechia, Sri Lanka, Romania, Portugal, Mexico, Vietnam, France, South Korea, United States, Austria, Slovenia, Thailand, South Africa, Slovakia, Ukraine, Taiwan, United Arab Emirates, Luxembourg, Peru, Philippines, Brazil, Egypt, Lithuania, Estonia, Malaysia, Sweden, Canada, Algeria, Croatia, Argentina, North Macedonia, Pakistan, Bangladesh, Iraq, Poland, Belarus, New Zealand, Kazakhstan, Finland, Azerbaijan, Colombia, Ireland, Singapore, Norway, Ecuador, Iran, Kuwait, Russia, Latvia, Saudi Arabia, Indonesia, Hong Kong, Oman, Trinidad and Tobago, Turkmenistan, Uzbekistan, Qatar, Venezuela
Not included
Iceland

3.2.3. Figures (average transition paths or club trajectories)

Following are the average transition paths or club trajectories (Figures 1–9).

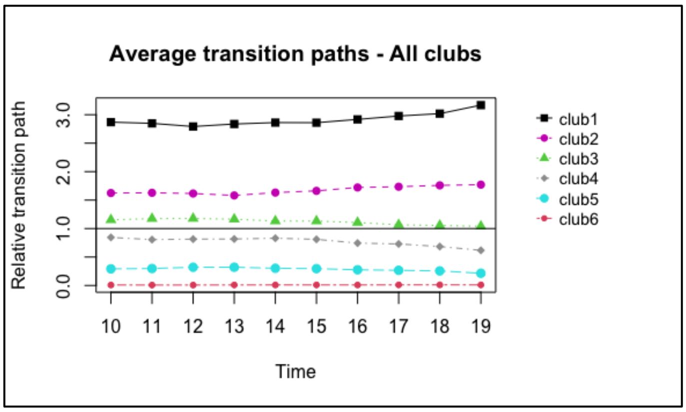

Figure 1. Average transition paths coal.

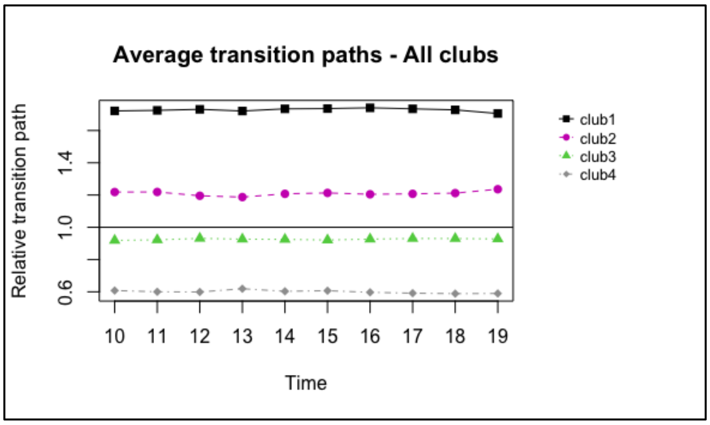

Figure 2. Average transition paths oil.

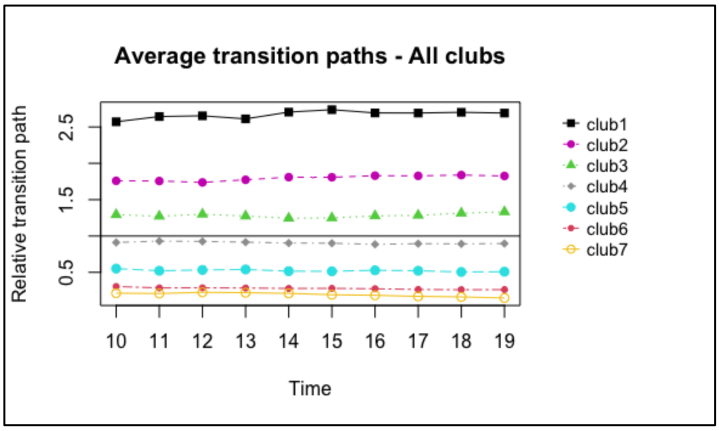

Figure 3. Average transition paths gas.

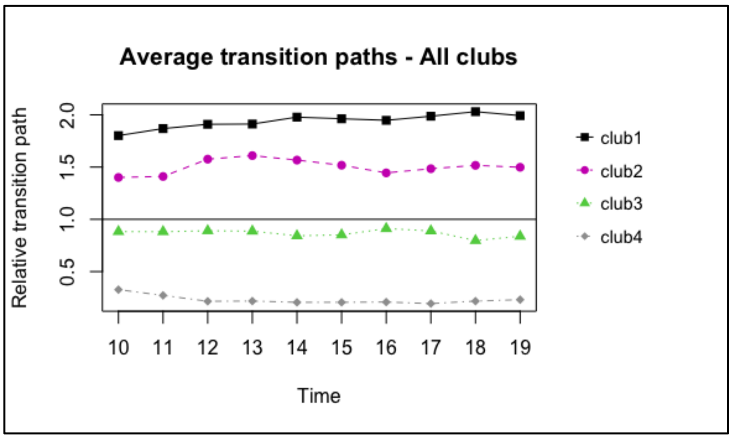

Figure 4. Average transition paths nuclear.

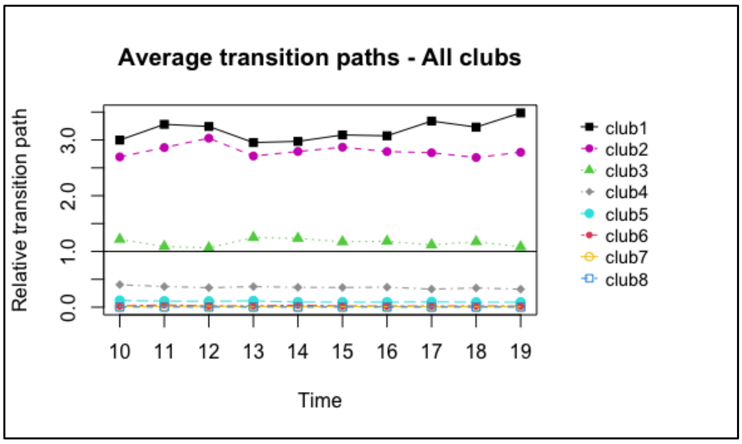

Figure 5. Average transition paths hydro.

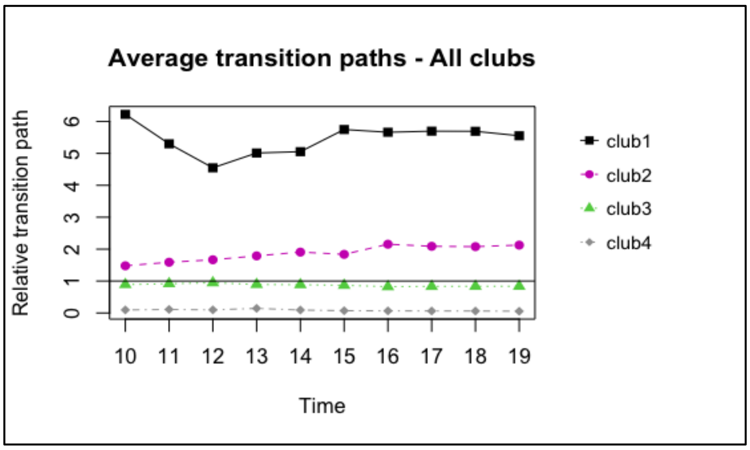

Figure 6. Average transition paths biofuels.

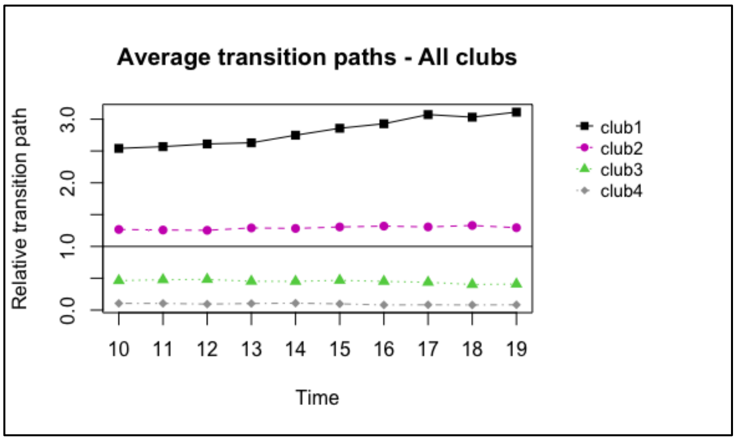

Figure 7. Average transition paths other renewables.

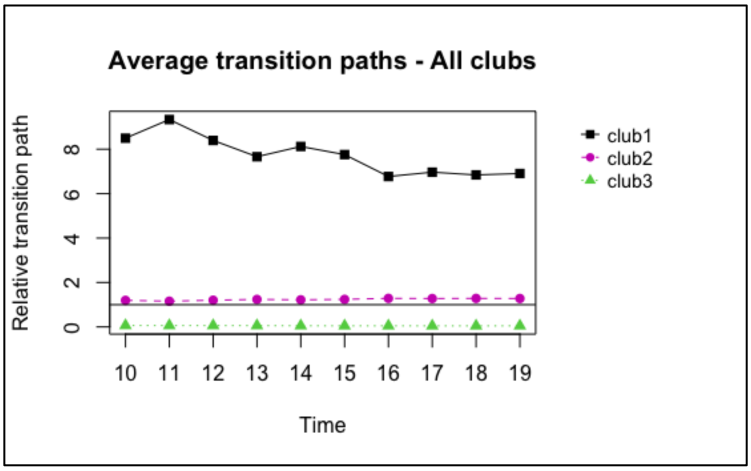

Figure 8. Average transition paths wind.

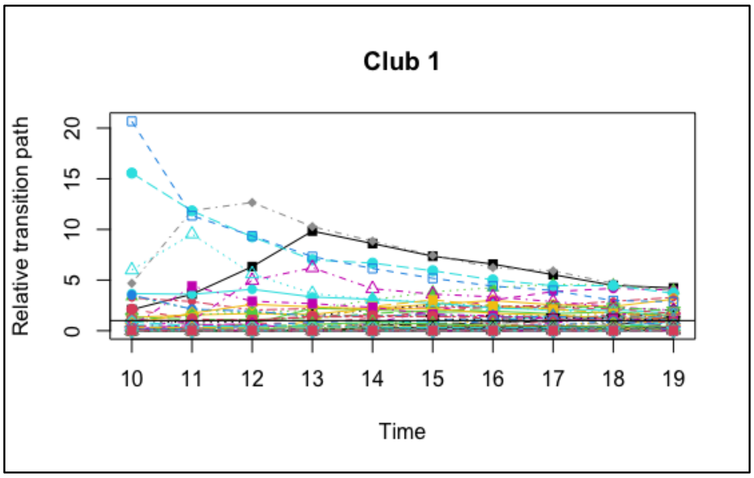

Figure 9. Average transition paths solar.

4. Results and discussion

4.1. Results

4.1.1. Coal

Coal represents 28% of the total fossil fuel consumption and 44% of the total fossil fuel carbon emissions (IEA, 2024). 96% (76 of 79) of the economies in our sample use coal. The panel's mean share of coal in the energy portfolio is 16.09%[1]. Coal consumers failed to converge as far as coal shares in individual portfolios are concerned. Instead, they diverged into 6 convergence clubs and 2 divergent units. Three clubs (clubs 1 to 3) have a high level of consumption, and 3 (clubs 4 to 6) have a low level of consumption. Club 3 has a medium-high consumption, and Club 4 has a medium-low consumption. Average club consumption magnitudes range from 0 to −3. Clubs 1, 2, and 6 converge by increasing consumption, while clubs 3 to 5 converge by decreasing consumption. Club 1 and 2 total 22 members, of which 20 are big consumers. Among the members of club 2, Japan and South Korea have no internal coal production, yet allocate over 20% of their energy portfolio to coal. Club 5 is the most populous club, with 30 members. Club 6 unites the smallest consumers. With the exception of Switzerland, the members of clubs 6 are net exporters of oil or gas[2]. They have little, if any, renewables in their portfolio, relying exclusively on fossil fuels.

The ratio of small to big consumers is 1.6. Individual consumption magnitudes range from 0 to −4. South Africa (4.43*panel mean) and China (3.99*panel mean) are the biggest consumers. Azerbaijan (0.002*panel mean), one of the divergent units, is the smallest consumer. Overall, there are severe inequalities in consumption (0.55 GC), due to the large number of small consumers (0.82 LA). There is relative equality among the big consumers (0.24 GC) and big inequality among the small consumers (0.5 GC). Extremely high consumption levels are identified among the big consumers (1.15 LA). A total of 45% (34 of 76) of the consumers of coal have positive growth rates. Fourteen of them belong to clubs 1 and 2, while 3 belong to club 6. South Africa, the biggest consumer, has a modest positive growth rate of 0 magnitude. The biggest growth rate, of +3 magnitude, belongs to Singapore, a small consumer. The smallest growth rate belongs to Turkey, of 0 magnitude. Turkey is a big consumer and is a member of Club 2.

In descending order, the top 10 world coal producers in 2019 are[3] China, US, India, Indonesia, Australia, Russia, South Africa, Kazakhstan, Colombia, and Poland. China, India, Indonesia, South Africa, Poland, and Kazakhstan belong to Club 1. Australia belongs to Club 2. Russia belongs to Club 3. The US and Colombia belong to Club 4. With the exception of Russia and Colombia, all are big consumers. With the exception of US and Colombia, all belong to clubs with high consumption. Indonesia, US, Australia, Russia, South Africa, and Kazakhstan are net exporters of coal. On average, the top coal producers consume 51% of the coal produced.

[1] Calculations based on data available at: https://ourworldindata.org/energy-production-consumption

[2] Calculations based on data available at: https://www.eia.gov/international/overview/country/

[3] https://www.eia.gov/international/rankings/world

4.1.2. Oil

Oil represents 30% of the total fossil fuel consumption and 32% of the total fossil fuel carbon emissions (IEA, 2024). The panel's mean share of oil in the energy portfolio is 39.7%[4]. Consumers diverge into 4 convergence clubs and 1 divergent club (3 units). Two clubs (Clubs 1 and 2) have an above the mean consumption, and 2 (clubs 3 and 4) have a below the mean consumption. Average club consumption magnitudes range from 0 to −1. Club 4 converges by decreasing consumption, while the remaining clubs converge by maintaining a steady average. Club 4 has 18 members and unites the smallest consumers. The largest club is Club 3, with 37 members. Club 3 is the closest in consumption to the panel mean. 70% of the economies (55 out of 79) allocate below the mean % of their portfolio to oil.

The ratio of small to big consumers is 1.3, the lowest ratio among the three fossil fuels (oil, coal, and gas). Individual consumption magnitudes range from 0 to −1. Cyprus (2.43*panel mean) and Singapore (2.19*panel mean), 2 of the 3 divergent units, are the biggest consumers. None of them is an oil producer, and both are heavily dependent on energy imports. A third divergent unit, Trinidad and Tobago (0.28*panel mean), has the second smallest share of oil and relies heavily on gas. Uzbekistan (0.23*panel mean) is the smallest consumer. Overall, there is adequate equality in consumption (0.22 GC). There is perfect equality among the big consumers (0.14 GC) and small consumers (0.15 GC). Extremely high consumption levels are identified among the big consumers (1.29 LA). A total of 56% (44 of 79) of the oil consumers have positive growth rates. A total of 75% (33 of 44) of the consumers belong to clubs with low consumption. Among them, 30% (10 of 33) belong to club 4. Cyprus, the biggest consumer, has a modest negative growth rate of −1 magnitude. The biggest growth rate, of +1 magnitude, belongs to Bangladesh, a small consumer. The smallest growth rate belongs to France, a small consumer.

In descending order, the top 10 world oil producers in 2019 are[5]: US, Russia, Saudi Arabia, Canada, Iraq, UAE, China, Iran, Kuwait, and Brazil. Saudi Arabia and Iraq belong to Club 1. Kuwait belongs to Club 2. The US, Canada, UAE, and Brazil belong to club 3. Russia, China, and Iran belong to Club 4. With the exception of Saudi Arabia, Iraq, and Kuwait, all are classed as small consumers. 6 of the top 10 producers are net exporters of oil[6]: Russia, Saudi Arabia, Iraq, UAE, Iran, and Kuwait. On average, they consume 33.1% of the oil produced. With the exception of Iran, they mostly rely on gas to populate their energy portfolio.

4.1.3. Gas

Gas represents 23% of the total fossil fuel consumption and 22% of the total fossil fuel carbon emissions (IEA, 2024). A total of 96% (76 of 79) of the economies in our sample are using gas. The 3 economies that do not use gas are Cyprus, Iceland, and Sri Lanka. These economies are over-reliant

[4] Calculations based on data available at: https://ourworldindata.org/energy-production-consumption

[5] https://www.eia.gov/international/rankings/world

[6] Calculations based on data available at: https://www.eia.gov/international/overview/country/

on oil and hydro. The panel's mean share of gas in the energy portfolio is 29.26%[7]. Economies polarized into 7 convergence clubs and 1 divergent unit. Three clubs (Clubs 1 to 3) have a high consumption, and 4 clubs (Clubs 4 to 7) have a low consumption. Clubs 3 and 4 have a medium-high and a medium-low consumption. Average club consumption magnitudes range from 0 to −1. 5 clubs exhibit trends in their consumption. Clubs 1 and 3 converge by maintaining a steady average consumption. Club 2 converges by increasing consumption, while Clubs 4 to 7 converge by decreasing consumption. The largest club is Club 4, with 26 members. Club 2 has 14 members, out of which 10 are big consumers. Among the members of Clubs 2 and 3, Belarus and Italy stand out as they have no internal gas production. With the exception of Iraq and Kuwait, all other members cover at least 80% of their gas needs from internal sources, and 9 are net exporters. Among the members of Club 4, 8 are big consumers.

The ratio of small to big consumers is 1.7. Individual consumption magnitudes range from 0 to −2. The biggest consumer is Trinidad Tobago (3.03*panel mean), a net exporter of gas. The smallest consumer is Sweden (0.06*panel mean), the divergent unit. Overall, there is adequate equality in consumption (0.38 GC). There is perfect equality among the big consumers (0.19 GC) and relative equality among the small consumers (0.28 GC). Extremely high consumption levels are identified among the big consumers (1.02 LA). A total of 49% (37 of 76) of the consumers of gas have positive growth rates. Twelve of them belong to high consumption clubs that converge either by maintaining or increasing consumption. Trinidad and Tobago, the biggest consumer, has a modest positive growth rate of 0 magnitude. The biggest growth rates belong to North Macedonia and China, of +2 magnitude, both small consumers. The smallest growth rate belongs to Switzerland, a small consumer.

In descending order, the top 10 world gas producers in 2019 are[8]: US, Russia, Iran, Qatar, Canada, China, Australia, Norway, Saudi Arabia, and Algeria. Iran belongs to Club 1. Russia, Qatar, and Algeria belong to Club 2. Saudi Arabia belongs to Club 3. The US, Canada, and Australia belong to Club 4. China and Norway belong to Club 6. The US, Canada, China, Australia, and Norway have small shares of gas in their portfolios, while Russia, Iran, Qatar, Saudi Arabia, and Algeria are big consumers. Norway belongs to club 6, a small consumers club. Norway is unique among the gas producers in that it uses only 4% of its gas production internally, while relying heavily on hydro. With the exception of China and Saudi Arabia, the top 10 gas producers are net exporters of gas. On average, they consume 71% of their production internally. Saudi Arabia has the capacity to cover 100% of its gas consumption internally[9].

4.1.4. Nuclear

Only 38% (30 of 79) of the economies in our sample and 15% of the world economies are using nuclear. The panel's mean share of nuclear in the energy portfolio is 9.38%[10]. Consumers diverge into 4 convergence clubs and 1 divergent unit. Two clubs have a high consumption (Clubs 1 and 2) and 2 (Clubs 3 and 4) have

[7] Calculations based on data available at: https://ourworldindata.org/energy-production-consumption

[8] https://www.eia.gov/international/rankings/world

[9] Calculations based on data available at: https://www.eia.gov/international/overview/country/

[10] Calculations based on data available at: https://ourworldindata.org/energy-production-consumption

a low consumption. Club 3 has a medium-low consumption. Average club consumption magnitudes range from 0 to −1. Club 1 converges by increasing consumption. The remaining clubs converge by maintaining a steady average. The largest club is Club 4, with 12 members. The US, Russia, and Canada, the technology leaders, are small consumers and belong to Club 3. The ratio of small to big consumers is 1.6. Individual consumption magnitudes range from 0 to −2. France (3.73* panel mean), the divergent unit, is the biggest consumer. Iran is the smallest consumer, of −2 magnitude. Overall, there are big inequalities in consumption (0.47 GC), due to the large number of small consumers (0.87 LA). There is perfect equality among the big consumers (0.16 GC) and big inequality among the small consumers (0.41 GC).

A total of 57% (17 of 30) of the consumers of nuclear have positive growth rates. Six of them (Ukraine, Finland, Slovakia, Slovenia, Sweden, and Bulgaria) belong to club 1, the only club that converges by increasing its share of nuclear power. A total of 53% (9 of 17) of the positive growth rate consumers are among the small consumers, belonging to Clubs 3 and 4. The biggest growth rate, of +3 magnitude, belongs to Iran, the smallest consumer. The smallest growth rate belongs to Canada, one of the pioneers in the field.

The big fossil fuel producers tend to have relatively small shares of nuclear, if any, in their portfolios. Australia, Indonesia, and Iraq aside, all top 5 producers of coal, oil, and gas use nuclear power, and based on their club affiliation, are classed as small consumers. The top 10 economies by uranium production in 2019 are[11]: Kazakhstan, Canada, Australia, Namibia, Uzbekistan, Niger, Russia, China, Ukraine, and India. Kazakhstan is by far the biggest producer, with production figures up to 4 times higher than those of Canada and covering 42% of the total. Only 12 of the 30 nuclear users have had recent uranium production: Canada, China, Germany, Hungary, India, Iran, Netherlands, Pakistan, Russia, South Africa, Ukraine, and the US. Of these, only Canada and South Africa had the capacity to cover demand internally[12]. France, the biggest consumer of nuclear, stopped production in 2011.

4.1.5. Hydro

A total of 89% (70 of 79) of the economies in our sample are using hydro. The panel's mean share of hydro in the energy portfolio is 9.61%[13]. Consumers diverge into 8 convergence clubs and 2 divergent units. Three clubs (Clubs 1 to 3) have a high consumption, and 5 clubs (Clubs 4 to 8) have a low consumption. Club 3 has a medium-high consumption. Club average consumption magnitudes range from 0 to −3. Clubs 3 and 4 are the largest clubs, with 19 and 18 members. Clubs 4 and 5 converge by decreasing their average share of hydro, while all other clubs converge by maintaining a steady mean consumption.

The ratio of small to big consumers is 1.6, similar to that of coal. Individual consumption magnitudes range from 0 to −4. The divergent units are Norway (6.96*panel mean) and Turkmenistan (0.0003*panel mean). Norway is the biggest consumer, while Turkmenistan is the smallest consumer. Iceland (6.14*panel

[11] https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/7555_uranium_-_resources_production_and_demand_2020__web.pdf

[12] Calculations based on data in the document at footnote 11

[13] Calculations based on data available at: https://ourworldindata.org/energy-production-consumption

mean) is the second biggest consumer. Overall, there are severe inequalities in consumption (0.62 GC), due to the large number of small consumers (0.86 LA). The big consumers benefit from relative equality (0.29 GC), while among the small consumers, there are big inequalities in consumption (0.5 GC). 44% (31 of 70) of the hydro consumers benefit from positive growth rates. Although 65% of the positive growth rates are encountered among the small consumers, these are not sufficient to push them into the high consumption clubs. Exceptions are China, France, Italy, Malaysia and Russia (club 3). The biggest growth rate belongs to Belarus, of +2 magnitude. Although not water stressed, Belarus has little, if any, hydro potential.

Economies with big fossil fuel resources tend to have small shares of hydro in their portfolios. All the top 5 producers of coal, oil, and gas are using hydro energy[14]. Canada belongs to Club 2. Russia and China belong to Club 3. The US, Iraq, Iran, India, Indonesia, and Australia belong to Club 4. Iran and India are extremely water-stressed economies. Canada allocates a big share of its energy portfolio to hydro. The remaining top producers have small shares of hydro in their energy portfolios. There are 6 extremely water-stressed economies in our sample[15]: Pakistan (Club 3), India, Iran, Egypt (Club 4), Israel (Club 8), and Turkmenistan (divergent). Nine economies are severely water stressed: Turkey, Chile, Italy (Club 3), Spain, Greece, Mexico, Uzbekistan (Club 4), Morocco (Club 5), Algeria, and Belgium (Club 7). With the exception of Pakistan, Turkey, and Chile, all the above economies are small consumers of hydro. Club 1 is the only club that does not contain severely or extremely water stressed members. Nine economies are not geographically suitable for hydro, while being hydrographically well endowed: Japan (Club 4), Belarus, South Korea (Club 5), Hungary, South Africa (Club 6), Belgium, Estonia (Club 7), and Denmark and the Netherlands (Club 8). All are small consumers. The Philippines makes an interesting case. The Philippines (Club 4) has a low water stress score and benefits from appropriate topography. However, the Philippines lacks public support for hydrographic projects. Therefore, the Philippines is a small consumer.

4.1.6. Biofuels

A total of 72% (57 of 79) of the economies in our sample are using biofuels. The panel's mean share of biofuels in the energy portfolio is 0.7%[16]. Consumers diverge into 4 convergence clubs and 1 divergent unit. Two clubs (Clubs 1 and 2) have high consumption levels and 2 clubs (Clubs 3 and 4) have a low consumption. Club 2 has a medium-high consumption, and Club 3 has a medium-low consumption, with the latter almost touching the panel mean consumption. Average club consumption magnitudes range from 0 to −2. The largest club is club 3, with 39 members. Club 1 converges by maintaining a steady pace. Club 2 converges by increasing its share of biofuels. Clubs 3 and 4 converge by decreasing their share of biofuels.

The ratio of small to big consumers is 1.3, similar to that of oil. Individual consumption magnitudes range from 0 to −3. Brazil (8.18*panel mean) is the biggest consumer. Together with the US (2.04*panel mean), Brazil is the leader in the field. The US belongs to club 3. Taiwan, the divergent

[14] Calculations based on data available at: https://www.eia.gov/international/overview/country/

[15] https://worldpopulationreview.com/country-rankings/water-stress-by-country

[16] Calculations based on data available at: https://ourworldindata.org/energy-production-consumption

unit, is a small consumer of −2 magnitude. Russia, with vast biomass resources, is a late adopter and has the smallest share of biofuels, of −3 magnitude. Overall, there are severe inequalities in consumption (0.68 GC), due to the large number of small consumers (0.85 LA). There is relative equality among the big consumers (0.27 GC) and big inequality among the small consumers (0.5 GC). A total of 51% (29 of 57) of the consumers of biofuels have positive growth rates. Five of them, Argentina, Lithuania, Indonesia, Thailand, and Sweden, belong to Club 2, a club that converges by increasing its share of biofuels. A total of 77% (23 of 29) of the positive growth rate consumers are among the small consumers, the majority belonging to Club 3, the club with the closest consumption to the panel mean. The biggest growth rate belongs to Iceland, of +4 magnitude. Iceland is a small consumer. The smallest growth rate belongs to Taiwan of −1 magnitude.

Big fossil fuel producers tend to have relatively small shares of biofuels in their portfolios. Iran and Iraq aside, all the top 5 producers of coal, oil, and gas use biofuels. Indonesia belongs to Club 2. Canada, India, and the US belong to Club 3, while Australia, China, and Russia belong to Club 4. Indonesia is the only top producer of fossil fuels that is a big consumer of biofuels and belongs to a high consumption club. All other top producers are small consumers of biofuels.

4.1.7. Other Renewables

A total of 86% (68 of 79) of our panel members use other renewables. The panel mean share of other renewables in the energy portfolio is 2.05%[17]. Economies diverge into 4 convergence clubs and 1 divergent unit. Two clubs (Clubs 1 and 2) have a high consumption level, and 2 club (Clubs 3 and 4) have a low consumption level. Club average consumption magnitudes range from 0 to −2. Club 1 converges by increasing its share of other renewables, while Clubs 2 to 4 converge by decreasing their shares of other renewables. Club 2 and Club 4 are the most numerous, with 22 and 23 members. A total of 69% (18 of 26) of the EU economies in our sample belong to Clubs 1 and 2, which are high consumption clubs. With the exception of New Zealand, all Club 1 members are or have been EU members.

The ratio of small to big consumers is 2.4. Individual consumption magnitudes range from 0 to −4. The biggest consumer is Iceland (11.05*panel mean), the divergent unit. Iceland is the pioneer and innovator in the field of geothermal. Dubbed ‘energy for the people’ by Fridleifsson (2000), geothermal is an important source of low-carbon-emission heat generation. The smallest consumer is Kazakhstan (0.0002*panel mean), a late adopter and an important fossil fuel producer. Overall, there are severe inequalities in consumption (0.65 GC), due to the large number of small consumers (0.93 LA). There is adequate equality among the big consumers (0.36 GC), and there are big inequalities among the small consumers (0.49 GC). 54% (37 out of 68) of the consumers of other renewables benefit from positive growth rates. A total of 62% (23 of 37) of the consumers showing positive growth rates are small consumers. The biggest growth rate belongs to Bulgaria, of +3 orders of magnitude. The smallest growth rate, of 0 order of magnitude, belongs to Germany, a Club 2 member.

Economies with big fossil fuels resources tend to have relatively small shares of other renewables in their portfolios. With the exception of Iraq, all the top 5 producers of coal, oil, and gas use other

[17] Calculations based on data available at: https://ourworldindata.org/energy-production-consumption

renewables. Indonesia belongs to Club 2. The US, Canada, China, India, and Australia belong to Club 3. Russia and Iran belong to Club 4. With the exception of Indonesia, all top producers of fossil fuels are small consumers of other renewables.

4.1.8. Wind

A total of 89% (70 out of 79) of our panel members use wind. The panel's mean share of wind in the energy portfolio is 1.72%[18]. Economies diverge into 3 convergence clubs. Two clubs (Clubs 1 and 2) have high consumption levels, and 1 club (Club 3) has a low consumption. Club 3 is a medium-low consuming club. Average club consumption magnitudes are 0 (Club 1 and Club 2) and −2 (Club 3). This sudden drop (unlike for the other energies, where the drop is gradual) indicates large inequalities in consumption between the big and the small consumers. The gap in consumption between the members of Club 3 (25) and those of Club 2 (43) increases throughout the interval. There are no divergent units. This is unique among all the energy sources reviewed. Three clubs exhibit trends in their consumption. Club 2 converges by maintaining a steady mean consumption. Clubs 1 and 3 converge by decreasing their consumption of wind. With 43 members, Club 2 is the biggest club. The club has an almost even split between small (22) and big (22) consumers and a high average consumption, suggesting high consumption levels among the big consumers and potential for the small consumers to become big consumers.

The ratio of small to big consumers is 2.1. Individual consumption magnitudes range from 0 to −5. Denmark (10.1*panel mean) and Portugal (6.7*panel mean) have the biggest % of their portfolio allocated to wind. Denmark is the pioneer and innovator in the field of wind energy. The smallest share belongs to Saudi Arabia (0.00006*). Overall, there are severe inequalities in consumption (0.52 GC), due to the large number of small consumers (0.81 LA). There is adequate equality among the big consumers (0.4 GC) and severe inequality among the small consumers (0.6 GC). A total of 63% (44 of 70) of the consumers of wind benefit from positive growth rates. A total of 73% (32 of 44) of those with a higher consumption in 2019 than in 2010, or in the first year of data, belong to Club 2. The remaining 27% (12 of 44) belong to Club 3. Peru, a small consumer, has the largest growth rate, of +4 orders of magnitude. The smallest growth rate belongs to Ireland.

Economies with big fossil fuel resources tend to have small shares of wind in their energy portfolios. All the top 5 producers of coal, oil, and gas use wind. Australia, the US, China, Canada, and India belong to Club 2, while Iran, Indonesia, Russia, and Saudi Arabia belong to Club 3. Only Australia and the US are big consumers. Iraq started using wind in 2024.

4.1.9. Solar

A total of 78 of the 79 economies in our sample are using solar. The exception is Iceland, with adverse geographic conditions. The panel's mean share of solar in the energy portfolio is 1.42%[19]. The ratio of small to big consumers is 2.5, with 70% of the economies in our sample classed as small

[18] Calculations based on data available at: https://ourworldindata.org/energy-production-consumption

[19] Calculations based on data available at: https://ourworldindata.org/energy-production-consumption

consumers. The solar consumers converge by increasing the percentage of solar in their energy mix. Overall, there are severe inequalities in consumption (0.7 GC), due to the large number of small consumers (0.89 LA). There is adequate equality among the big consumers (0.39 GC) and severe inequality among the small consumers (0.59 GC).

Individual consumption magnitudes range from 0 to −3. Italy, Spain, Germany, Greece, and Czechia have the largest shares of solar in their energy portfolios. They are identifiable on the graph (Figure 1) as the furthest up from the mean and have remarkable trajectories. The smallest consumer is Uzbekistan. China, the leader in solar technology, is a small consumer. Consumers converge by increasing their average share of solar. A total of 80% of the solar consumer benefit from positive growth rates, the highest percentage among all energy types. Spectacular growth rates are encountered, with magnitudes as high as +5 for Brazil and Chile. All the top 5 producers of coal, oil, and gas are using solar: The US, Russia, Saudi Arabia, Canada, Iraq, China, Iran, India, Indonesia, and Australia. Among them, only Australia has a share of solar in its energy mix that is above the panel mean. Canada has a negative growth rate.

4.2. Discussion

Starting with Arrhenius in the 19th century, numerous studies have demonstrated that carbon emissions play a significant role in climatic changes through their impact on global warming [1,3,5,6]. Fossil fuels, the main resource of economic activity worldwide, are an important source of carbon emissions, contributing therefore to climate change [2,4]. There is strong evidence that a decrease in the consumption of fossil fuels, coupled with an increase in the consumption of renewables, results in a decrease in atmospheric carbon dioxide levels [14,38]. Therefore, a gradual transition of the world economies from fossil fuels to renewables is seen as the most important mitigator of climate change. Within this context, in 2015, the Paris Agreement was signed by 194 countries and became legally binding in 2016. The agreement stipulates a 45% reduction in carbon dioxide emissions by 2030 from 2010 levels, with net zero achieved in 2050. With 25 years left to 2050, how prepared and how willing are the world economies to implement such initiatives? While the nexus between economic growth, energy consumption, fossil fuel, and renewables consumption is not clear-cut, there is no ambiguity about the impact of fossil fuels and renewables on carbon emissions. This conundrum may dampen efforts to reduce carbon emissions, as economies are balancing economic growth and the duty of care. The recent withdrawal of the USA from the Paris Agreement signals that, at least in the short term, the world's leading economy will increase its renewables capabilities solely on a profit basis.

We conducted this study with the hope that its findings would provide potential answers to a number of questions regarding energy consumption, questions that would help us understand the progress that has been made by world economies in the energy transition. We hoped that a club convergence analysis applied to the energy consumption of a large number of world economies during the interval 2010–2019 would enable us to supply answers to the following questions: 1) Is there evidence that at least some of the world economies decrease their fossil fuel consumption? 2) Is there evidence that at least some of the world economies increase their renewables consumption? 3) Is there evidence that at least some economies have similar energy consumption patterns? 4) Is there evidence for a worldwide effort to mitigate the effects of climate change?

We found that with the exception of solar, as economies diverge into convergent and divergent clubs, there is no evidence for a uniform consumption level to be attained in the near future (classic convergence). However, the presence of clubs indicates that there are groups of economies that approach a common consumption level (club convergence). These clubs can be used to tailor energy transition policies. The club consumption trends may signal groups of economies where consumption can be encouraged or deterred. These groups transcend geographical and developmental boundaries. As a general rule, big producers of fossil fuels tend to have small shares of renewables in their energy portfolios. Below, we present the findings of our study, and we offer tentative answers to the questions that we raised above.

4.2.1. Non-Renewables, including fossil fuels

4.2.1.1. Coal

The overwhelming majority of the economies in our sample are using coal as an energy source. Close to half consumed more in 2019 than in 2010 or the first year of consumption. The capacity to source coal internally is key to the consumption of coal, and the abundance of the resource is reflected in the share of the energy portfolio that is allocated to coal. The overwhelming majority of the top producers have the biggest shares of coal in their energy portfolios. Legacy infrastructures may constrain less fortunate coal consumers to heavy export dependencies, as in the case of Japan and South Korea. The relatively large number of clubs (6 convergent and 1 divergent) suggests big disparities in consumption levels and trajectories among the coal consumers. Internal access to coal and legacy infrastructures may be two of the factors behind these disparities. The high consumption average of coal points towards a difficult energy transition process. The medium to low consumption clubs show signs of decreasing their consumption. The high consumption clubs increase their consumption.

Cai et al. (2023) investigated the convergence of coal consumption in 39 developed (26) and developing (13) countries during the time period 1960–2017 [24]. They found that the developed countries and all but 5 of the developing countries converged in their individual coal consumption. Ireland, China, Indonesia, Vietnam, and South Africa diverged. The authors recommended that the developing economies in general and the divergent economies in particular should concentrate on energy transition policies. All 39 economies are included in our sample. China, Indonesia, Vietnam, and South Africa belong to club 1. Club 1 unites the world's biggest consumers of coal and shows an upward trend in its average consumption of coal. Ireland belongs to club 5. Club 5 is the most numerous club, with the second smallest consumers and a downward trend in consumption. Cai et al. (2023) concentrated on coal consumption in million tons for the time period 1960–2017, while we used the share of coal in the energy portfolio during 2010–2019. Although direct comparisons cannot be made, we believe the two studies can complement each other.

4.2.1.2. Oil

Oil is the only energy source that is used by all the economies in our sample. The consumption of oil has some unique characteristics that distinguish it from all other energy sources. The concentration of oil in the energy mix is generally high, with extremes of 85% for Singapore and 94% for Cyprus. Even among the economies that are least dependent on oil, consumption is high in comparison to other energy sources. Regardless of consumer type, oil has the highest consumption rates and the lowest growth rates across all energy types. The relatively small number of clubs (4 convergent and 1 divergent) points toward compact groups of economies. Economies are geared to consume oil, yet they may have reached the maximum of their capabilities, or oil is becoming less attractive. As a rule, big oil producers do not allocate large proportions of their energy portfolio to oil. They rely on internal energy sources to populate a large part of their portfolio. Unlike coal and gas, oil is seen first as a commodity, as currency that can be traded internationally, and then as a resource to be internally consumed. In contradistinction, economies with little, if any, internal oil production are heavily dependent on oil. All these are signs of a mature, global market.

The relatively small number of densely populated clubs, the smallest among fossil fuels, suggests that there are sufficiently large groups of economies that approach a common consumption level. This may be due to stable supply chains and firm legacy infrastructures. The identified consumption groups transcend geographical and developmental boundaries. The staggeringly high consumption average and the polarization of most of the economies into clubs that fail to show a downward trend raise questions as to how and when the energy transition is going to be completed.

We have identified only one study where the authors concentrated on oil convergence, Nazlioglu et al. (2022) [23]. They identified a divergent trend among 15 major oil consumers. The 15 economies diverged into 5 clubs, 4 convergent and 1 divergent. In order of their club membership, these economies were: Australia, Netherlands, US, Finland, Norway (Club 2), Switzerland, Germany, Spain, Japan, Sweden (Club 3), Denmark, France, UK (Club 4), Canada, Italy, and Portugal (Club 5). Our analysis allocated most of these economies (10 of 15) to Club 3, a club with medium-low consumption and no trend. The remaining 5 economies were allocated to Clubs 2 (Netherlands, Spain, and Denmark) and 4 (Sweden and Norway), clubs with a high and a low consumption, respectively. The Nordic economies failed to unite under one club, a similar result to that of Nazlioglu et al. (2022). We consider that this result is in accordance with the energy consumption particularities of these economies. Although united by the same geographic space and benefitting from integrated energy systems, these economies differ significantly in their energy consumption patterns. Similar to Nazlioglu et al. (2022), we failed to further restrict the number of clubs with the aid of the merging algorithm.

An important point to make is that the two studies entailed different variables of interest and time intervals (oil consumption per capita versus share of oil in the energy portfolio, 1994–2017 versus 2010–2019). Although direct comparisons cannot be made, we do believe that the two studies complement each other. Both studies suggest that the world economies do not converge in their consumption of oil. Instead, they polarize into clubs based on consumption patterns. We welcome further studies in this area.

4.2.1.3. Gas

The overwhelming majority of the economies in our sample are using gas as an energy source. The three economies that do not use gas are Cyprus, Iceland, and Sri Lanka. These economies are over-reliant on oil and hydro. Unlike oil, gas is seen first as a resource for internal consumption and then as a revenue source. Indeed, the energy portfolio of the top 10 gas producers is heavily skewed towards gas. We can speculate that among those with significant gas resources, advanced economies tend to use less gas internally than less advanced economies. For example, Australia consumes only 32% of the gas produced, while Saudi Arabia consumes all the gas that it produces. The only country that applies the oil model to gas, i.e., gas as a commodity, is Norway. With the recent technological and infrastructure advances that have been made by the US in the area of LG, we can speculate that more economies are expected to follow the example set by Norway. The relatively large number of clubs (7 Clubs and 1 divergent unit), the largest among fossil fuels, indicates a high level of fragmentation among the gas consumers in our sample. Gas is a relatively new resource, the youngest among fossil fuels, and the consumption paths are heavily influenced by development levels and geopolitics. Net exporters of gas are predominantly found among the big consumers; however, some are also found among the small consumers. The high consumption average indicates that the energy transition process will be difficult to complete. Reassuringly, most clubs converge by decreasing consumption. However, these are clubs with low consumption. On the other hand, the clubs with high consumption do not show signs of decreasing consumption. Unfortunately, we have not been able to identify a multinational study on gas convergence. We are looking forward to such studies.

4.2.1.4. Nuclear

More than a third of our panel members are using nuclear. Nuclear is the most exclusive of the energy sources available, with only 33 current users in the world (Armenia, Belarus, and UAE are missing from our sample) and an additional 8 near future users (Turkey, Egypt, Indonesia, Kenya, Kazakhstan, Bangladesh, Uzbekistan, and the Philippines). Nuclear is a carbon free, non-renewable energy source that is expected to play an important role in the transition to a carbon neutral economy [39–42]. There is evidence that, at least in the short run, nuclear energy contributes to a reduction in carbon dioxide emissions [13]. Unique to nuclear, the economies that benefit from it are leading world economies or economies with a strong government involvement. A total of 57% are European countries, with the former satellite states of Eastern Europe extremely well represented.

Brook et al. (2014) classify nuclear energy as sustainable, unlike renewables and fossil fuels, and see no impediment in its commodification in terms of technology and supply [42]. The authors recommend the gradual replacement of part of the fossil fuel electricity-generating capacity with nuclear. Undoubtedly, there are going to be some changes within the exclusive club of nuclear users, as several economies have phasing out policies in the pipeline, while others are embarking on ambitious nuclear energy projects. Given the costs and constraints that are associated with nuclear energy, this energy is unlikely to become widespread, at least in the near future. Nevertheless, the increased demands placed on energy by AI and the competition among the AI technology leaders may result in additional capacity creation among current and prospective users. We conjecture that capacity increase will depend not only on economic strength or government involvement, but also on access to uranium production. We speculate that the current status quo in nuclear consumption is dependent on important producers of uranium not having an internal nuclear energy program. Indeed, Kazakhstan and Australia, the world's biggest producers, and many African countries with important uranium resources do not produce nuclear energy. None of the current nuclear consumers has the capacity to cover their uranium needs internally. An important point to make is that the uranium mining sector is fraught with human rights and environmental abuses. The constraints and limitations that are characteristic to nuclear usage are reflected in our data. Only 7 consumers converge by increasing their consumption of nuclear energy. These are the biggest consumers, with the exception of France, and are all European. However, none of the clubs decrease consumption, and over half their members consumed more in 2019 than in either 2010 or the first year of consumption.

4.2.2. Renewables

We single out Soba and Negpah (2022) as the closest match to our study [31]. Similar to Soba and Negpah (2022), we relied on the methodology of Phillip and Sul (2007) and operationalized renewable energy consumption as the % of renewable energy of the total final consumption [21,31]. However, our sample was more restrictive (79 versus 183 counts) and our time interval shorter (2010–2019 versus 2000–2018). Unlike Soba and Negpah (2022), who considered renewable energy as a whole, we opted for individual energy types. While the two studies are not directly comparable, we believe that they complement each other. The 183 countries selected by Soba and Negpah (2022) failed to converge at the panel level, diverging instead into 2 convergence clubs. For each of the renewable energy types, apart from solar, the economies in our sample failed to converge at the panel level, diverging into as few as 3 clubs (wind) and as many as 9 clubs (hydro). Soba and Negpah (2022) explained the lack of panel convergence as reluctance from the advanced economies to share products and knowledge with less advanced economies, and through the gap in economic growth and development. We would like to tentatively add internal access to fossil fuels and legacy infrastructures as potential explanatory factors and invite researchers to test this relationship. Another point that we would like to make is that manufacturing giants such as China, the US, and Japan have relatively small percentages of renewables in their energy mixes. For economies with a strong manufacturing component, significant increases in renewables consumption will depend on streamlining the manufacturing processes, including the creation of new industries and the complete reshuffling of old ones. Particularly challenging is the petrochemical industry, an industry with high market entry barriers and little to no power of influence coming from the end consumer [43].

Regardless of the degree of economic growth and development, the ease of access to fossil fuels, and the existing infrastructure, the economies in our sample converge in their use of solar. As far as solar energy is concerned, convergence speed can be generalized. We believe that favorable national and transnational policies are the major factors behind solar convergence. It is within the context created by these policies that product and knowledge have been successfully shared. Examples of such policies are the EU renewable policies. The EU members converge in renewable energy consumption, as found by Butnaru et al. (2020), or diverge into 2 convergence clubs, as found by Presno and Landajo (2021) [28,29]. Berk et al. (2020) concluded that only 14 EU economies converge [27]. All the EU economies use solar, and the biggest solar consumers are among them. The performance of the EU regarding renewables may be explained by the strength of its institutions. The positive impact of institutional quality on renewable energy consumption and carbon emissions reduction is evidenced by the scientific studies [16,44,45].

Reboredo (2015) and Bigerna et al. (2021) investigated the convergence of a diverse and numerous sample in renewables consumption, with Reboredo (2015) concentrating on developed and developing countries [24,29]. Their time intervals and methodologies differed considerably from ours. However, similar to us, they operationalized renewable energy consumption as the contribution of renewable energy to the energy supply. Reboredo (2015) found that countries diverge in their consumption of renewable energy. Only a handful of countries converged, all with significant and growing renewable industries (Reboredo, 2015). Among these countries, we noticed Brazil (the top consumer of biofuels), Iceland (the top consumer of geothermal), Norway (the top consumer of hydro), and Portugal (the second largest consumer of wind). The remaining countries were: Austria, New Zealand, Sweden, and Switzerland. With the exception of Norway and Iceland, all converging countries are big consumers of at least 4 of the 5 renewable energies that we included in our study. Similar to Reboredo (2015), solar energy aside, we did not find support for the convergence hypothesis. Bigerna et al. (2021) found evidence for convergence in the consumption of renewable energy of 176 countries during the time interval 1990–2015. This is a rather remarkable finding that we unfortunately did not find support for, as our convergence evidence was limited to solar energy. Unfortunately, we have not identified multinational studies on convergence for hydro, solar, wind, biofuels, and other renewables on an individual basis. We hope that our paper signals this need, and we are looking forward to such studies.

4.2.2.1. Hydro

Most of our panel members are using hydro. Hydro, a renewable energy source, is the world's third-largest electricity generation source after coal and gas[20] and should not be underestimated in the effort to minimize the impact of human activity on the climate. Hydro has been used successfully for large-scale electricity supply for over a century. As a downside, the sustainable aspect of hydro continues to be a hotly debated topic, hindering its appeal. A more flexible definition of sustainability, as far as hydro is concerned, may increase its use as a climate change mitigator [46]. Most hydro consumers (66% or 46 of 70) are small consumers, consuming below the panel average. The large number of clubs (8 convergence and 1 divergent clubs), the largest among all energy sources, suggests big disparities in consumption levels and trajectories among the hydro consumers.

Geography and politics may be key factors behind these disparities. Indeed, economies with big fossil fuel resources and those that are water-stressed, or topographically less endowed, tend to have small shares of hydro in their energy portfolios. The mid-range consumption clubs are the most numerous, while those at the extreme are sparse. Regardless, none converge by increasing consumption. As a caveat, the hydro potential is significantly affected by climate change. Fortes et al. (2022) found that climate change lowers hydropower generation by 20% [47]. In Europe, fossil fuels are likely to

[20] https://www.iea.org/reports/hydropower-special-market-report/executive-summary

supplant hydro, which is lost due to climate change, jeopardizing the carbon neutral efforts in the region [48]. Factors such as climate, geography, and politics significantly hinder the potential of hydro. The best to illustrate the dependency of hydro on politics is the Ethiopian Renaissance dam, of which we do not have data. The identification of convergence clubs may contribute towards efforts to minimize the impact of politics and maximize the hydro potential where geography allows it.

4.2.2.2. Biofuels

Over half our panel members are using biofuels. Biofuels have played an important role in reducing carbon emissions and are expected to work in tandem with electric batteries toward a carbon-neutral transportation system [49]. A total of 51% consumed more in 2019 than in either 2010 or the first year of consumption. As a general rule, big producers of fossil fuels tend to have small shares of biofuels in their energy portfolios. Only big consumers converge by increasing their share of biofuels. Small consumers, representing 58% of the total, converge by decreasing their share of biofuels. This is disappointing, considering that the average share of biofuels in the energy portfolio is 0.7%. There is potential for increased inequality between the big and small consumers, as consumption growth is restricted only to the big consumers, while the small consumers are characterized by low rates of consumption and decreasing trends. Hindrances for future development are environmental concerns and the potential impact of climate. Developments in the battery sector may also determine the extent to which the consumption of biofuels can develop. Easy access to fossil fuels may suppress the appetite for biofuels.

4.2.2.3. Other renewables

The vast majority of the economies in our sample are using other renewables. A total of 70% (48 of 68) are small consumers, consuming below the panel average. Moreover, 54% of the consumers of other renewables consumed more in 2019 than in either 2010 or the first year of consumption. The biggest growth rates are encountered among the small consumers; however, 90% converge by decreasing their consumption. The concentration of EU consumers among the big consumers may suggest successful EU policies. The relatively small number of clubs (4 convergent and 1 divergent unit) suggests that there are sufficiently large groups of economies that approach a common consumption level. As a general rule, big producers of fossil fuels tend to have small shares of other renewables in their energy portfolios. Given the low rates of consumption and the downward trends in club trajectories, one can speculate that other renewables, geothermal in particular, are becoming less appealing. Ease of access to fossil fuels and the increased attractiveness of wind and solar may hinder the development of other renewables capabilities.

4.2.2.4. Wind and solar

Together, wind and solar have the potential to become the dominant energy sources of electricity in the near future and are instrumental in reaching carbon neutrality targets, as they do not affect carbon dioxide emissions [15,41,50]. Reassuringly, the solar consumers converge in their consumption. There is also enough consensus among the wind consumers to restrict the number of convergence clubs to 3, with no divergent units. These results may be explained by long-term policies and investments. For decades, solar and wind have been receiving the highest R&D support, with the balance skewed toward the former [50]. As our results show, this long-term investment paid off. Although solar is more popular than wind (78 versus 70 users), the number of economies that allocate above the mean portfolio shares to these energies is almost identical (23 versus 22 or close to 30%). Nevertheless, the number of economies with shares of above 1% is 11 for solar and 32 for wind, with maximum allocations of 2.78% for solar and 16.6% for wind[21]. These slight differences between the two energy sources might be explained by the fact that wind was qualified earlier than solar for deployment at a global level [50]. As a word of caution, these two most important sources of energy in the mediation of climate change are prone to the adverse influence of climate change. In a study by Fortes et al. (2022), the cost-effectiveness of solar photovoltaic (PV) and offshore wind power generation is affected by climate change [47].

4.2.2.4.1. Wind

The small number of clubs that unite the consumers of wind (3 convergent), the smallest among all non-convergent energy sources, suggests a worldwide effort to disseminate and increase the consumption of wind. Indeed, after solar, wind has been receiving the highest R&D investment among renewable energy sources [50]. There is an almost equal split between big (46%) and small consumers (54%) of wind. There is also evidence of an increase in the consumption of wind, as 60% of the consumers of wind consumed more in 2019 than in 2010 or in the first year of consumption, with some spectacular growth rates among the small consumers. Unlike solar, none of the clubs converge by increasing their consumption of wind. This is disappointing, considering that the average share of wind in the energy portfolio is 1.72%. The smallest consumers (club 3), representing 36% of the total, converge by decreasing their consumption of wind. Given the low rates of consumption and the lack of an upward trend in any of the club trajectories, one can hypothesize that wind is losing steam and that perhaps the increase in solar consumption may come at a cost for wind. Ease of availability of fossil fuels may diminish the appeal of wind. Hindrances to the future development of wind are environmental concerns (see the case of Uzbekistan) and the potential impact of climate change.

4.2.2.4.2. Solar

All but one of the economies in our sample are using solar. The consumers of solar converge by increasing the share of solar in the energy mix. This may testify to the successful global implementation of solar energy policies. An example of successful policy implementation in the area of solar is the EU. All EU economies in our sample use solar, and among them, we can identify the biggest consumers of solar. Favorable geography aside, the EU's renewable policies are undoubtedly behind the successful implementation of solar among all EU countries.

[21] Calculations based on data available at: https://ourworldindata.org/energy-production-consumption

A key factor that can explain the success of solar energy may be resource independence, as exemplified by the EU. Indeed, the biggest consumers of solar are EU economies. An important point to make is that all EU members are net importers of energy, with internal production covering a minimum of less than 1% (Cyprus) to a maximum of 70% (Romania)[22]. The top 3 consumers of solar energy are Italy, Spain, and Germany less than 28% of their energy needs from internal production, and are among the top 4 EU economies. Italy and Spain are classed as having the highest potential for solar in the EU, while only part of Germany (Southern Germany) is classed as having good solar potential [51]. Nevertheless, favorable policies propelled Germany to the top 3. Geopolitics and resource independence might have been behind the successful use of solar in the EU and beyond, as exemplified by the cooperation between the EU and Morocco.

As a caveat, our sample is restricted to the most developed economies in the world. We can speculate that up to a certain development level, and regardless of geography, but excluding Africa, economies benefit from a unified solar energy plan, including trading infrastructure. Hindrances to the future development of solar are environmental concerns and the potential impact of climate change (see the case of Uzbekistan). Ease of access to fossil fuels may be detrimental to the development of solar infrastructure. The exception comes from the world's top oil exporter and importer, the latter being also the leading innovator and producer of solar technology. Recent cooperation between China and Saudi Arabia in the area of solar energy resulted in the largest energy storage project in the world. By 2025, Saudi Arabia's power grid will benefit from solar energy.

5. Conclusions

As the title of this article suggests, based on our analysis, there is little to indicate in the recent energy consumption data of the most developed economies that decarbonization can be achieved partially by 2030 and completely by 2050, unless gargantuan efforts are made by all the world economies. Steering toward an economy fueled by renewables may have to be based not only on economic growth forecasts, but also on a duty of care.

Most of the economies in our sample benefit from a diversified energy portfolio. With a few exceptions, this is dominated by fossil fuels. With the exception of coal, the big consumers of fossil fuels either increase their consumption or continue at previous levels. Only the smallest of the big consumers of coal decrease their consumption of coal. With the exception of coal, the small consumers of fossil fuels either decrease their consumption or continue at previous levels. Only the smallest consumers of coal decrease their consumption. With the exception of France, the biggest consumers of nuclear power are increasing their consumption. All other consumers of nuclear energy maintain previous levels of consumption. The top 2 biggest consumers aside, the big consumers of biofuels increase their consumption. With the exception of Iceland, the big consumers of other renewables increase their consumption levels. For all renewable energy types except solar, consumers, regardless of size, either decrease or maintain their consumption levels.

The evidence for a decrease in fossil fuel consumption and that for an increase in renewables consumption are weak. As the consumption levels of China and the US show, a sustained decrease in

[22] Calculations based on data available at: https://www.eia.gov/international/overview/country/

fossil fuel consumption, coupled with a sustained increase in renewables consumption, is only possible with an economic reorientation. Sustainable growth powered by innovation-driven development, as advised by Tu (2024), may be the solution [52]. The evidence for an increase in nuclear consumption is also lacking.

In the case of solar, the big and small consumers progress toward a common consumption level. The performance that is achieved by solar can be explained by successful policies, technology dissemination, and scientific cooperation. The versatility of this energy type is undoubtedly a contributor to its success. Another remarkable result is that of wind, where most consumers belong to high-consuming clubs. Unfortunately, none of them converge by increasing the share of wind. Historically, wind has received the second-largest investment after solar. Only in the case of solar and to a smaller extent in that of wind can one argue for a successful international effort to mitigate the effects of climate change. However, this effort is restricted to the developed and the most developed of the developing economies. Paradoxically, the three types of renewable energy that are supposed to replace fossil fuels in order to restrict climate change (wind, solar, and hydro) are the energies that are most prone to the negative impacts of climate change.

With the exception of hydro, all renewables benefit from a relatively small number of clubs. The large number of clubs for hydro, coal, and gas may reflect the fact that, with some exceptions, the consumption of these energy types depends on internal production, legacy infrastructures, and politics. Nuclear, the non-renewable bridging energy, benefits from a relatively small number of clubs, yet overall membership is extremely limited. The clustering of economies around common transition paths suggests that economies share similarities with each other as far as energy consumption is concerned. Awareness of such 'clubs' may prove useful not only in developing targeted group policies, but also in developing partnerships and cooperation agreements aimed at hastening the energy transition. Examples of successful partnerships and agreements are those in the area of solar energy between the EU and Morocco and China and Saudi Arabia. The advent of AI may usher in a new era for nuclear energy. Furthermore, A new sustainable chemical industry may use renewables and not fossil fuel feedstock.

We hope that this article is a positive addition to the literature on club convergence and energy usage. As a novelty, we are the first to conduct a convergence analysis on data disaggregated by energy type. We hope that the specifics that emerged from our analysis will inspire the adoption of such practice and support energy policy and cooperation. We invite researchers to address the gaps and limitations that we highlighted.

Use of AI tools declaration

No AI tools were used.

Conflict of interest

The author declares no conflicts of interest in this paper.

References

1. Arrhenius S, Holden ES (1897) On the influence of carbonic acid in the air upon the temperature of the earth. *PublAstron SocPac* 9: 14–24. https://doi.org/10.1086/121158
2. Plass GN (1956) The carbon dioxide theory of climatic change. *Tellus* 8: 140–154. https://doi.org/10.3402/tellusa.v8i2.8969
3. Callendar GS (1958) On the amount of carbon dioxide in the atmosphere. *Tellus* 10: 243–248. https://doi.org/10.3402/tellusa.v10i2.9231
4. Meadows DH, Randers J, Meadows DL (1972) The limits to growth: A report for the club of rome's project on the predicament of mankind. New York: Universe Books. https://doi.org/10.1349/ddlp.1
5. Raymo ME, Lisiecki LE, Nisancioglu KH (2006) Plio-pleistocene ice volume, antarctic climate, and the global $\delta^{18}O$ record. *Science* 313: 492–495. https://doi.org/10.1126/science.1123296
6. Haywood AM, Dowsett HJ, Valdes PJ, et al. (2009) Introduction. Pliocene climate, processes and problems. *Philos Trans A Math Phys Eng Sci* 367: 3–17. https://doi.org/10.1098/rsta.2008.0205
7. Barreiro M, Philander G, Pacanowski R, et al. (2006) Simulations of warm tropical conditions with application to middle Pliocene atmospheres. *Clim Dyn* 26: 349–365. https://doi.org/10.1007/s00382-005-0086-4
8. Molnar P, Cane MA (2002) El Niño's tropical climate and teleconnections as a blueprint for pre-ice age climates. *Paleoceanography* 17: 1–11. https://doi.org/10.1029/2001PA000663
9. Jansen E, Overpeck J, Briffa KR, et al. (2007) Palaeoclimate. In: Solomon S, Qin D, Manning M, et al., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. Available from: https://www.giss.nasa.gov/pubs/abs/ja05100g.html.
10. United nations environment programme, European Union (2022) Climate change and security partnership project-final report: march 2017-february 2022. Available from: https://wedocs.unep.org/20.500.11822/40549.
11. IPCC (1992) Climate change. the IPCC 1990 and 1992 assessments. Available from: https://www.ipcc.ch/report/climate-change-the-ipcc-1990-and-1992-assessments/.
12. IPCC (2023) Summary for Policymakers. In: Lee H, Romero J (eds.), *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC, 1–34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001
13. Apergis N, Payne JE, Menyah K, et al. (2010) On the causal dynamics between emissions, nuclear energy, renewable energy, and economic growth. *Ecol Econ* 69: 2255–2260. https://doi.org/10.1016/j.ecolecon.2010.06.014

14. Sebri M, Ben-Salha O (2014) On the causal dynamics between economic growth, renewable energy consumption, CO_2 emissions and trade openness: Fresh evidence from BRICS countries. *Renewable Sustainable Energy Rev* 39: 14–23. https://doi.org/10.1016/j.rser.2014.07.033
15. Magazzino C, Mele M, Schneider N (2021) A machine learning approach on the relationship among solar and wind energy production, coal consumption, GDP, and CO_2 emissions. *Renewable Energy* 167: 99–115. https://doi.org/10.1016/j.renene.2020.11.050
16. Giganti P, Barr C, Falcone PM (2025) Unveiling the nexus of institutional quality and renewable energy utilizing a topic modelling approach. *Renewable Sustainable Energy Rev* 214: 115516. https://doi.org/10.1016/j.rser.2025.115516
17. Huang BN, Hwang MJ, Yang CW (2008) Causal relationship between energy consumption and GDP growth revisited: A dynamic panel data approach. *Ecol Econ* 67: 41–54. https://doi.org/10.1016/j.ecolecon.2007.11.006
18. Baz K, Cheng J, Xu D, et al. (2021) Asymmetric impact of fossil fuel and renewable energy consumption on economic growth: A nonlinear technique. *Energy* 226: 120357. https://doi.org/10.1016/j.energy.2021.120357
19. Kerr C (1983) Laws of motion of industrial societies. In: *The future of industrial societies: Convergence or continuing diversity?* Cambridge and England: Harvard University Press, 8–32. https://doi.org/10.4159/harvard.9780674497627
20. Galor O (1996) Convergence? Inferences from theoretical models. *The Econ J* 106: 1056–1069. https://doi.org/10.2307/2235378
21. Phillips PC, Sul D (2007) Transition modelling and econometric convergence tests. *Econometrica* 75: 1771–1855. https://doi.org/10.1111/j.1468-0262.2007.00811.x
22. Tomal M (2024) A review of Phillips-Sul approach-based club convergence tests. *J Econ Surv* 38: 899–930. https://doi.org/10.1111/joes.12563
23. Nazlioglu S, Kassouri Y, Kucukkaplan I, et al. (2022) Convergence of oil consumption: A historical perspective with new concepts. *Energy Policy* 168: 113–150. https://doi.org/10.1016/j.enpol.2022.113150
24. Cai Y, Chang YC, Chang T, et al. (2023) Stochastic convergence of coal consumption-fresh evidence with sharp and smooth breaks. https://doi.org/10.21203/rs.3.rs-2695727/v1
25. Reboredo JC (2015) Renewable energy contribution to the energy supply: Is there convergence across countries? *Renewable Sustainable Energy Rev* 45: 290–295. https://doi.org/10.1016/j.rser.2015.01.069
26. Cai Y, Menegaki AN (2019) Convergence of clean energy consumption—panel unit root test with sharp and smooth breaks. *Environ Sci Pollut Res* 26: 18790–18803. https://doi.org/10.1007/s11356-019-04911-x
27. Berk I, Kasman A, Kilinç D (2020) Towards a common renewable future: The System-GMM approach to assess the convergence in renewable energy consumption of EU countries. *Energy Econ* 87: 103922. https://doi.org/10.1016/j.eneco.2018.02.013
28. Butnaru GI, Haller AP, Clipa RI, et al. (2020) The nexus between convergence of conventional and renewable energy consumption in the present European Union states. Explorative study on parametric and semi-parametric methods. *Energies* 13: 5272. https://doi.org/10.3390/en13205272

29. Presno MJ, Landajo M (2021) EU-28's progress toward the 2020 renewable energy share: A club convergence analysis. *Environ Sci Pollut Res* 28: 66830–66844. https://doi.org/10.1007/s11356-021-15084-x
30. Bigerna S, Bollino CA, Polinori P (2021) Convergence in renewable energy sources diffusion worldwide. *J Environ Manage* 292: 112784. https://doi.org/10.1016/j.jenvman.2021.112784
31. Saba CS, Ngepah N (2022) Convergence in renewable energy consumption and their influencing factors across regions: Evidence from convergence algorithm approach. *Environ Sci Pollut Res* 29: 61412–61445. https://doi.org/10.1007/s11356-022-19731-9
32. Helmi MH, Catik AN, Coskun N, et al. (2023) Renewable energy consumption convergence in G-7 countries. *Int J Energy Econ and Policy* 13: 203–210. https://doi.org/10.32479/ijeep.14505
33. IEA (2020) Global Energy Review 2020. Available from: https://www.iea.org/reports/global-energy-review-2020.
34. IEA (2021) Global Energy Review 2021. Available from: https://www.iea.org/reports/global-energy-review-2021.
35. IEA (2022) World Energy Outlook 2022. Available from: https://www.iea.org/reports/world-energy-outlook-2022.
36. Sichera R, Pizzuto P (2019) ConvergenceClubs: A package for performing the Phillips and Sul's club convergence clustering procedure. *The R J* 11: 142–151. https://doi.org/10.32614/RJ-2019-021
37. Phillips PCB, Sul D (2009) Economic transition and growth. *J Appl Econ* 24: 1153–1185. https://doi.org/10.1002/jae.1080
38. Salim A, Rafiq S (2012) Why do some emerging economies proactively accelerate the adoption of renewable energy? *Energy Econ* 34: 1051–1057. https://doi.org/10.1016/j.eneco.2011.08.015
39. Muradov N (2014) Carbon-Neutral Energy Sources. Liberating energy from carbon: Introduction to decarbonization. In: Lecture Notes in Energy, New York: Springer. 330–332. https://doi.org/10.1007/978-1-4939-0545-4_6
40. Liu L, Guo H, Liu M, et al. (2023) The role of nuclear energy in the carbon neutrality goal. *Prog Nucl Energy* 162: 104772. https://doi.org/10.1016/j.pnucene.2023.104772
41. Williams JH, Jones RA, Haley B, et al. (2021) Carbon-neutral pathways for the United States. *AGU Adv*, 2. https://doi.org/10.1029/2020AV000284
42. Brook BW, Alonso A, Meneley DA, et al. (2014) Why nuclear energy is sustainable and has to be part of the energy mix. *Sustainable Mater Technol* 1–2: 8–16. https://doi.org/10.1016/j.susmat.2014.11.001
43. Falcone PM, Hiete M (2019) Exploring green and sustainable chemistry in the context of sustainability transition: The role of visions and policy. *Curr Opin Green Sustainable Chem* 19: 66–75. https://doi.org/10.1016/j.cogsc.2019.08.002
44. Nguyen QK, Dang V (2023) Renewable energy consumption, carbon dioxide emission and financial stability: Does institutional quality matter? *Appl Econ* 56: 8820–8837. https://doi.org/10.1080/00036846.2023.2293675
45. Fatima N, Zheng Y, Guohua N (2022) Globalization, institutional quality, economic growth and CO_2 emission in OECD countries: An analysis with GMM and quantile regression. *Front Environ Sci*, 10. https://doi.org/10.3389/fenvs.2022.967050

46. Frey GW, Minke DM (2002) Hydropower as a renewable and sustainable energy resource meeting global energy challenges in a reasonable way. *Energy Policy* 30: 1261–1265. https://doi.org/10.1016/S0301-4215(02)00086-1
47. Fortes P, Simoes SG, Amorim F, et al. (2022) How sensitive is a carbon-neutral power sector to climate change? The interplay between hydro, solar and wind for Portugal. *Energy* 239: 122106. https://doi.org/10.1016/j.energy.2021.122106
48. Carlino A, de Vita A, Giuliani M (2021) Hydroclimatic change challenges the EU planned transition to a carbon neutral electricity system. *Environ Res Lett* 16: 104011. https://doi.org/10.1088/1748-9326/ac243f
49. Liu Y, Cruz-Morales P, Zargar A (2021) Biofuels for a sustainable future. *Cell* 184: 1636–1647. https://doi.org/10.1016/j.cell.2021.01.052
50. Badcock J, Lenzen M (2010) Subsidies for electricity-generating technologies: A review. *Energy Policy* 9: 5038–5047. https://doi.org/10.1016/j.enpol.2010.04.031
51. Šúri M, Huld TA, Dunlop ED, et al. (2007) Potential of solar electricity generation in the European Union member states and candidate countries. *Sol Energy* 81: 1295–1305. https://doi.org/10.1016/j.solener.2006.12.007
52. Tu X (2024) Chinese economy resilient to fluctuations. *China Dly*, 12. Available from: https://epaper.chinadaily.com.cn/china/2024-07/18.

Appendix 1.

1. Sample descriptive statistics

Table A1. Coal.

MAX	AVG	MED	MIN	2019	GR
ZAF	ZAF	ZAF	ZAF	ZAF	SGP
CHN	CHN	CHN	CHN	EST	KWT
EST	EST	EST	EST	CHN	LKA
KAZ	KAZ	IND	IND	IND	QAT
IND	IND	KAZ	KAZ	KAZ	EGY
POL	POL	POL	POL	VNM	BGD
VNM	MKD	MKD	CZE	POL	UZB
MKD	CZE	CZE	MKD	MKD	PAK
CZE	VNM	TWN	TWN	PHL	ARE
BGR	TWN	BGR	AUS	IDN	BLR
AUS	AUS	VNM	UKR	CZE	OMN
PHL	BGR	AUS	BGR	TWN	MAR
IDN	UKR	UKR	VNM	UKR	VNM

Continued on next page

MAX	AVG	MED	MIN	2019	GR
TWN	PHL	PHL	KOR	MAR	PHL
UKR	KOR	KOR	TUR	AUS	IDN
ISR	IDN	TUR	PHL	BGR	CHL
MAR	TUR	ISR	IDN	KOR	SAU
KOR	ISR	IDN	JPN	TUR	CYP
HKG	JPN	JPN	HKG	JPN	JPN
TUR	HKG	HKG	ISR	HKG	ISL
JPN	DEU	DEU	SVK	MYS	MYS
GRC	MAR	GRC	DEU	ISR	IRN
DEU	GRC	MAR	MAR	CHL	UKR
MYS	SVK	SVK	ROU	SVK	IND
ROU	CHL	CHL	MYS	DEU	TWN
USA	MYS	MYS	SVN	PAK	NOR
SVK	ROU	ROU	CHL	SVN	NLD
CHL	USA	USA	THA	LKA	MEX
FIN	SVN	SVN	FIN	ROU	BRA
DNK	FIN	FIN	USA	THA	ZAF
SVN	THA	THA	GRC	FIN	NZL
GBR	DNK	LKA	RUS	USA	KOR
PAK	RUS	DNK	COL	RUS	HKG
LKA	IRL	IRL	HUN	GRC	TUR
THA	GBR	GBR	AUT	BGD	EST
IRL	COL	RUS	NLD	COL	LTU
RUS	LKA	COL	IRL	AUT	THA
PRT	HUN	HUN	MEX	HUN	RUS
COL	PRT	PRT	DNK	NLD	MKD
NLD	NLD	NLD	NZL	MEX	BEL
HUN	AUT	AUT	PRT	NZL	AUT
BGD	PAK	ESP	BEL	IRL	DZA
ESP	ESP	ITA	BRA	DNK	CZE
AUT	ITA	HRV	PAK	HRV	CHN
ITA	HRV	PAK	ITA	BRA	POL
HRV	MEX	MEX	CAN	BLR	SVN
NZL	NZL	NZL	HRV	PRT	ESP
MEX	CAN	CAN	ESP	BEL	PRT
CAN	BGD	BRA	SWE	ITA	SVK
BEL	BEL	BEL	GBR	CAN	KAZ
BRA	BRA	BGD	LTU	UZB	BGR
BLR	SWE	SWE	FRA	ESP	ROU
SWE	FRA	FRA	BGD	SWE	DEU
LTU	LTU	LTU	PER	LTU	LUX

Continued on next page

MAX	AVG	MED	MIN	2019	GR
UZB	BLR	PER	BLR	GBR	COL
FRA	PER	BLR	ISL	FRA	AUS
PER	UZB	UZB	UZB	PER	HRV
LVA	ISL	ISL	NOR	EGY	HUN
EGY	NOR	NOR	LUX	ISL	SWE
ISL	LVA	ARE	LVA	NOR	CHE
ARE	ARE	LVA	LKA	ARE	ECU
NOR	ARG	ARG	ARG	LUX	FRA
ARG	LUX	LUX	ARE	LVA	PER
LUX	EGY	EGY	EGY	ARG	FIN
SGP	DZA	SGP	CHE	DZA	ARG
DZA	IRN	DZA	IRN	CYP	ISR
KWT	SGP	KWT	DZA	IRN	CAN
CYP	CHE	IRN	VEN	SGP	ITA
IRN	KWT	CHE	ECU	KWT	USA
CHE	CYP	VEN	OMN	CHE	VEN
OMN	VEN	OMN	SAU	OMN	GRC
VEN	OMN	CYP	QAT	VEN	IRL
ECU	ECU	ECU	KWT	QAT	LVA
QAT	QAT	QAT	CYP	ECU	DNK
SAU	SAU	SAU	SGP	SAU	GBR
AZE	AZE	AZE	AZE	AZE	AZE

Table A2. Oil.

MAX	AVG	MED	MIN	2019	GR
CYP	CYP	CYP	CYP	CYP	BGD
SGP	SGP	SGP	SGP	SGP	HUN
IRQ	IRQ	IRQ	IRQ	LUX	MKD
LKA	ECU	ECU	LUX	LKA	BGR
ECU	LKA	LUX	LKA	HKG	ROU
LUX	LUX	LKA	ECU	IRQ	KAZ
MAR	MAR	MAR	SAU	ECU	UKR
HKG	HKG	HKG	HKG	SAU	CZE
SAU	SAU	SAU	MAR	MAR	QAT
KWT	KWT	KWT	KWT	GRC	LVA
GRC	GRC	GRC	GRC	KWT	ISL
LTU	BEL	MEX	BEL	LTU	LTU
MEX	MEX	NLD	NLD	LVA	POL
ISR	LTU	BEL	IRL	BEL	SVK
BEL	NLD	LTU	PHL	NLD	EST

Continued on next page

MAX	AVG	MED	MIN	2019	GR
NLD	IRL	IRL	CHL	PRT	RUS
PHL	PHL	PHL	MEX	IRL	CHN
LVA	CHL	CHL	LTU	ESP	GBR
CHL	PRT	PRT	PRT	PHL	LUX
IRL	ESP	ESP	THA	THA	BLR
PRT	LVA	THA	ESP	DNK	ARE
ESP	ISR	IDN	PER	CHL	DNK
EGY	THA	EGY	ISR	MEX	AZE
IDN	IDN	LVA	LVA	PER	NZL
JPN	PER	PER	DNK	KOR	ZAF
VEN	EGY	ISR	JPN	ISR	OMN
THA	JPN	JPN	KOR	ARE	FIN
DNK	DNK	DNK	TWN	HRV	HKG
PER	KOR	HRV	ITA	MKD	SVN
KOR	HRV	KOR	IDN	JPN	AUS
HRV	TWN	ARE	ARE	TWN	COL
ARE	ARE	VEN	BRA	ITA	KOR
TWN	BRA	TWN	HRV	COL	HRV
BRA	ITA	BRA	USA	GBR	IND
MKD	VEN	ITA	CHE	USA	USA
ITA	COL	COL	COL	NZL	TUR
DZA	CHE	CHE	EGY	SVN	NLD
COL	USA	MKD	ARG	IDN	THA
CHE	DZA	USA	MYS	MYS	DEU
IRN	MKD	DZA	NZL	BRA	BEL
GBR	ARG	MYS	GBR	CHE	AUT
USA	MYS	ARG	DZA	EGY	GRC
MYS	GBR	SVN	DEU	AUS	ESP
NZL	SVN	GBR	SVN	AUT	FRA
ARG	NZL	AUS	AUS	HUN	PRT
SVN	AUS	NZL	AUT	DEU	CYP
AUS	AUT	AUT	MKD	ARG	MYS
BLR	DEU	DEU	VEN	DZA	SGP
VNM	IRN	PAK	FRA	FIN	JPN
PAK	PAK	AZE	FIN	OMN	PER
AUT	AZE	FIN	CAN	BLR	CAN
AZE	FIN	IRN	OMN	FRA	IRL
HUN	CAN	HUN	BLR	CAN	SAU
DEU	FRA	CAN	AZE	ROU	ARG
FIN	HUN	FRA	IRN	POL	CHE
OMN	VNM	VNM	VNM	AZE	ITA

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MAX	AVG	MED	MIN	2019	GR
CAN	OMN	OMN	HUN	VEN	LKA
FRA	BLR	BLR	IND	TUR	TWN
ROU	TUR	TUR	TUR	IND	ISR
POL	IND	IND	PAK	IRN	BRA
TUR	POL	ROU	ROU	QAT	PHL
IND	ROU	POL	POL	BGR	CHL
BGD	QAT	QAT	SWE	VNM	NOR
SWE	SWE	SWE	QAT	PAK	SWE
QAT	TKM	BGD	TKM	SVK	KWT
BGR	BGD	TKM	EST	SWE	IRQ
TKM	BGR	EST	SVK	BGD	UZB
SVK	EST	BGR	CZE	EST	TKM
EST	SVK	SVK	ZAF	CZE	DZA
CZE	KAZ	KAZ	RUS	KAZ	IDN
KAZ	CZE	RUS	BGR	RUS	ECU
ZAF	ZAF	ZAF	NOR	TKM	MAR
NOR	RUS	CZE	KAZ	ZAF	MEX
RUS	NOR	NOR	BGD	NOR	EGY
CHN	CHN	CHN	CHN	CHN	PAK
ISL	ISL	ISL	ISL	ISL	IRN
TTO	UKR	UKR	UKR	UKR	VNM
UKR	TTO	TTO	UZB	UZB	VEN
UZB	UZB	UZB	TTO	TTO	TTO

Table A3. Gas.

MAX	AVG	MED	MIN	2019	GR
TTO	TTO	TTO	TTO	TTO	MKD
UZB	UZB	UZB	UZB	UZB	CHN
TKM	TKM	TKM	TKM	TKM	ISR
BGD	QAT	QAT	QAT	QAT	KAZ
QAT	BGD	BGD	OMN	IRN	GRC
OMN	OMN	OMN	BGD	OMN	IRQ
IRN	BLR	BLR	AZE	AZE	CHE
BLR	IRN	IRN	BLR	DZA	MEX
AZE	AZE	AZE	IRN	BGD	USA
DZA	DZA	DZA	DZA	BLR	POL
ARE	ARE	ARE	ARE	EGY	VEN
EGY	RUS	RUS	RUS	ARE	SGP
RUS	EGY	EGY	EGY	RUS	AUS
PAK	ARG	ARG	ARG	ARG	JPN

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MAX	AVG	MED	MIN	2019	GR
ARG	PAK	PAK	PAK	PAK	PRT
KWT	KWT	KWT	MYS	KWT	KWT
LTU	MYS	MYS	KWT	MEX	CAN
VEN	VEN	LTU	HUN	VEN	BRA
MYS	LTU	ITA	ITA	ITA	EGY
MEX	HUN	VEN	TWN	SAU	DZA
HUN	ITA	HUN	NLD	MYS	IRN
NLD	TWN	MEX	SAU	NLD	COL
GBR	MEX	TWN	GBR	HUN	SAU
ITA	NLD	NLD	VEN	ISR	KOR
UKR	SAU	GBR	MEX	GBR	NOR
TWN	GBR	SAU	LTU	TWN	ESP
SAU	UKR	UKR	UKR	USA	TKM
ISR	LVA	LVA	ROU	LTU	BGR
LVA	ROU	ROU	IRL	IRQ	DEU
TUR	TUR	ISR	HRV	UKR	ARG
HRV	HRV	TUR	USA	LVA	TTO
ROU	USA	USA	SVK	HRV	PER
USA	IRL	HRV	LVA	CAN	AZE
IRL	CAN	IRL	CAN	IRL	HRV
IRQ	ISR	CAN	PER	ROU	ZAF
PER	PER	PER	TUR	AUS	MAR
CAN	SVK	SVK	BEL	SVK	SWE
SVK	BEL	IDN	AUS	PER	UZB
LUX	AUS	BEL	DEU	KAZ	ITA
AUS	IDN	AUS	AUT	DEU	RUS
BEL	DEU	DEU	COL	TUR	NZL
IDN	COL	JPN	IDN	BEL	OMN
KAZ	LUX	COL	ESP	COL	FRA
DEU	JPN	LUX	NZL	ESP	CZE
JPN	AUT	AUT	JPN	JPN	PAK
COL	ESP	KAZ	LUX	PRT	QAT
AUT	IRQ	ESP	CZE	AUT	TWN
DNK	NZL	NZL	IRQ	IDN	BEL
ESP	KAZ	IRQ	DNK	NZL	IRL
NZL	DNK	DNK	PRT	GRC	SVN
PRT	PRT	PRT	KAZ	POL	ARE
CZE	CZE	CZE	KOR	CZE	BLR
GRC	POL	POL	FRA	CHE	NLD
POL	FRA	FRA	POL	LUX	SVK
CHE	KOR	KOR	BGR	KOR	AUT

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MAX	AVG	MED	MIN	2019	GR
KOR	CHE	CHE	CHE	FRA	MYS
VNM	GRC	GRC	CHL	DNK	GBR
FRA	BGR	BGR	GRC	CHL	ROU
CHL	CHL	VNM	SGP	SGP	HUN
BGR	VNM	CHL	SWE	BGR	CHL
SGP	SGP	SGP	SVN	SVN	LVA
BRA	BRA	BRA	ISR	SWE	BGD
SVN	SVN	SVN	BRA	BRA	TUR
HKG	SWE	SWE	VNM	MKD	EST
SWE	HKG	HKG	HKG	HKG	HKG
FIN	PHL	PHL	NOR	NOR	UKR
PHL	NOR	NOR	PHL	VNM	ECU
IND	FIN	FIN	EST	CHN	IDN
MKD	EST	EST	IND	PHL	PHL
EST	IND	IND	FIN	EST	LTU
NOR	MKD	CHN	MAR	IND	IND
CHN	CHN	MAR	CHN	FIN	DNK
MAR	MAR	MKD	MKD	MAR	LKA
ECU	ECU	ECU	ECU	ECU	LUX
ZAF	ZAF	ZAF	ZAF	ZAF	FIN
LKA	LKA	LKA	LKA	LKA	VNM

Table A4. Nuclear.

MAX	AVG	MED	MIN	2019	GR
FRA	FRA	FRA	FRA	FRA	IRN
SWE	SWE	SWE	SWE	SWE	CHN
UKR	SVK	SVK	SVK	UKR	PAK
SVK	UKR	UKR	BGR	SVK	MEX
CHE	CHE	CHE	SVN	BGR	UKR
SVN	BGR	BGR	CHE	CHE	IND
BGR	SVN	SVN	FIN	FIN	FIN
FIN	FIN	FIN	UKR	SVN	SVK
BEL	HUN	HUN	HUN	CZE	CZE
HUN	CZE	CZE	CZE	HUN	RUS
CZE	BEL	BEL	BEL	BEL	NLD
KOR	KOR	KOR	KOR	KOR	ARG
JPN	ESP	ESP	ESP	ESP	SVN
ESP	USA	USA	USA	USA	SWE
DEU	ROU	GBR	ROU	ROU	BGR
USA	GBR	ROU	GBR	GBR	HUN

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MAX	AVG	MED	MIN	2019	GR
TWN	TWN	TWN	CAN	RUS	CAN
GBR	DEU	CAN	RUS	CAN	FRA
ROU	CAN	DEU	DEU	TWN	GBR
CAN	RUS	RUS	TWN	DEU	ESP
RUS	JPN	ZAF	ZAF	JPN	BRA
ZAF	ZAF	ARG	ARG	PAK	ROU
PAK	ARG	PAK	BRA	ARG	CHE
ARG	PAK	MEX	IND	ZAF	USA
CHN	CHN	IND	PAK	CHN	ZAF
MEX	MEX	BRA	MEX	MEX	BEL
IND	IND	JPN	NLD	IND	KOR
BRA	BRA	CHN	CHN	BRA	TWN
NLD	NLD	NLD	JPN	NLD	DEU
IRN	IRN	IRN	IRN	IRN	JPN

Table A5. Hydro.

MAX	AVG	MED	MIN	2019	GR
NOR	NOR	NOR	NOR	NOR	BLR
ISL	ISL	ISL	ISL	ISL	MYS
BRA	BRA	BRA	BRA	ECU	IRN
SWE	CHE	CHE	CHE	BRA	ECU
ECU	SWE	SWE	SWE	CHE	GBR
CHE	NZL	NZL	NZL	VEN	IRL
COL	COL	AUT	CAN	SWE	CHN
NZL	AUT	COL	AUT	NZL	TWN
AUT	CAN	CAN	COL	COL	VEN
VEN	PER	PER	PER	PER	TUR
CAN	VEN	VEN	VEN	AUT	HUN
PER	ECU	VNM	HRV	CAN	FIN
HRV	VNM	HRV	ECU	HRV	RUS
VNM	HRV	ECU	VNM	SVN	CHE
LVA	LVA	LVA	CHL	VNM	USA
LKA	LKA	LKA	LVA	TUR	PER
SVN	SVN	SVN	SVN	LVA	SVN
MKD	CHL	CHL	LKA	CHL	LUX
CHL	MKD	MKD	MKD	LKA	VNM
PRT	FIN	ROU	FIN	ROU	AUT
FIN	ROU	PRT	ROU	FIN	NOR
TUR	TUR	TUR	ARG	MKD	ITA
ROU	PRT	FIN	TUR	PAK	COL

Continued on next page

MAX	AVG	MED	MIN	2019	GR
PAK	PAK	PAK	CHN	CHN	CAN
ARG	ARG	ARG	RUS	PRT	BEL
ITA	CHN	CHN	ITA	ARG	IND
CHN	ITA	ITA	PRT	ITA	DNK
PHL	SVK	SVK	SVK	SVK	FRA
AZE	RUS	RUS	PAK	RUS	DEU
BGR	PHL	FRA	FRA	MYS	JPN
ESP	FRA	PHL	IND	FRA	ISL
SVK	ESP	ESP	PHL	IND	KAZ
RUS	BGR	BGR	JPN	JPN	THA
FRA	IND	IND	BGR	PHL	SWE
MYS	GRC	GRC	EGY	ESP	EGY
IND	JPN	JPN	ESP	BGR	IDN
GRC	MEX	MEX	GRC	EGY	NZL
MEX	MYS	EGY	MEX	GRC	SVK
MAR	EGY	KAZ	UZB	KAZ	AUS
JPN	KAZ	MYS	KAZ	UZB	PAK
KAZ	AZE	UZB	USA	USA	BRA
UZB	UZB	USA	AUS	MEX	NLD
EGY	USA	AZE	AZE	IRN	EST
AUS	AUS	AUS	IDN	IDN	IRQ
USA	IDN	IDN	MYS	AZE	ROU
IRN	MAR	MAR	UKR	AUS	ARG
IRQ	UKR	UKR	LTU	IRQ	UZB
UKR	IRQ	IRQ	MAR	UKR	CZE
IDN	LTU	LTU	DEU	DEU	CHL
LTU	IRN	DEU	CZE	LTU	UKR
THA	DEU	IRN	IRL	MAR	HRV
DEU	THA	THA	IRN	IRL	KOR
CZE	CZE	CZE	TWN	THA	LVA
IRL	IRL	IRL	IRQ	CZE	POL
TWN	TWN	TWN	THA	TWN	TKM
BGD	BGD	GBR	BGD	GBR	ZAF
GBR	GBR	BGD	POL	LUX	GRC
LUX	LUX	LUX	GBR	BGD	ISR
POL	POL	POL	LUX	POL	PHL
ZAF	KOR	KOR	HUN	BLR	MEX
BLR	HUN	HUN	KOR	KOR	LTU
KOR	ZAF	ZAF	ZAF	HUN	BGD
HUN	BLR	BLR	BEL	ZAF	BGR
DZA	BEL	BEL	EST	BEL	ESP

Continued on next page

MAX	AVG	MED	MIN	2019	GR
EST	EST	EST	BLR	EST	PRT
BEL	DZA	DZA	DZA	DZA	DZA
ISR	ISR	ISR	DNK	DNK	LKA
NLD	DNK	DNK	NLD	ISR	MKD
DNK	NLD	NLD	ISR	NLD	AZE
TKM	TKM	TKM	TKM	TKM	MAR

Table A6. Biofuels.

MAX	AVG	MED	MIN	2019	GR
BRA	BRA	BRA	BRA	LUX	ISL
LUX	LUX	LUX	LUX	ITA	MYS
SWE	SWE	SWE	COL	MEX	CHE
AUT	COL	AUT	SWE	DEU	HRV
COL	AUT	COL	USA	ARG	TUR
IDN	USA	USA	PER	NZL	IDN
PRT	PER	PER	AUT	SWE	BGR
PER	ARG	ARG	LTU	ISR	DNK
ESP	THA	THA	ARG	TWN	ECU
ARG	PRT	DNK	FRA	AUT	RUS
USA	FRA	LTU	THA	PRT	HKG
FIN	LTU	FRA	PRT	CHN	ZAF
DNK	DNK	PRT	PHL	COL	EST
THA	ESP	PHL	ESP	CAN	ISR
FRA	PHL	ESP	IRL	HRV	NOR
LTU	FIN	FIN	SVK	JPN	UKR
DEU	IDN	DEU	DEU	GRC	FIN
PHL	DEU	ITA	HUN	UKR	NLD
ITA	ITA	IRL	CZE	KOR	ROU
HUN	IRL	HUN	FIN	SVK	LUX
SVN	HUN	IDN	GBR	POL	SWE
IRL	SVK	SVK	BEL	NOR	ARG
SVK	POL	SVN	POL	SVN	JPN
NOR	CZE	CZE	GRC	AUS	THA
CZE	SVN	POL	ROU	IRL	MEX
POL	BEL	BGR	CAN	CYP	SVN
LVA	LVA	BEL	ITA	MKD	CAN
BGR	ROU	LVA	NLD	EST	LTU
ROU	BGR	ROU	NOR	USA	IRL
BEL	GBR	GBR	SVN	NLD	GRC
GBR	GRC	GRC	CYP	CHE	SVK

Continued on next page

MAX	AVG	MED	MIN	2019	GR
CYP	CAN	CAN	IDN	LTU	KOR
CAN	NOR	NLD	LVA	CZE	GBR
NLD	NLD	NOR	IND	ROU	CZE
HRV	MYS	MYS	KOR	LVA	POL
CHE	HRV	HRV	BGR	ISL	LVA
MYS	CHE	IND	AUS	BGR	BRA
EST	IND	AUS	MEX	THA	IND
TUR	KOR	KOR	CHN	FIN	COL
AUS	AUS	ISL	JPN	FRA	PER
ISL	ISL	CHE	ISR	HKG	FRA
IND	EST	BLR	BLR	HUN	USA
KOR	BLR	CHN	CHE	BEL	BEL
BLR	TUR	MEX	UKR	MYS	ESP
HKG	CHN	EST	EST	IND	HUN
ISR	MEX	TUR	HKG	ZAF	CHN
CHN	ISR	JPN	ECU	RUS	DEU
ECU	JPN	ISR	ZAF	BRA	AUT
JPN	ECU	HKG	NZL	ESP	PRT
MEX	HKG	UKR	TUR	DNK	NZL
UKR	ZAF	ECU	MYS	IDN	CYP
TWN	UKR	ZAF	HRV	ECU	ITA
ZAF	TWN	TWN	RUS	GBR	AUS
MKD	NZL	NZL	MKD	PER	BLR
NZL	MKD	MKD	ISL	PHL	MKD
RUS	RUS	RUS	TWN	BLR	TWN

Table A7. Other renewables.

MAX	AVG	MED	MIN	2019	GR
ISL	ISL	ISL	ISL	ISL	BGR
FIN	FIN	FIN	FIN	FIN	HRV
PHL	NZL	NZL	NZL	DNK	KOR
NZL	DNK	DNK	DNK	NZL	LVA
DNK	PHL	PHL	SWE	EST	TUR
SWE	SWE	SWE	PHL	LVA	QAT
LVA	CHL	LVA	CHL	SWE	PAK
EST	EST	CHL	BRA	GBR	KAZ
CHL	BRA	BRA	DEU	PHL	ROU
BRA	LVA	EST	EST	CHL	LUX
GBR	DEU	DEU	PRT	BRA	GBR

Continued on next page

MAX	AVG	MED	MIN	2019	GR
AUT	AUT	ITA	AUT	DEU	LTU
ITA	ITA	AUT	ITA	ITA	MKD
DEU	PRT	GBR	HUN	PRT	CHN
PRT	GBR	PRT	GBR	AUT	UKR
HUN	CZE	CZE	BEL	CZE	BGD
CZE	HUN	HUN	CZE	IDN	THA
POL	BEL	SVK	POL	HRV	SVK
IDN	POL	BEL	CHE	SVK	IRL
SVK	SVK	POL	IDN	BGR	GRC
BEL	IDN	LTU	JPN	THA	CZE
HRV	NLD	THA	SVK	HUN	LKA
NLD	LTU	IDN	NLD	LTU	IDN
BGR	THA	NLD	THA	BEL	EST
THA	CHE	CHE	COL	POL	FRA
LTU	JPN	JPN	ESP	TUR	ITA
CHE	COL	COL	LTU	JPN	HKG
TUR	ESP	SVN	SVN	LUX	CHL
JPN	SVN	ESP	IND	NLD	CYP
LUX	HRV	IRL	USA	CHE	ISR
PER	IRL	USA	MEX	IRL	JPN
IRL	IND	IND	IRL	COL	COL
MEX	USA	PER	LUX	ESP	ESP
IND	LUX	MEX	CAN	IND	BRA
COL	MEX	LUX	FRA	FRA	DEU
ESP	CAN	CAN	ECU	SVN	DNK
SVN	PER	FRA	AUS	KOR	CHE
USA	TUR	HRV	LVA	CHN	AZE
CAN	FRA	TUR	CYP	USA	IND
FRA	AUS	AUS	TWN	MEX	ECU
KOR	BGR	ECU	ARG	CAN	FIN
ECU	ECU	CYP	PER	ECU	PRT
CHN	CYP	KOR	CHN	AUS	BLR
AUS	CHN	ARG	TUR	CYP	AUS
ARG	ARG	CHN	SGP	MKD	SVN
MYS	TWN	TWN	MKD	ARG	POL
CYP	KOR	BGR	GRC	TWN	BEL
TWN	MYS	ROU	MYS	PER	NZL
MKD	ROU	SGP	AZE	ROU	ISL
ROU	SGP	MYS	HRV	GRC	SGP
PAK	GRC	GRC	ROU	LKA	ZAF
GRC	MKD	LKA	NOR	MYS	TWN

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MAX	AVG	MED	MIN	2019	GR
SGP	LKA	NOR	LKA	SGP	SWE
LKA	NOR	AZE	BLR	PAK	VNM
NOR	AZE	MKD	ZAF	AZE	ARG
AZE	BLR	BLR	BGR	NOR	AUT
ISR	PAK	ISR	KOR	UKR	USA
BLR	ISR	ZAF	ISR	ISR	HUN
ZAF	ZAF	QAT	HKG	BLR	NLD
UKR	UKR	HKG	PAK	ZAF	CAN
QAT	HKG	UKR	UKR	HKG	RUS
HKG	QAT	VNM	VNM	QAT	MEX
VNM	VNM	RUS	RUS	VNM	IRN
VEN	RUS	PAK	QAT	RUS	NOR
RUS	VEN	IRN	VEN	BGD	PHL
IRN	IRN	VEN	BGD	KAZ	MYS
BGD	BGD	BGD	IRN	IRN	PER
KAZ	KAZ	KAZ	KAZ	VEN	VEN

Table A8. Wind.

MAX	AVG	MED	MIN	2019	GR
DNK	DNK	DNK	DNK	DNK	PER
PRT	PRT	PRT	PRT	IRL	THA
ESP	IRL	IRL	IRL	PRT	KAZ
IRL	ESP	ESP	ESP	DEU	AZE
SWE	DEU	DEU	DEU	ESP	ZAF
DEU	SWE	SWE	GRC	SWE	ARG
GBR	GBR	GBR	SWE	GBR	PAK
ROU	GRC	GRC	GBR	GRC	BLR
GRC	LTU	ROU	AUT	LTU	IDN
LTU	ROU	LTU	LTU	FIN	RUS
NZL	AUT	AUT	ITA	MAR	UKR
FIN	NZL	MAR	USA	ROU	FIN
AUT	MAR	NZL	FRA	AUT	BRA
MAR	ITA	ITA	AUS	BRA	ROU
BRA	EST	EST	NLD	HRV	ECU
HRV	USA	HRV	EST	BEL	DZA
CYP	HRV	USA	NZL	POL	MEX
ITA	FRA	POL	TUR	FRA	HRV
POL	POL	AUS	MAR	TUR	CHL
EST	AUS	FRA	BGR	AUS	PHL
BEL	NLD	NLD	IND	USA	POL

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MAX	AVG	MED	MIN	2019	GR
TUR	TUR	BEL	CHN	NLD	CYP
BGR	BEL	TUR	BEL	ITA	VNM
FRA	FIN	BGR	CAN	EST	BEL
USA	BGR	CYP	NOR	NOR	GBR
NLD	CYP	CAN	POL	CHL	LTU
AUS	BRA	FIN	HRV	CHN	NOR
CHN	CHN	CHN	MKD	NZL	KWT
NOR	IND	IND	LVA	CAN	CHN
CAN	CAN	BRA	CYP	MEX	SWE
IND	NOR	CHL	LUX	CYP	LUX
CHL	CHL	NOR	FIN	IND	ISR
MEX	MEX	MEX	HUN	BGR	MAR
HUN	HUN	LKA	ROU	LUX	TUR
LUX	LUX	HUN	LKA	ARG	LKA
ZAF	LKA	LVA	CHL	PER	CHE
MKD	LVA	MKD	BRA	EGY	FRA
LKA	EGY	LUX	MEX	ZAF	AUT
PER	MKD	EGY	EGY	LVA	AUS
ARG	PER	PER	CZE	MKD	SAU
EGY	ZAF	ZAF	TWN	LKA	CAN
LVA	TWN	TWN	JPN	PAK	LVA
PAK	CZE	CZE	KOR	HUN	DEU
TWN	JPN	JPN	CHE	THA	IRL
PHL	PHL	PHL	PHL	UKR	NLD
THA	PAK	UKR	VNM	PHL	GRC
JPN	ARG	PAK	UKR	CZE	IRN
CZE	UKR	ARG	ISL	TWN	USA
UKR	KOR	KOR	ARG	JPN	EGY
KOR	THA	CHE	SVN	KAZ	EST
KAZ	CHE	ECU	IRN	KOR	KOR
ECU	ECU	THA	PAK	VNM	SVN
VNM	VNM	VNM	ZAF	AZE	MKD
AZE	KAZ	COL	ISR	BLR	ITA
CHE	BLR	IRN	SVK	CHE	DNK
BLR	COL	KAZ	ECU	ECU	CZE
COL	IRN	ISL	BLR	IRN	IND
IRN	AZE	BLR	THA	IDN	VEN
ISR	ISL	ISR	BGD	ISR	JPN
ISL	ISR	VEN	AZE	COL	ISL
IDN	VEN	SVN	PER	ISL	BGR
VEN	SVN	SVK	KAZ	VEN	TWN

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MAX	AVG	MED	MIN	2019	GR
SVN	SVK	AZE	COL	SVN	PRT
SVK	IDN	BGD	KWT	RUS	HUN
BGD	BGD	RUS	DZA	SVK	ESP
DZA	RUS	DZA	IDN	DZA	COL
RUS	DZA	IDN	SAU	BGD	NZL
HKG	HKG	HKG	HKG	KWT	SVK
KWT	KWT	KWT	RUS	HKG	HKG
SAU	SAU	SAU	VEN	SAU	BGD

Table A9. Solar.

MAX	AVG	MED	MIN	2019	GR
ESP	ITA	ITA	ITA	ESP	CHL
DEU	ESP	DEU	DEU	BGR	BRA
ITA	DEU	GRC	ESP	AUS	POL
GRC	GRC	ESP	GRC	ITA	KAZ
CZE	CZE	JPN	AUS	DEU	BLR
BGR	JPN	BGR	BEL	ISR	TUR
JPN	BGR	CZE	JPN	PRT	MAR
SVK	BEL	BEL	CZE	GRC	RUS
CHL	AUS	AUS	ISR	CHE	HUN
BEL	ISR	ISR	PRT	BEL	ARG
PRT	SVK	CYP	CHE	FRA	ROU
AUS	CHL	CHE	FRA	TKM	PHL
ISR	CYP	DNK	AUT	CZE	MYS
ROU	PRT	SVN	LUX	KOR	EST
SVN	SVN	SVK	CYP	CHN	IRN
CYP	CHE	ROU	SVN	LTU	VNM
GBR	FRA	GBR	KOR	DNK	GBR
CHE	ROU	FRA	SVK	MYS	UKR
DNK	DNK	PRT	USA	AUT	ECU
LUX	GBR	CHL	BGR	TWN	MEX
FRA	LUX	AUT	PER	JPN	COL
MAR	AUT	LUX	CAN	PAK	AZE
CHN	USA	THA	BGD	SVN	IND
TUR	THA	USA	NLD	USA	IDN
HUN	KOR	KOR	THA	SGP	CHN
NLD	CHN	ZAF	LKA	ARG	DNK
IND	NLD	NLD	DNK	SVK	TWN
THA	IND	CHN	CHN	THA	ZAF
LKA	ZAF	PER	IND	NLD	ARE

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MAX	AVG	MED	MIN	2019	GR
AUT	LKA	IND	TWN	PER	LTU
USA	MAR	LTU	GBR	LUX	KWT
MEX	PER	LKA	PAK	BGD	HRV
VNM	TUR	CAN	ZAF	LKA	IRL
ZAF	HUN	BGD	MKD	CYP	NLD
KOR	LTU	TWN	DZA	UKR	BGR
PHL	PHL	UKR	UKR	DZA	OMN
PER	TWN	MKD	IRQ	ARE	SWE
UKR	BGD	HUN	LTU	CAN	THA
TWN	CAN	HRV	MEX	IND	MKD
ARE	UKR	PAK	HRV	EGY	EGY
BGD	MKD	EGY	SWE	CHL	SGP
LTU	EGY	ARE	ARE	SWE	LKA
EGY	MEX	MYS	NZL	GBR	DZA
BRA	ARE	PHL	EGY	EST	SAU
CAN	HRV	DZA	FIN	NZL	PER
MKD	PAK	NZL	MAR	NOR	PAK
HRV	DZA	SWE	NOR	ZAF	ISR
DZA	VNM	MEX	SGP	FIN	SVK
EST	MYS	IRQ	TTO	MEX	FIN
MYS	SWE	ECU	HUN	PHL	USA
PAK	BRA	TUR	MYS	IRQ	IRQ
SWE	NZL	EST	EST	HRV	GRC
ARG	EST	FIN	HKG	MKD	CYP
IRQ	IRQ	SGP	ROU	TUR	TKM
POL	BLR	NOR	KWT	TTO	NZL
BLR	ECU	KAZ	SAU	UZB	SVN
NZL	FIN	RUS	AZE	MAR	CHE
KAZ	POL	POL	TUR	SAU	FRA
FIN	AZE	TTO	COL	HKG	JPN
ECU	KAZ	AZE	IRL	IRL	LVA
AZE	ARG	BLR	UZB	IRN	AUT
TTO	SGP	VNM	ARG	QAT	AUS
NOR	NOR	SAU	LVA	ROU	KOR
COL	TTO	ARG	PHL	KWT	CAN
IRL	KWT	IRL	QAT	HUN	HKG
SGP	IRL	HKG	VNM	RUS	ITA
KWT	RUS	MAR	TKM	KAZ	NOR
IRN	SAU	LVA	ECU	AZE	UZB
RUS	HKG	TKM	OMN	LVA	QAT
SAU	IRN	BRA	CHL	ECU	BEL

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MAX	AVG	MED	MIN	2019	GR
LVA	LVA	QAT	BLR	BRA	LUX
OMN	COL	KWT	KAZ	VNM	PRT
HKG	OMN	OMN	IDN	IDN	CZE
IDN	TKM	VEN	POL	COL	DEU
VEN	QAT	IDN	BRA	OMN	BGD
TKM	IDN	IRN	RUS	BLR	ESP
QAT	VEN	COL	IRN	VEN	TTO
UZB	UZB	UZB	VEN	POL	VEN

2. Club descriptive statistics

2.1. Club ARTPs with RVs and OMs

Table A10. Coal.

Clubs	Interval			2019		
	ARTP	RV	OM	ARTP	RV	OM
Club 1	2.92	+1.92	0	3.17	+2.17	0
Club 2	1.67	+0.67	0	1.77	+2.17	0
Club 3	1.12	+0.12	0	1.04	+0.04	0
Club 4	0.77	−0.23	−1	0.62	−0.38	−1
Club 5	0.28	−0.72	−1	0.22	−0.88	−1
Club 6	0.009	−0.991	−3	0.01	−0.99	−2

Table A11. Oil.

Club	Interval			2019		
	ARTP	RV	OM	ARTP	RV	OM
Club 1	1.73	+0.73	0	1.71	+7.1	0
Club 2	1.21	+0.21	0	1.24	+2.4	0
Club 3	0.93	−0.07	−1	0.93	−0.07	−1
Club 4	0.6	−0.4	−1	0.59	−0.41	−1

Table A12. Gas.

Clubs	Interval			2019		
	ARTP	RV	OM	ARTP	RV	OM
Club 1	2.67	+1.67	0	2.69	+1.69	0
Club 2	1.8	+0.8	0	1.83	+0.83	0
Club 3	1.28	+0.28	0	1.33	+0.33	0
Club 4	0.9	−0.1	−1	0.89	−0.11	−1
Club 5	0.52	−0.48	−1	0.51	−0.49	−1
Club 6	0.28	−0.72	−1	0.26	−0.74	−1
Club 7	0.19	−0.81	−1	0.15	−0.85	−1

Table A13. Nuclear.

Clubs	Interval			2019		
	ARTP	RV	OM	ARTP	RV	OM
Club 1	1.94	94	0	1.99	99	0
Club 2	1.5	50	0	1.5	50	0
Club 3	0.9	−10	−1	0.87	−13	−1
Club 4	0.23	−77	−1	0.23	−77	−1

Table A14. Hydro.

Clubs	Interval			2019		
	ARTP	RV	OM	2019	RV	OM
Club 1	3.13	+2.13	0	3.49	+2.49	0
Club 2	2.8	+1.8	0	2.8	+1.8	0
Club 3	1.17	+0.17	0	1.08	+0.08	−1
Club 4	0.36	−0.64	−1	0.32	−0.68	−1
Club 5	0.1	−0.9	−1	0.09	−0.91	−2
Club 6	0.02	−0.98	−2	0.02	−0.98	−2
Club 7	0.01	−0.99	−2	0.009	−0.991	−3
Club 8	0.002	−0.998	−3	0.002	−0.998	−3

Table A15. Biofuels.

Clubs	Interval			2019		
	ARTP	RV	OM	ARTP	RV	OM
Club 1	5.45	+4.45	0	5.55	+455	0
Club 2	1.87	+0.87	0	2.13	+113	0
Club 3	0.82	−0.18	−1	0.8	−20	−1
Club 4	0.09	−0.91	−2	0.06	−94	−2

Table A16. Other renewables.

Clubs	Interval			2019		
	ARTP	RV	OM	ARTP	RV	OM
Club 1	2.81	+1.81	0	3.11	+211	0
Club 2	1.29	+0.29	0	1.3	+0.3	0
Club 3	0.45	−0.54	−1	0.41	−59	−1
Club 4	0.09	−0.91	−2	0.08	−92	−2

Table A17. Wind.

Clubs	Interval			2019		
	ARTP	RV	OM	ARTP	RV	OM
Club 1	7.73	+6.73	0	6.91	+591	0
Club 2	1.24	+0.24	0	1.28	+0.28	0
Club 3	0.05	−0.95	−2	0.05	−95	−2

2.2. Club make up (small and big consumers). Numbers and percentages (in brackets)

Table A18. Coal.

Group	Units	Interval ARTP		2019 RTP		Club ARTP	
		>1	<1	>1	<1	>1	<1
Total	76	29 (38)	47(62)	31 (41)	45 (59)		
Club 1	11	11 (100)		11 (100)		YES	
Club 2	11	9 (82)	2 (18)	11 (100)		YES	
Club 3	11	7 (64)	4 (36)	7 (64)	4 (36)	YES	
Club 4	6	2 (33)	4 (67)		6 (100)		YES
Club 5	30		30 (100)		30 (100)		YES
Club 6	5		5 (100)		5 (100)		YES
DIV	2		2 (100)		2 (100)		

Table A19. Oil.

Group	Units	Interval ARTP		2019 RTP		Club ARTP	
		>1	<1	>1	<1	>1	<1
Total	79	34 (43)*	45 (57)	22 (28)	47 (72)		
Club 1	7	7 (100)		7 (100)		YES	
Club 2	14	14 (100)		3 (100)		YES	
Club 3	37	11 (30)	26 (70)	10 (27)	27 (73)		YES
Club 4	18		18 (100)		18 (100)		YES
Div	3	2 (40)	3 (60)	2 (40)	3 (60)		

Table A20. Gas.

Group	Units	Interval ARTP		2019 RTP		Club ARTP	
		>1	<1	>1	<1	>1	<1
Total	76	28 (37)	48(53)	29(38)	47(52)		
Club 1	4	4 (100)		4 (100)		YES	
Club 2	14	12 (86)	2 (14)	14 (100)		YES	
Club 3	5	4 (80)	1 (20)	5 (100)		YES	
Club 4	26	8 (33)	18 (67)	6 (23)	20 (77)		YES
Club 5	13		13 (100)		13 (100)		YES
Club 6	10		10 (100)		10 (100)		YES
Club 7	3		3 (100)		3 (100)		YES
DIV	1		1 (100)		1 (100)		

Table A21. Nuclear.

Group	Units	Interval ARTP		2019 RTP		Club ARTP	
		>1	<1	>1	<1	>1	<1
Total	30	12 (38)*	18 (62)	12 (38)	18 (62)		
Club 1	7	7 (100)		7 (100)		YES	
Club 2	2	2 (100)		2 (100)		YES	
Club 3	8	2 (25)	6 (75)	2 (25)	6 (75)		YES
Club 4	12		12 (100)		12 (100)		YES
Div	1	1 (100)		1 (100)			

Table A22. Hydro.

Group	Units	Interval ARTP		2019 RTP		Club ARTP	
		>1	<1	>1	<1	>1	<1
Total	70	24 (34)*	46 (66)	23 (33)	47 (67)		
Club 1	7	7 (100)		7 (100)		YES	
Club 2	4	4 (100)		4 (100)		YES	
Club 3	19	12 (63)	7 (37)	11 (58)	8 (42)		YES
Club 4	18		18 (100)		18 (100)		YES
Club 5	12		12 (100)		12 (100)		YES
Club 6	2		2 (100)		2 (100)		YES
Club 7	3		3 (100)		3 (100)		YES
Club 8	3		3 (100)		3 (100)		YES
Div	2	1 (50)	1 (50)	1 (50)	1 (50)		

Table A23. Biofuels.

Group	Units	Interval ARTP		2019 RTP		Club ARTP	
		>1	<1	>1	<1	>1	<1
Total	57	25 (44)*	32 (56)	23 (40)	34 (60)		
Club 1	2	2 (100)		1 (50)	1 (50)	YES	
Club 2	6	6 (100)		3 (50)	3 (50)	YES	
Club 3	39	16 (41)	23 (59)	16 (41)	23 (59)		YES
Club 4	9		9 (100)	2 (22)	7 (88)		YES
Div	1	1 (100)		1 (100)			N/A

Table A24. Other renewables.

Group	Units	Interval ARTP		2019 RTP		Club ARTP	
		>1	<1	>1	<1	>1	<1
Total	68	20 (29)*	48 (71)	22 (32)	46 (68)		
Club 1	7	6 (86)	1 (14)	7 (100)		YES	
Club 2	22	12 (56)	11 (54)	10 (45)	12 (55)	YES	
Club 3	15	1 (7)	14 (93)	3 (20)	12 (80)		YES
Club 4	23		23 (100)	1 (4)	22 (96)		YES
Div	1	1 (100)		1 (100)			

Table A25. Wind.

Group	Units	Interval ARTP		2019 RTP		Club ARTP	
		>1	<1	>1	<1	>1	<1
Total	70	23 (33)*	47 (64)	27 (39)	43 (61)		
Club 1	2	2 (100)		2 (100)		YES	
Club 2	43	21 (49)	22 (51)	25 (58)			YES
Club 3	25		25 (100)		25 (100)		YES

2.3. Group Gini and Lasym measures

Table A26. Coal.

Group	Interval	
	Gini	Lasym
Total	0.55	0.82
>=1	0.24	1.05
<1	0.5	0.71
Club 1	0.19	0.87
Club 2	0.2	0.72
Club 3	0.17	0.93
Club 5	0.46	0.88
Club 6	0.48	1.14

Table A27. Oil.

Group	Interval	
	Gini	Lasym
Total	0.22	1.02
>=1	0.14	1.29
<1	0.15	0.76
Club 2	0.08	1.24
Club 3	0.1	0.9
Club 4	0.17	1.17

Table A28. Gas.

Group	Interval	
	Gini	Lasym
Total	0.38	0.97
>=1	0.19	1.02
<1	0.28	0.84
Club 2	0.17	0.85
Club 4	0.15	0.94
Club 5	0.16	0.8
Club 6	0.17	0.92

Table A29. Nuclear.

Group	Interval	
	Gini	Lasym
Total	0.47	0.87
>=1	0.16	1.44
<1	0.41	0.81
Club 4	0.42	1.17

Table A30. Hydro.

Group	Interval	
	Gini	Lasym
Total	0.62	0.86
>=1	0.29	0.997
<1	0.5	0.77
Club 3	0.23	0.23
Club 4	0.21	0.96
Club 5	0.34	0.34

Table A31. Biofuels.

Group	Interval	
	Gini	Lasym
Total	0.52	0.81
>=1	0.27	1.2
<1	0.5	0.9
Club 3	0.39	0.73

Table A32. Other renewables.

Group	Interval	
	Gini	Lasym
Total	0.65	0.93
>=1	0.36	1.2
<1	0.49	0.74
Club 2	0.35	0.98
Club 3	0.3	0.89
Club 4	0.57	0.89

Table A33. Wind.

Group	Interval	
	Gini	Lasym
Total	0.68	0.85
>=1	0.4	1.19
<1	0.63	0.85
Club 2	0.47	1.12
Club 3	0.73	1.03

Table A34. Solar.

Group	Interval		
	Units	Gini	Lasym
Total	78	0.7	0.89
>=1	22 (28%)	0.35	1.13
<1	56 (72%)	0.59	0.79

2.4. Trend statistics by club

Table A35. Coal.

Club	Mann Kendall			Durbin Watson	
	Statistic (Z)	Sen's slope	Pvalue	Statistic	Pvalue
Club 1	2.68	0.037	0.007	0.32	<0.001
Club 2	2.5	0.02	0.01	0.22	<0.001
Club 3	−3.22	−0.017	0.001	0.18	<0.001
Club 4	−2.68	−0.02	0.007	0.27	<0.001
Club 5	−2.33	−0.01	0.02	0.34	<0.001
Club 6	2.32	0.0003	0.02	0.96	0.03

Table A36. Oil.

Club	Mann Kendall			Durbin Watson	
	Statistic (Z)	Sen's slope	Pvalue	Statistic	Pvalue
Club 4	−2.33	−0.002	0.02	1.1	0.06

Table A37. Gas.

Club	Mann Kendall			Durbin Watson	
	Statistic (Z)	Sen's Slope	Pvalue	Statistic	Pvalue
Club 2	3.04	0.01	0.002	0.29	<0.001
Club 4	−2.5	−0.004	0.01	0.48	0.001
Club 5	−2.15	−0.004	0.03	1.16	0.07
Club 6	−2.86	−0.002	0.004	0.443	<0.001
Club 7	−3.04	−0.01	0.002	0.202	<0.001

Table A38. Nuclear.

Club	Mann Kendall			Durbin Watson	
	Statistic (Z)	Sen's slope	Pvalue	Statistic	Pvalue
Club 1	3.21	0.02	0.001	0.39	<0.001

Table A39. Hydro.

Club	Mann Kendall			Durbin Watson	
	Statistic (Z)	Sen's slope	Pvalue	Statistic	Pvalue
Club 4	−2.68	−0.007	0.007	0.65	0.005
Club 5	−2.86	−0.003	0.004	0.63	0.004

Table A40. Biofuels.

Club	Mann Kendall			Durbin Watson	
	Statistic (Z)	Sen's slope	Pvalue	Statistic	Pvalue
Club 2	3.04	0.08	<0.001	0.3	<0.001
Club 3	−2.49	−0.01	<0.001	0.3	<0.001
Club 4	−3.04	−0.006	0.1	0.8	0.1

Table A41. Other renewables.

Club	Mann Kendall			Durbin Watson	
	Statistic (Z)	Sen's slope	Pvalue	Statistic	Pvalue
Club 1	4.71	0.07	<0.001	0.15	<0.001
Club 3	−2.68	−0.008	0.007	0.49	0.001
Club 4	−2.15	−0.003	0.03	0.6	0.003

Table A42. Wind.

Club	Mann Kendall			Durbin Watson	
	Statistic (Z)	Sen's slope	Pvalue	Statistic	Pvalue
Club 1	−2.68	−0.24	0.007	0.52	0.001
Club 3	−3.04	−0.0002	0.002	0.18	<0.001

Table A43. Solar.

Club	Mann Kendall			Durbin Watson	
	Statistic (Z)	Sen's slope	Pvalue	Statistic	Pvalue
Club 1	3.93	0.08	<0.001	0.14	<0.001