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Convergence of clubs between per capita carbon dioxide emissions from fossil fuels and cement production

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ABSTRACT

Various studies have addressed the issue of convergence in carbon dioxide emissions at an aggregate level, ignoring the analysis of such emissions at a higher level of disaggregation. In order to cover this gap, the present study offers a new perspective to the hypothesis of relative convergence in carbon dioxide emissions from the combustion of fossil fuels and the manufacture of cement for a sample of 139 countries in the period 1960 to 2017 through the methodology of Phillips and Sul (2007, 2009). This methodology enables the flexibility to explore whether the units under study converge to a common equilibrium state in per capita carbon dioxide emissions or whether they converge into different groups. The results show that per capita carbon dioxide emissions converge into different groups and not into a single one as is the case of countries considered lower-middle income and upper-middle income countries. In contrast, countries classified as low-income and high-income do converge in their respective groups. These results show that countries currently contribute unequally to climate change policies, a differential that could be determined by their level of development and economic growth. The above highlights the need to take into account differences in economic development and growth prospects when examining emissions convergence between countries.

1. Introduction

The results of empirical research that analyses emissions of greenhouse gases of carbon dioxide is the most important and which contributes almost 65 % of global emissions of these gases (IPCC, 2014) suggest that these emissions have an impact on the global climate (Baek and Pride, 2014; IPCC, 2014; Rehman et al., 2021), becoming a very urgent problem (Williston, 2018). These investigations consider that CO_2 emissions are the main cause of global warming and climate change (Lotfalipour et al., 2010; Acaravcı and Erdogan, 2016).

Despite the fact that developed countries are the most polluting due to their dependence on energy sources that emit carbon dioxide, with coal combustion and industrialization being the main sources (Ziabakhsh-Ganji and Kooi, 2014) in addition to oil, gas from power plants and cars, environmental problems are considered not only to pertain to this group of developed countries, but to the whole world due to their global effects. However, the responsibility for carbon dioxide emissions does not only belong to developed countries since they can also be influenced by other factors such as the population size and the economic structure of each country (Ziabakhsh-Ganji and Kooi, 2014).

Since the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, countries have negotiated several commitments to stabilize and reduce greenhouse gas emissions in order to prevent them from continuing to accumulate in the atmosphere. These agreements have focused over the years on either the allocation of emission rights, i.e., sharing resources, or on reduction commitments, which involve

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burden sharing (Pan et al., 2014). Their aim is to mitigate the negative impact of carbon dioxide on climate by reducing current global emissions by at least half by 2050 in order to limit the increase in the global average temperature by 2 °C or even less (Council, 1996).

These commitments have been numerous since 1992. In 1997, the Kyoto-COP-KYOTO Protocol agreed on emission reductions, in 2007 COP13-Bali (Bali Road Map), COP15-Copenhagen in 2009 (long-term financing, 2 °C challenge), COP18_DOHA in 2012 approved the Doha amendment, which is the 2nd phase of the Kyoto Protocol, COP17-Durban in 2011 (Durban platform), COP16-CANCUN in 2010 (Cancun agreements), COP19-WARSAW in 2013 (Warsaw International Mechanism), COP20-Lima in 2014 (contributions to a global agreement), COP21-Paris in 2015 (Paris agreement), COP22-Marrakech in 2016 (Paris Agreement enters into force), COP23-Fiji in 2017 (held in Bonn), COP24-Katowice in 2018 (Paris Agreement rules), COP25-Chile held in Madrid in 2019 and COP26-Glasgow in 2021 (adopted the Glasgow Climate Pact).

The objective of the first agreement (UNFCCC), as well as subsequent ones, was to share the burden of the global mitigation effort between countries, so the debate on global climate policies tends to focus on the economic costs, as well as the equity and viability of the mitigation plans proposed in the conventions (Pettersson et al., 2014). In this sense, countries must contribute equitably, in accordance with their responsibilities and economic capabilities, take active mitigation measures to control and reduce current and future greenhouse gas emissions (Pan et al., 2014).

According to Pettersson et al. (2014:2), citing Aldy (2006), the allocation of emission CO_2 obligations among countries in recent decades "*has not been based on explicit allocation rules, but has rather been ad hoc, reflecting variations in the energy mix, economic development, climate, land-use patterns, etc*." In recent years, many researchers have worked on carbon emission quota allocation schemes (Golombek et al., 2013; Zhang et al., 2018; Wang et al., 2018; Chang et al., 2020). In turn, international negotiations on climate change increasingly put forward different allocation principles, which are clearly related to the specific circumstances of each country, and which are governed by the principle of *common but differentiated responsibilities* proposed in the Kyoto Protocol-COP in 1997, advocating for determining allocation by following principles of equity and efficiency. For this reason, countries should reduce their emissions to a lesser or greater extent by considering, on the one hand, the principle of equity, which is related to the so-called retributive justice, acquired rights and historical responsibility (Ringius et al., 1998) and on the other hand, the principle of efficiency related to carbon emissions (Ciscar et al., 2013; Zhou and Wang, 2016).

In this context, different allocation schemes have been proposed in recent years. Several schemes propose making the allocation based on the convergence of emissions or the status quo (Böhringer and Welsch, 2004), while others propose allocation based on historical responsibilities, economic levels and development needs (Pan et al., 2014). Pan et al. (2014) collected the main allocation schemes in their research, taking into account the principles followed by them; capacity/responsibility (Den Elzen and Berk, 2005), current emission and emission intensity (Winkler et al., 2002), emission per capita (Gupta and Bhandari, 1999; Persson et al., 2006; Höhne et al., 2006; Baer et al., 2000), multi-indicator (Den Elzen and Berk, 2005), sector emission (Sijm et al., 2001; Groenenberg et al., 2004).

Considering the fact that the atmosphere is a common resource for all mankind, many studies have suggested considering per capita emissions as the basis of equity (Pan et al., 2014). As is well known, although the geographical distribution of emissions is irrelevant, the distribution of per capita emission rights can influence the political economy, especially in the negotiation of multilateral agreements (Aldy, 2006).

Given that the atmosphere is a common resource for all human beings, many studies suggest considering the principle of equity of cumulative emissions per capita (Pan et al., 2014). This principle seeks to achieve an equitable carbon emissions space worldwide (Pan et al., 2014) and gives rise to the equal per capita annual emission (EPC) scheme. This scheme provides each citizen in the world an equal emission right in each year straightway (Wicke, 2005). However, the effectiveness and ethical justification of this principle of distribution can also be questioned, because it ignores the payment capacity of each country, its historical responsibility and the aspects of efficiency in the distribution of emissions, unless the negotiated agreement is accompanied by international emissions trading (Pettersson et al., 2014). Nevertheless, the principle of per capita burden sharing has been supported by several countries (Ghosh, 2010), non-governmental organizations and academics (Mattoo and Subramanian, 2010; Frankel, 2007). In the research conducted by Bodansky (2004), it is observed that there are many proposals based on per capita emission allocation schemes.

A variant of the equal per capita annual emission (EPC) scheme is the contraction and convergence (CC) scheme of the Global Commons Institute (GCI, 2005). This scheme proposes that the per capita annual emission in developed countries gradually decreases, while it rises in developing countries. Eventually, the annual per capita emission in developed and developing countries would converge to the same level at a given point in time. However, such an implementation of future allocation would allow per capita emission in developing countries to always be lower than that of developed countries (Pan et al., 2014).

Numerous investigations have been conducted on the convergence of per capita carbon dioxide emissions between countries, recent research showing some evidence of convergence between developed countries (OECD), however, at the global level there seem to be relatively persistent gaps or divergences. Zhang et al. (2020) state that these divergences are derived from the choice of the econometric approach and the data set (different samples).

For all these reasons, Zhang et al. (2020:4) states that "*conflicting results were reported as some studies show that* per capita *emissions are convergent, while others indicate that they are divergent. Thus, further and extensive studies on the subject matter are still required*".

There are several reasons why the study of convergence in greenhouse gas emissions is important: *i)* While total emissions continue to increase in most countries, global per capita emissions seem to have stabilized. If this is the case, the per capita target scheme may represent a more acceptable basis for political commitments than absolute levels (Ordás Criado and Grether, 2011); *ii)* The feedback between population growth and income is a major obstacle for countries to develop without damaging environmental quality (Danish et al., 2019); *iii)* As population increases, natural resource use increases and thus environmental degradation increases.

These policies can be expected to be supported by developing countries, which generally have the lowest per capita emissions. In turn, these countries expect those with the highest emissions (developing countries) to focus their efforts on mitigating climate change through their environmental policies. However, the distribution of rents implicit in a per capita scheme taking into account the current state of emissions distribution would probably not be supported by developed countries. In case of diverging carbon emissions, a per capita emissions allocation rule would lead to significant resource transfers through international carbon trading or the relocation of emissions-intensive economic activities (Aldy, 2006). Conversely, if they converge over time, these concerns may become less important and other countries may be more likely to support such commitments. Finally, another reason to study convergence in CO_2 emissions is that many climate change scenarios predict convergence. This applies to many variables, such as income, energy consumption and emissions. It is therefore important to assess whether this assumption is correct.

Therefore, this paper evaluates the relative convergence hypothesis in a database of per capita CO_2 carbon dioxide emissions from the combustion of fossil fuels and cement manufacturing by country, which has hardly been explored and is provided by Gilfillan et al. (2020) using the methodology of Phillips and Sul (2007, 2009). This database differs from those that have been commonly used in other studies on the convergence of carbon dioxide emissions. One of the questions the present study seeks to answer is whether per capita carbon dioxide (CO_2) emissions for all the countries in the sample, and by income groups, converge in a single group or whether there are multiple convergence clubs or stationary states. This seeks to contribute to the empirical evidence that has been provided on the topic, which has focused mainly on the aggregate emissions of this indicator and has ignored the analysis of databases with more disaggregated information. We consider that research carried out with more disaggregated data can contribute to a better understanding and understanding of the behavioral patterns of carbon dioxide emissions at an aggregate level.

The paper proceeds as follows. The second section provides a review of the CO_2 convergence literature and briefly explains each of the approaches that have been used to test the hypotheses of convergence in per capita carbon dioxide emissions. The third section presents the data and the methodology. The fourth section shows the results, and the last section states the conclusions.

2. Convergence of CO_2 emission

2.1. Antecedents

Brännlund et al. (2015) divide the studies on CO_2 convergence into two groups in their research work. The first group refers to those studies that investigate the convergence of CO_2 emissions between countries worldwide. The literature covering research whose sample includes countries at a global level is very extensive. This can be seen in the literature review study conducted by Pettersson et al. (2014). These authors group the investigations by taking into account the methodology; β- and σ-Convergence Studies (Strazicich and List, 2003; Nguyen Van, 2005; Stegman and McKibbin, 2005; Aldy, 2006; Panopoulou and Pantelidis, 2009; Brock and Taylor, 2010; Jobert et al., 2010; Camarero et al., 2013a), Stochastic Convergence Studies (Strazicich and List, 2003; Barassi et al., 2008; Romero-Ávila, 2008; Westerlund and Basher, 2008; Lee and Chang, 2008; Chang and Lee, 2008; Nourry, 2009; Yavuz and Yilanci, 2013; Camarero et al., 2008) and Convergence Studies Using the Intra-Distributional Dynamics Approach (Stegman, 2005; Nguyen Van, 2005; Aldy, 2006; Ezcurra, 2007; Ordás Criado and Grether, 2011; Herrerias, 2011). The second group are those studies that address the subject at the level of regions (Aldy, 2007; Baldwin and Wing, 2013; Burnett, 2016; Huang and Meng, 2013; Zhao, 2014) or sectors (Moutinho et al., 2014; Wang and Zhang, 2014).

The conclusions obtained from the study by Pettersson et al. (2014:23) "*that the hypothesis of convergence in* per capita *emissions of carbon dioxide is only partly* supported*, and the results also appear to be sensitive to the econometric approach used and the data set used (e.g., the length of the time series, geographical coverage). The empirical evidence is therefore mixed, although some general patterns emerge*". Following this same line, Ordás Criado and Grether (2011) state, as already mentioned, that there are several studies that empirically observe convergence in a sample of OECD countries (Stegman, 2005; Nguyen Van, 2005; Aldy, 2006; Ezcurra, 2007) although others also show divergence (Aldy, 2006; Barassi et al., 2008), or convergence only between the most heterogeneous OECD countries (Westerlund and Basher, 2008; Panopoulou and Pantelidis, 2009). However, at the global level, studies show persistent divergences or gaps in the convergence of CO_2 emissions.

Following this review of the literature by Pettersson et al. (2014), there are many investigations carried out at a global level or in smaller contexts of countries. In this regard, Zhang et al. (2020) conducted a review of the literature on this subject, focusing on those studies published after the review by Pettersson et al. (2014) (see Table 1 of the study by Zhang et al., 2020:3). These researchers noted that in the studies conducted by Runar et al. (2017), Churchill et al. (2020) and Presno et al. (2018), the existence of convergence of per capita CO_2 emissions at a global level is empirically proven. On the contrary, in other studies, it was observed that convergence depended on two

Table 1
Convergence Club Test (1960–2017). All countries.

Convergence Test			
Club	$\hat{b}$	*t-statistic*	*Countries*
Unique	−1.6038	−11.5600	139
Convergence Club Tests			
Club	$\hat{b}$	*t-statistic*	*Countries*
1	−1.513	−0.701	105
Club 1 countries: "| Albania | Algeria | Antigua & Barbuda | Argentina | Australia | Austria | Bahamas | Bahrain | Barbados | Belgium | Belize | Bermuda | Brazil | Brunei (Darussalam) | Bulgaria | Canada | Cayman Islands | Chile | China (Mainland) | Colombia | Comoros | Costa Rica | Cote D Ivoire | Cuba | Cyprus | Denmark | Dominica | Dominican Republic | Ecuador | Egypt | El Salvador | Faeroe Islands | Fiji | Finland | France (Including Monaco) | French Polynesia | Gabon | Gambia | Gibraltar | Greece | Greenland | Grenada | Guatemala | Guyana | Hong Kong Special Adminstrative Region Of China | Hungary | Iceland | India | Indonesia | Iraq | Ireland | Islamic Republic Of Iran | Israel | Italy (Including San Marino) | Japan | Jordan | Kuwait | Lao People S Democratic Republic | Lebanon | Libyan Arab Jamahiriyah | Luxembourg | Macau Special Adminstrative Region Of China | Mauritania | Mauritius | Mexico | Mongolia | Morocco | Netherlands | New Caledonia | New Zealand | Norway | Paraguay | Peru | Philippines | Plurinational State Of Bolivia | Poland | Portugal | Qatar | Republic Of Cameroon | Republic Of Korea | Romania | Saint Lucia | Samoa | Sao Tome & Principe | Saudi Arabia | Senegal | Singapore | South Africa | Spain | St. Pierre & Miquelon | St. Vincent & The Grenadines | Suriname | Sweden | Switzerland | Taiwan | Thailand | Tonga | Trinidad And Tobago | Tunisia | Turkey | United Arab Emirates | United Kingdom | United States Of America | Uruguay | Venezuela |United Arab Emirates | United Kingdom | United States Of America | Venezuela"			
Club	$\hat{b}$	*t-statistic*	*Countries*
2	1.799	0.978	2
Club 2 countries "| Equatorial Guinea | Malta |"			
Club	$\hat{b}$	*t-statistic*	*Countries*
3	1.798	14.029	7
Club 3 countries "| Angola | Cape Verde | Democratic People S Republic of Korea | Honduras | | Nicaragua | Sri Lanka | Syrian Arab Republic |"			
Club	$\hat{b}$	*t-statistic*	*Countries*
4	1.326	35.669	7
Club 4 countries "| Benin | Congo | Djibouti | Ghana | Myanmar (Formerly Burma) | Nigeria | Papua New Guinea |"			
Club	$\hat{b}$	*t-statistic*	*Countries*
5	0.118	0.362	2
Club 5 countries "| Solomon Islands | Togo |"			
Club	$\hat{b}$	*t-statistic*	*Countries*
6	1.030	24.848	10
Club 6 countries "| Afghanistan | Guinea | Guinea Bissau | Haiti | Kenya | Liberia | Madagascar | Mali | Mozambique | Sierra Leone |"			
Club	$\hat{b}$	*t-statistic*	*Countries*
7	0.231	0.386	3
Club 7 countries "| Central African Republic | Chad | Uganda |"			
Club	$\hat{b}$	*t-statistic*	*Countries*
8	0.318	0.205	2
Club 8 countries "| Democratic Republic of The Congo (Formerly Zaire) | Somalia"			
Non-Convergent Group | Jamaica |			

variables, on the one hand, the inclusion of different countries in the sample and, on the other hand, the methodology used in the studies (Herrerias, 2013; Li and Lin, 2013; Yavuz and Yilanci, 2013; Robalino-López et al., 2016; Ahmed et al., 2017; Cai et al., 2018;

Fernández-Amador et al., 2019; Cai and Wu, 2019; Erdogan and Acaravci, 2019; Haider and Akram, 2019b; Karakaya et al., 2019; Churchill et al., 2020). Finally, they found a set of studies in which no evidence of convergence of per capita CO_2 emissions was observed in the full sample (Li and Lin, 2013; Evans and Kim, 2016; Kounetas, 2018; Erdogan and Acaravci, 2019; Solarin, 2019).

Zhang et al. (2020) also reviews the studies belonging to the second group, which is formed by those that use individual countries and subnational data in their sample (see Table 2 of their study). These authors observed that as in the case of studies with global samples at the country level, there are studies that support the convergence of per capita CO_2 emissions for regions or sectors, such as those by Baldwin and Wing (2013), Huang and Meng (2013), Wang and Zhang (2014), Wu et al. (2016), Yang et al. (2016), Acar and Yeldan (2018), Tong (2020), and following the same line, it was observed that in the studies by Li et al. (2014), Wang et al. (2014), Burnett (2016), Apergis and Payne (2017), Oliveira and Bourscheidt (2017), it was empirically proven that there is convergence in some regions or sectors. In contrast, other studies found no evidence at the country level (Baldwin and Wing, 2013; Wang et al., 2014).

2.2. *Analysis methodologies*

The study of the convergence of CO_2 emissions has been approached from different methodologies, which can be classified into four main approaches: beta (β), sigma (σ), stochastic convergence and relative convergence. Some of them can be divided into "conditional (relative) and unconditional (absolute) convergence" (Brännlund et al., 2015:228). In addition to these approaches and traditional measures of convergence, both cross-sectional and panel conventional parametric approaches, as well as panel unit root tests are also applied (Zhang et al., 2020). In this section, an account of the most representative papers is given, and in each case, what each methodological approach consists of is briefly stated.

2.2.1. *Sigma and beta convergence*

Absolute β-convergence tests derive from the neoclassical literature on economic growth, one of its exponents being Solow (1956). The β-absolute convergence approach assumes the same steady state level for all countries, while the β-conditional convergence approach, taking into account cross-country similarities, assumes different steady states. Neither approach adequately addresses the dynamics of the growth process in a panel data context, with few time observations, so it is difficult to infer some properties adequately. Evidence for β-convergence in per capita CO_2 emissions is provided by Strazicich and List (2003), Nguyen Van (2005); and Brock and Taylor (2010) for OECD countries.

By analysing the distributional dynamics of emissions, the σ-convergence measures the gaps between the time series and examines whether the cross-section decreases. Several researchers have addressed this methodology (Aldy, 2006; Panopoulou and Pantelidis, 2009). Stegman and McKibbin (2005) used two samples of countries. The first one consists of 97 countries from the period 1950 to 1999, while the second one, from 1900 to 1999 includes only 26 countries. Their results show little evidence of convergence for the broad sample of countries, but they do find evidence of convergence in OECD countries. A similar result is found by Aldy (2006) for the group of OECD countries (88 countries).

Nguyen Van (2005) finds evidence of both conditional σ-convergence and β-convergence for 26 of the countries with the highest emissions and for a sample of 100 countries. Meanwhile, Kounetas (2018) provides support for absolute β-convergence and σ-convergence for 23 countries of the European Union and Jobert et al. (2010) observed for a sample of European countries absolute and conditional convergence.

According to Brännlund et al. (2015:229), the σ-convergence methodology "has in turn led to the use of non-parametric testing procedures taking into account the dynamics of the full distribution of countries" and has been applied by researchers such as Ezcurra (2007) and Ordás Criado and Grether (2011). Belloc and Molina (2023) identify a process of absolute convergence in CO2 emissions per capita among 19 Latin American countries during the period 1970–2018.

2.3. *Stochastic convergence tests*

The stochastic convergence approach, on the other hand, examines through unit root or stationarity tests whether the emissions of country i relative to another country are stationary. Among the works that have tested the stochastic convergence approach are Strazicich and List (2003), Romero-Ávila (2008), Westerlund and Basher (2008), Chang and Lee (2008) for OECD countries, Nourry (2009) for a set of 127 countries and Yavuz and Yilanci (2013) for a sample of G7 countries,

Table 2
Club FusionTest (1960–2017). All countries.

Initial Groups									*Final Goups*
Club 1 [105]	Club 1 + 2 −1.650 −1.777								[105]
Club 2 [2]		Club 2 + 3 −1.000 −22.535							[2]
Club 3 [7]			Club 3 + 4 0.669 11.641						[-]
Club 4 [7]				Club 4 + 5 1.043 35.828					[-]
Club 5 [2]					Club 5 + 6 0.187 3.292				[16]
Club 6 [10]						Club 6 + 7 0.540 2.671			[-]
Club 7 [3]							Club 7 + 8 −0.030 −0.205		[13]
Club 8 [2]								Club 8 + 9 −0.650 −26.894	[2]

Apergis and Payne (2020) for North American countries. All of them show evidence of stochastic convergence.

In contrast, Barassi et al. (2008), Lee and Chang (2008) and Camarero et al. (2008) find evidence of divergence for OECD countries. Churchill et al. (2020) find mixed evidence of stochastic convergence for 17 emerging economies.

Payne and Apergis (2021) find evidence of stochastic convergence for countries classified as low income and lower-middle income countries using the pairwise approach proposed by Pesaran (2007). Erdogan and Solarin (2021) examine the hypothesis of stochastic convergence in carbon dioxide emissions in 151 countries and find mixed evidence at different income levels. Tiwari et al. (2021) examine the hypothesis of stochastic convergence in the carbon dioxide emissions of the 50 states of the American Union and their results show divergence. Nazlioglu et al. (2021) analyze this hypothesis for carbon dioxide emissions in 31 countries, their results also show divergence.

On the other hand, Lee et al. (2023) examine the convergence of CO2 emissions per capita in 30 OECD countries by applying a new LM test in 30 OECD countries, using the LM test with break, their results show that there is no convergence and that differences in carbon dioxide emissions exist and are persistent.

2.4. Relative convergence tests

On the other hand, the relative convergence approach captures growth dynamics and allows for the possibility of multiple convergence clubs, regardless of the stochastic characteristics of the relevant variable. Several investigations have tested the hypothesis of relative convergence using the methodology proposed by Phillips and Sul (2007, 2009), either in per capita CO_2 emissions or as a proportion of GDP, which include Panopoulou and Pantelidis (2009) for a sample of 128 countries, Camarero et al. (2013) for OECD countries, Haider and Akram (2019a) for a sample of 53 countries, Apergis et al. (2020) for a sample of Central American countries. Apergis and Payne (2020) for North American countries, Bhattacharya et al. (2020) for carbon emissions intensity based on consumption and territory for a sample of 70 countries. Payne and Apergis (2021) for developed countries, Dogah and Churchill (2022) on emissions from the production of coal, oil, natural gas and cement for the member states of the Association of Southeast Asian Nations (ASEAN). Cialani and Mortazavi (2021) examines the relative convergence hypothesis for 28 European Union countries in the industry and manufacturing sectors. All of them find divergence for all the countries considered, but convergence in certain clubs.

At the intranational level, Ivanovski and Churchill (2020) examine the convergence of greenhouse gas emissions across Australian states. Tiwari et al. (2021) address the stochastic convergence hypothesis for carbon dioxide emissions for the 50 states of the American Union. Like the works that address the relative convergence hypothesis at the international level, all of these works find evidence of convergence clubs at the intranational level.

2.5. Other approaches

Another approach that has frequently been used to analyze the convergence of CO_2 emissions is that of intra-distributional dynamics. Among the works that have used this approach are Stegman (2005), who studies a sample of 97 countries, Nguyen Van (2005) for a sample of 100 countries, Aldy (2006) for OECD countries, Ezcurra (2007) for a sample of 87 countries, Ordás Criado and Grether (2011) for a sample of 166 countries and Herrerias (2011) for a sample of European Union countries. Most of these works find evidence of convergence for developed countries. However, Stegman (2005) and Aldy (2006) do not find evidence of convergence for a much larger sample and Ezcurra (2007) for countries that are not developed.

In general, the results of previous investigations are very similar. There is evidence of divergence in carbon dioxide emissions in low-income countries as a group and convergence in emissions in developed countries, especially in the OECD country groups. There are several reasons for the global divergence and one of them is the uneven distribution of fossil fuels among countries.

3. Data and relative convergence model

3.1. Convergence and grouping test in clubs

The starting point is the panel data decomposition X_{it} as:

$$X_{it} = g_{it} + a_{it} \tag{1}$$

Where,

g_{it} represents the systematic components such as the common permanent components,
a_{it} incorporates the transient components.

To separate the common components from the idiosyncratic ones, it is possible to transform equation (1) a dynamic factor model as follows:

$$X_{it} = \left[\frac{g_{it} + a_{it}}{u_t}\right] u_t = \delta_{it} u_t \tag{2}$$

Where, u_t captures the stochastic trend behaviour and δ_{it} (the time-varying fit factor) measures the idiosyncratic distance between u_t and X_{it}.

In general, it is not possible to estimate the model directly. It becomes necessary without imposing some restrictions on δ_{it} y u_t. Phillips and Sul (2007) propose to remove the common factor as follows:

$$h_{it} = \frac{X_{it}}{\frac{1}{N}\sum_{i=1}^{N} X_{it}} = \frac{\delta_{it}}{\frac{1}{N}\sum_{i=1}^{N} \delta_{it}} \tag{3}$$

Where, h_{it} which measures the fit coefficient relative to the panel mean over time t. In other words, h_{it} plots a transition path of each element i relative to the average of the panel. Equation (3) indicates the cross-section mean of h_{it}. In this way, it captures the region's relative deviation from the common steady-state growth path u_t.

To formulate the null hypothesis of convergence, Phillips and Sul (2007) propose a semi-parametric model for the time-varying behavior of δ_{it} as follows:

$$\delta_{it} = \delta_{it} + \sigma_i \, \varepsilon_{it} L(t)^{-1} t^{-\propto} \quad t = 1, \ldots, T \tag{4}$$

Where, ε_{it} is a specific component of each region that is distributed identically and independently with mean 0 and unit variance between the different i, but weakly dependent over time, and $L(t)$ is a slowly varying function in which $L(t)\rightarrow\infty$ as $t\rightarrow\infty$. Phillips and Sul (2007) assume that the function $L(t)$ is a logarithmic function of t. The magnitude of $\propto$ determines the behavior (convergence or divergence) of δ_{it}. This ensures the convergence of the parameter of interest for all, which is the decay rate. Phillips and Sul (2007) consider the convergence expressed as:

$$lim_{k\rightarrow\infty}\left(\frac{\gamma_{it+k}}{\gamma_{jt+k}}\right) = 1 \; for \; all \; i \; and \; k \tag{5}$$

Which is called relative convergence and is equivalent to:

$$lim_{k\rightarrow\infty}\delta_{it+k} = \delta \; for \; all \; i \tag{6}$$

The convergence evaluation is carried out through a $Log\, t$ test and the following hypotheses are put forward:

$$H_0 : \delta_i = \delta \; for \; all \; i \; and \; a \geq 0 \tag{7}$$

$$H_0 : \delta_i = \delta \text{ for some } i \text{ or } a < 0 \tag{8}$$

The null hypothesis of convergence can be tested according to Phillips and Sul (2007) by considering the following equation:

$$\log\left(\frac{H_1}{H_t}\right) - 2\log L(t) = a + b\,logt + u_t \quad t = T_0, \dots, T_n \tag{9}$$

Where, $H_t = \frac{\sum_{i=1}^{N}(h_{it}-1)^2}{N}$; $T_0 = [rT]$ for some r; and $\log\left(\frac{H_1}{H_t}\right)$ is the root mean square cross-sectional transition differential and measures the distance of the panel from the common boundary. Phillips and Sul (2007) suggest $r = 0.3$ based on their simulation experiments. They also suggest using $Log\,(t)$ for (t) . The selection of the initial sample fraction r can influence the results of the previous regression (Du, 2017). Monte Carlo experiments indicate that when choosing $r \in [0.2, 0.3]$, a good result is obtained. More specifically, estabilishing $r = 0.3$ for a small or moderate sample size (≤ 50) and making $r = 0.2$ for a larger sample size (≥ 100) is suggested.

Phillips and Sul (2007) further show that $b = 2\alpha$ and that H_0 is conveniently tested through the weak inequality $\alpha \geq 0$, which implies a unilateral t-test. The limit distribution of the t regression statistic is:

$$t_b = \frac{\widehat{b} - b}{S_b} \rightarrow N(0,1) \tag{10}$$

Where, $\widehat{b}$ is the estimator of the coefficient b and S_b is the long-term standard error. Equation (10) implies that the null hypothesis of convergence is rejected at the 5 % significance level if $t_b \leq 1.65$. They show that the convergence hypothesis is tested through a t one-sided test with the parameter $b \geq 0$. Where:

$$s_b^2 = l\,\widehat{\mathrm{var}}\left(\widehat{u}_t\right)\left[\sum_{t=[rT]}^{T}\left(\log(t) - \frac{1}{T-[rT]+1}\sum_{t=[rT]}^{T}\log(t)\right)^2\right]^{-1} \tag{11}$$

and $l\,\widehat{\mathrm{var}}(\widehat{u}_t)$ is a conventional HAC estimate formed from the regression residuals.

Rejecting the null hypothesis of convergence for the entire panel cannot rule out the existence of convergence in the subgroups within. To investigate the possibility of convergence clubs, Phillips and Sul (2007) developed an algorithm based on the data, which consists of four steps.

1. Individuals are sorted in decreasing order considering the observations of the last period. If there is considerable volatility in the time series, the classification can be based on the time series average of the last observations [rT], with $r = 1/2$ *or* $1/3$ (Phillips and Sul, 2007).
2. This is followed by the formation of the core group of k^* individuals. The first subgroup of k individuals or regions (G_k) is selected by running the logt regression and the t_k convergence test statistic is calculated for this subgroup with $t_k > -1.65$. If the condition that k is not satisfied, the algorithm ends and it is concluded that there are no subgroups that converge on the panel. On the contrary, if the condition that $t_k > -1.65$ is fulfilled once the first k individuals in the panel have been selected, the core group of size k* is obtained by maximizing t_k over k according to the criterion $k^* = \arg\ \max$ subject to $\min\{t_k\} > -1.65$ (Phillips and Sul, 2007).
3. In the third step, the individuals in the panel that are not included in the first main group are added one at a time to the main group with k^* members, and the *logt* test is run again. The individual concerned should be included in the convergence club if the t associated statistic is greater than the critical value c (Phillips and Sul, 2007).
4. In the last step, a subgroup is formed with the remaining individuals who do not meet the inclusion criteria in step three. The *logt* test is run for this group. If the statistic is greater than -1.65, this subgroup forms another convergence club. Otherwise, steps 1 through 3 are repeated to see if this second subgroup can be subdivided into smaller convergence groups (Phillips and Sul, 2007).

3.2. Data

The data used in this work are estimates of national carbon dioxide emissions per capita, in metric tons of carbon, from the combustion of fossil fuels and cement manufacturing for a sample of 139 countries in the period from 1960 to 2017 and come from Gilfillan et al. (2020) (https://data.ess-dive.lbl.gov/view/doi:10.15485/1712447). It is necessary to mention that this database covers all countries from 1751 onwards, although the date from which the record is recorded is not homogeneous for all, however it constitutes a valuable tool to understand the historical trends of CO_2 emissions (Gilfillan and Marland, 2021). Additionally, Gilfillan and Marland (2021) compare CDIAC-FF estimates with other data sets and analyze emissions trends using a Kaya identity decomposition analysis.[1]

In addition, we classified these countries into groups depending on their income level as low, lower-middle, upper-middle and high, according to the World Bank classification. However, it should be noted that it was not possible to classify some countries according to this criterion, such as Venezuela and Taiwan. Therefore, some of them were not included in any of these groups. In all cases, the data were filtered using the Hodrick-Prescott filter.

4. Results

Table 1 shows the results of the $\log t$ convergence test applied to the per capita CO_2 emissions of the 139 countries considered in the analysis; the $\widehat{b}$ coefficient and t statistic estimated in the test are reported at the top of the Table. Given that the value of the t statistic is -29.43 and, therefore, lower than -1.65, the null hypothesis of relative convergence for all the countries considered in the period from 1960 to 2017 is rejected at the 5 % level. Due to the rejection of the convergence hypothesis for all the countries considered, convergence clubs are identified through the iterative process of the test. The results of the procedure are also shown in Table 1 and it is observed that eight clubs converge and one divergent group is identified; the first club contains the majority of the countries (105), while the rest of the clubs are made up of a small number of countries.

The results make it possible to identify a large club of countries in per capita carbon dioxide emissions, which includes three quarters of all the countries, while the rest, 25 %, makes up 7 small clubs, mainly the second and the fifth containing two countries. Table 2 shows the results of the Schnurbus et al. (2017) club merging tests applied to the results of the relative convergence tests for all the countries.

As shown in Table 2, the only clubs that can be merged are clubs 3, 7 and 5, thus forming a third club with 16 countries. Likewise, clubs 6 and 7 can also be merged, resulting in 5 clubs, instead of the initial eight, in addition to the divergent group formed only by Jamaica. These results reinforce the finding of the Phillips and Sul (2007) test applied to all the countries considered in the analysis.

In order to establish whether there is convergence in per capita CO_2 emissions in the countries considered according to their income level, we classify these countries according to the classification provided by the World Bank. More specifically, we built four groups: low income, lower-middle income, upper-middle income, and high income. The results of the test applied to low income countries are shown in Table 3. As shown in this table, the relative convergence test does not allow us to reject the null hypothesis of convergence for the low-income group, so the per capita CO_2 emissions of the low-income countries considered in

[1] The Kaya identity, also known as the Kaya equation, is an equation that represents the factors that influence carbon dioxide (CO_2) emissions. It was developed by Japanese economist Yoichi Kaya in 1993. The equation expresses CO_2 emissions as a product of four variables: population, GDP per capita (economic activity), energy intensity of GDP (energy efficiency) and carbon intensity of energy sources.

Table 3
Convergence test (1960–2017). Low income countries.

Convergence Test			
Club	$\hat{b}$	*t-statistic*	*Countries*
Unique	0.058	1.599	18

Countries that are members of the "Single Club".
"| Afghanistan | Central African Republic | Chad | Democratic People S Republic of Korea | Democratic Republic Of The Congo (Formerly Zaire) | Gambia | Guinea | Guinea Bissau | Liberia | Madagascar | Mali | Mozambique | Nigeria | Sierra Leone | Somalia | Syrian Arab Republic | Togo | Uganda |"

this base converge in a single group.

The results of the relative convergence test applied to the per capita carbon dioxide emissions of the lower-middle income countries are shown in Table 4. As can be seen in the Table for this group of countries, the hypothesis of relative convergence is rejected since the statistic was −17.491, well below the critical value of −1.65. Meanwhile, the convergence club tests detect five convergence clubs for the countries considered as lower-middle income, of which the fifth is the one that groups the largest number of countries, specifically 12 out of 36. As for the results of the club merging tests, these indicate that it is only possible to merge clubs 2 and 3, as shown in Table 5.

Regarding the carbon dioxide emissions of the group of countries considered as upper-middle income, the result of the relative convergence test is shown at the top of Table 6. Since the test statistic is less than −1.65, the relative convergence test is also rejected for the 33 countries identified as the group of upper-middle income countries. Therefore, the convergence club tests and their identification are performed, the results of which are also shown in Table 6. The results of the carbon dioxide emissions convergence club tests allow for the identification of 4 convergence clubs, of which the first one is the one that contains the highest number of countries, 18 of the 33 considered in this group of countries.

Meanwhile, the results of the club merging tests for the per capita carbon dioxide emissions of the countries in this upper-middle income group indicate that it is not possible to merge any of the adjacent clubs, as shown in the bottom panel of Table 7.

Finally, the results of the relative convergence test applied to the per CO2 emissions of the group of countries classified as high-income are shown in Table 8. As can be seen in this table, as in the case of the carbon dioxide emissions of the countries classified as low-income, for the emissions of this pollutant in per capita terms, it is not possible to reject the convergence hypothesis for the 48 countries considered within this group.

Therefore, the results show that when we classify the countries

Table 4
Convergence clubs test (1960–2017). Lower middle income countries.

Convergence Test			
Club	$\hat{b}$	*t-statistic*	*Countries*
Unique	−1.180	−17.491	36
Convergence Club Tests			
Club	$\hat{b}$	*t-statistic*	*Countries*
1	−1.741	−0.744	6
Club 1 countries: Algeria | Cayman Islands | Colombia | Islamic Republic of Iran | Mongolia | Tunisia |			
Club	$\hat{b}$	*t-statistic*	*Countries*
2	2.164	8.380	4
Club 2 countries: | Belize | India | Morocco | Plurinational State of Bolivia |			
Club	$\hat{b}$	*t-statistic*	*Countries*
3	0.286	3.138	4
Club 3 countries: | Angola | Indonesia | Lao People S Democratic Republic | Samoa |			
Club	$\hat{b}$	*t-statistic*	*Countries*
4	0.467	9.504	9
Club 4 countries: | Benin | Cape Verde | El Salvador | Honduras | Mauritania | Nicaragua | Papua New Guinea | Philippines | Sri Lanka |			
Club	$\hat{b}$	*t-statistic*	*Countries*
5	0.565	16.890	12
Club 5 countries: "| Comoros | Congo | Cote D Ivoire | Djibouti | Ghana | Haiti | Kenya | Myanmar (Formerly Burma) | Republic O of Cameroon | Sao Tome & Principe | Senegal | Solomon Islands |"			
Divergent Group			
| Egypt |			

Table 5
Club fusion test (1960–2017). Lower middle income countries.

Initial Groups	*Fusion tests*					*Final Groups*
Club 1 [6]	Club 1 + 2 −3.187 −5.674					[6]
Club 2 [4]		Club 2 + 3 0.465 3.460				[-]
Club 3 [4]			Club 3 + 4 0.068 0.590			[8]
Club 4 [9]				Club 4 + 5 −0.652 −42.878		[9]
Club 5 [12]					Club 5 + 6 −0.570 −43.654	[12]

Table 6
Convergence club test (1960–2017). Upper middle income countries.

Convergence Test			
Club	$\hat{b}$	*t-statistic*	*Countries*
Unique	−1.969	−34.416	33
Convergence Club Tests			
Club	$\hat{b}$	*t-statistic*	*Countries*
1	2.209	1.362	18
Club 1 countries: "| Argentina | Brazil | Bulgaria | China (Mainland) | Cuba | Ecuador | Gabon | Guyana | Iraq | Jamaica | Jordan | Lebanon | Libyan Arab Jamahiriyah | Mexico | Romania | South Africa | Suriname | Turkey |"			
Club	$\hat{b}$	*t-statistic*	*Countries*
2	1.316	10.065	3
Club 2 countries: "| Dominica | Dominican Republic | Grenada |"			
Club	$\hat{b}$	*t-statistic*	*Countries*
3	0.625	6.817	6
Club 3 countries: "| Albania | Costa Rica | Fiji | Peru | Saint Lucia | St. Vincent & The Grenadines |"			
Club	$\hat{b}$	*t-statistic*	*Countries*
4	−0.541	−0.253	2
Club 4 countries: "| Guatemala | Paraguay |"			
Divergent Group			
"| Equatorial Guinea | Mauritius | Thailand | Tonga |"			

Table 7
Club fusion test (1960–2017). Upper middle income countries.

Initial Groups	Fusion tests				Final Groups
Club 1 [18]	Club 1 + 2 −6.001 −3.587				[18]
Club 2 [3]		Club 2 + 3 −0.508 −3.728			[3]
Club 3 [6]			Club 3 + 4 −0.679 −6.107		[6]
Club 4 [4]				Club 4+G5 −5.001 −27.593	[4]

Table 8
Convergence clubs test (1960–2017). High income countries.

Convergence Test			
Club	$\widehat{b}$	*t-statistic*	*Countries*
1	−0.083	−1.010	48

Countries that are members of the "Single Club".
"| Antigua & Barbuda | Australia | Austria | Bahamas | Bahrain | Barbados | Belgium | Bermuda | Brunei (Darussalam) | Canada | Chile | Cyprus | Denmark | Faeroe Islands | Finland | France (Including Monaco) | French Polynesia | Greece | Greenland | Hong Kong Special Adminstrative Region Of China | Hungary | Iceland | Ireland | Israel | Italy (Including San Marino) | Japan | Kuwait | Luxembourg | Macau Special Adminstrative Region Of China | Malta | Netherlands | New Caledonia | New Zealand | Norway | Poland | Portugal | Qatar | Republic Of Korea | Saudi Arabia | Singapore | Spain | Sweden | Switzerland | Trinidad And Tobago | United Arab Emirates | United Kingdom | United States Of America | Uruguay |"

according to their income levels, the extreme groups, those of low-income and high-income, there is evidence of relative convergence. On the other hand, for the carbon dioxide emissions in per capita terms of the countries classified as lower-middle income and upper-middle income, there is evidence of convergence clubs within these groups, which shows evidence of a greater number of stationary states to which the countries considered to be both lower-middle income and upper-middle income countries converge.

When using an alternative database, as is done in this research work, the results are not strictly comparable with other investigations that analyze the relative convergence in per capita CO2 emissions, such as those of Panopoulou and Pantelidis (2009) for a sample of 128 countries, Pettersson et al. (2014) and Robalino-López et al. (2016) for developing countries. All of them use the World Bank Development Indicators as a basis. It is also not consistent with the research carried out by Herrerias (2013) for a sample of 162 countries and by Haider and Akram (2019b) for a sample of 53 countries, since both works use the Energy Information Administration database (EIA).

However, regardless of using one type of database or another, similar findings are shared in the sense that they all find convergence clubs in per capita carbon dioxide emissions. In particular, the work of Pettersson et al. (2014) finds evidence of three convergence clubs in low-income developing countries, which are not possible to merge, and of five convergence clubs when considering the lower-middle income countries. Of these results, the first one is not consistent with what we obtain in this work, since, on the contrary, evidence of convergence was found in the low-income group. In contrast, the second one is consistent with the findings, despite the fact that the classification of this research is based on a much larger sample of countries.

Because there is no evidence of relative convergence in carbon dioxide emissions per capita for all the countries considered in the sample, but it was found in some groups of countries classified according to their income levels, specifically in the low-income groups. income and high income, one of the policy recommendations that emerge from this study is that it is not convenient to assign the same scheme of emission rights based on carbon dioxide emissions for all countries, but that they should be differentiated depending on the income level group to which they belong.

Another recommendation is that the need to reevaluate the energy regulatory framework for all countries must be recognized in order to reduce carbon dioxide emissions generated by the combustion of fossil fuels and the manufacture of cement, in accordance as suggested by Churchill et al. (2020) for total carbon dioxide emissions.

Additionally, international carbon trading, also known as emissions trading or emissions trading, is a market-based approach to reducing greenhouse gas emissions. It involves the purchase and sale of emission rights between countries or entities. Under this system, a certain limit is established on the total amount of greenhouse gases that participating countries or entities can emit. These emission rights are distributed among them. If a country or entity emits less than its allocated allowances, it can sell its excess allowances to other countries or entities that exceed its limits. This creates an economic incentive to reduce emissions efficiently and allows flexibility to meet emissions reduction targets.

Another measure that can contribute to the reduction of carbon dioxide emissions is to promote technology transfer and capacity development. Developing countries often find it difficult to adopt cleaner technologies due to financial constraints or a lack of technical knowledge. Therefore, it is important to promote policies that promote technology transfer and allow these countries to transition towards more sustainable practices.

However, within the limitations of the study, it is necessary to keep in mind that these results correspond to the hypothesis of relative convergence, and we consider that for them to acquire a more general character they need to be corroborated with other approaches and tests of convergence, which suggests some future research lines on the topic. Another limitation of the present study is that we are only considering carbon dioxide emissions from the combustion of fossil fuels and cement production, although they are two of the main human activities that emit carbon dioxide, they are not the unique. For work, these two sources are important because in most countries, the use of automobiles is one of the sources of pollutants, and through the construction of infrastructure (buildings, houses, roads, etc.), cement is another of the fundamental sources.

5. Conclusions and policy implications

Understanding how per capita carbon dioxide (CO_2) emissions behave is important for designing international proposals on climate change (Aldy, 2006). In this work we contribute with the relative convergence of carbon dioxide emissions per capita from the combustion of fossil fuels and cement manufacturing of a set of 139 countries in the period from 1960 to 2017 whose source is Gilfillan et al. (2020). The methodology used to test the relative convergence hypothesis in this work is the one proposed by Phillips and Sul (2007, 2009), which determines, in the first instance, whether the carbon dioxide emissions of all the countries considered converge into a single country. group and if this is not the case, they converge into different subgroups or clubs, at the same time determining these clubs. This test was applied not only to all countries but also to four different groups made up according to their income level: low, lower-middle, upper-middle and high-income, according to the World Bank classification. In cases where it is found that countries converge into different clubs, the test of Schnurbus et al. (2017) is applied, which determines whether the number of clubs determined by the Phillips clustering algorithm has not been overestimated. and Sul (2007 and 2009) through a club merger test. The analysis of databases of carbon dioxide emissions from certain activities can contribute to understanding the way in which total carbon dioxide emissions behave, which are used in most studies on the subject.

The public policy implications of this type of study are relevant to establish regional emission mitigation policies to meet the objectives already stated, since it provides a clear picture of the status quo of carbon dioxide emissions (Wang et al., 2014).

The nonlinear time-varying factor methodology of Phillips and Sul (2007, 2009) reveals multiple convergence clubs both for the sample of all the countries considered in the study and for countries classified as lower-middle and upper-middle income. In contrast, for low income and high income countries, evidence of relative convergence was found in both groups. However, the tests conducted by Schnurbus et al. (2017) suggest that the number of clubs for all the countries and for lower-middle income countries is smaller, since in the first case, it is 5 instead of 8 and, in the second case, 5 to 4, plus a divergent group in both cases.

The existence of convergence clubs in per capita carbon dioxide emissions "may reflect similar natural resource endowments, climatic conditions and economic structure, all of which influence their energy consumption mix" (Payne and Apergis, 2021). In addition, in some cases, "geographical proximity can also indicate the potential for strategic interactions between governments regarding environmental policy actions whose economies are spatially linked in relation to other countries" (Fredriksson et al., 2004). "On the other hand, the quality of countries' institutions and governance structure can play a fundamental role in the effective implementation of the appropriate economic instruments (price- and rights-based measures) to mitigate emissions as their level of economic development evolves over time" (Payne and Apergis, 2021).

One of the implications derived from the existence of clubs is the recommendation that members of the same club consider possible opportunities for collaboration among themselves in order to curb carbon dioxide emissions (Dogah and Churchill, 2022; Panopoulou and Pantelidis, 2009). In fact, these authors hold that the common emission reduction strategy will only be successful among the same members of the club, since there is no total panel convergence.

Mandatory emission reduction measures may be introduced in cement production, as the demand for cement increases as a result of rapid urbanization and industrialization, increasing infrastructure and construction requirements (Dogah and Churchill, 2022), measures such as tradable industrial performance standards that require a reduction in the average intensity of CO_2 in the production of certain goods. By this logic, it would seem that the development of countries means greater pollution, because in doing so they demand more cement to construct the buildings, factories and infrastructure that progress requires, and therefore, also higher emissions of pollutants. Under this scheme, international agreements are important, not only between countries, but between companies, since by improving their production process they can reduce pollution.

If per capita carbon dioxide emissions do not converge, then an emissions allocation scheme based on this indicator would lead to large international resource transfers through trading and relocation of the most polluting industries to developing countries (Stegman and McKibbin, 2005; Aldy, 2006; Barassi et al., 2008; Haider and Akram, 2019b).

CRediT authorship contribution statement

Domingo Rodríguez-Benavides: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Roldán Andrés-Rosales:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **José Álvarez-García:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Festus Víctor Bekun:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

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Data availability

Data will be made available on request.

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