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Analysis of the international distribution of per capita CO_2 emissions using the polarization concept

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Abstract

The concept of polarization is linked to the extent that a given distribution leads to the formation of homogeneous groups with opposing interests. This concept, which is basically different from the traditional one of inequality, is related to the level of inherent potential conflict in a distribution. The polarization approach has been widely applied in the analysis of income distribution. The extension of this approach to the analysis of international distribution of CO_2 emissions is quite useful as it gives a potent informative instrument for characterizing the state and evolution of the international distribution of emissions and its possible political consequences in terms of tensions and the probability of achieving agreements. In this paper we analyze the international distribution of per capita CO_2 emissions between 1971 and 2001 through the adaptation of the polarization concept and measures. We find that the most interesting grouped description deriving from the analysis is a two groups' one, which broadly coincide with Annex B and non-Annex B countries of the Kyoto Protocol, which shows the power of polarization analysis for explaining the generation of groups in the real world. The analysis also shows a significant reduction in international polarization in per capita CO_2 emissions between 1971 and 1995, but not much change since 1995, which might indicate that polarized distribution of emission is still one of the important factors leading to difficulties in achieving agreements for reducing global emissions.

JEL codes: D39; Q43; Q56.

Keywords: climate change negotiations; international CO_2 distribution; polarization.

1. Introduction

There are strong differences in the levels of emissions caused by the inhabitants of different parts of the world. The analysis of the international distribution of CO_2 emissions is very important for analyzing climate change and designing policies to mitigate it. The inequality in per capita CO_2 emissions between countries shows different responsibilities in the generation of greenhouse gases and the contribution to climate change. Therefore, the analysis of this inequality sheds light on the debate about the different control and mitigation measures to be applied in different regions. In fact, distribution problems have become the most important issue to deal with in global climate change policy negotiations and agreements. Taking distribution problems properly into account in policy design leads to an increase in the perceived fairness of the measures and facilitates widespread participation.

Although rich countries are responsible for much higher emissions in per capita terms, the impressive rates of growth in absolute emissions in some expanding economies, such as China and India, means any solution involving the stabilization of greenhouse emissions (as mandated by the UNFCCC) requires the participation of both richer countries and developing economies in order to control global emissions. The climate change policy involves establishing limits to the level of global emissions and distributing this level among the different countries or groups of countries. These limitations might involve economic sacrifices. There are several approaches on the distribution of future emissions "entitlements" [1] and on the distribution of abatement

[1] The proposals for the distribution of entitlements are based on current emission levels (e.g. Pearce and Warford, 1993), on GNP shares (e.g., Wirth and Lashof, 1990; Cline, 1992), distribution of

costs[2]. The analysis of emissions distribution should also be useful for informing the debate on the distribution of emissions entitlements.

The above reasons explain why, in recent years, several works have appeared focusing on the distributive analysis of environmental issues and, in short, on the analysis of CO_2 emissions and energy consumption. Hedenus and Azar (2005) employ the Atkinson inequality index for analyzing the evolution of inequality in various natural resources. With respect to the analysis of the inequalities in energy intensity we can cite the papers by Sun (2002) and Alcántara and Duro (2004). The works by Heil and Wodon (1997, 2000), and Padilla and Serrano (2006) introduce various indexes taken from income distribution analysis for measuring and studying the evolution of the international inequality in CO_2 emissions. Heil and Wodon (1997) employ a group decomposition of the Gini coefficient for analyzing the inequality in per capita CO_2 emissions and the contribution of two income groups (rich and poor countries) to this inequality. Heil and Wodon (2000) employ this methodology for analyzing future inequality in per capita emissions using projections to year 2100, as well as considering the scenario under the impact of the Kyoto Protocol and other reduction measures. Padilla and Serrano (2006) employ concentration indexes and show that the inequality between rich and poor countries (inequality in emissions between countries ordered by the increasing value of per capita income) have been reduced less than the "simple" inequality in emissions, and use the decomposition of

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entitlements in per capita terms (e.g., Grubb, 1990; Agarwal and Narain, 1991; Meyer, 1995), and different combinations of these criteria.

[2] The proposals for distributing costs are mostly based on the "polluter pays" principle and indexes of ability to pay (see IPCC, 1996; section 3.5., pp. 103-112).

the Theil index for showing the contribution of four income groups to inequality. Duro and Padilla (2006) decompose the international inequality in CO_2 emissions into the different Kaya factors and two interaction terms, also undertaking the analysis between and within groups of countries, so explaining the main sources of emissions inequality.

However, the notion of inherent conflict or instability of the international distribution of emissions, which might be important in problems such as climate change where emissions' reduction needs from agreement, is not conveniently captured by the inequality approach[3]. In this sense, a concept which explicitly includes this aspect has recently been developed and extended to other academic fields: the concept of polarization.

The notion of polarization consists in examining the degree to which the observations of a distribution—in our case, countries and their per capita CO_2 emissions—are allocated around different poles, and therefore are forming significantly homogeneous groups which are different between them. Under the polarization approach, conflicts will depend on the degree to which internally compact groups and with antagonistic interests might be constituted. This duality in the distribution would be a more feasible scenario for the appearance of stress and instabilities than a scenario with low polarization. Therefore, this distributive notion seems particularly relevant, insofar as it is linked closely to the possibility of the outbreak of conflicts.

In the same way as happens with the measurement of inequality, in order to make operative the concept, the measurement of polarization requires the employment of

[3] The surveys by Theil (1967), Sen (1973) and Cowell (1995) are classic references on these issues.

synthetic indexes. Among the most important proposals in the literature, the group of indexes suggested by Esteban et al. (1999) is quite appealing and seems superior to other alternatives, such as the Wolfson (1994) index or the measure proposed by Zhang and Kanbur (2001).

The analysis of polarization has been applied mainly in the field of personal income distribution (see e.g., Esteban et al., 1999; Gradín, 2000, D'Ambrosio, 2001; and Duro, 2005). Its application to the analysis of environmental problems is still very rare[4]. However, current discussions on global environmental problems, such as climate change, reinforce the utility of extending polarization analysis to the study of international distribution of CO_2 emissions. These discussions are partly focused on the duality between more polluting and less polluting countries (i.e. the discussion between homogeneous groups of countries—in terms of their polluting behavior—which are heterogeneous between them). Moreover, the main objective of these discussions consists in controlling and reducing global emissions and redistributing them among countries by means of a multilateral negotiation. This leads to a logical formation of coalitions, which are typically related to countries with similar situations. In this negotiation, the likelihood of achieving agreement depends on the duality between countries.

Therefore, polarization analysis complements inequality analysis by giving a more complete characterization of the international distribution of per capita emissions. It gives us indications on the degree of inherent potential tensions of this distribution. It

[4] The only reference we have found is the recent work by Ezcurra (2007), who computes an index of polarization in CO_2 emissions for 87 countries among other instruments for analyzing CO_2 convergence.

might be the case that international inequality in per capita emissions had declined (see e.g. Heil and Wodon, 1997; Duro and Padilla, 2006; Padilla and Serrano, 2006) but polarization increased. Moreover, if both distributive measures evolved in a similar way, then they would reinforce the conclusions in informative terms.

But the utility of polarization analysis does not only centers on the evaluation of its time pattern. There is also great interest in knowing which are the groups “theoretically” conformed according to their polluting similarity, in knowing which are the members of these groups, and in contrasting if such predicted groups are verified in reality. In short, it is interesting checking if the groups predicted by the polarization approach are similar to the groups finally established in real negotiations, such as the Kyoto Protocol (e.g., Annex B and non-Annex B countries). Their coincidence would reinforce the capacity of polarization analysis as a tool predicting coalitions’ formation and, as a consequence, evaluating the potentiality of conforming agreements according to a given distribution.

The main aim of this article is therefore to adapt and apply these polarization indexes to analyze the international distribution of CO_2 emissions. To our knowledge, this is the first attempt to make use of the potential of the polarization concept and measurement for analyzing CO_2 emissions distribution. The available data will allow us to undertake the analysis for the time period 1971–2001 and include 116 countries, which is equivalent to more than 99% of estimated world population and emissions. Besides the reference polarization analysis of per capita CO_2 emissions, including all the countries and weighting through population-shares, we have developed two more exercises. Firstly, we have compared the results with the case where all countries were treated homogenously, independently of their population, following the typical practice developed by the income convergence literature. Secondly, we have verified the degree of variability of the results when China and India are excluded from the analysis, given their large size and their impressive recent development.

The paper is organized in the following way. Section 2 reviews the concept of polarization and the measures suggested in the literature. Section 3 carries out an empirical application adapting the more appropriate polarization measures for the analysis of international distribution of per capita CO_2 emissions. Section 4 computes polarization values when all countries are treated uniformly, independently of their population, and also when China and India are excluded from the sample. Section 5 concludes the paper.

2. Measuring polarization: some methodological aspects

The basic idea underlying the concept of polarization is its capacity to measure in an appropriate way the inherent potential instability in a given distribution. Unfortunately, the conventional indexes of inequality and convergence are ineffective as measures of polarization. Let us imagine a hypothetical distribution in which only one country—with a small relative population weight—has a positive level of CO_2 emissions per inhabitant while the other countries do not emit CO_2 at all. This extreme scenario would be perceived by the conventional indexes of inequality (like the Gini coefficient) as a situation of maximum inequality (the Gini would be 1). However, this would probably not be the worst possible situation in terms of conflict and instability. Probably, if this was the scenario, it would not be difficult to convince this country to modify its behavior, given its predictable small relative power associated with its marginal relative population weight. That is, small groups, with a small relative population weight, would be not very important in terms of potential instability, in clear contrast to the perception established by the traditional *inequality approach*. A much more complicated scenario would be described by a situation where half of the world population emitted a high level of CO_2 to the atmosphere while the other half did not emit. The existent split, descriptive of an extreme duality, would a priori significantly complicate the achievement of agreements for reducing emissions, given the divergence of interests and the “force” of the groups—force linked to the size of the groups. In this last situation, standard inequality indexes would show lower values than in the former extreme case. Therefore, in this case, the employment of inequality measures would predictably contribute to bias our valuation of the seriousness of the situation. In order to solve this clear incapacity of inequality measures to show the degree of duality in a given distribution and its nexus with instability, the polarization approach has been developed in recent years. In fact, many of the relevant questions concerning international distribution of per capita CO_2 emissions could probably be more consistently dealt with the concept of polarization than with inequality, as might indicate the frequent arguments between high-polluting and low-polluting countries and groups of countries.

Following the approach initially developed by Esteban and Ray (1994), polarization would depend on the following factors:

i) Polarization is a groups’ issue. A lower number of groups tends to increase polarization.

ii) Polarization depends on the size of groups. Groups of reduced size have small relevance for the generation of conflicts and polarization.

iii) The distance between groups. More heterogeneous groups increase the degree of polarization.

iv) The level of cohesion. Internally homogeneous groups increase polarization.

In order to make this notion operational, these authors initially proposed the ER indexes for income polarization measurement, with the following formulation, which we have adapted for the measurement of polarization in per capita CO_2 emissions:

$$ER(\alpha)=\sum_{i=1}^{n}\sum_{j=1}^{n}p_i^{1+\alpha}p_j\left|\frac{e_i}{e}-\frac{e_j}{e}\right| \qquad (1)$$

where p_i and p_j are the relative populations of countries "i" and "j"; and e_i and e_j are the per capita CO_2 emissions of both countries; e is the world average and α is a parameter measuring the level of sensitivity to polarization, which, by construction, would take values between 1 and 1.6. A greater value of α implies that the measure gives greater weight to the equalization of groups size than to other factors. In fact, the larger the value for α, the greater the difference between this index and standard inequality measures, such as the Gini index.

However, the ER index has some limitations, basically concerning its applicability. It does not provide criteria for grouping observations, meaning that its use is mainly advisable for analyzing predetermined groups. In order to resolve this restriction, Esteban et al. (1999) proposed the EGR indexes. These indexes would be consistent with endogenously defined groups and, as a consequence, their expression would include the groups' lack of cohesion. Formally, EGR indexes, which we have adapted to the analysis of CO_2 emissions, would be defined as:

$$EGR(\alpha,\beta)=\sum_{i=1}^{n}\sum_{j=1}^{n}p_i^{1+\alpha}p_j\left|\frac{e_i}{e}-\frac{e_j}{e}\right|-\beta(G-G_s) \qquad (2)$$

where β is a parameter showing the measure sensitivity to the groups' level of cohesion, G is the Gini coefficient of the original distribution and G_s is the Gini of grouped distribution (inter-group inequality).

With regard to the value to be taken by the parameter β, this is free. However, we can make some general indications. Note that ER and EGR indexes have the Gini coefficients as a reference. In short, the ER index, which is the first term of expression (2), is an index that can adopt values close to the Gini[5]. The second term in (2) is, in fact, a Gini difference. It would therefore seem reasonable, in terms of scale, to set a statistical value for β close to the unit.

Although the EGR index is not uniformly bounded, given its relationship with the Gini coefficient we can interpret that a value close to 1 is indicative of high polarization while a value close to zero indicates low polarization[6].

The procedure, then, consists of establishing the limits of groups in such a way that the internal disparities in each group are minimized (optimal groups). As far as the specific minimization procedure is concerned, this coincides with that suggested by Davies and Shorrocks (1989), in which the cut-off point between groups is defined by

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[5] Both indexes would coincide if α was equal to 0.

[6] In the field of inequality measurement there are also indexes, such as the Theil index, which are not uniformly upper-bounded (see Theil, 1967).

the average weighted emission (income in the original formulation) of the two adjacent groups.

With respect to the specific choice of the number of groups, several studies show that no significant explanatory gains take place from four groups upwards[7], which is clearly supported by our results shown in Table 4. It may be tempting to use the intra-group level of inequality (the internal cohesion of groups) for the precise selection of the appropriate number of groups. However, this method would tend to prioritize the distributions represented by a large number of groups, which reduces the own interest of polarization analysis. In our opinion, a useful criterion might be to observe the value thrown up by the EGR index. The underlying intuition is the following. Any increase in the number of groups, on the one hand, tends to lead to smaller aggregation errors, and therefore to produce higher EGR values but, on the other hand, also contributes to reduce the ER value and, as a consequence, the EGR. Therefore, the final value adopted by the index could be perceived as a broad indication of which is the prevailing channel.

These EGR indexes have been widely used with the object of characterizing the evolution of personal income distributions. For example, Esteban et al. (1999) show specific pioneer evidence for the case of Spain, Gradín and Rossi (2000) for Uruguay, and D'Ambrosio (2001) for Italy. For the international case there is, e.g. the work by Duro (2005).

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[7] See the evidence obtained by Davies and Shorrocks (1989), Esteban et al. (1999), Gradín (2000), and Duro (2006).

Nevertheless, some comments regarding other indexes of polarization may be instructive. Among the alternatives, we have to underline the measure proposed by Wolfson (1994). The main appeal of the Wolfson measure (W) is its direct derivation from the well-known Lorenz curve. In specific terms, its value would be graphically represented as all the area between the Lorenz curve and the tangent corresponding to average income (emission in our analysis). However, one of its main limitations is that it is only useful for analyzing the bipolarization case, meaning that it is inappropriate for examining other multipolar representations. Furthermore, as shown by Esteban et al. (1999), W may be interpreted as a particular case of EGR when the parameters α and β take a unitary value and median income (emission in our analysis) is used to separate the groups instead of the average. It is thus a measure with a low sensitivity to polarization, meaning that it might be interesting to check what happens with higher values of the parameter α. Zhang and Kanbur (2001), on the other hand, suggested the use of the inter-group inequality/intra-group inequality ratio as an indicator of the level of polarization for a given distribution (ZK index). However, this measure seems fairly unsatisfactory, as it violates most of the previously cited properties established by Esteban and Ray (1994) for a consistent measure of polarization. In short, for instance it does not fulfill the second of the properties, giving a very high value for isolated observations concentrating most of the income (emissions in our analysis)[8].

3. International Polarization in per capita CO_2 emissions: main empirical results

[8] Besides property 2, the ZK index does not fulfill properties 1 and 4 either.

Data on population and CO_2 emissions from fuel combustion have been taken from International Energy Agency (2003)[9]. After detailed analysis of the statistical information available, a sample of 116 countries covering the period 1971–2001 was considered. This sample is highly representative, insofar as it represents more than 99% of the world population and CO_2 emissions from fuel combustion. In order to save space, we provide the results for selected years[10].

Tables 1, 2, 3 and Figure 1 show the results obtained after applying the EGR indexes for the case of two, three and four optimal groups, respectively. In order to evaluate the general validity of the results we supply calculations for the various combinations illustrating polarization parameters.[11]

[TABLE 1 ABOUT HERE]

[TABLE 2 ABOUT HERE]

[TABLE 3 ABOUT HERE]

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[9] The emissions from the IEA do not include the emissions which do not derive from the combustion of fossil fuels, such as the generated by cement production and biomass burning. Thus, this data might tend to underestimate the emissions from poor countries as biomass combustion is relatively important in these countries, and it is not always burnt in a sustainable way.

[10] The data for other years is available on request to the authors. We have included 1992, year of the Earth Summit in Rio de Janeiro, and 1997, the year in which Kyoto Protocol negotiations took place.

[11] The results derived from other parameter combinations may be requested from the authors. They do not differ significantly from those reported in this paper. We have highlighted in bold letters the results for the parameter values which are most commonly used in the literature, α=1.3 and β=1.

[FIGURE 1 ABOUT HERE]

These results show a declining pattern referred to polarization during the period considered[12]. In fact, the values obtained for the EGR index for two, three and four groups show a clearly decreasing trend for any parametric combination. The reduction is especially significant for the analysis grouping countries into two and three groups, and less pronounced for the grouping of countries in four groups[13]. However, there is not too much reduction in polarization with respect to 1995, year in which there was abundant evidence of the phenomenon, nor with respect to 1997, when the negotiations on the Protocol took place. There has even been a small increase for the cases of 2 and 4 groups of countries. This might indicate that the unequal and polarized distribution of emissions across countries, which has not decreased in last few years, is still one of the important factors implying difficulties in the achievement of new arrangements going further than the Kyoto Protocol.

At this point, and besides the time analysis of polarization, we can also analyze which group classification is a more attractive description of the phenomenon of polarization. That is, which number of groups is more appealing for explaining the

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[12] CO_2 polarization was greater than income polarization at the beginning of the period (see, for example, Duro, 2005), although it has experienced a stronger reduction so they are now very similar. This similarity might indicate that the polarization in emissions could be explained to a great extent by the polarization in income.

[13] We have also carried out a comparative analysis of the time patterns followed by polarization and inequality values using the Gini index. We found that there has also been a clear reduction in CO_2 inequality over the period considered. Therefore, the measurements of both distributive conceptualizations have tended to a lower disequilibrium. Results are available upon request.

degree of per capita emissions polarization. An initial way of checking the capacity of the various cases analyzed could be to use the percentage with respect to the inequality of the original CO_2 distribution that represents the inequality between groups of the simplified distribution in groups, as an indicator of the error incurred by the grouping process. This would mean calculating the ratio Gs/G. Table 4 is attached for this purpose. A high explanatory capacity for the three cases can initially be seen. Thus, the simplification of the distribution in only two groups of countries contributes to explaining almost 80% of the international differences in per capita emissions. If we consider three groups instead of two, which logically produces an improvement in the fit, this allows to explain 90% of the differences, a very significant percentage. Note that changing from three to four groups does not involve an important explanatory improvement. Given that the additional objective, besides working with a small aggregation error, consists of simplifying the relevant number of groups, our analysis would lead to reject the more detailed description in four groups, in favor of the other two descriptions (two and three groups). However, choosing which of these two representations is more appealing is not easy. Despite the gain observed in the explanatory capacity with the distribution associated with three groups, this does not seem apparently sufficient to choose it instead of the two-group distribution, which is very simple and has a low-aggregation error. The value shown by the own polarization index may shed some light on this situation[14]. It is thereby confirmed that in most cases, the EGR value for two groups exceeds the one produced by the EGR

[14] As we previously noted, any increase in the number of groups, on one hand leads to smaller aggregation errors, and so to higher EGR values but, on the other hand, reduces the ER value (see property 1 above) and, as a consequence, the EGR one. Hence, the value of the index could be perceived as a broad indication of which is the prevailing channel.

for three groups. Only in the cases where the weighting of the aggregation error—the value of parameter β—is high, the choice would be the three groups alternative.

[TABLE 4 ABOUT HERE]

Therefore, there seems to be a clear superiority of the simplified representation in two groups, in front of the choice of three groups. Table 5 and Figure 2 show the main descriptive traits of these two groups, as well as their evolution in the selected years of the sample used. In this way, we can observe that the reduction in the distributive duality above mentioned is mainly attributed to the reduction in the differences in the (relative) average emissions of the two groups (i.e. a process of convergence to the mean among groups. The countries with below average per capita emissions have moved from emitting a level of 21% of the world average in 1971 to emitting 39% in 2001. Concerning the most polluting countries, they have moved from a level of emissions of 305% of the world average to 279%, always in per capita terms.

[TABLE 5 ABOUT HERE]

[FIGURE 2 ABOUT HERE]

Table 6 and Figure 3 show the main descriptive treats of the groups in the three-groups case, as well as their evolution over the years of the sample. We can see that, with division into three groups, at the end of the period the poles are more homogeneous, but the much lower differences between them explain the overall reduction in polarization.

[TABLE 6 ABOUT HERE]

[FIGURE 3 ABOUT HERE]

It should be highlighted that in the classification into two groups deriving from the analysis, the *Above-average group* broadly coincides with Annex B of the Kyoto Protocol (See Appendix A.1), with some oil suppliers countries and few more countries with relatively small population weights. Thus, all countries that pledged to target their greenhouse gases emissions under the Kyoto Protocol (Annex B of the Protocol) are included in this group. In the case of three groups, all these countries are placed in the *High-emissions group*, while in the less relevant case of four groups, these countries are placed in the *medium-high* and *high emissions* groups. Thus, the optimal groups determined by the polarization approach broadly coincide with the real groups formed in Kyoto negotiations. This evidence reinforces the validity of our analysis and opens new ways for understanding negotiation processes and their final results.

Table 7 shows the results for a polarization analysis with an exogenous grouping in Annex B and non-Annex B countries. That is, now the EGR indexes do not take the groups formed in an optimal way—by setting their limits according to their degree of similarity in terms of per capita emissions—but the groups that were formed in real negotiations. As we can see, the results are very similar to the endogenous two groups case. The last column shows the degree to which this exogenous classification into Annex B and non-Annex B countries is able to explain overall inequality, that is to say, the percentage that represents between groups' inequality with respect to overall inequality (G_S/G) (the aggregation error). These results show polarization between these groups has undergone a greater reduction than polarization between the endogenously determined groups. While at the beginning of the period the grouping into Annex B and non-Annex B countries explained 81.4% of total inequality (only three points less than the inequality between endogenous groups), it now explains 69.1% of it (9.4 points less than the inequality between endogenous groups). In spite of this reduction, this is still a very remarkable percentage of overall inequality.

[TABLE 7 ABOUT HERE]

Nevertheless, although the analysis of polarization in emissions shows a significant part of the picture, it also should be taken into account that there are other distributive issues to be taken into account in order to undertake a more comprehensive analysis of the convergence in interests across countries and so in the environment for achieving agreements in climate change policies. It would be an interesting field for future research to contrast these results with other distributions related to climate change that might affect the convergence/divergence of interests, such as the distribution of the impacts of climate change, differences in income, differences in the vulnerability and capacity of adaptation to climate change, and differences in the economic effects of international emissions reduction policies[15].

4. Results for the case without population weighting and for a reduced sample excluding China and India

[15] As a reviewer noticed, taking this last point into account, it is not strange that oil exporting countries are the countries that made more opposition to climate change policies.

The results of the previous section are based on weighted polarization indexes; that is, the observations of countries have a non-uniform treatment, but are weighted according to their population. We think this is the most reasonable option. In any case, in this scenario the behavior over time of countries with larger populations, such as China or India, might cause a great impact on the polarization values and the results obtained in the previous section. However, it might be thought that in terms of political conflict, the weight of countries might not be exactly proportional to their population share. It is therefore interesting to compare the previous results with the results under other assumptions. In this case, we have recomputed the polarization index values considering the different observations in a uniform way. Table 8 shows the results.

[TABLE 8 ABOUT HERE]

It must be highlighted that the values found for polarization under this assumption are much lower. However, the results do not lead to different qualitative conclusions than the computations with population weightings, and also show a reduction in per capita CO_2 polarization across countries. However, these results should be taken into account with caution, as not weighting the observations for countries implies considering countries with less than 500,000 inhabitants, such as Gibraltar, Iceland or Brunei, and countries such as China (1,300 millions) or India (1,000 millions) in the same way.

China and India have experienced a great economic growth, as well as a great increase in emissions in recent years. Given their large populations it would be interesting to check to what extent global polarization results have been influenced by the behavior of these countries. We have recomputed the polarization indexes excluding China and India from the sample, countries whose great population and impressive increase in emissions might have strongly influenced the evolution of global polarization values computed in the previous section. Table 9 shows the results, for the polarization indexes for average polarization parameters[16].

[TABLE 9 ABOUT HERE]

These results contrast with the evidence indicated for the complete sample. Polarization values at the beginning of the period are much lower than in the complete sample, and there is a very small reduction, so that at the end of the period the values are even larger than in the complete sample. There is even an increase for the case of four groups. Given the EGR polarization index values obtained, it seems that the simplification of the distribution in two groups is again the most appealing one.

Excluding these two countries from the sample, polarization values at the end of the period are very similar to the ones at the beginning. Therefore, these results clearly show the great importance in the global reduction of polarization played by the behavior of these countries, which have experienced a great increase in emissions, increasing their per capita levels, and bringing the level of emissions of the low-level group nearer the level of emissions of the high-level group[17].

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[16] In this case we fix α=1.3 and β=1. The results for the rest of parameter combinations may be requested to the authors. They do not differ significantly from those reported in this paper.

[17] In this case there might be differences in the time trends of polarization and inequality indexes. In short, while reference polarization measures slowly decline and were stable since 1990, the inequality

5. Concluding Remarks

The analysis of polarization provides a useful analytical framework from which understanding the inherent degree of conflict in the international distribution of per capita CO_2 emissions. The analysis of the potentiality of conflict between countries by means of the distributive polarization approach is quite appealing as the current international context is characterized by the need of achieving agreements between countries with different interests which tend form groups in order to maximize negotiation achievements. In this sense, the paper maintains the hypothesis that a greater split by groups of countries in the international distribution of CO_2 would imply a scenario of greater potential appearance of conflicts and, therefore, of difficulties to achieve agreement. Moreover, inequality measures are not appropriate for analyzing distributive rupture.

In this paper, the level of polarization in the international distribution of per capita CO_2 emissions has been analyzed for the period 1971-2001 adapting to this analysis the EGR index (Esteban et al., 1999) originally designed for income distribution analysis. According to the results obtained, the following comments may be made.

First, international polarization in emissions has been reduced in a significant way over the last thirty years. This lower level of fragmentation has been proved for the description with two, three and four groups, and for various parametric combinations of the polarization indexes. The trend since 1990, reference year for the Kyoto

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measure, where countries are not weighted, experienced a significant growth. More details are available on request to the authors.

Protocol, is also a declining one. However, there is not much reduction with respect to 1995, nor with respect to 1997. Then, the polarization in the distribution of international emissions in 2001 does not show a better situation for facilitating agreements than the one in 1997, when the negotiations on the Kyoto Protocol took place. It would be of great interest to analyze the evolution of polarization in emissions in the future in order to analyze how emissions distribution—among other factors to be considered that we have previously cited—might facilitate or not future agreements on reductions.

Second, the most appealing structure for the polarization analysis is the one with two groups, given that it better combines the condition of considering a minimum number of groups with a reduced aggregation error. The simplification that provides worst results is the one with four groups. Regarding the classification into two optimal groups derived from the polarization analysis, the *Above average group* broadly coincides with Annex B of the Kyoto Protocol (see Appendix A.1), with some oil-supplying countries and few more countries with a relatively small population weighting. All countries that pledged to target their greenhouse gas emissions under the Kyoto Protocol are included in this group. In the case of three groups, all these countries are placed in the *High emissions group*. Therefore, polarization analysis with these endogenously determined groups broadly coincides with the polarization between Annex B parties and other groups of countries. Furthermore, the groups endogenously chosen (theoretical groups) broadly coincide with the groups formed in the real Kyoto negotiations. This analogy, among other aspects, reinforces the usefulness of the analysis and opens up new ways for understanding negotiation processes and their final results.

Finally, various additional exercises have been undertaken. The computation of the indexes in their non-weighted version has shown a clear decline in polarization over the period considered, coinciding with the previous results. The exclusion of China and India from the sample leads to lower polarization values at the beginning of the period and a much smaller reduction over the period, which shows the importance of the increase in emissions in these large countries in explaining global polarization values and their decreasing trend.

Polarization indexes constitute a good instrument for undertaking a distributive analysis especially different from the distributive analysis undertaken in other environmental studies. In short, this analysis contributes to clarify the degree of potential tension and instability that arises from the international distribution of emissions, tension that would be associated to the existence of groups with opposing interests, which have internal cohesion and are of great size. Therefore, both polarization and inequality indexes are useful tools for the examination of international distribution of emissions and its potential consequences.

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Appendix A. Groups of countries derived from polarization analysis

A.1. Optimal Groups: two groups case, year 2001

Below average group: Democratic Republic of Congo, Ethiopia & Eritrea, Mozambique, United Republic of Tanzania, Myanmar, Nepal, Other Africa, Zambia, Cameroon, Haiti, Other Asia, Togo, Sudan, Bangladesh, Congo, Benin, Kenya, Ghana, Côte d'Ivoire, Nigeria, Senegal, Angola, Yemen, Paraguay, Sri Lanka, Vietnam, Pakistan, Nicaragua, Honduras, Guatemala, El Salvador, Philippines, Peru, Zimbabwe, Bolivia, India, Albania, Morocco, Costa Rica, Colombia, Gabon, Indonesia, Uruguay, Ecuador, Panamá, Egypt, Brazil, Tunisia, Dominican Republic, Algeria, China, Thailand, Turkey, Cuba, Jordan, Chile, Syria, Argentina, Other Latin America, Dem. People's Republic of Korea, Iraq, Lebanon, Mexico.

Above average group: Jamaica, Romania, Former Yugoslavia, Malaysia, Iran, Venezuela, Malta, Sweden, Hungary, Bulgaria, Hong-Kong, Portugal, Switzerland, France, Spain, South Africa, Slovak Republic, Italy, Lybia, Iceland, Poland, Former USSR, Cyprus, Austria, Greece, Norway, New Zealand, Japan, United Kingdom, Korea, Denmark, Oma, Taipei, Israel, Germany, Netherlands, Singapore, Ireland, Czech Republic, Finland, Belgium, Trinidad, Saudi Arabia, Brunei, Gibraltar, Canada, Australia, Luxembourg, United States, Bahrain, United Arab Emirates, Kuwait, Qatar.

A.2. Optimal Groups: three groups case, year 2001

Low emissions group: Democratic Republic of Congo, Ethiopia & Eritrea, Mozambique, United Republic of Tanzania, Myanmar, Nepal, Other Africa, Zambia, Cameroon, Haiti, Other Asia, Togo, Sudan, Bangladesh, Congo, Benin, Kenya, Ghana, Côte d'Ivoire, Nigeria, Senegal, Angola, Yemen, Paraguay, Sri Lanka, Vietnam, Pakistan, Nicaragua, Honduras, Guatemala, El Salvador, Philippines, Peru, Zimbabwe, Bolivia, India, Albania, Morocco, Costa Rica, Colombia, Gabon, Indonesia, Uruguay, Ecuador.

Medium emissions group: Panamá, Egypt, Brazil, Tunisia, Dominican Republic, Algeria, China, Thailand, Turkey, Cuba, Jordan, Chile, Syria, Argentina, Other Latin America, Dem. People's Republic of Korea, Iraq, Lebanon, Mexico.

High emissions group: Jamaica, Romania, Former Yugoslavia, Malaysia, Iran, Venezuela, Malta, Sweden, Hungary, Bulgaria, Hong-Kong, Portugal, Switzerland, France, Spain, South Africa, Slovak Republic, Italy, Lybia, Iceland, Poland, Former USSR, Cyprus, Austria, Greece, Norway, New Zealand, Japan, United Kingdom, Korea, Denmark, Oma, Taipei, Israel, Germany, Netherlands, Singapore, Ireland, Czech Republic, Finland, Belgium, Trinidad, Saudi Arabia, Brunei, Gibraltar, Canada, Australia, Luxembourg, United States, Bahrain, United Arab Emirates, Kuwait, Qatar.

A.3. Optimal Groups: four groups case, year 2001

Low emissions group: Democratic Republic of Congo, Ethiopia & Eritrea, Mozambique, United Republic of Tanzania, Myanmar, Nepal, Other Africa, Zambia, Cameroon, Haiti, Other Asia, Togo, Sudan, Bangladesh, Congo, Benin, Kenya, Ghana, Côte d'Ivoire, Nigeria, Senegal, Angola, Yemen, Paraguay, Sri Lanka, Vietnam, Pakistan, Nicaragua, Honduras, Guatemala, El Salvador, Philippines, Peru, Zimbabwe, Bolivia, India, Albania, Morocco, Costa Rica, Colombia, Gabon, Indonesia, Uruguay, Ecuador.

Medium-low emissions group: Panamá, Egypt, Brazil, Tunisia, Dominican Republic, Algeria, China, Thailand, Turkey, Cuba, Jordan, Chile, Syria, Argentina, Other Latin America, Dem. People's Republic of Korea, Iraq, Lebanon, Mexico.

Medium-high emissions group: Jamaica, Romania, Former Yugoslavia, Malaysia, Iran, Venezuela, Malta, Sweden, Hungary, Bulgaria, Hong-Kong, Portugal, Switzerland, France, Spain, South Africa, Slovak Republic, Italy, Lybia, Iceland, Poland, Former USSR, Cyprus, Austria, Greece, Norway, New Zealand, Japan, United Kingdom, Korea, Denmark, Oma, Taipei, Israel, Germany.

High emissions group: Netherlands, Singapore, Ireland, Czech Republic, Finland, Belgium, Trinidad, Saudi Arabia, Brunei, Gibraltar, Canada, Australia, Luxembourg, United States, Bahrain, United Arab Emirates, Kuwait, Qatar.

Table 1. Inter-country two groups polarization of per capita CO_2 emissions, weighted computations, complete sample, 1971-2001

	$\beta = 0.5$			$\boldsymbol{\beta = 1}$			$\beta = 1.5$		
	$\alpha = 1$	$\alpha = 1.3$	$\alpha = 1.6$	$\alpha = 1$	$\boldsymbol{\alpha = 1.3}$	$\alpha = 1.6$	$\alpha = 1$	$\alpha = 1.3$	$\alpha = 1.6$
1971	0.5178	0.4289	0.3597	0.4653	**0.3764**	0.3073	0.4128	0.3239	0.2548
1975	0.5051	0.4182	0.3506	0.4535	**0.3666**	0.2990	0.4019	0.3150	0.2474
1980	0.4893	0.4056	0.3405	0.4363	**0.3526**	0.2875	0.3833	0.2996	0.2346
1985	0.4659	0.3869	0.3258	0.4099	**0.3309**	0.2698	0.3540	0.2750	0.2139
1990	0.4420	0.3661	0.3072	0.3846	**0.3087**	0.2499	0.3273	0.2513	0.1925
1992	0.4244	0.3516	0.2953	0.3652	**0.2924**	0.2361	0.3060	0.2332	0.1769
1995	0.3935	0.3253	0.2728	0.3306	**0.2624**	0.2099	0.2677	0.1995	0.1470
1997	0.3891	0.3209	0.2682	0.3248	**0.2566**	0.2039	0.2605	0.1922	0.1395
2001	0.3931	0.3255	0.2734	0.3306	**0.2629**	0.2108	0.2680	0.2003	0.1482

Source: Own elaboration based on International Energy Agency (2003) data.

Table 2. Inter-country three groups polarization of per capita CO_2 emissions, weighted computations, complete sample, 1971-2001

	β = 0.5			**β = 1**			β = 1.5		
	α = 1	α = 1.3	α = 1.6	α = 1	**α = 1.3**	α = 1.6	α = 1	α = 1.3	α = 1.6
1971	0.4644	0.3794	0.3175	0.4393	**0.3543**	0.2925	0.4143	0.3292	0.2674
1975	0.4427	0.3536	0.2889	0.4144	**0.3253**	0.2605	0.3860	0.2970	0.2322
1980	0.4308	0.3458	0.2842	0.4023	**0.3173**	0.2557	0.3738	0.2888	0.2271
1985	0.3379	0.2338	0.1600	0.3091	**0.2050**	0.1312	0.2803	0.1762	0.1024
1990	0.3330	0.2343	0.1642	0.3053	**0.2065**	0.1364	0.2775	0.1787	0.1086
1992	0.3266	0.2301	0.1615	0.2992	**0.2026**	0.1340	0.2717	0.1751	0.1064
1995	0.3171	0.2238	0.1574	0.2900	**0.1967**	0.1303	0.2629	0.1696	0.1032
1997	0.3143	0.2209	0.1545	0.2867	**0.1934**	0.1270	0.2592	0.1659	0.0995
2001	0.3086	0.2152	0.1488	0.2802	**0.1868**	0.1205	0.2519	0.1585	0.0921

Source: Own elaboration based on International Energy Agency (2003) data.

Table 3. Inter-country four groups polarization of per capita CO_2 emissions, weighted computations, complete sample, 1971-2001

	$\beta = 0.5$			$\boldsymbol{\beta = 1}$			$\beta = 1.5$		
	$\alpha = 1$	$\alpha = 1.3$	$\alpha = 1.6$	$\alpha = 1$	$\boldsymbol{\alpha = 1.3}$	$\alpha = 1.6$	$\alpha = 1$	$\alpha = 1.3$	$\alpha = 1.6$
1971	0.3074	0.2071	0.1406	0.2954	**0.1951**	0.1286	0.2834	0.1831	0.1166
1975	0.3047	0.2063	0.1406	0.2923	**0.1940**	0.1283	0.2800	0.1816	0.1159
1980	0.3008	0.2043	0.1396	0.2879	**0.1914**	0.1267	0.2751	0.1786	0.1139
1985	0.2988	0.2031	0.1390	0.2855	**0.1898**	0.1257	0.2722	0.1766	0.1125
1990	0.2867	0.1947	0.1332	0.2735	**0.1816**	0.1201	0.2604	0.1685	0.1070
1992	0.2818	0.1930	0.1331	0.2680	**0.1791**	0.1192	0.2541	0.1653	0.1053
1995	0.2769	0.1914	0.1335	0.2645	**0.1789**	0.1210	0.2520	0.1664	0.1085
1997	0.2753	0.1902	0.1327	0.2625	**0.1774**	0.1199	0.2497	0.1646	0.1070
2001	0.2772	0.1928	0.1354	0.2642	**0.1797**	0.1223	0.2511	0.1667	0.1093

Source: Own elaboration based on International Energy Agency (2003) data.

Table 4. International inequality (Gini) explained by simplified distributions

	Two groups	Three Groups	Four groups
1971	84.5%	92.6%	96.4%
1975	84.4%	91.4%	96.3%
1980	83.7%	91.2%	96.0%
1985	82.3%	90.9%	95.8%
1990	81.3%	91.0%	95.7%
1992	80.3%	90.9%	95.4%
1995	78.4%	90.7%	95.7%
1997	77.9%	90.5%	95.6%
2001	78.5%	90.2%	95.6%

Source: Own elaboration based on International Energy Agency (2003) data.

Table 5. Two groups case. Description of groups

	Low emissions group		High emissions group	
	p	e_i/e	p	e_i/e
1971	0.72	0.21	0.28	3.05
1975	0.72	0.23	0.28	3.00
1980	0.73	0.25	0.27	2.99
1985	0.74	0.29	0.26	2.98
1990	0.73	0.33	0.27	2.88
1992	0.74	0.35	0.26	2.85
1995	0.74	0.39	0.26	2.78
1997	0.74	0.39	0.26	2.74
2001	0.75	0.39	0.25	2.79

Source: Own elaboration based on International Energy Agency (2003) data.

Table 6. Three groups case. Description of groups

	Low emissions group		Medium emissions group		High emissions group	
	p	e_i/e	P	e_i/e	p	e_i/e
1971	0.69	0.18	0.20	1.83	0.11	4.58
1975	0.66	0.19	0.16	1.37	0.18	3.66
1980	0.67	0.21	0.17	1.49	0.16	3.80
1985	0.39	0.11	0.37	0.54	0.24	3.13
1990	0.45	0.16	0.33	0.74	0.22	3.21
1992	0.45	0.17	0.33	0.76	0.22	3.10
1995	0.46	0.19	0.33	0.79	0.21	3.05
1997	0.43	0.18	0.36	0.78	0.21	3.04
2001	0.43	0.19	0.35	0.72	0.22	3.02

Source: Own elaboration based on International Energy Agency (2003) data.

Table 7. Exogenous grouping in Annex B and non-Annex B countries

	β = 0.5			β = 1			β = 1.5			Explanatory Power
	α = 1	α = 1.3	α = 1.6	α = 1	α = 1.3	α = 1.6	α = 1	α = 1.3	α = 1.6	
1971	0.4871	0.3991	0.3303	0.4244	0.3364	0.2676	0.3617	0.2737	0.2049	81.4%
1975	0.4759	0.3917	0.3261	0.4145	0.3304	0.2648	0.3532	0.2690	0.2035	81.4%
1980	0.4528	0.3738	0.3125	0.3877	0.3086	0.2474	0.3226	0.2435	0.1822	79.9%
1985	0.4255	0.3520	0.2954	0.3561	0.2826	0.2260	0.2867	0.2132	0.1566	78.1%
1990	0.3957	0.3281	0.2764	0.3229	0.2553	0.2036	0.2501	0.1825	0.1308	76.3%
1992	0.3717	0.3077	0.2589	0.2949	0.2309	0.1821	0.2181	0.1542	0.1054	74.5%
1995	0.3286	0.2707	0.2266	0.2440	0.1861	0.1421	0.1595	0.1016	0.0575	71.0%
1997	0.3174	0.2612	0.2186	0.2292	0.1730	0.1304	0.1409	0.0847	0.0421	69.7%
2001	0.3114	0.2569	0.2157	0.2216	0.1671	0.1259	0.1318	0.0772	0.0361	69.1%

Source: Own elaboration based on International Energy Agency (2003) data.

Table 8. Inter-country polarization of per capita CO_2 emissions, non-weighted indexes, 1971-2001

	EGR-2	EGR-3	EGR-4
1971	0.2847	0.2407	0.1819
1975	0.2636	0.2296	0.1765
1980	0.2467	0.2198	0.1627
1985	0.2357	0.2171	0.1714
1990	0.2214	0.2068	0.1506
1992	0.2149	0.2060	0.1524
1995	0.2113	0.2058	0.1573
1997	0.2092	0.2041	0.1561
2001	0.2134	0.2064	0.1636

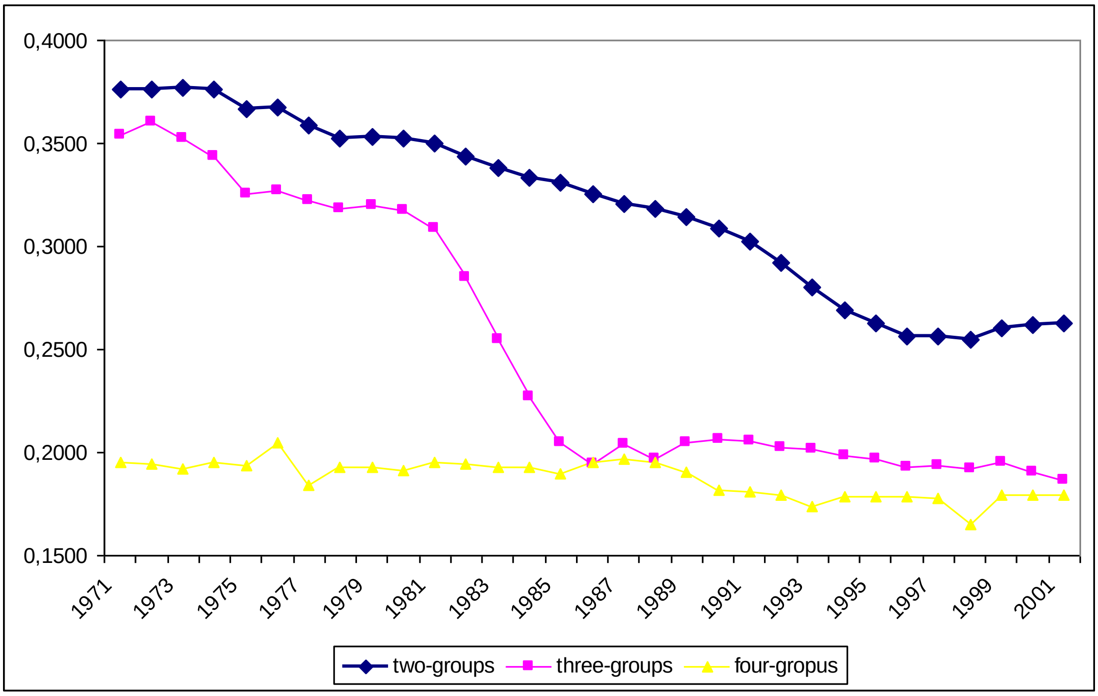
Source: Own elaboration based on International Energy Agency (2003) data.

Table 9. Inter-country polarization of per capita CO_2 emissions, China and India excluded 1971–2001

	EGR-2	EGR-3	EGR-4
1971	0.2595	0.2475	0.1331
1975	0.2677	0.2455	0.1693
1980	0.2662	0.2184	0.1673
1985	0.2659	0.2186	0.1672
1990	0.2586	0.2302	0.1618
1992	0.2588	0.2256	0.1635
1995	0.2512	0.2279	0.1677
1997	0.2429	0.2312	0.1726
2001	0.2470	0.2320	0.1630

Source: Own elaboration based on International Energy Agency (2003) data.

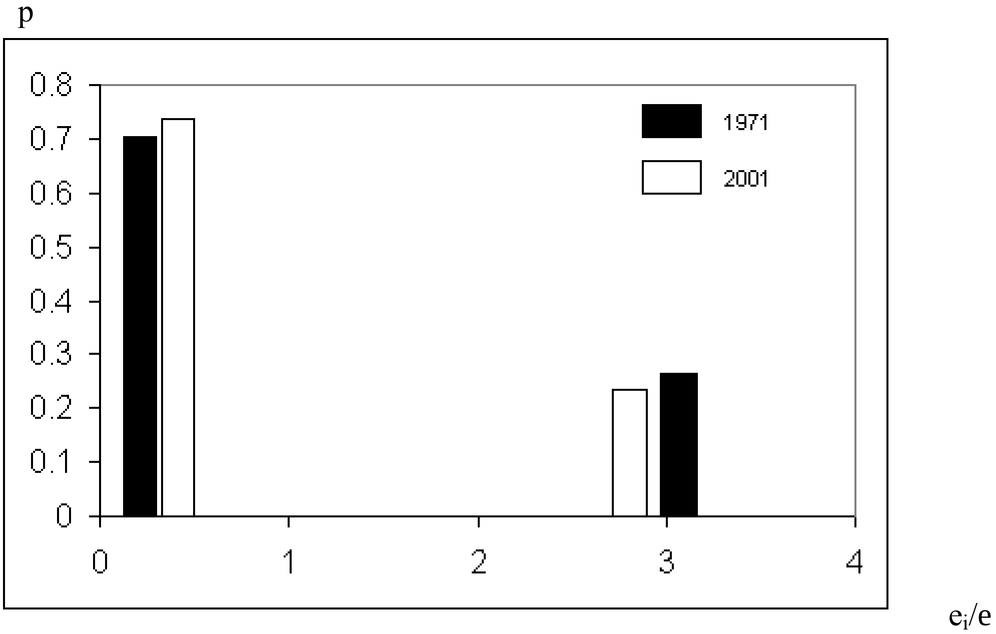
Figure 1. Inter-country polarization of CO_2 emissions, complete sample, 1971–2001



Source: Own elaboration based on International Energy Agency (2003) data.

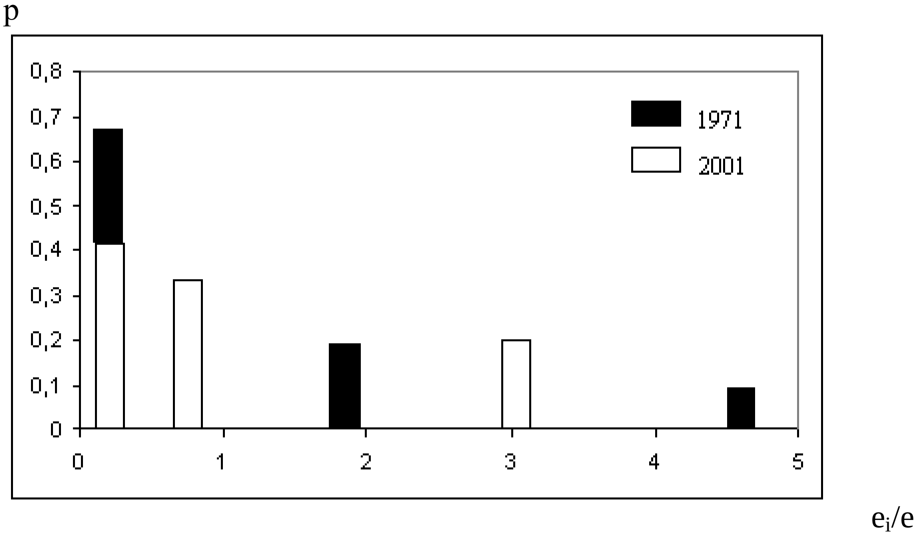
Note: EGRs are computed for polarization parameters α=1.3 and β=1.

Figure 2. Two groups representation. Comparison between 1971 and 2001



Source: Own elaboration based on International Energy Agency (2003) data.

Figure 3. Three groups representation. Comparison between 1971 and 2001.



Source: Own elaboration based on International Energy Agency (2003) data.