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Ensayos sobre Energía y Economía Sostenible: un enfoque metodológico basado en el análisis de la desigualdad

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Essays on Energy and Sustainable Economy: a methodological approach based on the analysis of inequality

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Introducción

Introducción

El cambio climático es uno de los retos más importantes a los que se enfrenta la comunidad internacional en la actualidad. Sus posibles consecuencias a largo plazo para los ecosistemas y para la calidad de vida de cientos de millones de personas, lo convierten en un tema prioritario para la agenda global, tal y como recogen el Tercer y Cuarto Informe de Evaluación del Grupo Intergubernamental de Expertos sobre el Cambio Climático –IPCC, según sus siglas en inglés– (IPCC, 2001a, 2007a).

Los primeros avances hacia las negociaciones internacionales sobre cambio climático tuvieron lugar con la creación del IPCC en 1988. La misión fundamental de este organismo es investigar y evaluar los acontecimientos más recientes vinculados al cambio climático. El IPCC fue promovido por la Organización Meteorológica Mundial y por el Programa de las Naciones Unidas para el Medio Ambiente. El objetivo era diseñar políticas para afrontar los impactos y los riesgos futuros del cambio climático a través de diferentes medidas de adaptación y mitigación.

El IPCC está integrado por tres grupos de trabajo: el primero se ocupa de las bases físicas del cambio climático; el segundo evalúa la vulnerabilidad y la exposición de los sistemas humanos y naturales al cambio climático y las diferentes opciones de adaptación al mismo; y el tercero analiza las distintas alternativas para mitigar el cambio climático, mediante la limitación de las emisiones de gases de efecto invernadero (GEI) y la promoción de prácticas que los eliminen de la atmósfera.

El primer paso histórico para combatir el crecimiento de las emisiones de GEI a nivel mundial tuvo lugar en 1992, durante la celebración de la Convención Marco de las Naciones Unidas sobre el Cambio Climático (CMNUCC)[1]. El objetivo último de la CMNUCC fue la:

> "… estabilización de las concentraciones de gases de efecto invernadero en la atmósfera a un nivel que impida interferencias antropógenas peligrosas en el sistema climático. Ese nivel debería lograrse en un plazo suficiente para permitir que los ecosistemas se adapten naturalmente al cambio climático, asegurar que la producción de alimentos no se vea amenazada y permitir que el desarrollo económico prosiga de manera sostenible".
>
> (United Nations, 1992, Article 2).

Sin embargo, la ausencia de objetivos cuantificables y de plazos específicos para lograr reducir las emisiones hizo necesario consolidar los compromisos. Así, en 1997 se adoptó el Protocolo de Kyoto (United Nations, 1998), el cual incluía, por primera vez, compromisos cuantitativos legalmente vinculantes para conseguir que los países desarrollados redujeran sus emisiones de GEI. Fue entonces cuando el objetivo de la CMNUCC se implementó, de acuerdo con el principio de "responsabilidades comunes pero diferenciadas" bajo la siguiente premisa: todos los países son responsables de la protección del medio ambiente, pero de acuerdo a las diferencias históricas en su

[1] La CMNUCC, junto con el Convenio sobre la Diversidad Biológica y la Convención de Lucha contra la Desertificación, fue adoptada en la "Cumbre de la Tierra de Río" en 1992. El objetivo de las mismas fue desarrollar sinergias en sus actividades de interés mutuo.

contribución al cambio climático –entre los países desarrollados y los países en desarrollo–, así como, a sus respectivas capacidades para hacer frente al mismo.

Durante el primer período del Protocolo de Kyoto (2008-2012), los países desarrollados se comprometieron a reducir sus emisiones de GEI en al menos un 5 por ciento, con respecto a los niveles registrados en 1990. Sin embargo, este acuerdo tuvo un alcance limitado dado que no fue ratificado por Estados Unidos y además las economías emergentes no adquirieron ningún compromiso (United Nations, 1998). A lo largo del segundo período (2013-2020), la Unión Europea se ha comprometido a reducir las emisiones de GEI de 1990 en al menos un 20 por ciento. Sin embargo, a nivel global, la participación ha sido todavía más limitada en esta ocasión. Estados Unidos no se ha adherido aún al Protocolo, y otros países como Canadá, Japón, Rusia y Nueva Zelanda no han especificado una reducción concreta de sus emisiones. De esta forma, los países que han adquirido un compromiso en esta segunda fase del Protocolo de Kyoto representan sólo el 15 por ciento de las emisiones globales (United Nations, 2012).

Desde la celebración de la CMNUCC han tenido lugar diferentes Conferencias de las Partes[2] (COPs) para negociar el futuro plan de actuación sobre cambio climático. La COP es el órgano supremo de la CMNUCC y se celebra todos los años, a menos que las Partes decidan lo contrario, para evaluar los progresos realizados en la consecución del objetivo último de la Convención y adoptar por consenso las decisiones necesarias para promover su aplicación efectiva.

[2] Las denominadas “Partes” en la Convención son los grupos de países que la han ratificado. Las Partes que se encuentran en el Anexo I son los países industrializados que eran miembros de la Organización para la Cooperación y el Desarrollo Económico (OCDE) en 1992 y los países con economías en transición mientras que, en el Anexo II únicamente se hallan los países miembros de la OCDE del Anexo I. Por último, las Partes no incluidas en el Anexo I son principalmente países en desarrollo.

La última COP se celebró en París a finales del año 2015. Las negociaciones dieron como resultado la adopción del Acuerdo de París que establece las medidas para reducir las emisiones de GEI a partir del año 2020[3]. Este acuerdo multilateral sobre el cambio climático se basa en la introducción de las Contribuciones Previstas y Determinadas a Nivel Nacional –INDCs, por sus siglas en inglés– por las Partes, que son las medidas que los países tienen previsto implementar para lograr el objetivo de la Convención. Estas decisiones determinarán, en gran parte, el cumplimiento de los objetivos a largo plazo del Acuerdo de París: limitar el aumento de la temperatura global a 1,5 grados centígrados con respecto a los niveles preindustriales y conseguir cero emisiones netas de GEI en la atmósfera en la segunda mitad de este siglo (United Nations, 2015).

El cambio climático junto con el aumento de las desigualdades económicas[4] son dos desafíos clave que condicionarán la toma de decisiones de las próximas décadas. Para afrontar estos problemas es necesario comprender la relación entre ambos, a través de las *desigualdades ambientales* (Chancel y Piketty, 2015). Existen diferentes tipos de desigualdades ambientales: las desigualdades en la contribución a la contaminación (Chakravarty y Ramana, 2012), las desigualdades en términos de la exposición a la degradación del medio ambiente (IPCC, 2014), las desigualdades derivadas de la implementación de determinadas políticas ambientales (Sterner, 2012) y las desigualdades asociadas a la puesta en funcionamiento de políticas ambientales específicas (Martínez-Alier, 2003).

La medición de las desigualdades ambientales dependerá en gran medida del tipo de desigualdad considerado. Milanovic (2005) identifica tres conceptos

[3] Este acuerdo únicamente entrará en vigor si es ratificado por 55 países que generen al menos el 55 por ciento de las emisiones globales de GEI.

[4] Para profundizar en este tema véanse Piketty (2014) y OCDE (2011), entre otros.

para analizar la desigualdad en la distribución de los ingresos, distinción que es perfectamente extensible al ámbito medioambiental. El primero de ellos hace referencia a la *desigualdad no ponderada*, que considera a cada país como una unidad con independencia del tamaño de su población. Desde el punto de vista ambiental este concepto puede parecer poco representativo debido a que el tamaño de la población es ampliamente reconocido como uno de los principales impulsores de la degradación ambiental (Jorgenson y Clark, 2013). El segundo concepto refleja la *desigualdad ponderada*, el cual asume que la distribución interna de cada país es totalmente igualitaria –todas las personas que pertenecen a un mismo país emiten el nivel medio de emisiones en ese país–, estando cada país representado por el tamaño de su población. Por último, el tercer concepto contempla la *desigualdad entre individuos*, teniendo en cuenta la situación particular de cada sujeto con respecto a la variable de estudio. Este enfoque proporciona conclusiones más realistas sobre la distribución analizada, pero su cálculo requiere datos desglosados a nivel individual.

Los análisis que descomponen la desigualdad de forma aditiva son muy útiles para medir y comprender las causas que la originan. La descomposición de un índice consiste en determinar qué parte de la desigualdad total observada es atribuible a cada una de sus componentes. Así, la descomposición por grupos de población permite saber si la desigualdad proviene de las diferencias entre las medias de los grupos considerados o de las disparidades dentro de los mismos (Shorrocks, 1980). Por su parte, la descomposición factorial permite conocer las principales fuentes impulsoras de la desigualdad (Duro y Esteban, 1998; Duro y Padilla, 2006). Con el fin de llevar a cabo estudios basados en la descomposición, la medida de desigualdad empleada tiene que satisfacer el axioma de descomponibilidad (Bourguignon, 1979; Cowell, 2000, 2011) lo que implica que puede ser expresada en términos de sus partes constituyentes, a través de grupos de población o factores multiplicativos, por ejemplo. Cabe señalar que la familia de medidas de entropía generalizada es la única que satisface el axioma de descomposición aditiva (Shorrocks, 1980, 1984; Cowell, 1980).

Varios artículos sobre Economía de la Energía han analizado las desigualdades ambientales[5] a nivel global, empleando los índices utilizados tradicionalmente para estudiar la desigualdad en la distribución de la renta –como el índice de Gini o el índice de Theil (Theil, 1967)– (Heil y Wodon, 1997, 2000; Sun, 2002; Alcántara y Duro, 2004; Hedenus y Azar, 2005; Duro y Padilla 2006; Padilla y Serrano, 2006; Groot, 2010; Lawrence *et al*., 2013; Xu y Ang, 2013; Oxfam, 2015 y Chancel y Piketty, 2015, entre otros).

Inevitablemente, durante las próximas décadas tendrá lugar un mayor calentamiento global, la cuestión es si se podrá limitar el incremento de la temperatura a 1,5 grados centigrados (IPCC, 2014). Dados los niveles actuales de emisiones y las tecnologías disponibles, autores como Tol (2015) dudan de la viabilidad de tal objetivo. A pesar de que la distribución geográfica de las emisiones de GEI[6] no influye en el impacto climático de las mismas (Aldy, 2006), las diferencias en los niveles de emisión de GEI entre los países pueden afectar a la implementación de un acuerdo multilateral más sólido sobre el cambio climático. Por lo tanto, la evidencia de una disminución de la desigualdad en las emisiones de GEI podría alentar a los países a establecer unos INDCs más ambiciosos, evitando que las emisiones

[5] En la actualidad, existe una alta concentración de emisiones de dióxido de carbono (CO_2): el 10 por ciento de los países que más contaminan emiten el 45 por ciento de las emisiones globales mientras que, el 50 por ciento de los países menos contaminantes genera el 13 por ciento de las mismas.

[6] De acuerdo con Chancel y Piketty (2015), la distribución geográfica de las emisiones de GEI cambia constante y radicalmente. En la década de 1820, Europa Occidental representó más del 95 por ciento de las emisiones globales. Cien años más tarde, América del Norte fue la región con mayores emisiones en el mundo (50 por ciento). Hoy en día, Europa Occidental y América del Norte representan el 9 y el 16 por ciento de las emisiones globales, respectivamente, siendo Asia la región más contaminante.

globales puedan conducir a un nivel de calentamiento global más elevado que el objetivo establecido.

En este contexto, el objetivo de la presente Tesis Doctoral es analizar la desigualdad en la distribución de las emisiones atmosféricas a través de la familia de índices de entropía generalizada. Este trabajo se compone de cuatro capítulos, independientes pero relacionados, que abordan la desigualdad en las emisiones desde perspectivas complementarias, utilizando los datos disponibles en cada caso. En el primer capítulo se analiza la descomposición de la desigualdad en las emisiones de CO_2 –dado que es el GEI más abundante en la atmósfera– para diferentes sectores; en el segundo capítulo se ahonda en las principales causas que originan la desigualdad en las emisiones de CO_2; el tercer capítulo complementa a los anteriores mediante un análisis de desigualdad y polarización desde una perspectiva multidimensional; y por último, con un enfoque más teórico, en el cuarto capítulo se presentan las expresiones de los índices de Theil para las distribuciones paramétricas más relevantes. A continuación, se describen en profundidad los análisis llevados a cabo en cada uno de los capítulos.

En el Capítulo 1 se realiza una descomposición de la desigualdad en las emisiones de CO_2 por grupos de países, analizando las particularidades de los siguientes sectores: el sector eléctrico, el sector industrial, el aglomerado “otras industrias energéticas”, el sector transporte, el sector transporte por carretera, el conjunto “otros sectores” y, por último, el sector inmobiliario. Para ello se utiliza el índice de Theil, herramienta que permite otorgar un peso diferente a cada país en base a su participación en la población mundial. La agrupación de países se realiza de acuerdo a las regiones de países consideradas por el Programa de Naciones Unidas para el Desarrollo (PNUD). La dimensión geográfica contemplada permite la incorporación de los resultados obtenidos para el año 2009 en el diseño de políticas ambientales, tanto a nivel global como a nivel regional. A diferencia de otros estudios previos, los resultados obtenidos proporcionan una mayor importancia a la componente intrarregional. Es por ello que, esta investigación se replica usando la familia de índices de entropía generalizada. Dado que cada índice de esta familia hace hincapié en la desigualdad existente en una parte diferente de la distribución, este segundo análisis permite estudiar la sensibilidad del peso de ambas componentes en la desigualdad total.

El uso de energía es la mayor fuente de emisiones de CO_2 procedentes de las actividades humanas, siendo las emisiones derivadas de la quema de combustibles fósiles las más habituales. Dado que un solo indicador no proporciona la imagen completa del comportamiento de las emisiones de CO_2 de un país, en el segundo capítulo, se recurre a los factores de Kaya (Kaya, 1989; Yamaji *et al*., 1991) para analizar nuevas fuentes que originen la desigualdad en las emisiones de CO_2. En particular, la desigualdad se descompone en cuatro factores que no habían sido analizados con anterioridad: las emisiones de CO_2 por unidad de electricidad producida, la intensidad de la producción eléctrica en el Producto Interior Bruto (PIB), la productividad media de la población ocupada y la tasa de ocupación. La desigualdad de las emisiones de CO_2 se estudia a través de las regiones consideradas por la Agencia Internacional de la Energía (AIE) en el periodo 1990-2010, lo cual va a permitir tomar como referencia los resultados obtenidos en los acuerdos que se tengan que adoptar en un futuro próximo. Para abordar este objetivo se utiliza el índice de Theil, el cual va a permitir, en este caso, descomponer la desigualdad total tanto por grupos de población como por factores multiplicativos. La aportación metodológica de este estudio radica en que la descomposición de la desigualdad por factores multiplicativos es generalizada al caso de k factores, lo cual permite estudiar un mayor número de elementos que los enfoques tradicionales.

La actividad humana llevada a cabo durante la era industrial ha dado lugar a un incremento drástico tanto de las emisiones de CO_2 como de otros GEI con menor presencia en la atmósfera. Estos últimos juegan también un papel importante en el conocimiento del cambio climático global y en la lucha contra el mismo. Como se ha señalado previamente, las diferencias en los niveles de emisión de GEI entre los países pueden determinar su grado de compromiso en los acuerdos multilaterales. Por este motivo, en el Capítulo 3 se analiza dicha desigualdad desde una perspectiva multidimensional, considerando las emisiones de CO_2, de metano (CH_4), de óxido nitroso (N_2O) y de gases fluorados (F-gases) durante el período 1990-2011. Para ello, se utilizan las medidas multidimensionales de entropía generalizada propuestas por Maasoumi (1986). Por otro lado, dado que en el ámbito ambiental las negociaciones sobre la reducción de emisiones se construyen a través de alianzas de grupos de países, además de los análisis de la desigualdad, es necesario llevar a cabo estudios de polarización que permitan capturar el posible conflicto de intereses inherente a la distribución de GEI. Es por ello que en este capítulo se investiga también la polarización multidimensional a través de los índices desarrollados por Gigliariano y Mosler (2009), los cuales recurren a la descomposición por grupos de población de las medidas de desigualdad multidimensional previamente consideradas. Cabe destacar que se trata del primer estudio que analiza de manera conjunta la distribución global de las emisiones de GEI.

El conocimiento de la distribución de los GEI favorece el análisis del nivel de desigualdad asociado a los mismos. En el último capítulo se presenta una expresión de los índices de Theil que permite estudiar la desigualdad a través de las distribuciones paramétricas más relevantes y derivar expresiones cerradas para versiones multivariadas de los mismos. En particular, se realiza una revisión de las fórmulas para las distribuciones paramétricas más comunes y se obtienen para aquellas que no estaban disponibles en la literatura existente, tales como la distribución Champernowne (1952), las distribuciones gamma generalizada (GG) y beta generalizada de primera y segunda especie (GB1 y GB2, respectivamente) (McDonald, 1984), la distribución κ-generalizada (Clementi *et al*., 2007) y varias distribuciones de tipo Pareto y gamma. También se incluyen los momentos de estas familias para facilitar el cálculo de los índices de entropía generalizada. A nivel empírico se analiza la desigualdad en las emisiones de CO_2 en el año 2012. Para ello, se ajusta la distribución GB2 a los datos de emisiones y se calculan diferentes medidas de entropía generalizada relativas al modelo adoptado, utilizando las fórmulas desarrolladas en este capítulo.

Diferentes versiones de los cuatro capítulos se han presentado en diversos congresos de tipo científico tanto nacionales como internacionales. Asimismo, los resultados de esta Tesis Doctoral se han publicado, o tienen superada la primera fase del proceso de revisión, en revistas académicas. En particular, distintas versiones de los Capítulos 1, 2 y 3 se han publicado (en colaboración) en *Estudios de Economía Aplicada* (Remuzgo y Sarabia, 2013), *Economics Bulletin* (Remuzgo y Sarabia, 2015a), *Environmental Science & Policy* (Remuzgo y Sarabia, 2015b) y *Physica A* (Remuzgo *et al*., 2016). Además, la parte metodológica del Capítulo 4 ha sido aceptada para su publicación (en colaboración) en *Review of Income and Wealth* (Sarabia *et al*., 2016).

Introduction

Introduction

Climate change is one of the most important challenges facing the international community nowadays. Given its possible far-reaching consequences for ecosystems and the quality of life of hundreds of millions of people, climate change is a political issue on the global agenda as it was firmly established in the Third and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC, 2001a, 2007a).

The first steps towards climate change international negotiations took place with the introduction of the IPCC in 1988. The IPCC's principal task is to review and assess the most recent science related to climate change. The IPCC was promoted by the World Meteorological Organization (WMO) and the United Nations Environment Programme to provide policies to combat the impacts and future risks of climate change, as well as, adaptation and mitigation measures.

The IPCC's work is shared among three Working Groups: Working Group I assesses the physical scientific aspects of the climate system and climate change; Working Group II evaluates the vulnerability of socio-economic and natural systems to climate change and options for adapting to it; and, Working Group III analyses options for mitigating climate change through limiting or preventing greenhouse gas (GHG) emissions and enhancing activities that remove them from the atmosphere.

The first historic step in global effort to reduce the growth of GHG emissions was taken with the celebration of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992[7]. The ultimate objective of the UNFCCC was the:

> "… stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner".
>
> (United Nations, 1992, Article 2).

However, the lack of specific quantitative targets and timelines for achieving real emission reductions made necessary to strengthen the compromises. Then, in 1997, the Kyoto protocol (United Nations, 1998) was adopted including for the first time quantitative legally binding commitments for developed countries to reduce GHG emissions. The objective of the UNFCCC was implemented according to the principle of "common but differentiated responsibilities" that includes two basic elements: the first refers to the common responsibility of all the countries for the protection of the environment and the second concerns the need to take into account the historical differences in the contributions of developed and developing countries to climate change and the disparities in their respective capacities to tackle it.

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[7] The UNFCCC, together with the United Nations Convention on Biological Diversity and the United Nations Convention to Combat Desertification, was adopted at the "Rio Earth Summit" in 1992. The three were set up to develop synergies in their activities on issues of mutual concern.

During its first commitment period (2008-2012), developed countries committed to reduce their GHG emissions by at least 5 percent compared to the 1990 levels. However, it had a limited scope given that it was not ratified by the USA and the emerging economies did not have commitments under it (United Nations, 1998). Throughout the second commitment period (2013-2020), the European Union has committed to reduce its GHG emissions by at least 20 percent below 1990 levels; however, in this occasion the participation has been even more limited. The USA is still not in, and some other countries, such as Canada, Japan, Russia and New Zeland, do not commit to specific quantified reductions. Then, the countries with commitments under this second phase of the Kyoto Protocol represent only 15 percent of the global emissions (United Nations, 2012).

Since the celebration of the UNFCCC, different Conferences of the Parties[8] (COPs) have taken place to negotiate the future climate change regime. The COP is the supreme body of the UNFCCC and it is celebrated every year, unless the Parties decide otherwise, to review the progress made in achieving the ultimate objective of the Convention and take by consensus the necessary decisions to promote its effective implementation.

The last COP meeting was held in Paris at the end of the year 2015. Negotiations resulted in the adoption of the Paris Agreement which establishes the measures for reducing GHG emissions from 2020 onwards[9]. This multilateral climate change agreement is based on the Intended

[8] The so-called “Parties” to the Convention are groups of countries that have ratified it. Annex I Parties are the industrialized countries that were members of the Organisation for Economic Cooperation and Development (OECD) in 1992 plus countries with economies in transition while, Annex II Parties only consist of the OECD members of Annex I. Finally, Non-Annex I Parties are mostly developing countries.

[9] The agreement will enter into force only if 55 countries which produce at least 55 percent of global GHG emissions ratify it.

Nationally Determined Contributions (INDCs) of the Parties that are the climate actions which countries are intended to take under this international agreement in order to achieve the objective of the Convention. These INDCs will largely determine whether the world achieves the long-term goals of the Paris Agreement: to limit the global temperature increase to 1.5 degrees Celsius compared to pre-industrial levels and to achieve net zero emissions in the second half of this century (United Nations, 2015).

Climate change together with increasing economic inequalities[10] are two key challenges for policymakers in the near future. In order to address these problems, it is essential to better understand the relation between both of them through the *environmental inequalities* (Chancel and Piketty, 2015). In particular, the following types of environmental inequalities can be distinguished: inequalities in contribution to pollution (Chakravarty and Ramana, 2012), inequalities in terms of exposure to environmental degradation (IPCC, 2014), inequalities produced by environmental policies (Sterner, 2012) and inequalities related to policy making differences (Martinez-Alier, 2003).

The computation of the environmental inequalities will largely depend on the concept of inequality considered. Milanovic (2005) differentiates between three concepts of income inequality, distinction that can be easily extended to the environmental field. The first one refers to the *unweighted inequality* that considers each country as a unit, regardless of the size of its population. From the environmental point of view, this concept may seem unrepresentative because population size is widely recognized as one of the primary drivers of environmental degradation (Jorgenson and Clark, 2013). The second concept reflects the *weighted inequality* which means that the internal distribution of

[10] For more information on this topic see Piketty (2014) and OECD (2011), among others.

each country is totally fair –all the individuals who belong to the same country are assumed to emit the average emission level in that country–, being each country represented by its population size. Finally, the third concept contemplates the *inequality among individuals* considering the particular situation of each individual with respect to the variable under study. This approach provides more realistic conclusions about the analysed distribution, but its calculation requires disaggregated data at the individual level.

Additive decomposition analyses are very useful in measuring and understanding the causes of observed inequalities. Decomposing an index consists of determining which part of the total inequality observed is attributable to each of its components. Thus, the sub-group decomposition allows knowing whether inequality comes from mean differences in regional world groups or from inequalities within those groups (Shorrocks, 1980). Meanwhile, the factorial decomposition allows us to know the main driving sources behind the inequality (Duro and Esteban, 1998; Duro and Padilla, 2006). In order to carry out decomposition analyses, the inequality tool has to satisfy the property of decomposability (Bourguignon, 1979; Cowell, 2000, 2011) which implies that the inequality measure can be expressed in terms of its constituent parts: population sub-groups or multiplicative factors, for instance. It should be noted that the family of generalised entropy measures is the only one that satisfies the decomposability axiom in an additive way (Shorrocks, 1980, 1984; Cowell, 1980).

Several papers on Energy Economics had analysed international environmental inequalities[11] applying the indices traditionally used to study

[11] Nowadays, global carbon dioxide (CO_2) emissions remain highly concentrated: while the top 10 percent emitters contribute to 45 percent of the global emissions, the bottom 50 percent contribute to 13 percent of them.

income inequalities –such as the Gini index or the Theil index (Theil, 1967)– (Heil and Wodon, 1997, 2000; Sun, 2002; Alcántara and Duro, 2004; Hedenus and Azar, 2005; Duro and Padilla, 2006; Padilla and Serrano, 2006; Groot, 2010; Lawrence *et al*., 2013; Xu and Ang, 2013; Oxfam, 2015 and Chancel and Piketty, 2015, amongst others).

Further warming will ineluctably take place over the next several decades, the question is whether it can be limited to 1.5 degrees Celsius' rise (IPCC, 2014). Given the current levels of emissions and the available technologies, some observers (e.g. Tol, 2015) doubt that such a target is feasible. Despite the fact that the geographic distribution of GHG emissions[12] does not influence the climatic impact of these emissions (Aldy, 2006), differences in GHG emission levels between countries may affect the implementation of a stronger multilateral climate change agreement. Thus, evidence of a decrease in inequality of GHG emissions could encourage countries to establish more ambitious INDCs, avoiding these aggregate emissions may lead to global warming beyond the agreed targets.

In this context, the objective of this Doctoral Thesis is to analyse the inequality of the distribution of atmospheric emissions using the family of generalised entropy measures. It consists of four independent but connected chapters that deal with the study of different and complementary aspects of emission inequality, using the data available in each case. The first chapter analyses the decomposition by population sub-groups of the inequality in CO_2 emissions –as it is the most abundant GHG in the atmosphere– by sector; the second chapter studies the main drivers behind the inequality in

[12] According to Chancel and Piketty (2015), the geographical distribution of GHG emissions changes constantly and radically. In the 1820s, Western Europe accounted for more than 95 percent of the global emissions. A hundred years later, North America was the highest emitting region in the world (50 percent). Today, Western Europe and North America represent 9 and 16 percent of the global emissions, respectively; being Asia the current top emitting region.

CO_2 emissions; the third chapter complements the previous ones by analysing inequality and polarization from a multidimensional perspective and, finally, from a more theoretical point of view, the fourth chapter presents the expressions of the Theil indices for the most relevant families of parametric distributions. Next, what is done in each of these chapters is described in more detail.

In Chapter 1, the inequality in CO_2 emissions by sector is decomposed by population sub-groups, analysing the particularities of the following sectors: electricity and heat production, manufacturing and construction, other energy industries, transport, road transport, “others” sectors and residential. For this purpose, the Theil index is used which allows giving a different weight to each country based on its share of the world population. The variable CO_2 emissions is studied across the regions covered by the United Nations Development Program (UNDP) in 2009. The geographical dimension contemplated in this analysis permits the incorporation of the obtained results in the design of environmental economic policies in the future, both at global and regional level. Unlike previous studies, the results provide a greater relative importance to the within-group inequality component. Thus, this research is replicated using the family of generalised entropy measures because each index of this family emphasizes inequality in a different part of the distribution, allowing studying the sensitivity of the weight of both components in total inequality.

Among all the human activities, the energy use is the largest source of CO_2 emissions. Within the energy sector, CO_2 emissions resulting from fuel combustion dominates the total emissions. As no single indicator can provide a complete picture of a country’s CO_2 emissions performance, in the second chapter, other driving forces behind the inequality in CO_2 emissions are studied, based on the Kaya factors (Kaya, 1989; Yamaji *et al.*, 1991). In particular, CO_2 emissions inequality is decomposed into four contributing factors which had not previously been analysed: carbon intensity of electricity production, electricity intensity of gross domestic product (GDP), economic growth in terms of labour production and employment rate. With the aim of using the obtained results as a reference for agreements which will be taken in the near future, the CO_2 emissions inequality is studied across the regions considered by the International Energy Agency (IEA) in the period 1990-2010. For this purpose, the Theil index is used which allows decomposing total inequality by population sub-groups and by multiplying factors. The methodological contribution of this study lies in the inequality decomposition provided which allows us to take a greater number of factors than the traditional decomposition approaches.

Human activity which took place during the industrial era has led to a dramatic increase of both CO_2 emissions and non-CO_2 GHG emissions, the last ones playing an important role in understanding and curbing global climate change. As it has been pointed out before, differences in GHG emissions levels between countries may determine the implementation of a stronger multilateral climate change agreement. Thus, in Chapter 3, such inequality is analysed from a multidimensional perspective considering the CO_2, methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (F-gases) emissions in the period 1990-2011 and using the multidimensional generalised entropy measures proposed by Maasoumi (1986). However, in the environmental field, global negotiations on reducing emissions are constructed through alliances of groups of countries with conflicting interests given their different environmental responsibilities and level of development. Consequently, apart from inequality analyses, it is necessary to carry out polarization studies in order to capture the potential conflict related to the GHG distribution. Then, in this chapter, multidimensional polarization is also investigated using the indices developed by Gigliariano and Mosler (2009) which are constructed taking into account the decomposition by population sub-groups of the multidimensional inequality measures proposed by Maasoumi (1986). Thus, this is the first attempt to use multidimensional inequality and polarization measures for analysing, in a joint manner, the global distribution of GHG emissions.

Finally, since the information concerning the statistical distribution of the GHGs can be used to investigate the level of inequality associated with them, in the last chapter, a convenient expression for the Theil indices is presented which allows us to obtain these inequality measures for the most relevant families of parametric distributions and to derive closed expressions for multivariate versions of them. In particular, these formulas are reviewed for the most common parametric distributions and obtained for those that were not available in the existing literature: the Champernowne (1952) distribution, the generalised gamma (GG) and generalised beta of first and second kind (GB1 and GB2, respectively) distributions (McDonald, 1984), the κ-generalised distribution (Clementi *et al*., 2007) and several Pareto and gamma-type distributions. The moments of these families are also included to facilitate the computation of the generalised entropy measures. As an empirical application, inequality in CO_2 emissions in the year 2012 is investigated. The emission distribution is modeled assuming the GB2 distribution and then, different generalised entropy measures relative to this model are computed using the formulas developed in this chapter.

Note, that different versions of the four chapters have been presented in a variety of national and international conferences. Furthermore, the results obtained in this Doctoral Thesis have been published, or have passed the first stage of the review process, in academic journals. Particularly, versions of Chapters 1, 2 and 3 have been published (in collaboration) in *Estudios de Economía Aplicada* (Remuzgo and Sarabia, 2013), *Economics Bulletin*

(Remuzgo and Sarabia, 2015a), *Environmental Science & Policy* (Remuzgo and Sarabia, 2015b) and *Physica A* (Remuzgo *et al*., 2016). In addition, the methodological part of the Chapter 4 has been accepted for publication (in collaboration) in *Review of Income and Wealth* (Sarabia *et al*., 2016).

Chapter 1

Sub-group decomposition of inequality in CO_2 emissions

Introduction

The activity which takes place in the different sectors originates atmospheric emissions that cause climate change, being that CO_2 is the most abundant GHG in the atmosphere. Nowadays CO_2 emissions are still rising, a trend incompatible with stabilizing atmospheric concentrations of GHGs and avoiding climate change. Thus, as it has been indicated in the recent COPs, a greater commitment to reduce such emissions and stop global warming is necessary.

Income inequality[13] between the different regions of the world is another important reason why it is urgent to curb global CO_2 emissions. Such inequality can cause an inequitable distribution of the consequences of these emissions, existing an inverse relationship between the responsibility for them and the fragility to their effect.

[13] See Duro and Esteban (1998), Goerlich (2001), Navarro and Hernández (2004), Sala-i-Martin (2002, 2006), Milanovic (2005) and Bourgignon and Morrison (2002).

Therefore, it is important to consider the inequality in the distribution of CO_2 emissions when designing policies to curb climate change. During the last two decades there have been several attempts to analyse the international evolution of inequality in CO_2 emissions, such as the papers presented by the IPCC (1996).

In several works on Energy Economics, the indices traditionally used to study income inequality have been introduced as an analytical tool to study environmental disparities. In this sense, Heil and Wodon (1997) employed the decomposition of the Gini index –proposed by Yitzhaki and Lerman (1991)– to study the inequality in per capita CO_2 emissions[14]. Similarly, Heil and Wodon (2000) applied the same methodology to analyse the future inequality in per capita CO_2 emissions through projections to the year 2010, with the ultimate aim of studying the impact of the Kyoto Protocol on the evolution of this inequality. Meanwhile, Hedenus and Azar (2005) considered the use of the Atkinson index as reasonable (Atkinson, 1970), since it fulfills the basic axioms of an inequality index: it is decomposable by population sub-groups, scale invariant and independent of the size of the population and, it satisfies the Pigou-Dalton criterion[15] (Sen, 1973).

In the work of Sun (2002) and after dividing the countries of the OECD into different groups, the inequality within each group was examined for the period 1971-1998. To do this, the mean deviation was adopted as inequality tool, considering that all countries have the same importance. In this line, Alcántara and Duro (2004) completed the study initiated by Sun (2002),

[14] In the work of Heil and Wodon (1997), it is proposed that each country must reduce its future emissions according to its current emissions.

[15] According to the Pigou-Dalton criterion, any transfer of a country with a high level of emissions to another with a lower level, which do not reverse their relative positions, should reduce or at least not increase the value of the index.

proposing and using the Theil index (Theil, 1967), as a suitable alternative to analyse the inequality in energy intensities in the OECD countries[16].

On the other hand, Padilla and Serrano (2006) decomposed the inequality in CO_2 emissions into the between- and within-group inequality components for four groups of countries with different levels of income[17], for the period 1971-1999. This analysis allows us to study whether a reduction of the inequality in CO_2 emissions is due to a greater equity in income between rich and poor countries or due to a greater equity between countries with the same level of income.

In the interim, Groot (2010) and Lawrence *et al*. (2013) measured the inequality in CO_2 emissions and in per capita energy consumption, respectively, based on the Lorenz concentration curve. Finally, applying the Theil index, Chancel and Piketty (2015) studied CO_2 emissions inequalities between individuals from the Kyoto protocol in 1998 to the Paris Climate Conference (COP21) in 2015. In this line, Oxfam (2015) demonstrated the extreme nature of global carbon inequality[18] both globally and within key countries.

Given the importance of reducing CO_2 emissions, all sectors must be less intensive in CO_2; however, this does not imply that all sectors must reduce their emissions in the same proportion as their prospects of evolution are different.

[16] In this line, Duro and Padilla (2011) analysed the role of energy transformation and final energy consumption on global inequality in energy intensities.

[17] Based on the classification made by the World Bank's World Development Report (World Bank, 2002), countries are divided into four income groups: low, lower-middle, upper-middle and high.

[18] Such inequalities will be horizontal as well as vertical –women will face greater risks than men and rural areas will be more exposed than urban ones.

In this context, in this chapter, inequality in CO_2 emissions by sector is decomposed by population sub-groups using the Theil index. This inequality tool allows us to give a different weight to each country based on its share in the world population. The variable CO_2 emissions is studied across the regions covered by the UNDP in 2009 and categorized into the economic activities that lead to their production in order to provide an approach of how emissions patterns vary between sectors. In addition, the geographical dimension contemplated in this analysis permits the incorporation of the obtained results in the design of environmental economic policies in the future, both at global and regional level.

Unlike previous studies, the results provide a greater relative importance to the within-group inequality component. Thus, this research is replicated using the family of generalised entropy measures because of each index of this family emphasizes inequality in a different part of the distribution, allowing studying the sensitivity of the weight of both components in total inequality.

The contents of this chapter are the following. After this introduction, the global distribution of CO_2 emissions by sector is detailed, including a descriptive analysis of the same. In Section 1.2, the decomposition of the Theil index by population sub-groups is described. The results derived from the inequality analysis are shown in Section 1.3. Next, a sensitivity analysis of the weight of both inequality components is carried out employing the family of generalised entropy measures. Finally, the main conclusions of the chapter are presented and some policy implications are commented.

1.1 Global distribution of CO_2 emissions by sector

In this section, the global distribution of CO_2 emissions by sector is examined. The data used in this analysis have been taken from the IEA (2011a). The variable CO_2 emissions from fuel combustion[19], measured in million tonnes, is studied across the regions considered by the UNDP[20] –Arab States, East Asia and Pacific, Europe and Central Asia, Latin America and the Caribbean, OECD, South Asia and Sub-Saharan Africa– in 2009 because it is the last year with available data. Total CO_2 emissions are classified according to the sectors from which they come. In particular, this analysis includes the following sectors: electricity and heat production, manufacturing and construction, “other energy industries”, transport, road transport, “others” sectors and residential[21].

Figure 1.1 shows the global distribution of CO_2 emissions by sector in 2009[22]. It can be seen that, in 2009 the production of electricity and heat was by far the largest generator of CO_2 emissions –it caused 42 percent of global emissions. The previous fact is due to this sector relying heavily on coal

[19] This approach only includes the emissions originated when the fuel is actually combusted. Emissions have been calculated following the guidelines proposed by the IPCC (2006) for national GHG inventories.

[20] In the Appendix 1.1 it is detailed the classification of the countries analysed, based on the regions considered by the UNDP.

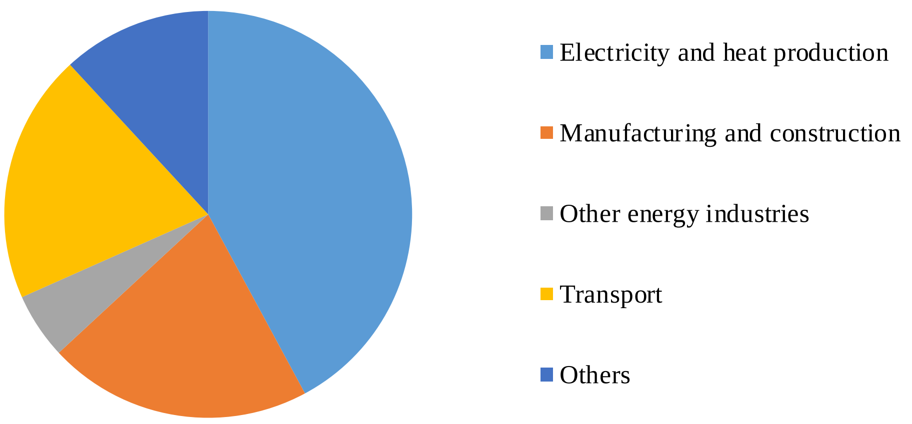
[21] “Electricity and heat production” contains the emissions from the producers whose main activity is the electricity and heat generation; “manufacturing and construction” is composed of the emissions from combustion of fuels in industry; “other energy industries” includes the emissions from fuel combusted in oil refineries for the manufacture of solid fuels, coal mining, oil and gas extraction and other energy-producing industries; “transport” encloses the emissions from the combustion of fuel for all transport activities, regardless of the sector, except for international marine and aviation bunkers; “road transport” contains the emissions arising from fuel use in road vehicles, including the use of agricultural vehicles on highways; “others” sectors admits the emissions from commercial and institutional activities, agriculture, forestry, fishing, residential and other emissions not specified elsewhere; and, finally, “residential” comprehends all emissions from fuel combustion in households (IEA, 2011a).

[22] The emissions values for each sector are presented in the Appendix 1.2.

which is the most carbon-intensive of fossil fuels and a prime source of pollution that encourages global warming. It is expected that electricity demand will rise by 75 percent between 2008 and 2035 due to an increase in population and income in developing countries. This increase is very likely to favour the expansion of the number of electrical processes and devices in homes and commercial buildings. However, the evolution of these emissions will depend mainly on the type of fuels used to produce electricity and the development of renewable energies[23]. In addition, getting power supply with a low level of emissions would reduce CO_2 emissions in all sectors, especially in the industrial sector.

Figure 1.1

World CO_2 emissions by sector in 2009



Note: Emissions from road transport and residential sectors account for about 17 and 7 percent of total emissions, respectively.

[23] Cámara *et al.* (2011) analysed and quantified the environmental impact of atmospheric emissions from the electricity sector in Spain.

Emissions from manufacturing and construction accounted for 21 percent of total CO_2 emissions. According to the studies carried out by the IEA (2010), the creation of a global emissions trading system can facilitate the transition to a cleaner technology in this sector. In addition, governments need to ensure legislative reforms to submit all countries to the emissions restriction[24].

On the other hand, the mobility of goods and people is fundamental to the economic development and social cohesion. However, in turn, it is responsible for a series of social and environmental problems such as air pollution, noise, congestion and road traffic accidents. In this regard, the transport sector in 2009 represented 20 percent of global CO_2 emissions. It should be highlighted that most of them came from road transport because passenger traffic stood for the largest share of global consumption of transport fuels[25]. The relevance of this sector in the distribution of CO_2 emissions is mainly due to two facts concerning the crude. On the one side, the absence of alternative fuels that could replace oil and the slight market introduction of alternative technologies[26] mean that the hydrocarbon demand is inelastic to changes in price. On the other side, economic growth experienced by the emerging economies favours the increase of oil demand (IEA, 2011b).

Emissions from buildings signified 7 percent of the total. Since in most developed countries the existing buildings will stand in the year 2050, the route of savings in this sector will come through the modernization of the facilities using cleaner technologies. However, in the developing countries

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[24] According to Esteban *et al.* (2003), to reduce CO_2 emissions in the Spanish industrial sector it is necessary that the government establishs some kind of energy regulation.

[25] Likewise, this activity was the source of CO_2 emissions with a further growth.

[26] For example, as the built in the electric vehicles.

where building is booming, the strategy will be to incorporate new technologies in the new ones. In addition, to reduce the emissions from the residential sector, a package of policy measures that increase consumer awareness about the energy efficiency of new technologies is necessary.

1.1.1 Descriptive analysis

Table 1.1 shows the means and standard deviations of CO_2 emissions by sector and region in 2009. Considering all the sectors, it can be observed that East Asia and Pacific was the region with the largest mean of CO_2 emissions (787.70), followed far behind by the OECD (447.98). The difference in average emissions between these two geographical areas is due in part to the early implementation of environmental measures by the second one. The previous behaviour of East Asia and Pacific can also be appreciated in the case of the electricity and heat production and the manufacturing and construction sectors; although, in these sectors, South Asia was the second biggest polluter on average.

It should be noted that, on average, the OECD was the largest emitter in the transport (124.88) and road transport (110.77) sectors. This can be associated with the widespread use of automobiles in this region. On the opposite side, Sub-Saharan Africa was, on average, the region with the lowest levels of emissions both globally (24.04) and sectoral. Additionally, it is exhibited that Latin America and the Caribbean and the Arab States were regions with relatively low average emissions level.

Table 1.1

Descriptive statistics of CO_2 emissions by sector and region in 2009

Sector / Region	Arab States		East Asia and Pacific		Europe and Central Asia		Latin America and the Caribbean		OECD		South Asia		Sub-Saharan Africa		Total	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Electricity and heat production	30.89	37.85	363.70	977.66	53.09	145.99	14.75	25.77	174.72	434.80	175.68	307.09	12.23	48.40	89.68	359.80
Manufacturing and construction	17.05	21.15	258.81	673.16	18.93	50.56	14.45	22.93	60.50	113.27	87.59	122.97	3.35	10.73	44.91	208.16
Other energy industries	9.12	15.12	35.23	81.45	6.62	13.84	8.75	14.01	26.07	52.86	16.74	20.45	0.82	1.54	13.69	37.34
Transport	18.87	23.15	71.75	135.76	15.94	40.63	22.74	41.26	124.88	316.10	51.80	58.48	5.45	11.02	41.84	150.42
Road transport	18.40	22.51	59.20	103.68	12.06	25.30	21.27	38.86	110.77	274.55	48.47	54.36	5.17	10.43	36.86	129.65
Others	5.13	5.75	61.74	155.20	16.08	30.34	6.40	10.98	63.98	119.85	58.10	74.02	2.53	7.47	25.12	75.16
Residential	3.83	4.72	32.50	85.43	11.62	23.91	3.66	5.95	35.33	66.54	33.46	41.60	1.57	4.41	14.90	42.92
Total	80.54	94.03	787.70	2017.65	108.70	276.32	64.44	106.11	447.98	1026.02	387.12	565.90	24.04	77.67	211.57	771.51

Note: Emissions are expressed in million tonnes.

Table 1.2

Descriptive statistics of per capita CO_2 emissions by sector and region in 2009

Sector / Region	Arab States		East Asia and Pacific		Europe and Central Asia		Latin America and the Caribbean		OECD		South Asia		Sub-Saharan Africa		Total	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Electricity and heat production	4.28	4.82	1.13	1.07	2.57	2.05	0.74	0.86	2.95	2.21	0.52	0.60	0.33	1.00	2.02	2.68
Manufacturing and construction	2.94	4.36	0.62	0.55	0.72	0.52	1.19	3.68	1.40	0.60	0.40	0.58	0.15	0.26	1.12	2.40
Other energy industries	1.87	3.41	0.13	0.19	0.34	0.45	0.48	1.22	0.55	0.55	0.10	0.17	0.02	0.02	0.55	1.53
Transport	1.92	1.74	0.48	0.42	0.96	0.60	0.79	0.49	2.94	2.13	0.38	0.54	0.30	0.34	1.26	1.51
Road transport	1.90	1.74	0.44	0.42	0.87	0.59	0.72	0.49	2.70	2.11	0.36	0.54	0.28	0.32	1.18	1.47
Others	0.33	0.23	0.23	0.20	0.82	0.77	0.24	0.21	1.48	0.80	0.38	0.67	0.11	0.17	0.61	0.74
Residential	0.25	0.18	0.11	0.10	0.44	0.30	0.13	0.13	0.80	0.59	0.27	0.52	0.06	0.09	0.34	0.42
Total	11.23	12.68	2.57	2.08	5.33	3.20	3.30	5.96	9.32	4.10	1.76	2.52	0.90	1.62	5.46	6.82

Note: Emissions are expressed in tonnes.

Given that population is an important factor; regional level comparisons must be analysed on per capita basis[27]. Table 1.2 shows the means and standard deviations of per capita CO_2 emissions by sector and region in 2009.

It is observed that, on a per capita basis, the divergences in the region's emissions are considerably larger than in the absolute case. In general, the Arab States (11.23) and the OECD (9.32) emitted, on average, far larger amounts of per capita CO_2 emissions. However, it is foreseen that some rapidly expanding economies, such as East Asia and Pacific, will increase significantly their per capita emissions in the near future.

Figure 1.2 illustrates the box plots of per capita CO_2 emissions by sector and region in 2009. Emissions are expressed in logarithms because it is easier to analyse the distribution in terms of log transformed emissions than in terms of the original values. The box plots are useful for identifying the skewness of the data and detecting outliers and extreme values[28].

It is noted that in all the sectors the distribution of per capita CO_2 emissions had an asymmetric character. Considering all the sectors, it is observed that Sub-Saharan Africa was the region with the lowest variability in the distribution of CO_2 emissions since it had the box plots with the lowest amplitude. Moreover, this behaviour can be extended to the case of each sector. On the opposite side, the OECD, East Asia and Pacific and South Asia displayed a greater dispersion in this distribution.

[27] In 2009, the United States alone produced 18 percent of world CO_2 emissions, despite a population of less than 5 percent of the global total. Conversely, India, with 17 percent of world population, contributed more than 5 percent of world CO_2 emissions.

[28] The bottom and top of the box are always the first and third quartiles, and the band inside the box is always the second quartile (the median). Two vertical lines, called whiskers, extend from the front and back of the box: the front whisker goes from the first quartile to the smallest non-outlier in the data set and, the back whisker goes from the third quartile to the largest non-outlier. If the data set includes one or more outliers, they are plotted separately as points on the chart. Meanwhile, the vertical bars determine the range of 95 percent of cases.

Figure 1.2

Skewness of per capita CO_2 emissions by sector and region in 2009

Note: Emissions are expressed in logarithms.

Finally, we can observe the following outliers: Albania, Iceland, Mozambique, Switzerland and Tajikistan in the electricity and heat production sector; Haiti and Trinidad and Tobago in the manufacturing and construction sector; Macedonia, Moldova and Slovenia in the “other energy industries” sector; Eritrea, Luxembourg, Tajikistan and the United States in the transport sector; Eritrea, Haiti, Luxembourg, Tajikistan and the United States in the road transport sector; Sudan in the “others” sector; Iceland, Mozambique, Myanmar, Sudan, Sweden and Zimbabwe in the residential sector and, finally, Tajikistan and Trinidad and Tobago if all the sectors are considered as a whole.

1.2 Decomposition of the Theil index by population sub-groups

In this section, inequality in the global distribution of per capita CO_2 emissions by sector is decomposed by population sub-groups. The aim of this inequality analysis is to know what percentage of total inequality can be attributed to differences between population sub-groups and what share to differences within each group. Among the different inequality measures which are additively decomposable[29], the Theil index (Theil, 1967) is chosen because it is the only index that is differentiable, symmetric, scale invariant and satisfies the decomposability property and the Pigou-Dalton criterion (Sen, 1973; Bourguignon, 1979; Cowell, 1998).

[29] Choosing the most appropriate measure of inequality is bounded between those that are additively decomposable because they allow us to study inequality from different perspectives.

The Theil index can be defined as:

$$T^{(S)}(\underline{c}, p) = \sum_{i=1}^{n} p_i \cdot \log\left(\frac{\bar{c}}{c_i}\right),$$

where $\underline{c} = (c_1, \ldots, c_n)$ and c_i denotes the per capita CO_2 emissions of country i for each sector, which is $c_i = CO_{2i} / N_i$ where CO_{2i} and N_i are the CO_2 emissions for each sector and the population of country i, respectively; p_i represents the share of country i in the world population; $\bar{c}$ is the world average in per capita CO_2 emissions for each sector and, finally, log is the natural logarithm.

This index is called population-weighted Theil index or Mean Log Deviation (*MLD*) index[30]. Its lower limit is zero while its upper limit depends on the size of the sample. Thus, a value close to zero is indicative of an equitable situation while an elevated value shows a high inequality scenario. Similarly, the Theil index is characterized by being more sensitive to the transfers at the bottom tail of the distribution (Shorrocks, 1980; Jenkins and Van Kerm, 2009), being very interesting in the income and wealth inequality research (Bourguignon, 1979).

The Theil index can be decomposed into a between- and a within-group inequality component. The first component shows the inequality when it is only considered the differences between average inequalities of each region

[30] Theil (1967) also proposed an alternative inequality index, the emission-weighted Theil index or Theil's entropy index that is calculated by interchanging the positions of $\bar{c}$ and c_i in the natural logarithm and replacing the population weight by the share of each country's emissions on the world total emissions. However, the Theil index weighted by the population is a more appropriate measure because of the following: i) to analyse the inequality in CO_2 emissions, the observations should be weighted according to the proportion that the population of each country represents on world population (Duro, 2004; Duro and Padilla, 2006), ii) there are some problems in interpreting the results from the decomposition by population sub-groups when using the Theil index weighted by CO_2 emissions (Davies and Shorrocks, 1978; Shorrocks, 1980).

while the second one is calculated as the weighted sum of the inequality values of each region (Theil, 1967; Shorrocks, 1980)[31].

Specifically, the decomposition of the total inequality into the between- and within-group inequality components is given by the following expression:

$$T^{(S)}(\underline{c}, p) = T_B^{(S)}(\underline{c}, p) + T_W^{(S)}(\underline{c}, p),$$

where $T_B^{(S)}(\underline{c}, p)$ is the between-group inequality component whose expression is the following:

$$T_B^{(S)}(\underline{c}, p) = \sum_{g=1}^{G} p_g \cdot \log\left(\frac{\bar{c}}{\bar{c}_g}\right),$$

and $T_W^{(S)}(\underline{c}, p)$ is the within-group inequality component which can be expressed as:

$$T_W^{(S)}(\underline{c}, p) = \sum_{g=1}^{G} p_g \cdot T_g^{(S)}(\underline{c}),$$

where p_g represents the share of region g in the world population; $\bar{c}_g$ is the regional average in per capita CO_2 emissions for each sector; $T_g^{(S)}(\underline{c})$ denotes the inequality in region g for each sector and, finally, G is the number of regions.

This decomposition allows us to analyse the importance of each group. A small contribution to total inequality of the between-group component reveals that the descriptive capacity of this technique is limited, requiring the

[31] It was not considered the decomposition of the Gini index proposed by Lerman and Yitzhaki because, although it identifies inequality within groups of countries, it does not determine the inequality between different groups as there is a percentage of inequality that is not decomposed (residual error) (Lambert, 1993).

review of other methodologies related to the concept of inequality as the polarization analysis[32].

1.3 Data and results

As specified in Section 1.1, the data used in this analysis have been taken from the IEA (2011a). The variable per capita CO_2 emissions from fuel combustion, measured in tonnes, is studied across the regions considered by the UNDP in 2009. Total CO_2 emissions are classified according to the sectors from which they come: electricity and heat production, manufacturing and construction, “other energy industries”, transport, road transport, “others” sectors and residential.

Table 1.3 shows the inequality in per capita CO_2 emissions by sector in 2009 for the UNDP’s regions using the Theil index, as well as, the decomposition of such inequality into the between- and within-group inequality components. It should be noted that the Theil index took the lowest value when all the sectors were considered as a whole (0.6120). A similar degree of inequality was manifested by the manufacturing and construction sector (0.6261). By contrast, the sector with the greatest inequality was the agglomerate “other energy industries” (0.9485), followed by the generation of electricity and heat (0.8216).

Based on the decomposition of total inequality into the between- and within-group inequality components, it can be appreciated that both components contributed to the explanation of total inequality in all the sectors. The

[32] As it is detailed in Chapter 3, the concept of polarization (Wolfson, 1994, 1997; Esteban and Ray, 1994) arises because inequality measures are not satisfactory in the formation of groups in a society. This concept allows, for a given distribution, the formation of heterogeneous groups whose internal disparities are minimal. Although initially polarization techniques were used to study the income distribution (Gradin, 2000), Duro and Padilla (2008) used this methodology to analyse the international distribution of CO_2 emissions.

previous fact justifies the importance of having chosen this methodology which considers the decomposition of total inequality into both components. In addition, the point that the between-group inequality component was significant confirms the relevance of the regions of countries considered in this analysis because there are large differences between all of them.

Table 1.3

Decomposition of inequality in per capita CO_2 emissions by sector by population sub-groups in 2009

Sector	$T(\underline{c}, p)$	$T_B(\underline{c}, p)$	$T_W(\underline{c}, p)$
Electricity and heat production	0.8216	0.3003	0.5213
Manufacturing and construction	0.6261	0.2674	0.3587
Other energy industries	0.9485	0.4357	0.5128
Transport	0.7783	0.5281	0.2502
Road transport	0.7904	0.5254	0.2650
Others	0.6976	0.3858	0.3118
Residential	0.7918	0.3872	0.4047
Total	0.6120	0.3030	0.3090

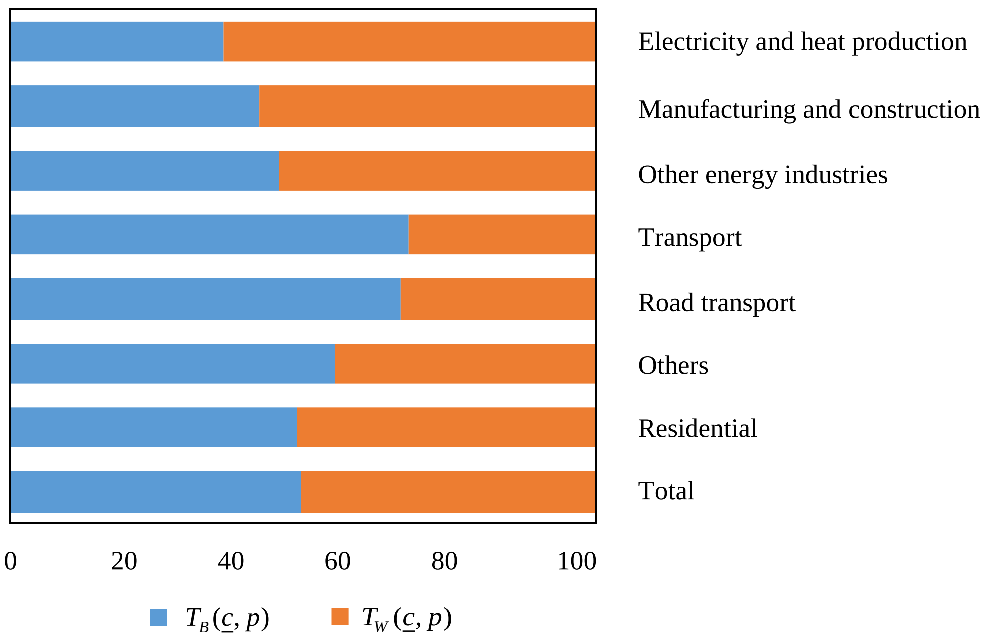
Figure 1.3 illustrates the contribution to inequality in per capita CO_2 emissions by sector of the between- and within-group inequality components in 2009[33]. The results show that the within-group inequality component was generally the largest contributor to total inequality, playing an important role in the electricity and heat production sector (63.45 percent) and in the manufacturing and construction sector (57.30 percent). This fact reveals that, at regional level, the sharing of responsibility of CO_2 emissions from these sectors is an aspect that can be controversial.

[33] The contribution to total inequality of both components, expressed in percentage, can be found in the Appendix 1.3.

On the other hand, the moderate contribution of this component to the existing inequality in the transport (32.14 percent) and road transport (33.53 percent) sectors should be remarked. In this case, the division of the responsibility of CO_2 emissions from these activities should be quite similar for all countries belonging to the same geographical area.

Figure 1.3

Contribution to inequality in per capita CO_2 emissions by sector of the between- and within-group inequality components in 2009



Note: The contribution is expressed in percentage.

Also, the importance of the between-group inequality component in the transport activities (67.86 and 66.47 percent in the global and road transport sectors, respectively) should be noted. This result indicates that in these sectors technological advances are propagated in two phases, as indicated in Duro and Padilla (2006). Firstly, low emissions technologies are diffused within each region and, secondly, technology transfers are expanded from one region to another.

Table 1.4 shows the internal inequality in per capita CO_2 emissions by sector in 2009 in the regions considered by the UNDP. Globally, the regions with the lowest inequality were the OECD (0.0859), Europe and Central Asia (0.1630), Latin America and the Caribbean (0.1696) and East Asia and Pacific (0.1896).

The degree of equality observed in the OECD and in Europe and Central Asia can be associated with a greater uniformity in the sectoral structures of the countries which belong to these geographical regions. Inequality in East Asia and Pacific was small when looking at the Theil index. However, the forces driving Asia's rapid growth –new technology, globalisation, and market-oriented reform– are expected to rise such inequality. For its part, the low inequality level observed in Latin America and the Caribbean can be given because it is mostly composed by countries with a medium or high level of human development, demanding all of them to use the same quantity of energy.

Unlike the previous groups of countries, South Asia and the Arab States had higher levels of inequality (0.2343 and 0.6454, respectively). In these cases, the expansion throughout the region of low emission technologies would attenuate inequality within them. The region with the greatest internal inequality was Sub-Saharan Africa (1.3036). The high level of inequality observed in this region may be due to the disparities in terms of income that it supports.

Table 1.4

Regional inequality in per capita CO_2 emissions by sector in 2009

Sector / Region	Arab States	East Asia and Pacific	Europe and Central Asia	Latin America and the Caribbean	OECD	South Asia	Sub-Saharan Africa
Electricity and heat production	0.8392	0.2934	0.2927	0.4047	0.1935	0.2691	2.5536
Manufacturing and construction	0.8687	0.2512	0.1982	0.2362	0.0641	0.2295	1.4734
Other energy industries	1.3194	0.2842	0.3593	0.5333	0.1667	0.6267	1.2765
Transport	0.4652	0.0767	0.1585	0.1263	0.1227	0.3540	0.7956
Road transport	0.4727	0.0940	0.1388	0.1446	0.1071	0.3995	0.7967
Others	0.2691	0.1324	0.1129	0.1975	0.0649	0.4009	1.3219
Residential	0.3275	0.1962	0.1179	0.2408	0.1135	0.5954	1.4581
Total	0.6454	0.1896	0.1630	0.1696	0.0859	0.2343	1.3036

Considering the distribution of emissions among the sectors, Sub-Saharan Africa and the Arab States were the regions with the major internal inequalities. Note that Sub-Saharan presented the highest level of concentration observed in this study. Specifically, this event occurred in the electricity and heat production sector where inequality reached a value of 2.5536.

1.4 Sensitivity analysis

In the analysis of inequality carried out in the previous section, the within-group inequality component had a greater relative importance in overall inequality in comparison to the other element. However, in most studies devoted to measuring inequality in CO_2 emissions which had used the Theil index, it was concluded that the between-group inequality component had a major capacity to explain total inequality, compared with the inequality within groups (Duro and Padilla, 2006; Padilla and Serrano, 2006).

Since each measure tends to emphasize the concentration existing in a different interval of the distribution, the results obtained in the analysis of inequality may vary depending on which index of inequality is chosen. Notwithstanding, given that in the three mentioned studies the analysis tool used was the same, it is possible to reject this motive as the origin of the divergence in the results. Consequently, the discrepancy in the results can be due mainly to two facts. On the one hand, while other authors studied the inequality in total CO_2 emissions, in this analysis the variable “CO_2 emissions by sector” is considered. On the other hand, while the others opted for doing a temporary analysis, in this research the behaviour of the variable is studied only in the year 2009.

In order to check the veracity of the previously exposed, in this section it is analysed whether the degree of inequality –total, between and within groups– depends on the sensitivity of the index to the CO_2 emissions transfers that may occur in the different parts of the distribution.

Among the great variety of inequality indicators that can be employed, the family of generalised entropy measures is chosen for three reasons. Firstly, because the Theil index belongs to this family of indices; secondly, because it allows us to study the sensitivity of the weight of both inequality components to the importance assigned to the different parts of the distribution and last but not least, because it has the desirable properties for any inequality measure (Shorrocks, 1982, 1984).

1.4.1 Decomposition of the generalised entropy index by population sub-groups

The population-weighted generalised entropy index can be defined as:

$$GE^{(S)}(\underline{c}) = \frac{1}{\theta^2 - \theta}\left[\sum_{i=1}^{N} p_i \left(\frac{c_i}{\bar{c}}\right)^{\theta} - 1\right], \quad \theta \neq 0,1,$$

where $\underline{c} = (c_1, \ldots, c_n)$ and c_i denotes the per capita CO_2 emissions of country i for each sector; p_i represents the share of country i in the world population and $\bar{c}$ is the world average in per capita CO_2 emissions for each sector.

The θ parameter measures the aversion that the society shows toward inequality. Depending on the value of θ, the inequality index assigns a distinct weight to the different parts of the distribution. Thus, as θ increases (decreases), the index becomes more sensible to the emissions transfers that take place in the upper (lower) tail of the distribution. In other words, when $\theta > 0$, the countries which emit more CO_2 emissions receive more weight, such that, the higher the θ value, the greater the weight given to these countries[34] (Shorrocks, 1980; Jenkins and Van Kerm, 2009).

The lower limit of the index is zero which is characteristic of an equitable distribution while, on the opposite side, the maximum inequality is given by the following expression:

$$\frac{n^{\theta-1}-1}{\theta^2-\theta},$$

or an ∞ value when $\theta \leq 0$ (Cowell, 2011).

The generalised entropy index can be decomposed into a between- and a within-group inequality component according to the following expression:

$$GE^{(S)}(\underline{c}) = GE_B^{(S)}(\underline{c}) + GE_W^{(S)}(\underline{c}),$$

where $GE_B^{(S)}(\underline{c})$ is the between-group inequality component whose expression is the following:

$$GE_B^{(S)}(\underline{c}) = \frac{1}{\theta^2-\theta}\left[\sum_{g=1}^{G} p_g \left(\frac{\overline{c}_g}{\overline{c}}\right)^{\theta} - 1\right], \quad \theta \neq 0,1,$$

and $GE_W^{(S)}(\underline{c})$ is the within-group inequality component which can be expressed as:

$$GE_W^{(S)}(\underline{c}) = \sum_{g=1}^{G} w_g \cdot GE_g^{(S)}(\underline{c}), \quad \theta \neq 0,1,$$

[34] For example, when $\theta = 2$, the index gives the same importance to a transfer of 10 tonnes of CO_2 emissions from a country which emits 2 tonnes of emissions to another that emits 10 tonnes than a transfer of 1 tonne of CO_2 emissions between two countries that emit 2 and 10 million tonnes of emissions, respectively.

where p_g represents the share of region g in the world population; $\bar{c}_g$ is the regional average in per capita CO_2 emissions for each sector; $GE_g^{(S)}(\underline{c})$ denotes the inequality in region g for each sector; w_g is the weight assigned to the regional inequality which can be expressed as:

$$w_g = f_g^{\theta} \cdot p_g^{1-\theta},$$

where f_g represents the share of region g in the world emissions, that is:

$$f_g = \frac{\bar{c}_g}{\bar{c}} \cdot p_g,$$

and, finally, G is the number of regions.

The between-group inequality component indicates that all countries which belong to the same region produce the average level of CO_2 emissions in that region, regardless of how these emissions are distributed internally in each group (Elbers *et al*., 2004). However, the within-group inequality component is not, generally, a weighted average of the regional inequalities. Specifically, this component is only a weighted average of the regional inequalities when θ takes the values 0 or 1, being then, the sum of the weights equal to 1.

In Table 1.5, the expressions for the family of generalised entropy measures are shown, as well as, their decomposition into the between- and within-group inequality components. Thus, making the appropriate calculations, the generalised entropy index is transformed into the *MLD* index when θ tends to zero and into the Theil's Entropy index when θ tends to one[35].

[35] As Anand and Segal (2008), between both Theil's indices, it has been chosen the *MLD* index to carry out the inequality analysis done in Section 1.2 because it is weighted by population-shares rather than emission-shares. In this context, it is more appropriate to use the *MLD* index as it is the country's population-share, not its emission-share, which should restrict the contribution that each country is allowed to make to global inequality.

Table 1.5

Expressions for the family of generalised entropy measures

Theta	Total inequality	Between-group inequality component	Within-group inequality component
$\theta \neq 0,1$	$GE^{(S)}(\underline{c}, p) = \frac{1}{\theta^2 - \theta}\left[\sum_{i=1}^{N} p_i \left(\frac{c_i}{\bar{c}}\right)^{\theta} - 1\right]$	$GE_B^{(S)}(\underline{c}, p) = \frac{1}{\theta^2 - \theta}\left[\sum_{g=1}^{G} p_g \left(\frac{\bar{c}_g}{\bar{c}}\right)^{\theta} - 1\right]$	$GE_W^{(S)}(\underline{c}, p) = \sum_{g=1}^{G} w_g \cdot GE_g^{(S)}(\underline{c})$
$\theta = 0$	$GE^{(S)}(\underline{c}, p) = \sum_{i=1}^{N} p_i \cdot \log\left(\frac{\bar{c}}{c_i}\right)$	$GE_B^{(S)}(\underline{c}, p) = \sum_{g=1}^{G} p_g \cdot \log\left(\frac{\bar{c}}{\bar{c}_g}\right)$	$GE_W^{(S)}(\underline{c}, p) = \sum_{g=1}^{G} p_g \cdot GE_g^{(S)}(\underline{c})$
$\theta = 1$	$GE^{(S)}(\underline{c}, p) = \sum_{i=1}^{N} p_i \cdot \frac{c_i}{\bar{c}} \cdot \log\left(\frac{c_i}{\bar{c}}\right)$	$GE_B^{(S)}(\underline{c}, p) = \sum_{g=1}^{G} p_g \cdot \frac{\bar{c}_g}{\bar{c}} \cdot \log\left(\frac{\bar{c}_g}{\bar{c}}\right)$	$GE_W^{(S)}(\underline{c}, p) = \sum_{g=1}^{G} f_g \cdot GE_g^{(S)}(\underline{c})$

Source: Adapted from Cowell (2011).

1.4.2 Results

Considering the expressions detailed in Table 1.5, the decomposition inequality analysis has been replicated using different values of the θ parameter[36]. The objective of this study is to observe the sensitivity of the weight of both inequality components to the variation of this parameter.

Figure 1.4 shows the contribution to inequality in per capita CO_2 emissions by sector of the within-group inequality component n 2009, considering different values for θ[37]. Despite the variations in the value of the θ parameter, the results show that the within-group inequality component remained the predominant contributor to global inequality in all the sectors.

Even though it is true that, when θ took the values 0, 1 and 2, the between-group inequality component represented a significant percentage in overall inequality in all the sectors, specially in the transport and road transport sectors. This fact shows that inequality between regions is a component which should not be disregarded, being the geographical dimension an aspect to consider in the analysis of inequality in the global distribution of CO_2 emissions by sector.

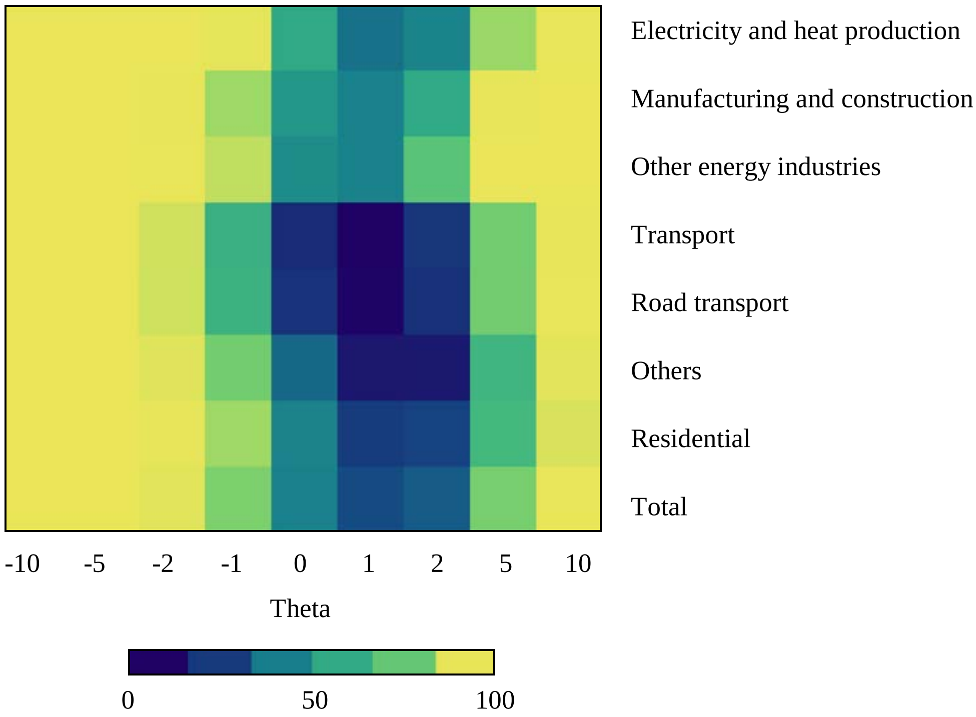
Similarly, all the sectors followed the same behaviour patterns. On the one hand, it is noteworthy that, when $\theta = 1$, the between-group inequality component reached its greatest relative importance in overall inequality. On the other hand, since the effect of this component was practically residual when $\theta = 10$ and $\theta = -10$, in these cases one hundred percent of total inequality can be attributed to the inequality within groups.

[36] In particular, the analysis has been replicated for $\theta = -10$, $\theta = -5$, $\theta = -2$, $\theta = -1$, $\theta = 1$, $\theta = 2$, $\theta = 5$ and $\theta = 10$.

[37] The contribution to total inequality of the within-group inequality component, expressed in percentage, is provided in the Appendix 1.4.

Figure 1.4

Contribution to inequality in per capita CO_2 emissions by sector of the within-group inequality component in 2009



Note: The contribution is expressed in percentage.

Table 1.6 shows the internal inequality in per capita CO_2 emissions by sector in 2009 when θ takes the values -1 and 1 in the regions considered by the UNDP. The results allow us to know which countries –the countries that produce more or less per capita CO_2 emissions– are the main contributors to global inequality. In this sense, when θ takes the value -1 (1), the index will be more sensitive to what happens in the bottom (upper) tail of the distribution and, therefore, a high value of the index will give evidence of the existence of high inequality between the least (most) polluting countries.

Table 1.6

Regional inequality in per capita CO_2 emissions by sector in 2009 (θ = -1 and θ = 1)

Sector / Region	Arab States		East Asia and Pacific		Europe and Central Asia		Latin America and the Caribbean		OECD		South Asia		Sub-Saharan Africa	
	θ = -1	θ = 1	θ = -1	θ = 1	θ = -1	θ = 1	θ = -1	θ = 1	θ = -1	θ = 1	θ = -1	θ = 1	θ = -1	θ = 1
Electricity and heat production	2.3204	0.7899	1.4681	0.1581	1.3070	0.1984	0.6009	0.3478	0.3364	0.1549	13.1359	0.1434	188.6828	1.9277
Manufacturing and construction	1.7865	0.9938	1.0924	0.1355	0.3393	0.1569	0.4554	0.3216	0.0734	0.0587	0.3296	0.2609	4.4721	1.4653
Other energy industries	4.6582	1.2881	1.2781	0.1432	2.6892	0.3450	2.2990	0.4372	0.1898	0.1688	2.1293	0.6344	10.6918	0.6481
Transport	0.6002	0.5026	0.1119	0.0777	0.3268	0.1273	0.1834	0.1085	0.1292	0.1220	0.3361	0.5383	2.1634	0.6910
Road transport	0.6012	0.5149	0.1123	0.1098	0.2712	0.1099	0.2352	0.1233	0.1115	0.1074	0.4034	0.6009	2.1776	0.6817
Others	0.7298	0.1690	0.2125	0.0958	0.1576	0.1020	0.3011	0.1936	0.0834	0.0566	0.4015	0.6086	2.9455	1.3216
Residential	0.7643	0.2415	0.7164	0.1156	0.2335	0.0822	0.3195	0.2418	0.2240	0.0846	0.5940	0.9647	5.9375	1.2740
Total	1.1525	0.6815	0.4813	0.1161	0.2946	0.1287	0.2264	0.1771	0.0942	0.0821	0.3366	0.2626	3.2422	1.3757

It is noteworthy that all the regions in all the sectors showed a higher inequality level when it was given more importance to the emissions transfers among the countries at the bottom tail of the distribution than at the upper one [$GE_{-1}^{(S)}(\underline{c}, p) > GE_{1}^{(S)}(\underline{c}, p)$].

Globally, Sub-Saharan Africa stood out as the geographical area with the highest degree of internal inequality when θ = -1 (3.2422) and θ = 1 (1.3757). Probably, this region showed such a very high degree of inequality between the least polluting countries because of the existence in this region of extremely poor countries which emit a very low level of CO_2 emissions, compared to the rest of countries of this region. In addition, the high level of inequality observed in this region between the most polluting countries may be due to South Africa being ranked, in the year 2009, among the world's top 12 largest CO_2 emitters, given its dependence on coal for electricity generation and an energy-intensive industrial and mining sector.

In general terms, the Arab States were the second most unequal region. It should be noted that this geographical area was associated with the maximum inequality value in the agglomerate "other energy industries" when θ = 1 (1.2881). For the time being, if it is not taken into account Sub-Saharan Africa, South Asia showed a very high level of internal inequality in the electricity and heat production sector when θ = -1 (13.1359).

The lowest inequality values were normally observed in the OECD. It can be seen that in this region there was a low degree of concentration in both tails of the distribution. This fact can be interpreted as a phenomenon of sectoral interdependence within this region which may have contributed to a reduction in the CO_2 emissions inequality between all the countries that belong to this geographical area.

It can also be observed that East Asia and Pacific showed the minimum inequality value in the transport sector regardless of the value of the θ parameter and in the agglomerate “other energy industries” when $\theta = 1$. Meanwhile, Europe and Central Asia and South Asia presented the lowest inequality values in the residential sector (0.0822) and electricity and heat production sector (0.1434) when $\theta = 1$, respectively.

Previous results show the complexity involved in the study of inequality in CO_2 emissions by sector and the need to take into account all available indicators to be able to define this phenomenon with accuracy.

1.5 Conclusions and policy implications

In this chapter, the inequality in the global distribution of CO_2 emissions by sector in 2009 is studied, using the data provided by the IEA. To analyse the decomposition of such inequality into their interregional and intraregional components, the regions covered by the UNDP are considered.

The global distribution of CO_2 emissions by sector reveals that, in 2009, the production of electricity and heat was by far the largest generator of CO_2 emissions, being the manufacturing and construction the second most polluting sector. Also, the descriptive analysis illustrates that the distribution of CO_2 emissions had an asymmetric character in all the sectors.

The inequality analysis has been carried out using the Theil index because it can be easily decomposed into the between- and within-group inequality components. Thus, while the manufacturing and construction sector was the one with least inequality in the distribution of CO_2 emissions; the agglomerate “other energy industries” was the sector with the greatest inequality, followed by the generation of electricity and heat.

The importance of the between-group inequality component in the transport activities points out that technological advances are propagated, firstly, within each region and secondly, from one region to another, as it was indicated by Duro and Padilla (2006).

Meanwhile, the within-group inequality component was generally the largest contributor to total inequality, playing an important role in the electricity and heat production and in the manufacturing and construction sectors. This fact reveals that, at regional level, the sharing of responsibility of CO_2 emissions from these sectors is an aspect that can be controversial.

As for the regional inequality in per capita CO_2 emissions by sector in 2009, it can be seen that, globally, the regions with the lowest inequality were the OECD, Europe and Central Asia, Latin America and the Caribbean and East Asia and Pacific. Unlike the previous groups of countries, South Asia and the Arab States had higher levels of inequality, being Sub-Saharan Africa the region with the greatest internal inequality.

To complete the previous study of inequality, it has been also studied whether the degree of inequality depends on the sensitivity of the index to the CO_2 emissions transfers that may occur in the different parts of the distribution, using the family of generalised entropy measures. Despite the variations in the value of the θ parameter, the results showed that the within-group inequality component remained the predominant contributor to global inequality in all the sectors.

Even though it is true that, as the between-group inequality component represented a significant percentage in overall inequality in all the sectors regardless of the value of the θ parameter, the geographical dimension is an aspect that must be considered in the analysis of inequality in the global distribution of CO_2 emissions by sector.

The analysis of the regional inequality in per capita CO_2 emissions by sector in 2009, for different values of the θ parameter, allows us to know which countries –the countries that produce more or less per capita CO_2 emissions– are the main contributors to global inequality in each of the regions covered by the UNDP. It is noteworthy that all the regions in all the sectors showed a higher inequality level when it was given more importance to the emissions transfers among the least polluting countries than among the most polluting ones.

In general terms, Sub-Saharan Africa stood out as the geographical area with the highest degree of internal inequality regardless of whether the index becomes more sensible to the emissions transfers that take place in the upper or lower tail of the distribution. On the one hand, this region probably showed such a very high degree of inequality between the least polluting countries because of the existence in this region of extremely poor countries which emit a very low level of CO_2 emissions, compared to the rest of countries of this region. On the other hand, the high level of inequality observed in this region between the most polluting countries may be due to South Africa being ranked, in the year 2009, among the world's top 12 largest CO_2 emitters.

On the opposite side, the OECD showed a low level of concentration in both tails of the distribution. This fact can be interpreted as a phenomenon of sectoral interdependence within this region which may have contributed to a reduction in the CO_2 emissions inequality between all the countries that belong to this geographical area.

Both studies show that developing countries were those with a higher degree of inequality in CO_2 emissions by sector. Therefore, it is recommended in terms of economic policy, the use of instruments to stimulate the economic growth in the poorest countries and, consequently, reduce the existing inequality in per capita CO_2 in emissions in these regions.

However, as to curbing climate change the equality in CO_2 emissions is not necessary but the reduction and control of them, it will be essential that environmental policies will be able to meet two objectives at the same time: on the one hand, these measures should allow the economic growth of developing economies and, on the other hand, should stabilize the number of global emissions.

Chapter 2

Factorial decomposition of inequality in CO_2 emissions

Introduction

In environmental research, CO_2 emissions have been considered a suitable indicator for designing global policies to restrain climate change[38]. There are many variables that determine the impact of air pollution on the environment. Traditionally, the following factors have been taken into account: population growth, economic growth and technological change. All these are contained in the identity known by the acronym *IPAT* (Ehrlich and Holdren, 1971; Ehrlich and Ehrlich, 1990) which stands for the following: "*I*" refers to the impact made on the environment, "*P*" represents the population; "*A*" symbolizes the affluence which is measured by the per capita GDP, and "*T*" is the technology, calculated by dividing the "impact" by the GDP (Common and Stagl, 2005).

[38] The current concentration of CO_2 emissions in the atmosphere converts this substance into the main pollutant which is responsible for climate change.

Along the same lines, the so-called Kaya identity (Kaya, 1989; Yamaji *et al*., 1991) is a tool which is frequently used to analyse the determinants of inequality in the global distribution of CO_2 emissions. By this identity, CO_2 emissions from a country or region are decomposed into four factors: CO_2 emissions per unit of energy or carbonization index (CO_{2i} / E_i), energy intensity (E_i / GDP_i), economic rent (GDP_i / P_i) and population (P_i).

However, this decomposition has two drawbacks. On the one hand, the factors can have dependencies between them. For example, countries with a higher GDP may develop cleaner technologies more easily. On the other hand, note that this decomposition implies unitary elasticity between factors, so it cannot be used for the study of the individual contribution of each factor to the global level of CO_2 in the atmosphere (Rosa and Dietz, 2012). In spite of these disadvantages, most of the literature dedicated to explaining the driving forces behind global CO_2 emissions levels in the atmosphere uses the Kaya identity.

In recent years, the study of territorial inequalities has provoked a great interest in different fields of research. Thus, although traditionally distributional aspects have been considered in the income analysis, its application is spreading to other domains. Regarding the environmental area, the study of inequality gains importance with the celebration of the UNFCCC in 1992, whose aim was to limit the global GHG emissions and stabilize their concentration in the atmosphere[39]. When the Kyoto Protocol became effective in 2005, an international agreement was reached on the importance of reducing the global level of CO_2 emissions. Therefore, in order to avoid a reversal of global convergence, the UNDP established that the following

[39] A study that provides a detailed review of the methodology used to study the inequality in the environmental field is presented in Ang and Zhang (2000).

progress in this area should be aimed at the reduction of environmental risks caused by the CO_2 emissions inequality (UNDP, 2011).

The complexity involved in stabilizing the global concentration of CO_2 in the atmosphere requires the participation of all the economies. However, while developing countries consider it opportune to restrict the CO_2 emissions of richer countries, developed countries fear that this decision could harm their economic growth[40].

In this respect, note that a number of authors have focused their work on analysing the factors causing inequality in CO_2 emissions at international level. Thus, Duro and Padilla (2006) used the Theil index to decompose global inequality in per capita CO_2 emissions into three multiplying factors and two interaction terms whereas, Xu and Ang (2013) investigated the relative contributions of various drivers to changes in the aggregate carbon intensity considering different emission sectors and countries.

There have been also several studies on the driving forces of CO_2 emissions at national level, especially for the principal developed countries (Kerr and Mellon, 2012; O'Mahony, 2013; Videras, 2014; Fernández-González *et al.*, 2014; Moutinho *et al.*, 2015; Shahiduzzaman and Layton, 2015) and emerging economies such as China (Liu *et al.*, 2012; Su and Ang, 2012; Zhang and Zhao, 2014; Wang and Liu, 2015), Thailand (Hoa and Limskul, 2013), Indonesia (Shahbaz *et al.*, 2013), Vietnam (Tang and Tan, 2015) and the Philippines (Sumabat *et al.*, 2016).

Among all the human activities, energy use is the largest source of CO_2 emissions. Within the energy sector, CO_2 emissions resulting from fuel

[40] Several authors (Stern *et al.*, 1996; Ekins, 1997; Suri and Chapman, 1998) have insisted on the possibility of explaining the relationship between the economic growth and its environmental pressure through the Environmental Kuznets curve with an inverted U-shaped.

combustion dominates the total emissions. The recent emissions trends by sector analysed by the IEA reveal that electricity generation and transport produce 42 and 22 percent of global emissions, respectively (IEA, 2013a). By 2035, the *World Energy Outlook 2013* (IEA, 2013b) projects that the demand of electricity will be nearly 70 percent higher than the current values. The carbon intensity of electricity production shows how the electricity generation contributes to climate change, being the most important component of the carbon intensity of energy use as a whole. This indicator suggests the availability of switching from fossil fuels to non-fossil fuels in electricity production so as to reduce CO_2 emissions.

Researchers have typically studied the effect of population growth on carbon emissions increase, using the aforementioned *IPAT* identity. Considering only population size we are assuming that all the individuals have the same consumption and production behaviour. However, these behaviour patterns are closely linked to both population size and population structure (Zhu and Peng, 2012). In this sense, many authors (Liddle, 2000; O'Neill *et al*., 2010; Zagheni, 2011) have paid attention to the relationship between CO_2 emissions and age structure. Other studies such as York *et al*. (2003) and Cole and Neumayer (2004) establish a positive correlation between CO_2 emissions and working-age people.

As no single indicator can provide a complete picture of a country's CO_2 emissions performance, the objective of this chapter is to study other driving forces behind the inequality in CO_2 emissions, based on the Kaya factors. At no time is the intention of the presented approach to replace the Kaya factors. In particular, CO_2 emissions inequality is decomposed into four contributing factors which had not been analysed previously: carbon intensity of electricity production, electricity intensity of GDP, economic growth in terms of labour production and employment rate. With the aim of using the obtained results as a reference for agreements which will be taken in the near future, the CO_2 emissions inequality is studied across the regions considered by the IEA in the period 1990-2010.

Unlike previous studies that have been done in this field, this investigation devotes more attention to analysing the effects of the carbon intensity of electricity production and the employment rate on the distribution of CO_2 emissions. The carbon intensity of electricity is an essential factor in designing policies aimed at CO_2 emissions abatement given the future emissions trends in the electricity sector. In addition, as energy use tends to increase with the fraction of the population employed, a distinction from previous works is made and the employment rate is taken as a factor to study the age distribution impact on CO_2 emissions. Because the factors used in this study had not been considered before, the findings differ substantially from the rest and they give a new point of view to design effective climate policies.

For this purpose, the Theil index is used which allows us to decompose total inequality by population sub-groups and multiplying factors. The methodological contribution of this study lies in the inequality decomposition provided which allows us to take a greater number of factors than the traditional decomposition approaches. In this chapter, the methodology to extend the factorial decomposition of the Theil index to k factors is also derived which had not been done before.

The rest of the chapter is organised as follows. After this introduction, the factorial decomposition of the Theil index into four factors is described. In Section 2.2, the factorial decomposition of the Theil index is extended to the case of k factors. The results obtained in the inequality analysis are shown in Section 2.3. Finally, some concluding remarks and policy implications are presented.

2.1 Factorial decomposition of the Theil index

The aim of this inequality analysis is to know the main driving sources behind global inequality in CO_2 emissions by active population. In this section, although a methodology employed in prior works has been taken as reference, it is extended from three to four factors in order to explain the evolution of inequality taking into account a greater number of variables.

Among the different inequality measures which are additively decomposable, the Theil index (Theil, 1967) is chosen because, as it was mentioned in Chapter 1, it is the only index that is decomposable by population groups, differentiable, symmetric, scale invariant and satisfies the Pigou-Dalton criterion (Sen, 1973; Bourguignon, 1979; Cowell, 1998).

Specifically, the Theil index can be defined as:

$$T(\underline{d}, e) = \sum_{i=1}^{n} e_i \cdot \log\left(\frac{\overline{d}}{d_i}\right),$$

where $\underline{d} = (d_1, \dots, d_n)$ and d_i denotes the CO_2 emissions by active population of country i, which is $d_i = CO_{2i} / A_i$ where CO_{2i} and A_i are the CO_2 emissions and the active population of country i, respectively; e_i represents the share of country i in the world active population; $\overline{d}$ is the world average in CO_2 emissions by active population and, finally, log is the natural logarithm.

The lower limit of the index is zero while its upper limit depends on the size of the sample so, a value close to zero is indicative of an equitable scenario while an elevated value shows a high inequality situation. In addition, the Theil index is characterized by being more sensitive to transfers at the bottom tail of the distribution (Shorrocks, 1980; Jenkins and Van Kerm, 2009) which is a desirable characteristic in studying inequality in income and wealth (Bourguignon, 1979).

To go further into the analysis of the sources of global inequality in CO_2 emissions by active population the Kaya identity is used as reference. Specifically, CO_2 emissions by active population of each country are decomposed into the product of four factors: carbon intensity of electricity production of country *i* (CO_{2i} / EP_i), electricity intensity of GDP of country *i* (EP_i / GDP_i), economic growth in terms of labour productivity of country *i* (GDP_i / O_i) and employment rate of country *i* (O_i / A_i). Then, the four factors are denoted as w_i, x_i, y_i and z_i as it is shown in the following expression:

$$d_i = \frac{CO_{2i}}{A_i} = \frac{CO_{2i}}{EP_i} \times \frac{EP_i}{GDP_i} \times \frac{GDP_i}{O_i} \times \frac{O_i}{A_i} = w_i \times x_i \times y_i \times z_i .$$

Next, the contribution of each factor to the global inequality index is measured. For this purpose, four hypothetical CO_2 emissions by active population vectors for each country are defined by permitting in each vector only the value of one factor diverges from the global average value[41]:

$$d_i^w = w_i \times \overline{x} \times \overline{y} \times \overline{z},$$

$$d_i^x = \overline{w} \times x_i \times \overline{y} \times \overline{z},$$

$$d_i^y = \overline{w} \times \overline{x} \times y_i \times \overline{z},$$

and

[41] This approach is similar to the shift-share technique (Dunn, 1960; Esteban-Marquillas, 1972; Haynes and Machunda, 1987). The shift-share analysis is a regional analysis tool that allows us to study the existence of geographical biases in the economic activity. Specifically, it consists of the decomposition of the variable into a number of factors that collect the difference between the variable growth rate at a regional level with the hypothetical growth that the variable would have experienced if its growth rate had been the same as the national one.

$$d_i^z = \overline{w} \times \overline{x} \times \overline{y} \times z_i,$$

where $\overline{w}$, $\overline{x}$, $\overline{y}$ and $\overline{z}$ represent the world averages of each factor, respectively.

Then, the degree of inequality related to each factor is calculated using the definition of the Theil index:

$$I^r(\underline{d}^r, e) = \sum_{i=1}^{n} e_i \cdot \log\left(\frac{\overline{d}^r}{d_i^r}\right), \quad r = w, x, y, z,$$

where

$$\overline{d}^r = \sum_{i=1}^{n} e_i \cdot d_i^r,$$

so that, each index measures the partial contribution of each factor to global inequality[42].

Now, adding the appropriate expression to the inequality indices of the *w*, *x* and *y* factors, the corresponding Theil index for these factors can be obtained using the global average of CO_2 emissions by active population as a reference:

$$I^r(\underline{d}^r, e) + \log\left(\frac{\overline{d}}{\overline{d}^r}\right) = \sum_{i=1}^{n} e_i \cdot \log\left(\frac{\overline{d}^r}{d_i^r}\right) + \log\left(\frac{\overline{d}}{\overline{d}^r}\right) = \sum_{i=1}^{n} e_i \cdot \log\left(\frac{\overline{d}}{d_i^r}\right)$$

$$= T(\underline{d}^r, e), \quad r = w, x, y.$$

[42] In several works, such as Duro (2004), it is proposed not to calculate the defined Theil indices. Instead, they advocate the use of dispersion indices which measure the deviation of each CO_2 emission fictitious vector with respect to the global average of CO_2 emissions, because taking the global average of the CO_2 emissions as a common reference for all factors allows us to interpret each factor's contribution to global inequality more intuitively.

Consequently, it can be written:

$$T(\underline{d}^{w},e)+T(\underline{d}^{x},e)+T(\underline{d}^{y},e)+T(\underline{d}^{z},e)$$

$$=\sum_{i=1}^{n} e_i \cdot \log\left(\frac{\bar{d}}{d_i^{w}}\right)+\sum_{i=1}^{n} e_i \cdot \log\left(\frac{\bar{d}}{d_i^{x}}\right)+\sum_{i=1}^{n} e_i \cdot \log\left(\frac{\bar{d}}{d_i^{y}}\right)+\sum_{i=1}^{n} e_i \cdot \log\left(\frac{\bar{d}}{d_i^{z}}\right)$$

$$=T(\underline{d},e),$$

where $T(\underline{d},e)$ is the Theil index of CO_2 emissions by active population worldwide.

Thus, for the four factors the factorial decomposition can be expressed as follows:

$$T(\underline{d},e)=\sum_{r=1}^{4} I^{r}(\underline{d}^{r},e)+\sum_{r=1}^{3}\log\left(\frac{\bar{d}}{\bar{d}^{r}}\right).$$

As noted, the second term of the previously sum measures the differences between the CO_2 emissions by active population average associated to the three first hypothetical vectors and the global average in the CO_2 emissions by active population. These adjusting components collect the interaction between the different factors considered in the analysis; that is, they are the factorial correlations.

In order to interpret the significance of these interaction terms, they are expressed as follows:

$$\log\left(\frac{\bar{d}}{\bar{d}^{w}}\right)=\log\left(1+\frac{\sigma_{w,xyz}}{\bar{d}^{w}}\right)=\text{inter}(w,xyz),$$

$$\log\left(\frac{\bar{d}}{\bar{d}^{x}}\right)=\log\left(1+\frac{\bar{w}\cdot\sigma_{x,yz}}{\bar{d}^{x}}\right)=\text{inter}(x,yz),$$

and

$$\log\left(\frac{\bar{d}}{\bar{d}^{y}}\right)=\log\left(1+\frac{\bar{w}\cdot\bar{x}\cdot\sigma_{y,z}}{\bar{d}^{y}}\right)=\mathrm{inter}(y,z),$$

where $\sigma_{w,xyz}$ represents the weighted covariance between the variables w and $x\cdot y\cdot z$, that is,

$$\sigma_{w,xyz}=\frac{1}{n}\sum_{i=1}^{n}(w_i-\bar{w})(x_i y_i z_i-\bar{x}\cdot\bar{y}\cdot\bar{z}),$$

where $\bar{w}$, $\bar{x}$, $\bar{y}$ and $\bar{z}$ represent the world averages of w_i, x_i, y_i and z_i, $i = 1,\ldots, n$, respectively.

A similar definition can be applied to $\sigma_{x,yz}$ and $\sigma_{y,z}$. In particular, $\sigma_{w,xyz}$ measures the covariance between the carbon intensity of electricity production and the electrical production by active population; $\sigma_{x,yz}$ tests the covariance between the electricity intensity of GDP and the average productivity of the active population and $\sigma_{y,z}$ quantifies the covariance between the economic growth in terms of labour productivity and the employment rate.

Finally, the term inter(w,xyz) represents the interaction between factor w and $x\cdot y\cdot z$. The same interpretation can be adopted for inter(x,yz) and inter(y,z).

The Theil index can also be decomposed into a between- and a within-group inequality component. The inequality analysis by population sub-groups allows us to know what inequality percentage can be attributed to differences between population groups and what differences within each group considered.

Specifically, the decomposition of the total inequality into the between- and within-group inequality components is given by the following expression,

$$T(\underline{d},e)=T_W(\underline{d},e)+T_B(\underline{d},e)=\sum_{g=1}^{G}e_g\cdot T_g(\underline{d},e)+\sum_{g=1}^{G}e_g\cdot\log\left(\frac{\bar{d}}{\bar{d}_g}\right),$$

where $T_W(\underline{d}, e)$ is the within-group inequality component, $T_B(\underline{d}, e)$ is the between-group inequality component, e_g represents the share of the region g in the world active population, $T_g(\underline{d}, e)$ is the inequality in the region g, $\bar{d}_g$ denotes the average CO_2 emissions by active population in the region g and, finally, G is the number of regions.

The expressions of the two inequality components show that both can be decomposed by multiplying factors. In the case of the within-group inequality component, it can be seen that it is a weighted average of the regional Theil indices. In relation to the between-group inequality component, note that it is an active population-weighted Theil index where the units of study are the regions covered by the IEA.

2.2 Extension to higher factors

The methodology procedure presented in the previous section can be easily extended to *k* factors, which allows us to take into account a greater number of variables, and applied to any field of research. Specifically, the factorial decomposition of the Theil index into *k* multiplicative factors can be done in two different ways: considering the partial contribution of each factor –the conventional decomposition where the factorial correlations represent the importance of each factor– and considering the interactions between factors as a whole. In addition, both decompositions can be extended to analyse the between- and within-group inequality components.

2.2.1 Considering the partial contribution of each factor

Let z_i be the variable of country i which is desirable to decompose by multiplying factors and defined, in turn, by the ratio of two variables: $z_i = x_i / y_i$.

The Theil index associated with z_i can be defined as:

$$T(\underline{z}, w) = \sum_{i=1}^{n} w_i \cdot \log\left(\frac{\overline{z}}{z_i}\right),$$

where $\underline{z} = (z_1, \ldots, z_n)$ and w_i represents the share of country i in the world value of the variable Y; $\overline{z}$ stands for the world average of the variable Z and, finally, log is the natural logarithm.

Let $F^{(1)}, F^{(2)}, \ldots, F^{(k)}$ be the k multiplying factors in which the variable Z is decomposed and let these k factors be defined by the ratio of two variables as follows:

$$Z = \frac{X}{Y} = F^{(1)} \times F^{(2)} \times \ldots \times F^{(k)} = \frac{X}{A^{(1)}} \times \frac{A^{(1)}}{A^{(2)}} \times \ldots \times \frac{A^{(k-1)}}{Y}.$$

Once the factorial decomposition is specified, the next step is to measure the contribution of each factor to the global inequality index. Then, it is defined k hypothetical vectors for the variable Z for each country by letting that, in each vector, only the value of one factor diverges from the global average value:

$$z_i^{F^{(1)}} = f_i^{(1)} \times \overline{F}^{(2)} \times \ldots \times \overline{F}^{(k)},$$

$$z_i^{F^{(2)}} = \overline{F}^{(1)} \times f_i^{(2)} \times \ldots \times \overline{F}^{(k)},$$

$$\vdots$$

$$z_i^{F^{(k)}} = \overline{F}^{(1)} \times \overline{F}^{(2)} \times \ldots \times f_i^{(k)},$$

where $\overline{F}^{(1)}, \overline{F}^{(2)}, \ldots, \overline{F}^{(k)}$ represent the world averages of each factor, respectively.

Then, it is calculated the degree of inequality related to each factor using the definition of the Theil index:

$$I^{F^{(r)}}(\underline{z}^{F^{(r)}}, w) = \sum_{i=1}^{n} w_i \cdot \log\left(\frac{\overline{z}^{F^{(r)}}}{z_i^{F^{(r)}}}\right), \quad r = 1,\ldots,k,$$

where

$$\overline{z}^{F^{(r)}} = \sum_{i=1}^{n} w_i \cdot z_i^{F^{(r)}},$$

so that, each index measures the partial contribution of each factor to global inequality.

Now, adding the appropriate expression to the previous inequality indices, it is obtained for the k factors their corresponding Theil index, using the global average of Z as a reference:

$$I^{F^{(r)}}(\underline{z}^{F^{(r)}}, w) + \log\left(\frac{\overline{z}}{\overline{z}^{F^{(r)}}}\right) = \sum_{i=1}^{n} w_i \cdot \log\left(\frac{\overline{z}}{z_i^{F^{(r)}}}\right) = T^{F^{(r)}}(\underline{z}^{F^{(r)}}, w), \quad r = 1,\ldots,k.$$

In consequence, it can be written:

$$\sum_{r=1}^{k} T(\underline{z}^{F^{(r)}}, w) = \sum_{r=1}^{k}\sum_{i=1}^{n} w_i \cdot \log\left(\frac{\overline{z}}{z_i^{F^{(r)}}}\right) = \sum_{i=1}^{n} w_i \cdot \log\left(\frac{\overline{z}}{z_i}\right) = T(\underline{z}, w),$$

where $T(\underline{z}, w)$ is the Theil index of the variable Z.

Thus, for the k factors, the factorial decomposition can be expressed as follows:

$$T(\underline{z},w)=\sum_{r=1}^{k} I^{F^{(r)}}(\underline{z}^{F^{(r)}},w)+\sum_{r=1}^{k}\log\left(\frac{\bar{z}}{\bar{z}^{F^{(r)}}}\right).$$

The second term of the previous sum measures the differences between the global average of the variable Z and the average of the variable Z associated to the k hypothetical vectors. These adjusting components collect the correlations between the different factors considered in the analysis and can be expressed as follows:

$$\sum_{r=1}^{k}\log\left(\frac{\bar{z}}{\bar{z}^{F^{(r)}}}\right)=\log\left(\frac{\sigma_{F^{(1)},F^{(2)}\cdots F^{(k)}}}{\bar{z}^{F^{(1)}}}+1\right)+\sum_{r=2}^{k}\log\left(\frac{\sigma_{F^{(r)},F^{(r+1)}\cdots F^{(k)}}\prod_{j=1}^{r-1}\bar{F}^{(j)}}{\bar{z}^{F^{(r)}}}+1\right),$$

where

$$\sigma_{F^{(r)},F^{(r+1)}\cdots F^{(k)}}=Cov(F^{(r)},F^{(r+1)}\cdots F^{(k)}),$$

represents the covariance between $F^{(r)}$ and the product $F^{(r+1)}\cdots F^{(k)}$.

2.2.2 Considering the interactions between factors as a whole

Sometimes, mostly when a few factors are considered, it is more appealing to know the effect of the interactions between factors jointly. In this case, the decomposition is the following.

Let z_i be the variable of country i which is desirable to decompose by multiplying factors and defined, in turn, by the ratio of two variables: $z_i = x_i / y_i$. Let $F^{(1)},F^{(2)},\dots,F^{(k)}$ be the k multiplying factors in which the variable Z is decomposed and let these k factors be defined by the ratio of two variables as follows:

$$Z = \frac{X}{Y} = F^{(1)} \times F^{(2)} \times \ldots \times F^{(k)} = \frac{X}{A^{(1)}} \times \frac{A^{(1)}}{A^{(2)}} \times \ldots \times \frac{A^{(k-1)}}{Y}.$$

Considering the world averages, the Theil index can be expressed as:

$$T(\underline{z}, w) = \sum_{i=1}^{n} w_i \cdot \log\left(\frac{\bar{z}}{z_i}\right) = \sum_{i=1}^{n} w_i \cdot \log\left(\frac{\bar{z}}{f_i^{(1)} \times f_i^{(2)} \times \ldots \times f_i^{(k)}}\right).$$

Define

$$\mu^{F^{(r)}} = \sum_{i=1}^{n} w_i \cdot f_i^{(r)},$$

if the inside of the logarithm of the Theil index is multiplied and divided by $\prod_{r=1}^{k} \mu^{F^{(r)}}$, it is obtained:

$$T(\underline{z}, w) = \sum_{i=1}^{n} w_i \cdot \log\left(\frac{\bar{z}}{f_i^{(1)} \times f_i^{(2)} \times \ldots \times f_i^{(k)}} \times \frac{\prod_{r=1}^{k} \mu^{F^{(r)}}}{\prod_{r=1}^{k} \mu^{F^{(r)}}}\right).$$

Then,

$$T(\underline{z}, w) = \sum_{r=1}^{k} \sum_{i=1}^{n} w_i \cdot \log\left(\frac{\mu^{F^{(r)}}}{f_i^{(r)}}\right) + \log\left(\frac{\bar{z}}{\prod_{r=1}^{k} \mu^{F^{(r)}}}\right)$$

$$= \sum_{r=1}^{k} I^{F^{(r)}}(\underline{z}^{F^{(r)}}, w) + \log\left(\frac{\bar{z}}{\prod_{r=1}^{k} \mu^{F^{(r)}}}\right),$$

where

$$\log\left(\frac{\bar{z}}{\prod_{r=1}^{k}\mu^{F^{(r)}}}\right)=\sum_{r=1}^{k-1}\log\left(\frac{\sigma_{F^{(1)}\cdots F^{(r)},F^{(r+1)}}}{\mu^{F^{(1\cdots r)}}\times\mu^{F^{(r+1)}}}+1\right),$$

where $\mu^{F^{(1\cdots r)}}=E(F^{(1)}\cdots F^{(r)})$ represents the mean of the product $F^{(1)}\cdots F^{(r)}$.

Note that there are different interaction terms as possible combinations between the factors considered in the decomposition. For example, if k = 3, there are three possible combinations:

$$\log\left(\frac{\mu^{F^{(1\cdots 3)}}}{\mu^{F^{(1)}}\cdot\mu^{F^{(2)}}\cdot\mu^{F^{(3)}}}\right)=\log\left(\frac{\mu^{F^{(12)}}}{\mu^{F^{(1)}}\cdot\mu^{F^{(2)}}}\times\frac{\mu^{F^{(1\cdots 3)}}}{\mu^{F^{(12)}}\cdot\mu^{F^{(3)}}}\right)=\log\left(\frac{\sigma_{F^{(12)},F^{(3)}}}{\mu^{F^{(12)}}\times\mu^{F^{(3)}}}+1\right),$$

$$\log\left(\frac{\mu^{F^{(1\cdots 3)}}}{\mu^{F^{(1)}}\cdot\mu^{F^{(2)}}\cdot\mu^{F^{(3)}}}\right)=\log\left(\frac{\mu^{F^{(13)}}}{\mu^{F^{(1)}}\cdot\mu^{F^{(3)}}}\times\frac{\mu^{F^{(1\cdots 3)}}}{\mu^{F^{(13)}}\cdot\mu^{F^{(2)}}}\right)=\log\left(\frac{\sigma_{F^{(13)},F^{(2)}}}{\mu^{F^{(13)}}\times\mu^{F^{(2)}}}+1\right),$$

$$\log\left(\frac{\mu^{F^{(1\cdots 3)}}}{\mu^{F^{(1)}}\cdot\mu^{F^{(2)}}\cdot\mu^{F^{(3)}}}\right)=\log\left(\frac{\mu^{F^{(23)}}}{\mu^{F^{(2)}}\cdot\mu^{F^{(3)}}}\times\frac{\mu^{F^{(1\cdots 3)}}}{\mu^{F^{(23)}}\cdot\mu^{F^{(1)}}}\right)=\log\left(\frac{\sigma_{F^{(23)},F^{(1)}}}{\mu^{F^{(23)}}\times\mu^{F^{(1)}}}+1\right).$$

2.2.3 Factorial decomposition of the between- and within-group inequality components

The decomposition of the total inequality into the between- and within-group components is given by the following expression,

$$T(\underline{z},w)=T_B(\underline{z},w)+T_W(\underline{z},w)=\sum_{g=1}^{G}w_g\cdot\log\left(\frac{\bar{z}}{\bar{z}_g}\right)+\sum_{g=1}^{G}w_g\cdot T_g(\underline{z},w),$$

where $T_B(\underline{z},w)$ is the between-group inequality component, $T_W(\underline{z},w)$ is the within-group inequality component, w_g represents the share of the region g in the world value of the variable Y, $\bar{z}_g$ denotes the average of the variable Z in the region g, $T_g(\underline{z},w)$ is the inequality in the region g and, finally, G is the number of regions.

The expressions of the two inequality components show that both can be decomposed by multiplying factors. In the case of the within-group inequality component, it can be seen that it is a weighted average of regional Theil indices. Therefore:

$$T_W(\underline{z},w) = \sum_{g=1}^{G} w_g \cdot T_g(\underline{z},w)$$

$$= \sum_{r=1}^{k}\sum_{g=1}^{G} w_g \cdot I_g^{F^{(r)}}(\underline{z},w) + \sum_{r=1}^{k}\sum_{g=1}^{G} w_g \cdot \log\left(\frac{\bar{z}_g}{\bar{z}_g^{F^{(r)}}}\right),$$

where

$$\bar{z}_g^{F^{(r)}} = \sum_{i\in g} w_i \cdot z_i^{F^{(r)}}.$$

In relation to the between-group inequality component, note that it is a population-weighted Theil index where the units of study are the regions.

2.3 Data and results

The variable CO_2 emissions from fuel combustion, measured in million tonnes, has been taken from the IEA (2012) [43]. The purchasing power parity is employed to measure the GDP, while the electricity production data are measured in terawatt hours. Both variables have also been provided by the IEA (2012). Data on active and employed population come from the International Labour Organization (ILO, 2014). All this variables are studied across the regions considered by the IEA[44] from 1990 to 2010.

Table 2.1 shows the results obtained in the factorial decomposition of global inequality in CO_2 emissions by active population using the Theil index. The results reveal that global inequality in CO_2 emissions by active population had declined by 22 percent between 1990 and 2010. This reduction can be observed over the whole period, although the major decrease occurred between the years 2000 and 2005 (a -8 percent). However, the global level of inequality was still significant in 2010.

During all the period, the inequality trend was mainly explained by the economic growth in terms of labour productivity (y_i). The second major component was the electricity intensity of GDP (x_i), while the carbon intensity of electricity production (w_i) caused just about 8 percent. Finally, the employment rate (z_i) explained the least degree of inequality.

[43] It is only included the emissions originated when the fuel is actually combusted which have been calculated following the guidelines proposed by the IPCC (2006) for national GHG inventories.

[44] In the Appendix 2.1 the classification of the countries analysed, based on the regions covered by the IEA, is detailed.

Table 2.1

Factorial decomposition of inequality in CO_2 emissions by active population from 1990 to 2010

Year	$T(\underline{d}, e)$	$I^w(\underline{d}, e)$	$I^x(\underline{d}, e)$	$I^y(\underline{d}, e)$	$I^z(\underline{d}, e)$	inter(w, xyz)	inter(x, yz)	inter(y, z)
1990	1.3046	0.1113	0.3208	1.2692	0.0007	-0.4862	0.1016	-0.0127
	(100.00)	(8.53)	(24.59)	(97.28)	(0.05)	(-37.27)	(7.79)	(-0.98)
1995	1.2141	0.0873	0.2922	1.1363	0.0009	-0.3856	0.0958	-0.0127
	(100.00)	(7.19)	(24.06)	(93.59)	(0.07)	(-31.76)	(7.89)	(-1.04)
2000	1.1737	0.0778	0.2298	1.0962	0.0009	-0.3201	0.0940	-0.0050
	(100.00)	(6.63)	(19.58)	(93.40)	(0.08)	(-27.27)	(8.01)	(-0.42)
2005	1.0834	0.0821	0.2132	1.0275	0.0007	-0.2778	0.0425	-0.0049
	(100.00)	(7.58)	(19.68)	(94.85)	(0.06)	(-25.64)	(3.93)	(-0.46)
2010	1.0180	0.0863	0.1855	0.9145	0.0007	-0.2117	0.0566	-0.0139
	(100.00)	(8.48)	(18.22)	(89.84)	(0.07)	(-20.80)	(5.56)	(-1.36)

Note: Percentage values are given in parentheses.

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As in Vehmas (2009), it is observed that the bulk of inequality was caused by the economic growth in terms of labour productivity (y_i), even though the inequality joined with this factor had decreased by 28 percent throughout the studied period. The partial contribution of y_i had only decreased about 8 percent from 1990 to 2010, so it held its relative importance in the total value.

Such inequality depends on the degree to which human work has been replaced by the adoption of new technologies and hence of energy use. The obtained result indicates the importance of technology transfers from developed countries to those that have a lower development to achieve greater convergence in the average productivity of the employees. It should be noted that knowledge transfers are as necessary as equipment diffusions so that developing countries can promote their own projects in the future.

On the other hand, z_i was the least contributor to overall inequality both in absolute and relative terms. The inequality related to the employment rate experienced an increase until the year 2000, and a contraction from there on. It can be expected that the greater population in working years, the greater CO_2 emissions releases into the atmosphere. However, in terms of inequality this factor seems to be irrelevant.

As for the inequality in the electricity intensity of the whole economy (x_i), it had declined by about 42 percent, from 0.3208 to 0.1855. Additionally, the importance of this factor in relative terms had decreased by around 26 percent from 1990 to 2010. The previous trend may come from several aspects like technological development within electricity production; changes from high to low energy intensive process in the electricity production; an alteration in the sector structure from industry to services in terms of GDP shares or the use of a diversified energy matrix, including natural gas and renewable energies, amongst others.

The effect of w_i refers to the contribution of the change of carbon intensity of electricity production to CO_2 emissions. In other words, the higher the carbon intensity, the more the country relies on fossil fuel sources of energy for electricity generation. In relation to this factor, it is observed that, although the inequality associated with this factor had declined by 22 percent; its involvement in global inequality had barely suffered a variation. In practice, inequality in carbon intensity of electricity production is mainly due to countries being at different stages of the change in the use of energy forms, that is, some countries use fuels with high carbon content while others use green sources of energy. So, its decreasing inequality trend may be due in part to the extension of new cleaner technologies worldwide.

Regarding the interaction components, the following facts can be deduced. The partial contribution to global inequality of the interaction component between the carbon intensity of electricity and the electricity production by active population, inter(w,xyz), had declined by 44 percent. Furthermore, its negative character indicates that countries which produce more electricity emit less CO_2 emissions into the atmosphere. This aspect indicates that the most developed countries have low emission technologies so spreading them to the least developed countries can reduce the international inequality in CO_2 emissions.

The small contribution of the component of the interaction between the economic growth in terms of labour productivity and the employment rate, defined as inter(y,z), had increased by 39 percent from 1990 to 2010. It also showed a negative sign which means that, if a country has a higher employment rate, its average productivity is lower in comparison to other countries with lower employment rates, ceteris paribus.

Finally, the participation in global inequality of the interaction term between the electricity intensity of GDP and the average productivity of the active population, inter(*x*,*yz*), was reduced by 29 percent. In consequence, the positive factor associated with this correlation indicates that the countries which are more intensive in electricity production tend to have a more productive active population on average.

Table 2.2 shows the findings obtained in the decomposition of global inequality in CO_2 emissions by active population into the between- and within-group inequality components using the Theil index. As it was mentioned before, the CO_2 emissions inequality is studied across the regions considered by the IEA: Africa, Asia, China, Middle East, OECD Americas, OECD Asia Oceania, OECD Europe, Non-OECD Americas and Non-OECD Europe and Eurasia.

Table 2.2

Decomposition of inequality in CO_2 emissions by active population by population sub-groups from 1990 to 2010

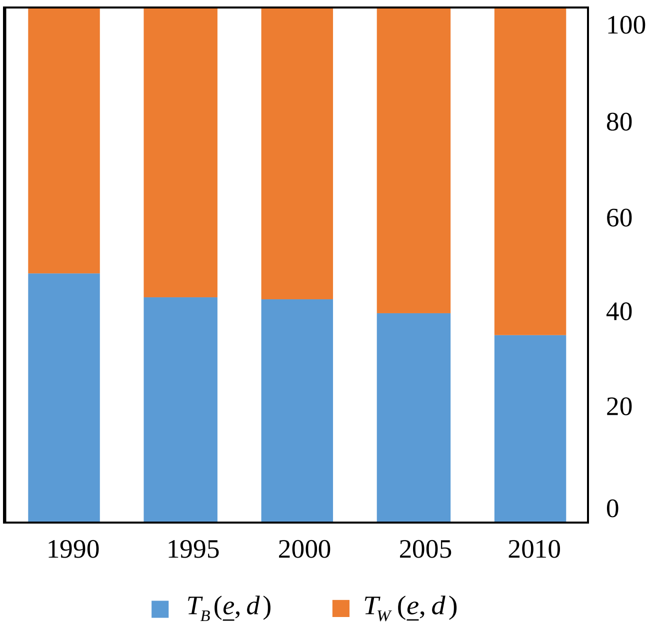
Year	$\boldsymbol{T(\underline{d},e)}$	$\boldsymbol{T_B(\underline{d},e)}$	$\boldsymbol{T_W(\underline{d},e)}$
1990	1.3046	0.6323	0.6724
1995	1.2141	0.5290	0.6851
2000	1.1737	0.5104	0.6632
2005	1.0834	0.4418	0.6416
2010	1.0180	0.3721	0.6458

According to the empirical analysis, it can be seen that both components contributed to the explanation of overall inequality during the studied period. This justifies the importance of choosing this methodology, which considers the decomposition of total inequality into both components. Moreover, the fact that the between-group inequality component was significant confirms the importance of the regions considered in this analysis since there are great differences between them.

It is also observed that the inequality associated with both inequality components had declined during the studied period. However, while the between-group inequality component had reduced its concentration of CO_2 emissions by 41 percent, from a value of 0.6323 in 1990 to that of 0.3721 in 2010, the inequality associated with the within-group inequality component had been slightly reduced passing from a value of 0.6724 in 1990 to that of 0.6458 in 2010. This result provides evidence that during the studied period, the set of measures to limit the concentration of CO_2 in the atmosphere had reduced the inequality between regions further than the inequality within each one.

Figure 2.1

Contribution to inequality in CO_2 emissions by active population of the between- and within-group inequality components from 1990 to 2010



Note: The contribution is expressed in percentage.

Figure 2.1 shows the contribution of the between- and within-group inequality components to total inequality from 1990 to 2010[45]. Note that the importance of the between-group inequality component had decreased over the studied period. Specifically, the representation of this component in total inequality had changed from 48 percent in 1990 to 37 percent in 2010.

It is then observed that the within-group inequality component had experienced the opposite trend, increasing its relative weight by about 12 percentage points. The growing importance of the within-group inequality component reveals that the distribution of responsibility for CO_2 emissions originating within each region should not be equitable to all countries within the same geographical area, being an aspect that can be controversial. Given that throughout the studied period both components had special importance, its factorial decomposition is then exposed.

Tables 2.3 and 2.4 show the results of the factorial decomposition of the between- and within-group inequality components in CO_2 emissions by active population using the Theil index, respectively. The results reveal similar behaviour patterns to those observed in the global inequality decomposition, that is, all the factors work in the same sense than in the global case. Thus, the economic growth in terms of labour productivity, y_i, was the factor that dominated the explanation of inequality in both inequality components.

[45] The contribution to total inequality of both components, expressed in percentage, can be found in the Appendix 2.2.

Table 2.3

Factorial decomposition of the between-group inequality component from 1990 to 2010

Year	$T_B(\underline{d},e)$	$I^w(\underline{d},e)$	$I^x(\underline{d},e)$	$I^y(\underline{d},e)$	$I^z(\underline{d},e)$	inter(w, xyz)	inter(x, yz)	inter(y, z)
1990	0.6323	0.0575	0.0763	0.7620	0.0003	-0.2604	0.0055	-0.0090
	(100.00)	(9.10)	(12.06)	(120.52)	(0.05)	(-41.18)	(0.88)	(-1.42)
1995	0.5290	0.0444	0.0637	0.6550	0.0004	-0.2182	-0.0059	-0.0105
	(100.00)	(8.40)	(12.05)	(123.83)	(0.08)	(-41.24)	(-1.12)	(-1.99)
2000	0.5104	0.0236	0.0400	0.6100	0.0004	-0.1564	-0.0048	-0.0024
	(100.00)	(4.63)	(7.83)	(119.50)	(0.08)	(-30.64)	(-0.95)	(-0.46)
2005	0.4418	0.0201	0.0431	0.5198	0.0003	-0.1151	-0.0219	-0.0045
	(100.00)	(4.54)	(9.77)	(117.66)	(0.06)	(-26.05)	(-4.95)	(-1.03)
2010	0.3721	0.0166	0.0449	0.4005	0.0003	-0.0881	0.0101	-0.0122
	(100.00)	(4.46)	(12.06)	(107.61)	(0.09)	(-23.67)	(2.72)	(-3.27)

Note: Percentage values are given in parentheses.

Table 2.4

Factorial decomposition of the within-group inequality component from 1990 to 2010

Year	$T_W(\underline{d},e)$	$\sum_{g=1}^{8} e_g \cdot I_g^w(\underline{d},e)$	$\sum_{g=1}^{8} e_g \cdot I_g^x(\underline{d},e)$	$\sum_{g=1}^{8} e_g \cdot I_g^y(\underline{d},e)$	$\sum_{g=1}^{8} e_g \cdot I_g^z(\underline{d},e)$	$\sum_{g=1}^{8} e_g \cdot \mathrm{inter}_g(w,xyz)$	$\sum_{g=1}^{8} e_g \cdot \mathrm{inter}_g(x,yz)$	$\sum_{g=1}^{8} e_g \cdot \mathrm{inter}_g(y,z)$
1990	0.6724	0.0573	0.1221	0.5125	0.0004	-0.2293	0.2185	-0.0091
	(100.00)	(8.52)	(18.16)	(76.23)	(0.05)	(-34.11)	(32.50)	(-1.36)
1995	0.6851	0.0437	0.1182	0.4851	0.0004	-0.1683	0.2119	-0.0060
	(100.00)	(6.38)	(17.26)	(70.80)	(0.06)	(-24.57)	(30.93)	(-0.87)
2000	0.6632	0.0486	0.1230	0.4961	0.0005	-0.1582	0.1657	-0.0125
	(100.00)	(7.33)	(18.55)	(74.80)	(0.07)	(-23.85)	(24.98)	(-1.88)
2005	0.6416	0.0550	0.1281	0.5133	0.0004	-0.1556	0.1063	-0.0060
	(100.00)	(8.57)	(19.97)	(80.01)	(0.07)	(-24.25)	(16.57)	(-0.93)
2010	0.6458	0.0232	0.0616	0.6806	0.0014	-0.0432	-0.1228	0.0174
	(100.00)	(3.60)	(9.54)	(105.39)	(0.21)	(-6.70)	(-19.01)	(2.69)

Note: Percentage values are given in parentheses.

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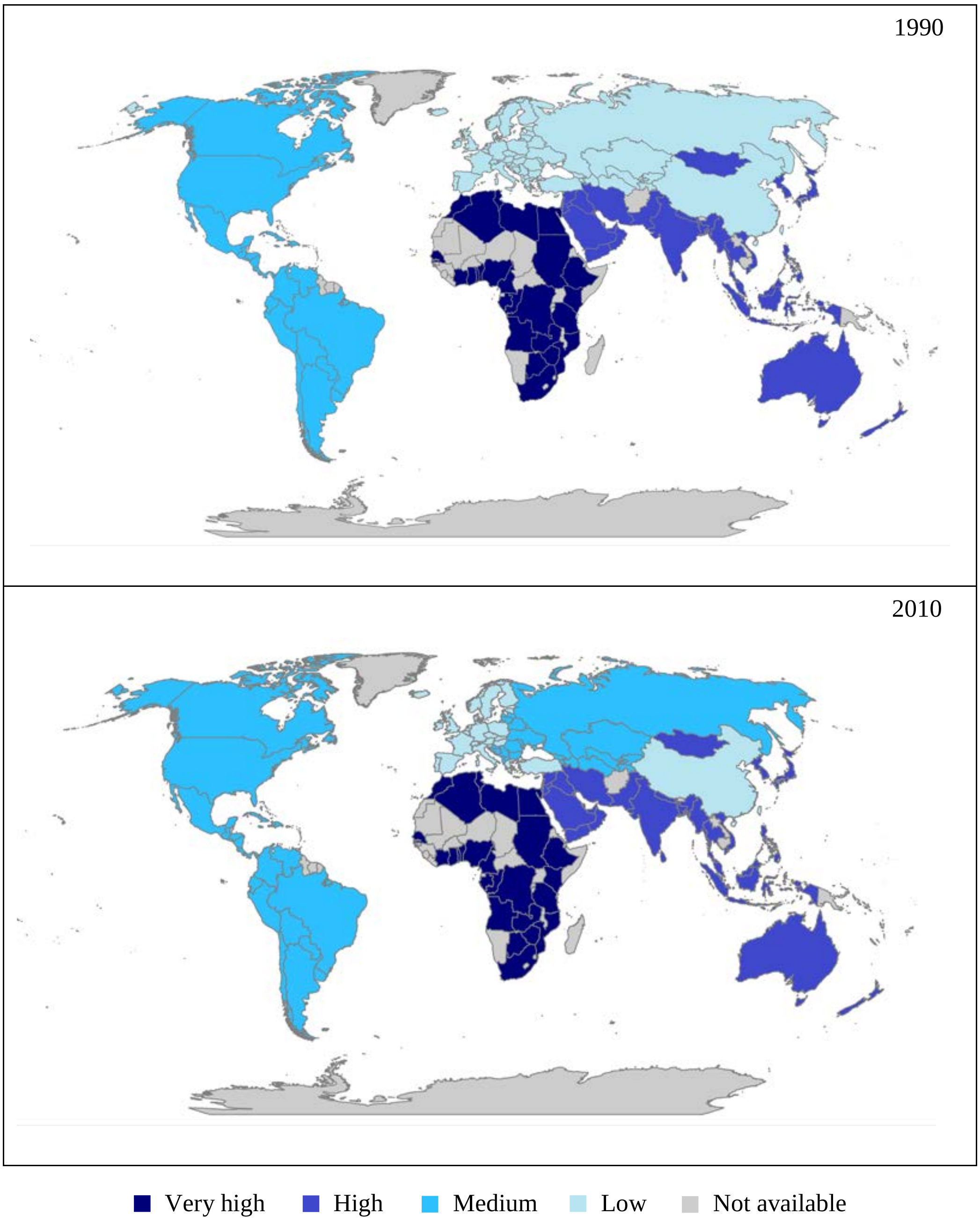
However, a different behaviour of this factor for both inequality elements is perceived. In relation to the within-group inequality component, such inequality had increased over the studied period by 33 percent while, with respect to the between-group inequality component, it had been reduced by around 47 percent. Similarly, it is found that while the partial contribution of this factor had increased by 38 percent in the case of the within-group inequality component, it had been reduced by 11 percent for the inequalities between regions.

It is observed that inequality in the electricity intensity of GDP, x_i, had been reduced in both components. Specially, it is perceived a reduction of about 50 and 41 percent for the inequality within regions and the disparities between groups, respectively. With respect to the inequality within regions, the relative weight of this factor had decreased from 18.16 to 9.54 percent over the whole period. Contrary to the previous component, the explanatory capacity of this factor in the disparities between regions had remained stable during all the time period.

Much lower is the importance of the electricity intensity of GDP factor, w_i, in both inequality components. However, it should be noted that the reduction of this factor was the main contributor to the reduction of both discrepancies. In this manner, its weight in the between and within-group inequality components had decreased by 51 and 58 percent, respectively. Finally, as in the global inequality analysis, the factor with the least contribution to both inequality components was the occupation rate, z_i.

Figure 2.2

Level of inequality in CO_2 emissions by active population within each region in 1990 and 2010



As for the three components of interaction, it should be pointed out that all keep the same sign observed in the factorial decomposition of global inequality in CO_2 emissions. That is, the interaction term between the carbon intensity of electricity production and the electricity production by active population, inter(w,xyz), and the interaction component referred to the economic growth in terms of labour productivity and the employment rate, inter(y,z), maintained its negative sign, while the interaction between the electricity intensity of GDP and the average productivity of the active population, inter(x,yz), had still associated a positive sign.

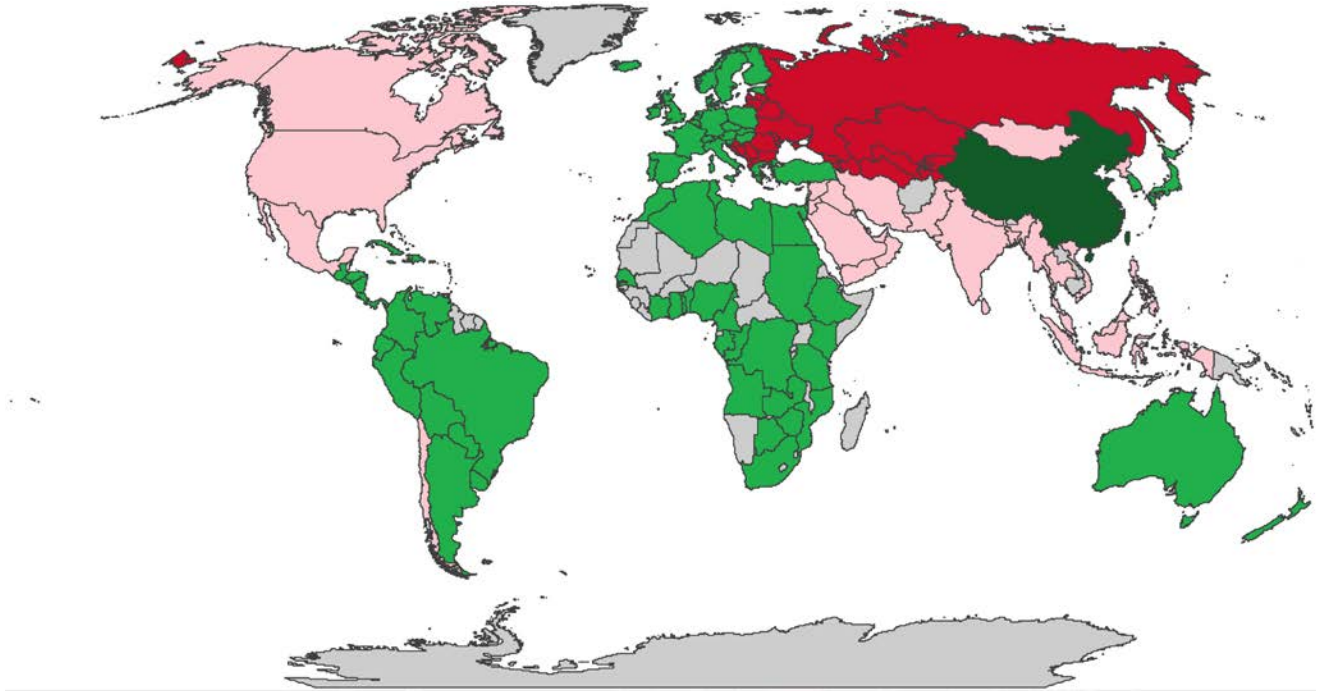
Figure 2.2 illustrates the level of inequality within each region considered by the IEA in 1990 and 2010[46]. On the one hand, Africa had been the region with the highest level of internal inequality during all the period, followed by Asia and Middle East. On the other hand, China had been the territory with the lowest within-group inequality. The internal disparities of the rest of regions –OECD Americas, OECD Asia Oceania, OECD Europe, Non-OECD Americas and Non-OECD Europe and Eurasia– had been of low significance.

Figure 2.3 shows the evolution of the internal inequality of each region from 1990 to 2010. Thus, CO_2 emissions inequality in Africa, China, OECD Asia Oceania, OECD Europe and Non-OECD Americas had experienced a reduction, being China the area with the greatest contraction. At the far side, the inequality had increased less than 10 percent in the other regions, excluding Non-OECD Europe and Eurasia whose inequality trend had enlarged by 236 percent.

[46] The values of the regional inequalities in CO_2 emissions by active population from 1990 to 2010 are presented in the Appendix 2.3, as well as, their factorial decomposition.

Figure 2.3

Evolution of the inequality in CO_2 emissions by active population within each region from 1990 to 2010



High reduction   Medium reduction   Low increase   High increase   Not available

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Although the contribution of the different factors to the inequality within each geographical zone had not been the same during the studied period, it is possible to extract some general trends (see Appendix 2.3). The economic growth in terms of labour productivity, y_i, had been the main factor in explaining the inequality in Africa, Asia, China, Middle East, and Non-OECD Europe and Eurasia for the period 1990-2010. So, this factor is responsible for both the decreasing inequality trend observed in China and the increasing inequality tendency displayed by Non-OECD Europe and Eurasia between 1990 and 2010.

The contribution of the factor x_i, electricity intensity of GDP, must be highlighted in the case of the region Non-OECD Americas as it had been the most important component during all the period. The evolution of the inequality within OECD Americas is principally described by the factor x_i in 1990. However, in 2010 the main component is the economic growth in terms of labour productivity, y_i. Considering the regions OECD Asia Oceania and OECD Europe, it should be noted that the internal inequality may be mainly explained by the carbon intensity of electricity production, w_i, at the end of the studied period. Finally, as in the global inequality study, the employment rate was the least contributor to the internal inequality in all the regions.

2.4 Conclusions and policy implications

In this chapter the determinants of the inequality in the global distribution of CO_2 emissions by active population are studied from 1990 to 2010, using the data provided by the IEA. The inequality analysis is carried out using the Theil index as it can be decomposed on the one hand by multiplying factors and, on the other hand, by population sub-groups.

Global inequality in CO_2 emissions by active population is decomposed into four different factors: carbon intensity of electricity production, electricity intensity of GDP, economic growth in terms of labour productivity and employment rate. The results of the factorial decomposition show that while global inequality in CO_2 emissions by active population had declined by 22 percent between 1990 and 2010, the global inequality level was still significant.

It is observed that the bulk of inequality was caused by the economic growth in terms of labour productivity. Thus, technology transfers from developed countries to those that have a lower development will allow a greater convergence in this factor and therefore in the CO_2 emissions. Although technology transfers provide environmental benefits, its effectiveness depends on the type of the transfer. The embodied technology transfers –use of imported high-tech equipment– make developing countries more productive at the beginning. However, the disembodied technology transfers enable the receiving countries to develop skills that can be used in their own coming projects (Popp, 2008, 2009). According to the United Nations Conference on Trade and Development (UNCTAD), a very notable part of the knowledge necessary for the reproduction of the technology is not easily transmittable (UNCTAD, 2014). In this sense, it should be noted that knowledge transfers are as necessary as equipment diffusions so that developing countries can promote their own projects in the future. On the opposite side, the employment rate was the least contributor to overall inequality both in absolute and relative terms.

The decreasing inequality trend of the electricity intensity of the whole economy may come from technological development within electricity production; changes from high to low energy intensive process in the electricity production or an alteration in the sector structure from industry to services in terms of GDP shares. In addition, the use of a diversified energy matrix including, for example, natural gas and renewable energies, is an important factor. While the use of renewable energies has spread across the globe, having a growing use in remote and rural areas of the developing world (REN21, 2014), natural gas is a necessary transitional fuel within the shift towards a low carbon energy future given that it provides a flexible power source which can counter the intermittency of renewable energy (Carraro *et al*., 2014). Meanwhile, the reduction in the inequality associated to the carbon intensity of electricity production may be due in part to the extension of new cleaner technologies worldwide.

The negative sign of the interaction component between the carbon intensity of electricity and the electricity production by active population indicates that the most developed countries have low emission technologies, so spreading them to the least developed countries can reduce the international inequality in CO_2 emissions.

The decomposition of global inequality in CO_2 emissions by active population into the between- and within-group inequality components, considering the regions of the IEA, shows that both components contributed to the explanation of overall inequality during the studied period. However, while the between-group inequality component had reduced its concentration of CO_2 emissions by 41 percent, the inequality associated with the within-group inequality component had been slightly reduced. The previous result provides evidence that during the studied period the set of measures to limit the concentration of CO_2 in the atmosphere had reduced the inequality between regions further than the inequality within each one. The growing importance of the within-group inequality component reveals that the distribution of responsibility for CO_2 emissions originating within each region should not be equitable to all countries within the same geographical area, being an aspect that can be controversial.

The results of the factorial decomposition of the between- and within-group inequality components reveal similar behaviour patterns to those observed in the global inequality decomposition, that is, all the factors work in the same sense as in the global case. Thus, unlike inter(w,xyz) and inter(y,z) which had reduced global inequality, the positive sign of the rest of components had favoured an increasing trend of inequality.

Finally, it should be noted that whereas Africa had been the region with the highest level of internal inequality during all the period, followed by Asia and Middle East; China had been the territory with the lowest within-group inequality. Moreover, inequality in OECD Asia Oceania, OECD Europe, Africa, Non-OECD Americas and China had experienced a reduction; in the time that, the inequality in Non-OECD Europe and Eurasia had enlarged by more than 200 percent.

From a policy perspective, a greatest reduction in CO_2 emissions inequality could facilitate the implementation of a more ambitious agreement applicable to all Parties by 2020. The observed decreasing inequality trend could facilitate that individual interests do not prevail in international negotiations. Furthermore, given that climate change will limit the choices of future generations, the faster we fight against climate change, the less we damage their interests.

Under the “Contraction and Convergence” proposal, all countries should move towards the same level of per capita emissions. However, the consideration of other indicators would provide a better picture of countries’ circumstances (Ashton and Wang, 2003). In this line, the fact that differences in the distribution of GDP in terms of labour productivity were the most relevant factor in explaining CO_2 emissions inequality means that, the economic growth is more relevant in explaining CO_2 emissions inequality than the carbon intensity of electricity generation or the different production structures. This conclusion is coherent with the results obtained by Duro and Padilla (2006) where per capita GDP inequality is the major factor in the explanation of past international inequalities in CO_2 emissions at a worldwide level. Thus, it is recommended that differences in per capita GDP should be nearly correlated to the efforts required to the different countries to improve the fairness of an international agreement to curb climate change.

In addition, the evolution of CO_2 emissions inequalities may affect the Kyoto Protocol principle “common but differentiated responsibility”. Through this principle, it is suggested that the responsibility that each country has for global warming depends on its history of emissions and its capacity to reduce them. Then, the considerable inequalities between and within regions in per capita CO_2 emissions observed in this study reinforce the application of the preceding postulate. Moreover, the findings of this analysis may be used to define the burden that each country has with climate change. From an equity perspective, the higher the per capita emissions of a country, the stronger should be its obligations. Meanwhile, countries in transition, like China and India, which are now making a greater contribution to global emissions rates than in past times, should no more have the same responsibility as the rest of developing countries.

Chapter 3

Multidimensional inequality and polarization in GHG emissions

Introduction

The increasing interest of physicists in complex economic and social systems has led to the emergence of the econophysics which is a new research field that applies the methods of statistical physics to problems in economics (Gao, 2015). These applications have provided important insights into income[47], wealth and consumption inequalities. In this sense, the econophysical models applied to income and wealth distributions in the works of Chakrabarti *et al*. (2013), Ghosh *et al*. (2014) and Inoue *et al*. (2015) should be highlighted.

Climate change is undoubtedly the main environmental problem facing humanity nowadays. The combustion of fossil fuels has released GHG emissions which had led to climate change threatening, at the same time, human health and settlement, ecological system, agriculture and water

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[47] Several papers have studied distributional aspects of income in the main world economies (Drăgulescu and Yakovenko, 2001a, 2001b; Banerjee *et al*., 2006; Jagielski and Kutner, 2013).

resources (Cao, 2003). For this reason, the aim of the celebration of the UNFCCC in 1992 was to limit global GHG[48] emissions and stabilize their concentration in the atmosphere (United Nations, 1992).

As it has been pointed out in the previous chapters, the study of inequality in CO_2 emissions has received special attention by many authors given that CO_2 is the most abundant GHG in the atmosphere. However, human activity which took place during the industrial era has led to a dramatic increase in both CO_2 emissions and non-CO_2 GHG emissions. In this sense, the non-CO_2 GHGs play an important role in understanding and curbing global climate change. A recent *Greenhouse Gas Bulletin* (WMO, 2013) shows that the concentration of CO_2, CH_4, N_2O has increased by 141, 260 and 120 percent since the year 1750, respectively. The increase in global CO_2 concentration is largely due to the use of fossil fuels, while the observed increment in the concentration of CH_4 and N_2O has its origin mainly in the agricultural practices (IPCC, 2007b). Unlike the previous GHGs, F-gases do not have natural sources and only come from human activities. The three main categories of F-gases are: HFCs, PFCs and SF_6. Despite the fact that the concentration of these gases is still low, they are the most potent and longest lasting type of GHGs emitted by human activities (U.S. Department of State, 2007).

Additionally, mitigating non-CO_2 GHGs can play an important role in global and regional climate strategy for two reasons. On the one hand, non-CO_2 GHGs contribute more to global warming per unit mass than CO_2 (U.S. EPA, 2012a). Thus, about 30 percent of anthropogenic greenhouse effect caused since preindustrial times can be attributed to them (IPCC, 2001b). On the

[48] Annex A of the Kyoto Protocol (United Nations, 1998) stated that the six main GHGs are: CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6).

other hand, reducing non-CO_2 GHG emissions is a relatively cheap complement to the cost associated to CO_2-only mitigation (U.S. EPA, 2006). Therefore, the only consideration of CO_2 emissions cannot reflect the real situation of the current problem of climate change, being necessary to incorporate such gases in climate economic analyses.

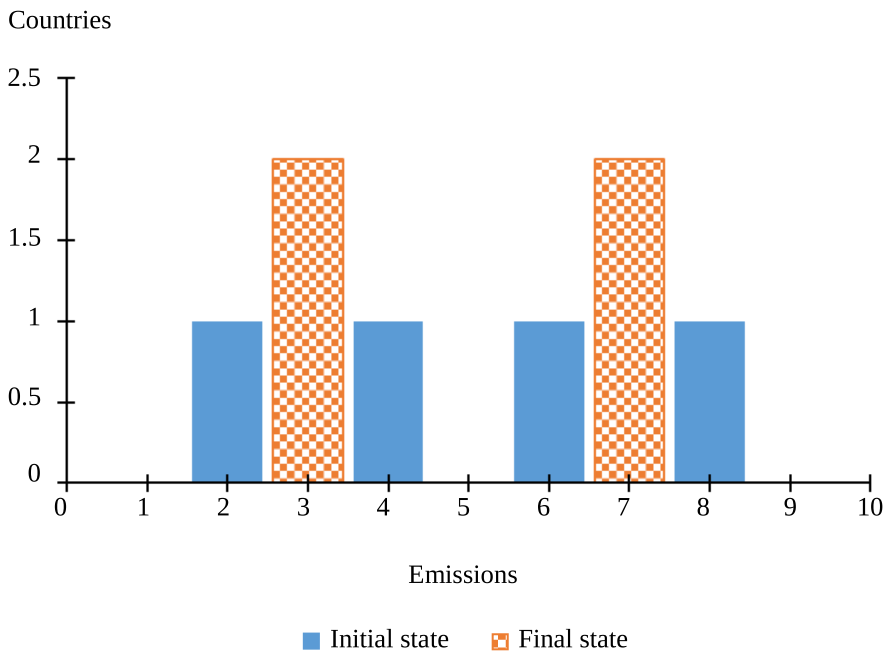
Inequality measures quantify the dispersion of a distribution with respect to a reference value –usually the arithmetic mean–. However, to study some social phenomena is interesting to use a measure of the degree to which population is clustered around a number of poles at a certain distance. The concept of polarization –regularly used in Political Sciences and Sociology– is directly related to the emergence of social tensions caused by a general dissatisfaction (Esteban and Ray, 1994; Wolfson, 1994). In statistical terms, the phenomenon of polarization leads to a distribution with more than one mode (Ezcurra *et al*., 2006).

The studies of polarization make it possible to capture the potential conflict related to a given distribution. Thus, social tensions are more likely in a population distributed around two poles, that is, in a population divided into two groups of significant size with distinct characteristics. On the contrary, in a population with a high level of inequality, where a single individual has a characteristic opposite to that which is shared by the rest of the population, the development of social conflicts is not relevant. Polarization is enhanced when it is observed in the distribution a small number of groups of similar size, characterized by a high degree of internal homogeneity and heterogeneity among all of them.

In order to understand the concept of polarization the following example is considered. Suppose a population composed of four countries whose emissions levels are 2, 4, 6 and 8 tonnes, respectively; being the global average of 5 tonnes and the Gini index of 0.25. Next, assume that the most polluting country transfers 1 tonne of emissions to the one which is below it, and the country below the average does the same with the least polluting country. As illustrated in Figure 3.1, the transfers of emissions lead to a distribution with less inequality –Gini index of 0.20– but with only two levels of contamination: two countries pollute 3 tonnes and the other two pollute 7 tonnes.

Figure 3.1

Polarization phenomenon



Although transfers have reduced inequality, the society is divided into two distinct groups, that is, a polarized society in which the emergence of social conflicts is more likely. Thus, although the concepts of inequality and polarization are linked to the study of disparities in a distribution, it is possible to make a clear distinction between the two notions. In this manner, the existence of a small group of highly polluting countries greatly influences inequality but is not relevant in the study of polarization (Gradín and Del Río, 2001).

In recent decades, several authors have proposed different indices of polarization, providing another perspective –additional to the inequality approach– to analyse the distribution of a phenomenon of interest. The best known polarization index was formulated by Esteban and Ray (1994) and its expression is:

$$ER(\alpha) = \sum_{i=1}^{n} \sum_{j=1}^{n} p_i^{1+\alpha} p_j \left| \frac{x_i}{\mu} - \frac{x_j}{\mu} \right|, \quad 1 \leq \alpha \leq 1.6,$$

where x_i and x_j represent the per capita emissions of the countries belonging to the groups i and j, respectively; p_i and p_j are the relative populations of the countries belonging to the groups i and j, respectively; μ is the world average of per capita emissions and α shows the level of sensitivity to polarization[49]. This parameter[50] makes a difference between inequality and polarization measures, since a greater value of α implies that the measure is more sensitive to the concentration in groups. The lower and upper limits of the index are 0 and 1, respectively (Esteban, 1996).

The main limitation of the *ER* index is that groups are predetermined, so it is not plausible to make groups of countries based on a specific criterion. Given the previous restriction, Esteban *et al*. (1999) proposed the *ERG* index which allows us to define groups endogenously:

$$ERG(\alpha, \beta) = ER(\alpha) - \beta(G - G_B), \quad 1 \leq \alpha \leq 1.6, \beta \geq 0,$$

[49] The α parameter falls in the interval [1-1.6] in order to be consistent with a set of axioms.

[50] The smaller the sensitivity parameter, the closer the notion of polarization to inequality. Indeed, when $\alpha = 0$, the *ER* index is a scalar transformation of the Gini index.

where $ER(\alpha)$ is the Esteban and Ray's index of polarization; G is the Gini coefficient of the original distribution; G_B is the Gini coefficient of the clustered distribution (inequality between groups) and β parameter measures the sensitivity to the internal cohesion of the groups (Esteban, 2002). It is reasonable that β takes a value close to 1 in order not to alter the scale of the measure.

The difference between the Gini indices includes the error caused by the heterogeneity within each group. In this case, both the choice of the number of poles and the location of the same remain exogenous. Although the *ERG* index is not uniformly bounded, a value close to 1 can be interpreted as a scenario of high polarization, while a value close to 0 would be indicative of low polarization.

Alternatively, Wolfson (1994, 1997) proposed the following polarization index:

$$P^W = \frac{\mu}{m}\left(\frac{1}{2} - L\left(\frac{1}{2}\right) - \frac{G}{2}\right),$$

where μ, m, L and G are the mean, the median, the Lorenz curve and the Gini index of the distribution. This measure is a particular case of the *EGR* index when the α and β parameters take unit values (Esteban *et al*., 1999). Its main limitation is that it only makes sense in the case of bipolarization, so it does not allow us to examine multimodal distributions.

Previous works have been followed by others such as Jenkins (1995, 1996), Quah (1997), Wang and Tsui (2000), Gradín (2000), Chakravarty and Majumder (2001), D'Ambrosio (2001), Zhang and Kanbur (2001), Duclos *et al*. (2004) and Chakravarty *et al*. (2007).

In the environmental field, global negotiations on reducing emissions are constructed through alliances of groups of countries with conflicting interests. Thus, developed and developing countries have polarized positions given their different environmental responsibilities and level of development. Some experts have suggested that climate change will intensify resource scarcity, population displacements and fuel conflicts, being these effects particularly serious in developing countries where infrastructure is missing (Salehyan, 2008).

Given that climate change may cause conflicts between the haves and the have-nots, increasing even global inequality, international polarization from a one-dimensional perspective, has already been analysed in various studies. Thus, Ezcurra (2007) analysed the convergence in per capita CO_2 emissions using the *EGR* indices for the period 1960-1999. Meanwhile, Duro and Padilla (2008) used this same measure to investigate the same fact between 1971 and 2001. Duro (2010) examined the polarization in per capita CO_2 emissions with exogenous groups based on the *Z-K* measure (Zhang and Kanbur, 2001), whose main differential advantage lies in its factor-decomposability. Duro and Padilla (2013) analysed the degree of polarization in the international distribution of per capita CO_2 emissions in the European Union, where the countries are grouped according to two criteria: their similarity in terms of emissions –endogenously– and their geographical location –exogenously. Finally, Duro and Teixidó-Figueras (2014) explored the distribution of per capita CO_2 emissions for the period 1992-2010 comparing different polarization measures.

The principal limitation of the previous studies is that they only considered the distribution of CO_2 emissions, not giving a real picture of the international situation. In this sense, the extension of the preceding works to the analysis of the international distribution of the main GHG emissions is quite useful. It would give complete information about the possible political consequences of the emissions distribution, in terms of conflicts, and the probability of implementing international agreements.

The use of multidimensional measures allows us to study inequality and polarization in the four main GHG emissions: CO_2, CH_4, N_2O and F-gases, also known as long-term gases. Methane damages the atmosphere about 28 times more than CO_2 over a 100-year period[51]. The importance of this gas is due to its lifetime in the atmosphere –approximately 12 years[52]– which converts it into a key gas for curbing global warming because atmospheric concentrations of CH_4 could respond to mitigation actions in the short term. Nitrous oxide is about 265 times more potent than CO_2 at warming the atmosphere over a period of 100 years, having a long atmospheric lifetime –about 121 years. F-gases are powerful GHGs with a global warming effect up to 23500 times greater than CO_2. While HFCs are relatively short-lived, PFCs and SF_6 can remain in the atmosphere for thousands of years (IPCC, 2013). In this sense, given that these gases have much shorter lifetimes than CO_2, reducing their emissions offers an extra opportunity to curb climate change (Montzka *et al*., 2011).

With the celebration of the COP17 in 2011, the negotiations to adopt a multilateral agreement on climate change advanced. As the evidence of a decreasing path in GHG emissions inequality could facilitate an international accord to reduce global GHG concentration[53] and bring the world closer to the state of maximal entropy, in this chapter, such inequality is analysed from

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[51] That is, the emission of 1 million tonnes of CH_4 is equivalent to emit 28 million tonnes of CO_2.

[52] CO_2 lifetime is not defined because it is not destroyed over time. Some of this gas is absorbed quickly but some will remain in the atmosphere for thousands of years (IPCC, 2007a).

[53] In addition, a decreasing trend of inequality in natural resources may lead to more social trust (Kolstad and Wiig, 2012).

a multidimensional perspective. In particular, CO_2, CH_4, N_2O and F-gases emissions are studied in the period 1990-2011, using the generalised entropy measures proposed by Maasoumi (1986). In addition, these measures allow us to analyse the contribution of the between- and within-group inequality components. Given that countries have different population sizes, it is pertinent to characterize each one by their per capita emissions, which in thermodynamic terminology are intensive variables.

The specification of the multidimensional inequality indices applied in this study (Maasoumi, 1986) is an extension of the one-dimensional generalised entropy indices (Theil, 1967; Shorrocks, 1982, 1984; Cowell, 2011) which are based on the concept of entropy of the information theory (Burbea and Rao, 1982a, 1982b). The generalised entropy indices consider the redundancy or non-randomness –measured as the difference of entropy with respect to the situation of maximum entropy. This concept is also closely related to the Shannon (1948) entropy, which comes from the statistical concept of entropy expressed by Boltzmann (1896) and Gibbs (1902). In these works, the entropy is defined as a measure of the probability of all possible states of an isolated system; being, in the first case, the symbols of an information source and, in the second one, in a classical example, the position and velocity of the particles in an ideal gas. This parallelism is also reflected in its mathematical formulation which makes the thermodynamic definition of entropy equivalent to the notion of entropy in information theory, when the last one is multiplied by the Boltzmann constant (Planck, 1901) using the natural logarithm.

Using the multidimensional inequality measures proposed by Maasoumi (1986), and considering their decomposition into the between- and within-group inequality components, it is possible to obtain polarization indices from a multidimensional perspective (Gigliariano and Mosler, 2009). Thus, in this chapter, these indices are applied to study the international polarization in the distribution of the principal GHG emissions: CO_2, CH_4, N_2O and F-gases. Specifically, the empirical analysis is carried out for the time period 1990-2011 considering an endogenous grouping of countries (Aghevli and Mehran, 1981; Davies and Shorrocks, 1989).

This is the first attempt to use multidimensional inequality and polarization measures for analysing, in a joint manner, the global distribution of GHG emissions. In this sense, the use of quantitative methods for analysing the historical trend of global inequality and polarization in GHG emissions is a significant step towards solving climate change problem. Moreover, modelling the social effects of global warming will facilitate the dialogue on this issue between national governments, international organizations, non-profit groups and multinational firms in order to design effective global polices.

The remainder of this chapter is structured as follows. The global warming potential, the main measure for comparing atmospheric emissions from various GHGs, is described in Section 3.1. Next, the methodology used in the multidimensional inequality and polarization analysis is detailed. The main results of the analysis are exposed in Section 3.3. Finally, with the conclusions of the chapter, some policy implications are discussed.

3.1 Global warming potential

Human activity releases into the atmosphere many gases that cause climate change. These gases have very different characteristics in terms of the amount emitted, the impact they have on the climate or their atmospheric lifetime. The design of climate policies which consider the joint action of various GHGs requires measures to establish equivalences among different emissions (Tol *et al*., 2008).

Among the measures proposed in the literature on climate change dedicated to this purpose, the global warming potential (GWP) is noted. The concept of GWP was introduced in 1990 (IPCC, 1990; Lashof and Ahuja, 1990; Rodhe, 1990; Victor, 1990) in order to compare emissions of different GHGs over a given time horizon[54]. The GWP index is based on the radiative properties of GHGs sufficiently mixed. It measures the radiative forcing[55] of a pulse emission of 1 kg of a gas *j* relative to that of 1 kg of the reference gas (CO_2).

The GWP of gas *j* is defined by:

$$GWP_j \equiv \frac{\int_0^{TH} RF_j(t)\,dt}{\int_0^{TH} RF_r(t)\,dt} = \frac{\int_0^{TH} a_j \cdot [C_j(t)]\,dt}{\int_0^{TH} a_r \cdot [C_r(t)]\,dt},$$

where GWP_j is the global warming potential of gas *j*, *TH* is the considered time horizon, RF_j denotes the global mean radiative forcing of gas *j*, a_j is the radiative forcing per unit mass increase in atmospheric abundance of gas *j* (radiative efficiency), C_j (*t*) represents the time-dependent abundance of gas *j* and *r* is the reference gas (CO_2).

The GWP of a gas represents the joint effect of two characteristics: the atmospheric lifetime of the gas and its relative effectiveness to absorb the thermal radiation from the atmosphere. The assumptions behind the concept of GWP are the following. Firstly, it considers a fixed time horizon over which the effects of the different emissions are compared. Secondly, any discount rate to the greenhouse effect caused by the gas during the time horizon is applied, being null the effect of the gas at the completion of that

[54] Rasmussen (1975) developed a methodology for comparing the risks caused by different GHG emissions over a fixed time horizon.

[55] Radiative forcing is defined as the change in the balance between radiation coming into and going out of the atmosphere as a result of internal changes in the composition of the atmosphere. Thus, a positive (negative) radiative forcing tends to warm (cool) the Earth's surface (IPCC, 2007a).

period of time. It also assumes that GHG concentration remains constant and, finally, that the impact caused by the gas is proportionate to its radiative forcing.

Current IPCC's estimates of GWPs values are based on time horizons of 20, 100 and 500 years. The establishment of a fixed time horizon to compare the effects of different GHG emissions is a drawback of this measure, given the existence of short- and long-lived gases in the atmosphere. Thus, some climate scientists suggest that the separation between short- and long-lived gases could provide a better framework for the implementation of climate policies (Manning *et al*., 2009). Another inconvenience of this measure is that GWPs are updated over time, incorporating changes in atmospheric concentrations of GHGs, as well as, new scientific knowledge in this area. This calculation could cause an increasing economic emphasis on reducing emissions of short-lived gases like the CH_4, delaying the reduction of long-lived gases, in particular CO_2. Thus, the problem of climate change could worsen[56].

However, despite the fact that the limitations of the GWP encourage the search for alternatives to compare different GHGs[57], most literature considers this measure as a benchmark to compare emissions. Thus, Manning *et al*. (2009) state that the other measures should be considered as complementary rather than substitute.

[56] In this sense, because of preventing the atmospheric concentration of GHGs could lead to confusion when setting policies to achieve the stabilization in the long-term, the UNFCCC proposed freezing the GWP values calculated in the Second Assessment Report of the IPCC (IPCC, 1996).

[57] Other measures that have received special attention to measure the effect of different GHGs are the global damage potential (Kandlikar, 1995), the global cost potential (Manne and Richels, 2001) and the global temperature potential (Shine *et al*., 2005; Shine *et al*., 2007). In this line, Tol *et al.* (2008) suggest that each measure is suitable for a specific perspective of climate change.

3.2 Multidimensional inequality and polarization indices

In this section, the methodology used in the multidimensional inequality and polarization analysis is detailed.

Consider a sample of N countries where we want to study, jointly, K dimensions related to climate change. These values are collected in the matrix **X**, of dimension $N \times K$:

$$\mathbf{X} = \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1K} \\ \vdots & & \vdots & & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{iK} \\ \vdots & & \vdots & & \vdots \\ x_{N1} & \cdots & x_{Nj} & \cdots & x_{NK} \end{bmatrix},$$

where each element of the matrix, x_{ij}, is the value of the dimension or variable j of country i. In this study, the values x_{ij} correspond to the per capita emissions of the four main GHGs –CO_2, CH_4, N_2O and F-gases– in each country, so that K = 4. These emissions are measured in million tonnes of CO_2-equivalent ($MtCO_2e$) taking into account the GWPs of each gas.

In order to analyse the evolution of inequality, the multidimensional inequality measures proposed by Maasoumi (1986) are considered. These measures are based on the concept of generalized entropy and they are defined as:

$$GEM_{\gamma}(\mathbf{X}) = \frac{1}{\gamma\,(1+\gamma)}\frac{1}{N}\sum_{i=1}^{N}\left[\left(\frac{s_i}{\bar{s}}\right)^{1+\gamma} - 1\right], \quad \gamma \neq -1, 0,$$

where the γ parameter[58] represents the weight assigned to the different parts of the distribution. When $\gamma > 0$ the countries which emit more GHG emissions receive more weight, such that, the higher the γ value, the greater the weight given to these countries.

When γ takes the values -1 –the least polluting countries received more weight– and 0 –it is assigned the same weight to all the parts of the distribution–, we are faced with the special cases of these measures, which are expressed, respectively, as:

$$GEM_{-1}(\mathbf{X}) = \frac{1}{N}\sum_{i=1}^{N}\log\left(\frac{\bar{s}}{s_i}\right),$$

$$GEM_0(\mathbf{X}) = \frac{1}{N}\sum_{i=1}^{N}\frac{s_i}{\bar{s}}\log\left(\frac{s_i}{\bar{s}}\right).$$

Whatever the case, different dimensions are aggregated for each country using a generalized mean of order -β:

$$s_i = \left(\sum_{j=1}^{K}\delta_j x_{ij}^{-\beta}\right)^{-1/\beta}, \quad i = 1, \ldots, N,$$

where $\bar{s}$ is the arithmetic mean of the values s_i.

Additionally, δ_j (j = 1, …, K, $0 \leq \delta_j \leq 1$) and β ($-1 \leq \beta \leq \infty$) are two parameters with a specific meaning. In particular, δ_j is the weight assigned to each variable j and β represents the elasticity of substitution among the dimensions considered.

Multidimensional inequality indices used (GEM_γ, GEM_{-1} and GEM_0) are additively decomposable, which allows analysing the between- and within-

[58] This parameter is equivalent to the θ parameter in Chapter 1 according to the expression $\gamma = \theta - 1$.

group inequality components. While inequality between regions only considers the differences between average inequalities of each region, the second component highlights the inequality between the countries which belong to the same region. Considering the methodology proposed by Maasoumi (1986) and Maasoumi and Nickelsburg (1988), the index GEM_γ supports the following decomposition:

$$GEM_\gamma(\mathbf{X}) = B_\gamma(\mathbf{X}) + W_\gamma(\mathbf{X}),$$

where $B_\gamma(\mathbf{X})$ is the between-group inequality component whose expression is the following:

$$B_\gamma(\mathbf{X}) = f\left(\sum_{g=1}^{G} \frac{N_g}{N} h(\bar{s}^g, \bar{s})\right),$$

and $W_\gamma(\mathbf{X})$ is the within-group inequality component which can be expressed as:

$$W_\gamma(\mathbf{X}) = \sum_{g=1}^{G} w_g f\left(\frac{1}{N_g} \sum_{i \in g} h(s_i, \bar{s}^g)\right),$$

where N_g is the number of countries which belong to region g; w_g is the weight attached to region g and, finally, G is the number of regions. In addition, f and h functions are continuous functions, f strictly increasing, whose arguments are specified in Table 3.1.

Table 3.1

Elements of the between- and within-group inequality components

Gamma	$f(y)$	$h(t;\bar{t})$	$w_g,\ g=1,\ldots,G$
$\gamma \neq 0,-1$	$\dfrac{y}{\gamma(1+\gamma)}$	$\left(\dfrac{t}{\bar{t}}\right)^{1+\gamma}-1$	$\dfrac{N_g}{N}\left(\dfrac{\bar{s}^g}{\bar{s}}\right)^{1+\gamma}$
$\gamma=-1$	y	$\log\left(\dfrac{t}{\bar{t}}\right)$	$\dfrac{N_g}{N}$
$\gamma=0$	y	$\dfrac{t}{\bar{t}}\log\left(\dfrac{t}{\bar{t}}\right)$	$\dfrac{N_g\bar{s}^g}{N\bar{s}}$

Source: Adapted from Gigliariano and Mosler (2009).

Table 3.1 shows the elements of these indices for the different values of γ parameter, where

$$s_i=\left(\sum_{j=1}^{K}\delta_j x_{ij}^{-\beta}\right)^{-1/\beta},\quad i\in g,$$

$\bar{s}$ is the arithmetic mean of the values s_i and $\bar{s}^g$ is the arithmetic mean of the values s_i over the individuals in region g.

Gigliriano and Mosler (2009) proposed different options to obtain a polarization index using the decomposition of the previous multidimensional inequality measures (GEM_γ, GEM_{-1} and GEM_0) into the between- and within-group inequality components.

Thus, keeping the previous notation, three different specifications for the polarization indices are considered[59]:

$$P_1(\mathbf{X})=\phi\left(\frac{B(\mathbf{X})}{W(\mathbf{X})+c}\right)\cdot S(\mathbf{X}),$$

[59] The parameter c has to be positive and depends on the values of $B(\mathbf{X})$ and $W(\mathbf{X})$. In this case, the value 0.1 has been considered appropriate.

$$P_2(\mathbf{X}) = \phi\left(B(\mathbf{X}) - W(\mathbf{X})\right) \cdot S(\mathbf{X}),$$

$$P_3(\mathbf{X}) = \phi\left(\frac{B(\mathbf{X})}{B(\mathbf{X}) + W(\mathbf{X}) + c}\right) \cdot S(\mathbf{X}),$$

taking into account that $\phi(\mathbf{X}) = \mathbf{X},$ given that $\phi(\mathbf{X})$ must be a continuous and strictly increasing function, and

$$S(\mathbf{X}) = \left[\left(\prod_{g=1}^{G}\left(\frac{N_g}{N}\right)^{-\frac{N_g}{N}}\right) - 1\right] \cdot \frac{1}{G-1}, \; g = 1, \ldots, G.$$

3.3 Data and results

The data used in the inequality and polarization analysis have been taken from the Climate Analysis Indicators Tool database (CAIT, 2014) developed by the World Resources Institute. As it has a large number of climate indicators, this tool is suitable for analysing issues related to climate change. Furthermore, this database allows us to compare the emissions from various GHGs[60].

The variables under study are the per capita emissions of the four main GHGs: CO_2, CH_4, N_2O and F-gases in each country, measured in $MtCO_2e$ using the 100-year GWPs published in the IPCC (1996). The annual emission indicator is used which shows the amount of GHGs emitted by a country

[60] Although GHG emissions data comes from various nongovernmental sources –International Energy Agency (IEA, 2012), Carbon Dioxide Information Analysis Center (Boden *et al*., 2011), United States Environmental Protection Agency (U.S. EPA, 2012b), Energy Information Administration (EIA, 2013) and Food and Agriculture Organization of the United Nations (FAO, 2013)–, such inventories are comparable since they are made using the methods proposed by the IPCC (2000, 2006).

during a given year. These variables are studied across all the countries with available information[61] from 1990 to 2011.

3.3.1 Multidimensional inequality analysis

In this subsection, the multidimensional inequality is analysed considering the per capita emissions of the four most important gases –CO_2, CH_4, N_2O and F-gases–, using the measures described in Section 3.2.

As seen in Section 3.1, to compare the effect of different GHG emissions it is necessary to take into account their relative contribution to the greenhouse effect, as well as, the amount of emissions which each gas releases into the atmosphere. As all the emissions are expressed in CO_2-equivalent using the 100-year GWPs published in the Second Assessment Report of the IPCC (1996)[62], the "damage" caused by each gas is collected in the elements of the matrix **X**. Therefore, the weight assigned to each of the pollutants corresponds to the "amount" of each of them, that is, the share of the atmospheric concentration of each gas, measured in CO_2-equivalent, in the year 2011[63]. Specifically, the δ parameter takes the value of 0.7394 for CO_2; 0.0955 for CH_4; 0.1624 for N_2O and 0.0028 for F-gases[64]. Thus, the

[61] This research starts in the year 1990 because in that year the negotiations on a global convention began. Then, the years 1992, 1994, 1997, 2005 and 2009 are analysed because in these years took place important advances for achieving an international treatment. Thus, in 1992 and 1994, the UNFCCC was adopted and came into force, respectively; in 1997 and 2005, the Kyoto Protocol was adopted and came into force, respectively; and in 2009, the COP-15 was celebrated in Copenhagen. Finally, it is studied the year 2011 which is the last year for which the WRI provides information on the variables under study.

[62] Although the GWP values were updated in the Third, Fourth and Fifth Assessment Report of the IPCC (2001a, 2007b, 2013), the estimates of emissions from these reports continue using the GWPs from the Second Assessment Report (IPCC, 1996) in order to be consistent with the global reports of the UNFCCC.

[63] It was considered the concentration of GHGs in 2011 provided by the IPCC (2013) because is the last year with available data.

[64] The concentration of CO_2, CH_4, N_2O and F-gases in 2011 was 391000000, 1803000, 324000 and 210.04 parts per trillion, respectively.

inequality measure contemplates the two characteristics which allow us to compare the emissions from different GHGs.

Then, firstly, it is considered that β = -1, namely, there is perfect substitution among contaminants. However, to consider the relative contribution to the greenhouse effect and the amount of each gas as the only factors taken into account to compare GHG emissions is an assumption that restricts the existence of other agents. Consequently, in this analysis different substitution degrees among dimensions are admitted. So that, as β parameter takes values above -1, for example, 0.5 and 9, the degree of substitution decreases[65]. Finally, γ parameter has been set to 1.5, -1 and 0, allowing us to study the sensitivity of the results to variations in the weight assigned to the different parts of the distribution.

Table 3.2 presents the multidimensional inequality indices for the four main pollutants over the period 1990-2011. The multidimensional inequality indices showed different behaviour patterns depending on the weight given to the different parts of the distribution.

When more weight was attached to the emission transfers between the most polluting countries (γ = 1.5), an increasing pattern in terms of inequality was observed from 1990 to 2011 when the substitution degree among gases was perfect (β = -1).

[65] In this type of analysis are often considered various values for β in order to observe the sensitivity of the results to the variation of this parameter (Gigliarano and Mosler, 2009). Apart from the scenario β = -1 –perfect substitution among contaminants–, it has been considered β = 0.5 and β = 9 as representative values of a high and low substitution degree among gases, respectively. In addition, the higher value taken by the β parameter is 9 because from this value onwards the inequality pattern was similar.

Table 3.2

Inequality in per capita GHG emissions from 1990 to 2011

Year	$GEM_{1.5}$			GEM_{-1}			GEM_{0}		
	β = -1	β = 0.5	β = 9	β = -1	β = 0.5	β = 9	β = -1	β = 0.5	β = 9
1990	0.5509	0.4834	5.3077	0.2328	0.2092	0.9875	0.1765	0.1611	0.6281
1992	0.6066	0.4468	4.8157	0.2241	0.1930	0.8228	0.1780	0.1502	0.5740
1994	0.6713	0.4733	3.7813	0.2305	0.1896	0.7526	0.1866	0.1516	0.5253
1997	0.6897	0.4744	2.4135	0.2239	0.1753	0.5985	0.1843	0.1453	0.4271
2005	0.8341	0.3915	0.8174	0.2215	0.1538	0.3528	0.1911	0.1275	0.2377
2009	0.6811	0.3863	0.6197	0.2096	0.1435	0.3117	0.1792	0.1199	0.2020
2011	0.6692	0.4068	0.6021	0.2114	0.1443	0.3068	0.1797	0.1215	0.1986

Under this assumption (γ = 1.5 and β = -1), the maximum level of inequality was reached in 2005 and, since then, inequality declined. It is noted that such a descent coincided with the entry into force of the Kyoto Protocol. Meanwhile, when the substitution degree among pollutants decreased (β = 0.5 and β = 9), a fall in GHG emissions inequality was perceived, being much more accentuated in the latter case. Specifically, the biggest fall in inequality was observed when γ and β took the values 1.5 and 9, respectively.

In contrast, under the scenarios where the changes in the least polluting countries prevailed on the rest of the distribution (γ = -1), the results showed a decrease in the concentration of GHG emissions during the period, regardless of the substitution degree among pollutants. Although it is true that, in relative terms, such a reduction was greater as the substitution degree among pollutants decreased. Thus, when it was assumed perfect substitution among gases (β = -1) the decline was quantified by 9 percent, whereas, inequality was reduced by about 69 percent when β was set to 9.

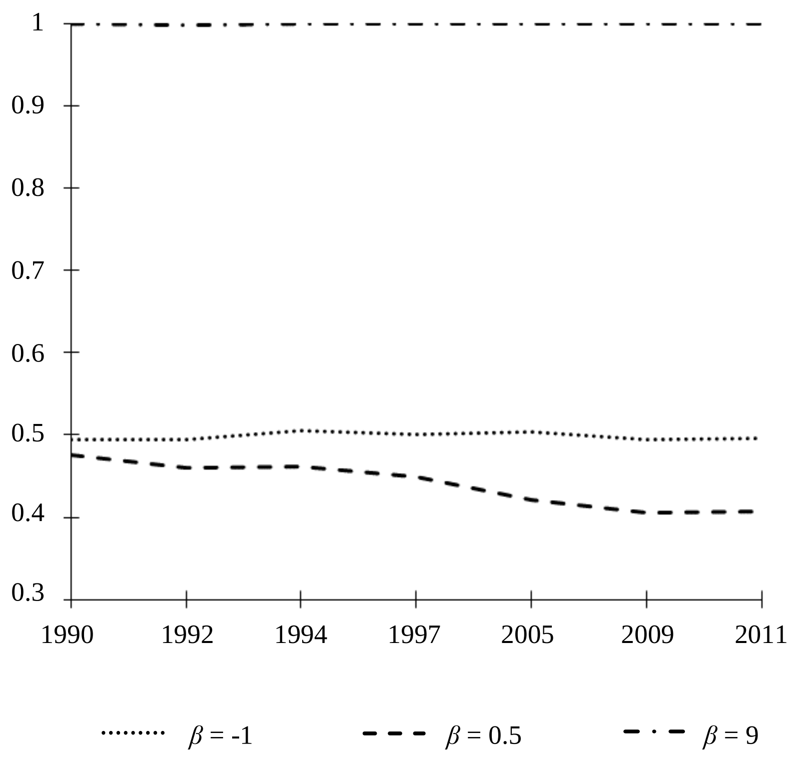
Finally, when all countries were equally weighted (γ = 0), inequality in GHG emissions suffered a little increase (by about 2 percent) over the period 1990-2011 when the elasticity of substitution among gases was perfect (β = -1). However, the results showed a decreasing pattern in terms of inequality as the substitution degree among pollutants decreased (β = 0.5 and β = 9). In this context, as happens in the previous cases, the disparities declined on the basis of the value of the β parameter in a way that, a greater reduction occurred as the substitution degree among GHGs decreased.

In order to evaluate the consistency of the results, the world inequality in GHG emissions has also been evaluated using the Gini index. It is defined as the area between the line at 45 degrees and the Lorenz curve divided by the area of the triangle which is below the diagonal line. It ranges from 0 –perfect equality– to 1 –perfect inequality.

Figure 3.2 shows the evolution of the Gini coefficient for per capita GHG emissions from 1990 to 2011. The Gini index is computed giving the same weight to all the countries and assuming different substitution degrees among pollutants: the dotted line represents a perfect substitution degree (β = -1), the dashed line a high substitution degree (β = 0.5) and the dashed-dotted line a low substitution degree (β = 9).

Figure 3.2

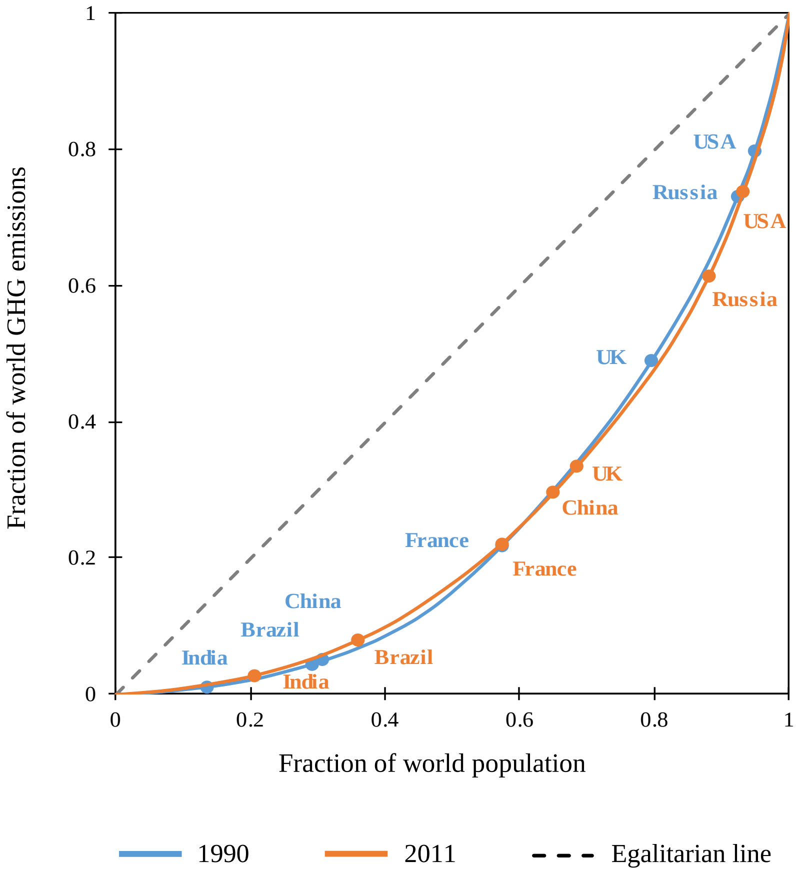
Gini index for per capita GHG emissions from 1990 to 2011 (γ = 0)



During the period 1990-2011, the evolution of the Gini coefficient for per capita GHG emissions was similar to the one experienced by the *GEM* index but when the elasticity of substitution among gases was low (β = 9). In the latter case, the *GEM* index showed a decreasing trend while the Gini index remained constant. Despite this small difference, in both indices the lowest and highest inequality level was observed when β = 0.5 and β = 9, respectively. Meanwhile, when the substitution degree among gases was perfect (β = -1) the value of the Gini index was around 0.5, being close to the theoretical equilibrium of an exponential distribution (Drăgulescu and Yakovenko, 2001a).

Figure 3.3

Lorenz plots for per capita GHG emissions in 1990 and 2011
(γ = 0 and β = -1)



The Lorenz plots when γ = 0 and β = -1 in 1990 and 2011 are shown in Figure 3.3. In addition, some results for different countries have been included. Again, it can be observed that the per capita GHG emissions were exponentially distributed in both years. Over this time period, the Lorenz plots had moved up just a little bit, evolving to a short more equal distribution. Regarding the countries order, the growth of the GHG emissions in China should be highlighted which is in accordance with its recent and fast economic growth.

Going back to the inequality analysis based on the *GEM* index, it is noted that the multidimensional indices used in this study can be additively decomposed by population sub-groups. In other words, this decomposition allows us to study which part of total inequality can be attributed to differences between groups and what to disparities within a group.

To analyse the decomposition of the generalised entropy measures in their interregional and intraregional components, in this study, it has been chosen to divide the population into different sub-groups considering the amount of GHG emissions released into the atmosphere by each country in 1990[66]. Thus, starting from a sample of 117 countries, which is ordered from the lowest emitting country to the highest one, 10 groups have been built, each one containing a 10 percent of observations. In such a way, the first (last) group of countries is formed by the 10 percent of countries that emitted less (more) GHG emissions in 1990.

[66] The classification of the countries can be found in the Appendix 3.1.

Figure 3.4

Decomposition of inequality in per capita GHG emissions by population sub-groups from 1990 to 2011

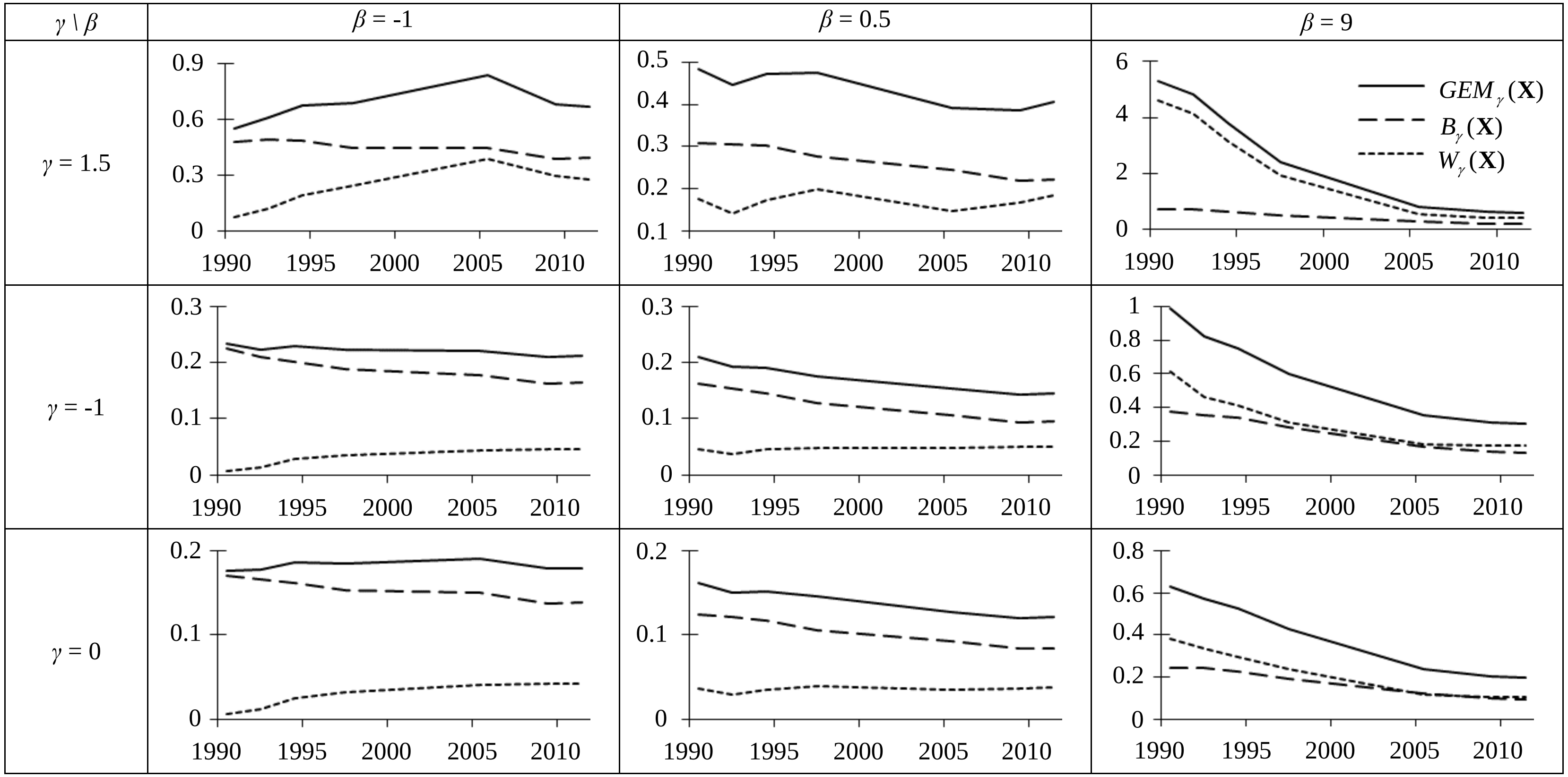


Figure 3.4 shows the results of the decomposition of multidimensional indices by population sub-groups[67]. The solid line represents the total inequality value shown in Table 3.2, the large-dashed line exhibits the between-group inequality component and the short-dashed line displays the within-group inequality. According to the results, both components contributed to the change in overall inequality from 1990 to 2011. This aspect supports the choice for the presented methodology, which considers the decomposition of total inequality into both components.

The between-group inequality component showed a declining trend from 1990 to 2011, regardless of the weight given to the different parts of the distribution and the substitution degree among pollutants. As in the global inequality case, the largest decline in inequality between regions took place when it was given more importance to the emission transfers between the most polluting countries (γ = 1.5) and the elasticity of substitution among gases was low (β = 9). However, when it was assumed a perfect or high substitution degree among pollutants (β = -1 and β = 0.5), the biggest inequality decrease occurred when the least polluting countries received more weight (γ = -1). A greater reduction in the inequality associated with this component was also detected as the substitution degree among gases decreased.

As for the within-group inequality component, it can be concluded that its evolution along the period depended on the substitution degree among pollutants. Thus, when it was assumed a low substitution degree among gases (β = 9), the inequality trend was decreasing; holding the opposite tendency as the β parameter took smaller values. In addition, while it was observed the largest descent when more weight was attached to the emission transfers

[67] The values of the decomposition of the inequality indices into their interregional and intraregional components from 1990 to 2011 are shown in the Appendix 3.2.

between the most polluting countries (γ = 1.5), the highest enlargement happened when all countries received the same importance (γ = 0).

As seen in Figure 3.4, the evolution of the weight of both inequality indices did not depend on the γ parameter; however, it was affected by the assumptions made in relation to the β parameter. Thus, while the interregional component was a predominant factor in the scenarios where the substitution degree among GHGs was perfect or high (β = -1 and β = 0.5), the intraregional inequality received a greater weight when a lower substitution degree among gases was admitted (β = 9). Despite the fact that, depending on the assumptions made about β, one or another component prevailed over global inequality in GHG emissions, it should be noted that, in all cases, the predominant component had been progressively reducing its weight in total inequality in favour of the other element.

3.3.1.1 Sensitivity analysis

To complete the previous study of inequality, in this section, two different sensitivity analyses are carried out. Firstly, the evolution of inequality in CO_2, CH_4, N_2O and F-gases emissions is studied, paying special attention to the substitution degree among pollutants. Secondly, the relative importance of the between- and within-group inequality components in global inequality is analysed.

Figure 3.5

Variation of inequality in per capita GHG emissions to the β parameter from 1990 to 2011 (1990 = 100)

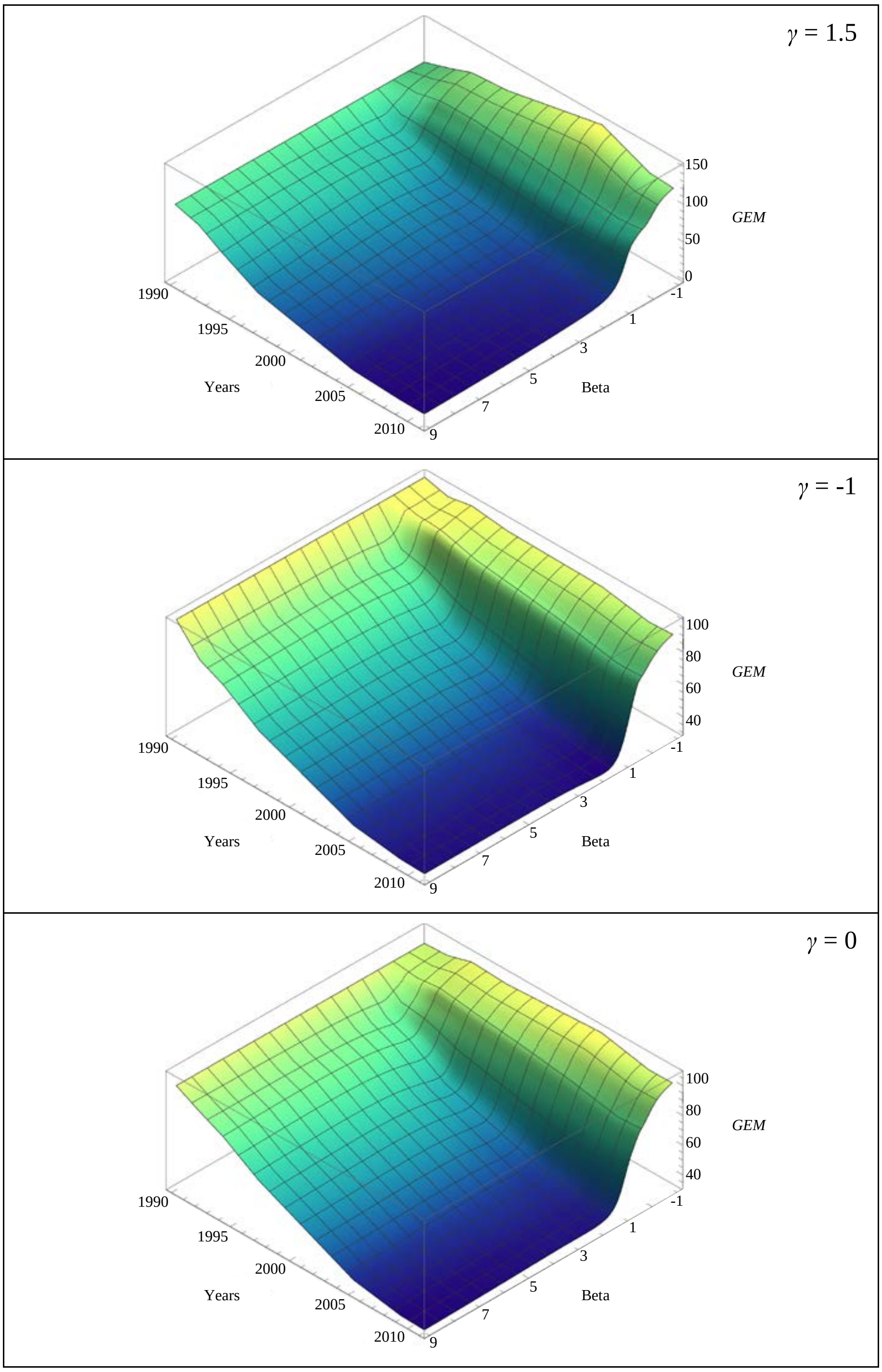


Figure 3.5 shows the variation of the *GEM* index to the β parameter[68] in the three scenarios defined by the γ parameter: when all countries are equally weighted (γ = 0), when more weight is attached to the emission transfers between the most polluting countries (γ = 1,5) and when the changes in the least polluting countries prevail on the rest of the distribution (γ = -1). In the three cases, the time period ranges from 1990 to 2011.

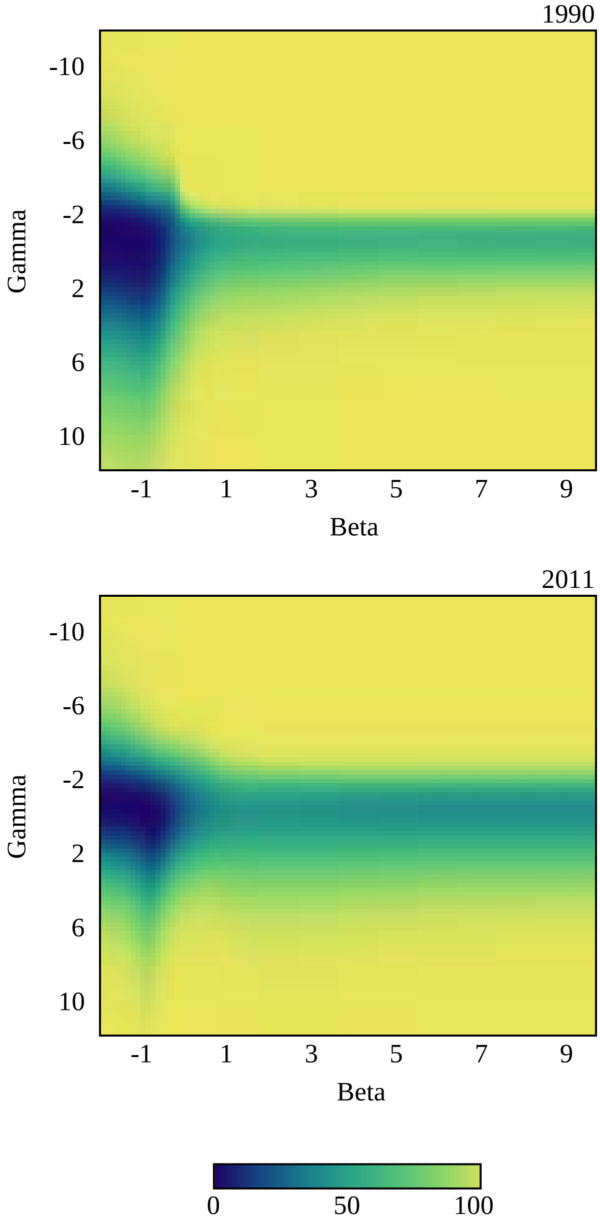
When all the countries were equally weighted (γ = 0), inequality increased by about 2 percent when β = -1, that is, when the substitution degree among gases was perfect. In addition, under this elasticity assumption, the maximum increment of inequality was reached in the year 2005. Inequality decreased from the value β = -0.6, in such a way that the minimum level was reached in 2011 when β = 9. It should be noted that the inequality decrease slowed down from β = 2, being the effect of the substitution degree on the inequality decrease much lower.

When more weight to the emission transfers between the most polluting countries (γ = 1.5) was attached, the maximum level of inequality was always reached in the year 2005 for low values of the β parameter (β < 0). In particular, the highest level was observed when the substitution degree among gases was perfect (β = -1). When β > 0, the minimum level of inequality was generally reached in 2009. However, as happens in the previous case, the lowest level of inequality occurred in the year 2011 when β was set to 9. It should be highlighted that, considering all cases together, the maximum and minimum levels of inequality took place when γ = 1.5.

[68] The β parameter ranges from -1 to 9 by increments of 0.01.

Figure 3.6

Contribution to inequality in per capita GHG emissions of the within-group inequality component in 1990 and 2011



Note: The contribution is expressed in percentage.

Supposing that the changes in the least polluting countries prevailed on the rest of the distribution (γ = -1), the results indicated that the maximum level of inequality was reached in the reference period (year 1990), irrespective of the β parameter value. Under this assumption, it was observed that inequality was reduced from β = -1 to β = 2, showing the opposite trend until β = 5. Finally, from β = 5 onwards, inequality decreased slightly.

This analysis reveals a general behaviour pattern: the elasticity of substitution plays an important role in the variation of inequality. Thus, the lower the substitution degree among gases, the lower inequality level. As it has been seen before, the GWP depends on the time horizon, the discount rate and the radiative forcing assumed. In this sense, the dependence between the increasing inequality trend and the β parameter value may be due to the existence of characteristics which had been omitted in the computation of the GWP.

Figure 3.6 presents the contribution to inequality in per capita GHG emissions of the within-group inequality component for several combinations of the γ and β parameters[69] in 1990 and 2011. This approach allows us to analyse the weight of the components in total inequality without assuming a specific substitution degree among contaminants and level of aversion to inequality.

In both graphs, the within-group inequality component predominated in most combinations of parameters. Even though, when it was attributed the same weight to all countries (γ = 0), the between-group inequality component prevailed if the substitution degree among gases was perfect or very high. Under this same context (γ = 0), the proportion of total inequality which was

[69] The β parameter ranges from -1 to 9 by increments of 0.01 while, the γ parameter ranges from -10 to 10 by increments of 0.5.

explained by each component seemed to be similar when a lower substitution degree among gases was admitted. Comparing both years –1990 and 2011–, it can be concluded again that the dominant component in 1990 had reduced its importance in total inequality in favour of the no predominant element.

3.3.2 Multidimensional polarization analysis

In this subsection, the multidimensional polarization in the per capita CO_2, CH_4, N_2O and F-gases emissions is studied, using the indices described in Section 3.2. In particular, these indices are constructed in two steps: in the first phase, the multidimensional inequality indices proposed by Maasoumi (1986) and Maasoumi and Nickelsburg (1988) are obtained while, the multidimensional polarization indices developed by Gigliariano and Mosler (2009) are calculated in a second stage.

As specified previously, these measures include three parameters. The δ parameter, which attaches the weight to each GHG in the overall index, has been fixed, as in the inequality analysis, considering the proportion of emissions that represented each pollutant in 2011[70]. For the β parameter, the value -1 has been considered which represents perfect substitution among the polluting gases included in the analysis. Finally, γ parameter has been set to 0 giving the same weight to the different countries.

It is noted that the multidimensional inequality indices used in this analysis can be additively decomposed by population sub-groups. In this study, the creation of groups has been made using the method proposed by Aghevli and Mehran (1981), technique which was later refined by Davies and Shorrocks (1989). This procedure involves minimizing disparities within each group considered. For this purpose, it is necessary to calculate the average emission

[70] Specifically, the δ parameter takes the value of 0.7394 for CO_2; 0.0955 for CH_4; 0.1624 for N_2O and 0.0028 for F-gases.

between adjacent groups to find the border between them. This process converges to two extreme solutions which, in case of not coinciding, delimit all the possibilities of grouping.

The difference from previous applications of this method of grouping lies in the use of the generalised entropy measures, instead of the Gini index, to analyse inequality between groups. Thus, to determine which number of groups is the most appropriate for explaining the degree of polarization, the percentage of total inequality that can be explained by the between-group inequality component ($B\gamma$ (**X**) / $GEM\gamma$ (**X**)) is calculated in each case. It should be highlighted that, although the consideration of a large number of poles allows us to explain a greater percentage of total inequality, it reduces, at the same time, the interest of the polarization analysis.

Table 3.3

Total inequality explained by the grouped distributions

Year	**Four groups (*k* = 4)**	**Eight groups (*k* = 8)**
1990	75	77
1992	80	84
1994	82	86
1997	83	88
2005	84	91
2009	88	96
2011	90	97

Note: Inequality is expressed as percentage of the total value.

Regarding the groups of countries considered in this analysis, the level of emissions released into the atmosphere in 2011 by each country has been taken into account in order to keep a consistent sample for the entire period. In particular, this analysis is carried out considering the sample divided into four (k = 4) and eight (k = 8) groups. In this case, four is the minimum number of groups that allows the between-group inequality component to explain, at least, 70 percent of total inequality in all the years. Meanwhile, eight is the maximum number of groups admitted in this study given that from this number onwards the percentage of total inequality explained by the between-group inequality component was similar and, therefore, increasing the number of poles did not involve an important explanatory improvement (see Table 3.3).

Figure 3.7 illustrates which countries belong to each group after applying the endogenous method of grouping mentioned before[71]. Figure 3.8 presents the multidimensional inequality indices for the four main pollutants over the period 1990-2011[72]. It also exposes the decomposition of the multidimensional indices by population sub-groups. The solid line represents the total inequality value, the large-dashed line displays the inequality between groups and the short-dashed line exhibits the within-group inequality component.

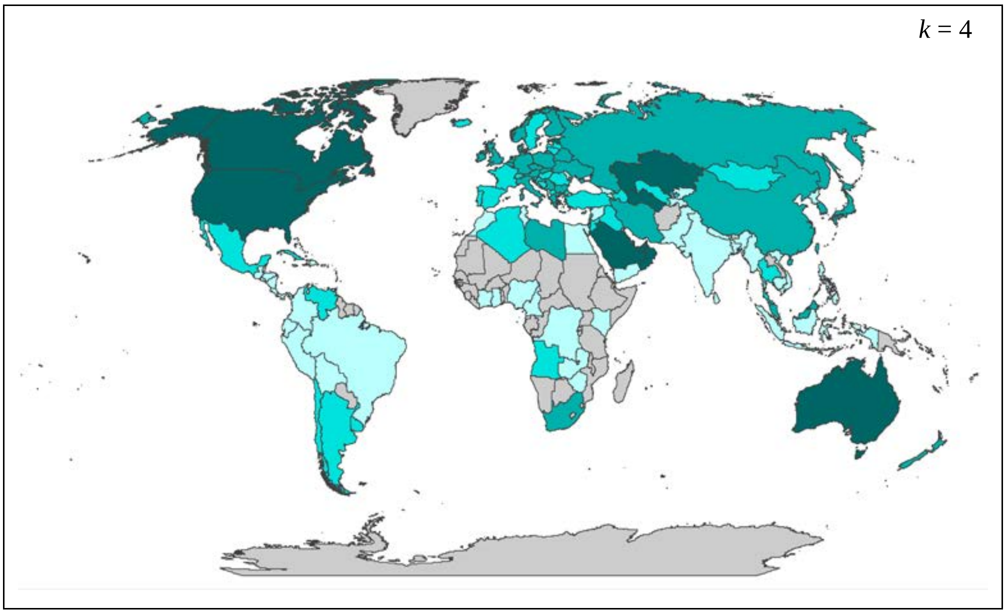
Considering that all countries are equally weighted (γ = 0) and a perfect elasticity of substitution among gases (β = -1), total inequality in GHG emissions remained constant over the period 1990-2011. An increasing pattern is observed until 1994; holding the opposite tendency until the year 1997. The maximum level of inequality was reached in the year 2005, followed by a decreasing path until 2009, and a stabilization in the last two years of study.

[71] The classification of the countries can be found in the Appendixes 3.3 and 3.4.

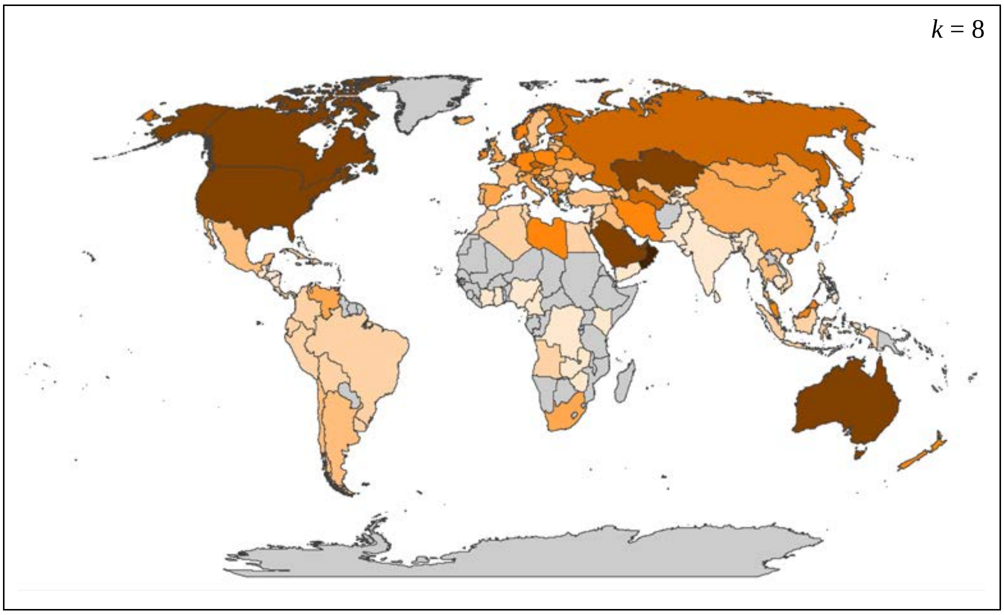
[72] The values of the decomposition of the inequality index into their interregional and intraregional components from 1990 to 2011 are shown in the Appendix 3.5.

Figure 3.7

Endogenous classification of countries into four and eight groups according to their level of per capita GHG emissions



Level 1 Level 2 Level 3 Level 4 Not available

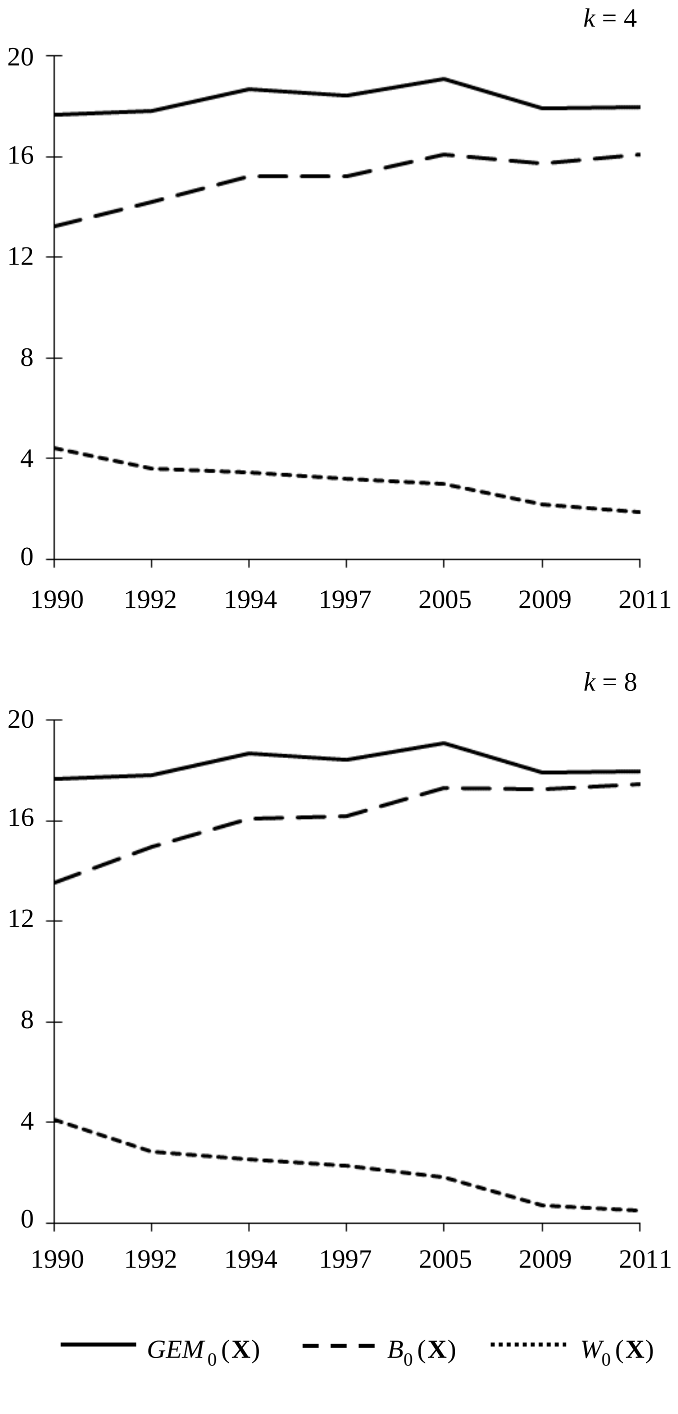


Level 1 Level 2 Level 3 Level 4 Level 5

Level 6 Level 7 Level 8 Not available

Figure 3.8

Decomposition of inequality in per capita GHG emissions by population sub-groups from 1990 to 2011 considering four and eight groups (β = -1)



In both cases, when the distribution was divided into four (k = 4) and eight groups (k = 8), the two inequality components showed a similar pattern between 1990 and 2011. Although both components contributed to the change in overall inequality from 1990 to 2011, the interregional inequality prevailed in the two scenarios.

The between-group inequality component showed an increasing trend from 1990 to 2011, however, such increment was bigger when it was considered more groups of countries. Thus, whereas this kind of inequality increased by 22 percent when k = 4, the same suffered an increment of 7 additional percentage points when k = 8.

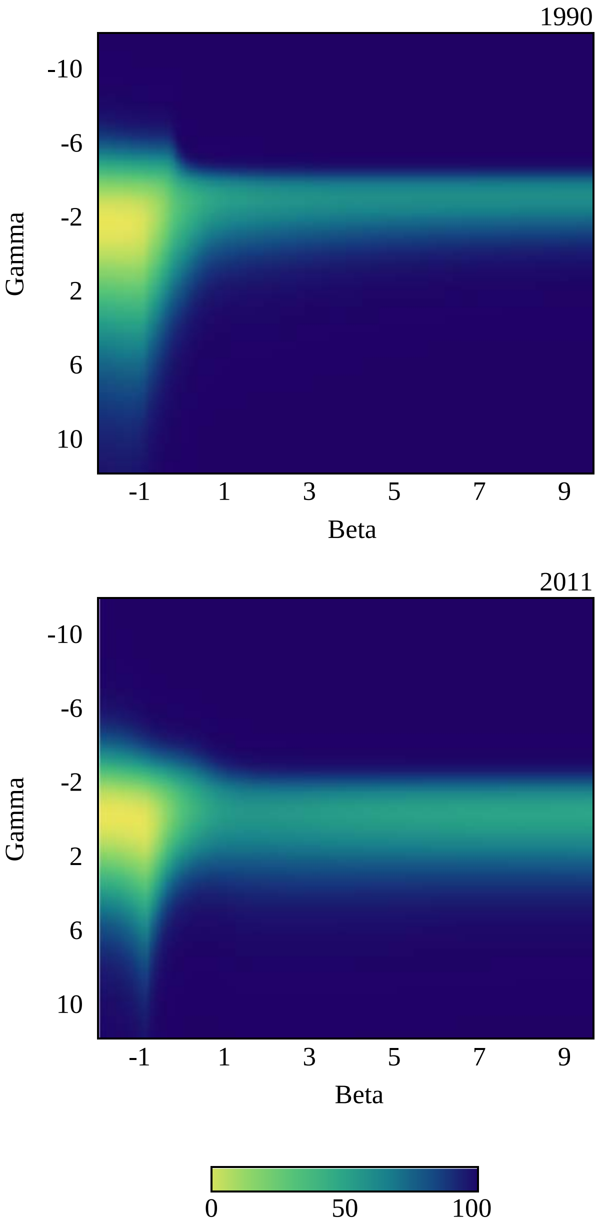
In relation to the within-group inequality component, a decreasing tendency was perceived, being much more accentuated when it was taken into account eight groups of countries –roughly 88 percent. These results are coherent given that the bigger the number of groups considered, the higher (smaller) the inequality between (within) groups.

Figures 3.9 and 3.10 present the contribution to inequality of the within-group inequality component for several combinations of the γ and β parameters[73] in 1990 and 2011 considering four and eight groups, respectively. This approach allows us to analyse the weight of both components in total inequality assuming neither a specific substitution degree among contaminants nor a level of aversion to inequality.

[73] The β parameter ranges from -1 to 9 by increments of 0.01 while, the γ parameter ranges from -10 to 10 by increments of 0.5.

Figure 3.9

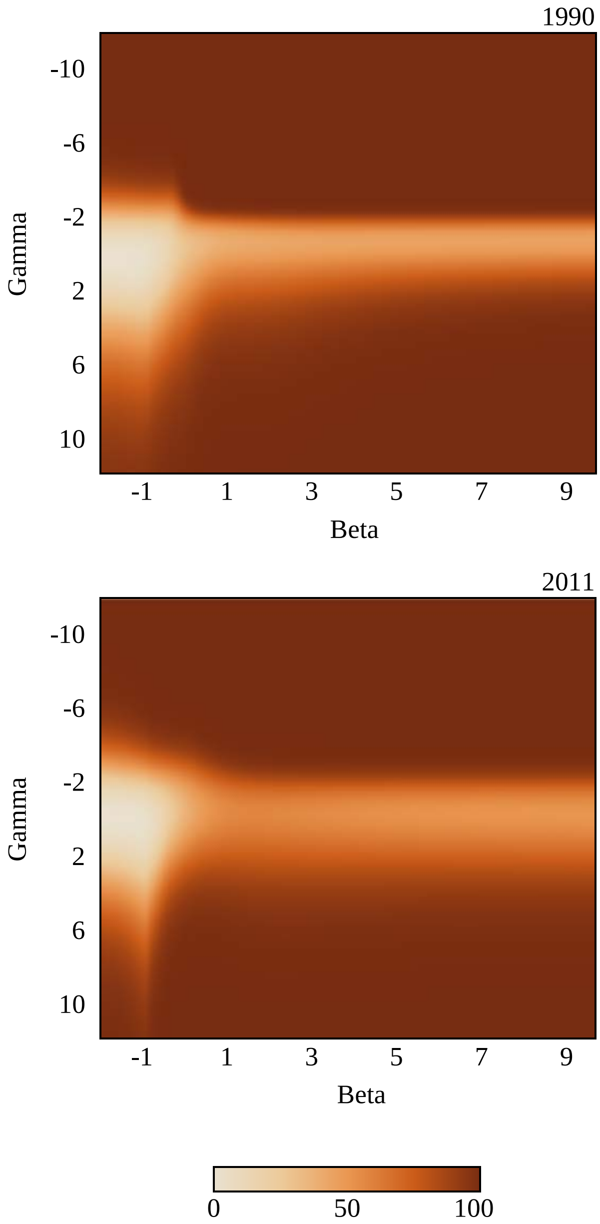
Contribution to inequality in per capita GHG emissions of the within-group inequality component in 1990 and 2011 considering four groups



Note: The contribution is expressed in percentage.

Figure 3.10

Contribution to inequality in per capita GHG emissions of the within-group inequality component in 1990 and 2011 considering eight groups



Note: The contribution is expressed in percentage.

It is observed in the four graphs that the within-group inequality component predominated in most combinations of parameters. When the same weight to all countries ($\gamma = 0$) was attributed, the between-group inequality component prevailed when the substitution degree among gases was perfect or very high. Under this same context ($\gamma = 0$), the proportion of total inequality which was explained by each component seemed to be similar when a lower substitution degree among gases was admitted.

Having analysed the evolution of inequality in GHG emissions from a multidimensional perspective, the polarization in the distribution of the four most important gases -CO_2, CH_4, N_2O and F-gases-, is studied in the same time period, 1990-2011, using the measures detailed in Section 3.2.

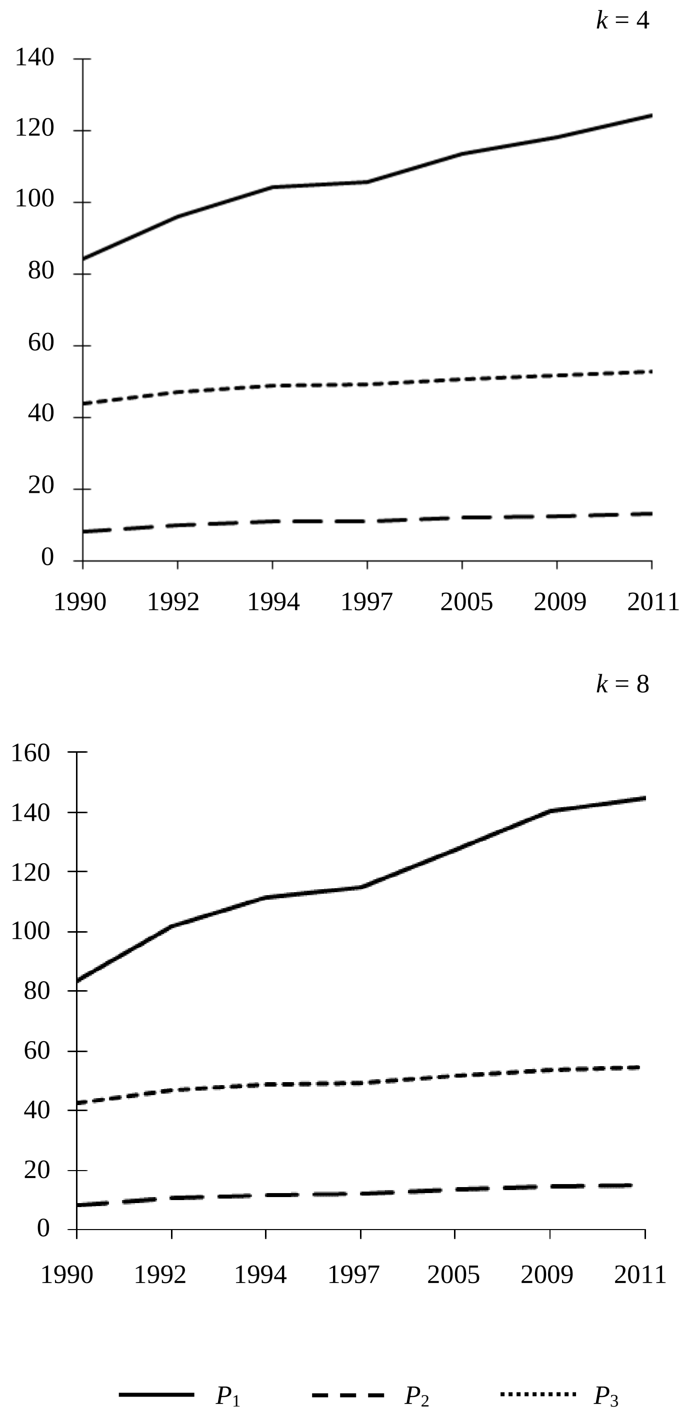
Figure 3.11 illustrates the evolution of the multidimensional polarization –using the P_1, P_2 and P_3 indices– for the four main pollutants over the period 1990-2011[74]. The solid line represents the P_1 index, the large-dashed line exhibits the P_2 index and the short-dashed line displays the P_3 index.

Considering that all countries are equally weighted ($\gamma = 0$) and a perfect elasticity of substitution among gases ($\beta = -1$), the multidimensional polarization indices evolved in the following way. Taking into consideration four groups, the P_1 index increased by 24 percent from 1990 to 1994, being this rate smaller from then on (around 19 percent). In the case $k = 8$, the growth of the polarization was bigger –by 34 and 30 percent until and after the year 1994, respectively–.

[74] The values of the polarization indices from 1990 to 2011 are specified in the Appendix 3.6.

Figure 3.11

Polarization in per capita GHG emissions from 1990 to 2011 considering four and eight groups (γ = 0 and β = -1)



The P_2 and P_3 indices showed a slightly increasing pattern that remained constant throughout the period. Comparing both scenarios, while the evolution of P_2 and P_3 was similar regardless of the number of groups considered, the P_1 index experienced an increase that was accentuated when a larger number of groups was considered.

To complete the previous study of polarization, a sensitivity analysis of the evolution of polarization in CO_2, CH_4, N_2O and F-gases emissions has been carried out, paying special attention to the degree of substitution among the preceding pollutants. Figures 3.12 and 3.13 show the evolution of the three polarization indices – P_1, P_2 and P_3– from 1990 to 2011, assuming different values for the β parameter and considering four and eight groups of countries, respectively.

The illustrations show that P_1 and P_3 indices exhibited quite similar behaviour patterns. In both cases, the maximum level of polarization was reached in the year 2011 when the elasticity of substitution among pollutants was perfect (β = -1). This result seems to be reasonable since the country grouping has been made taking as a reference that period. On the contrary, these indices reached the lowest value in 1990 when β = 9 when the grouping was done around four groups. When the double number of poles was considered, the minimum took place in 2011, assuming a higher elasticity of substitution among pollutants (β = 2).

With respect to the P_2 index of multidimensional polarization, the maximum value was also recorded in 2011 for β = -1, while the minimum was observed in the first year of study when the degree of substitution was low (β = 9).

Figure 3.12

Polarization in per capita GHG emissions from 1990 to 2011
assuming different elasticities of substitution among gases
and considering four groups ($\gamma = 0$)

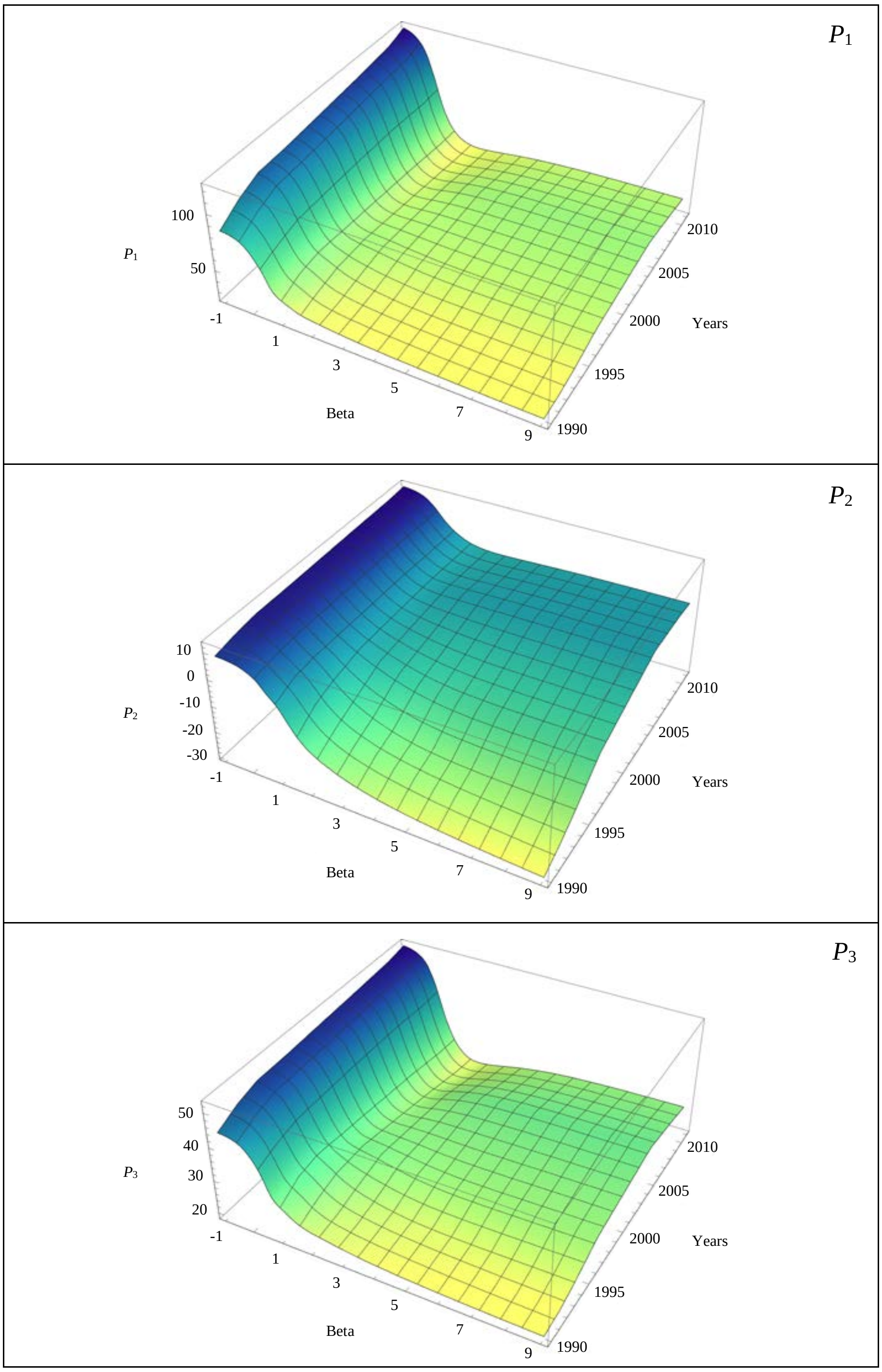
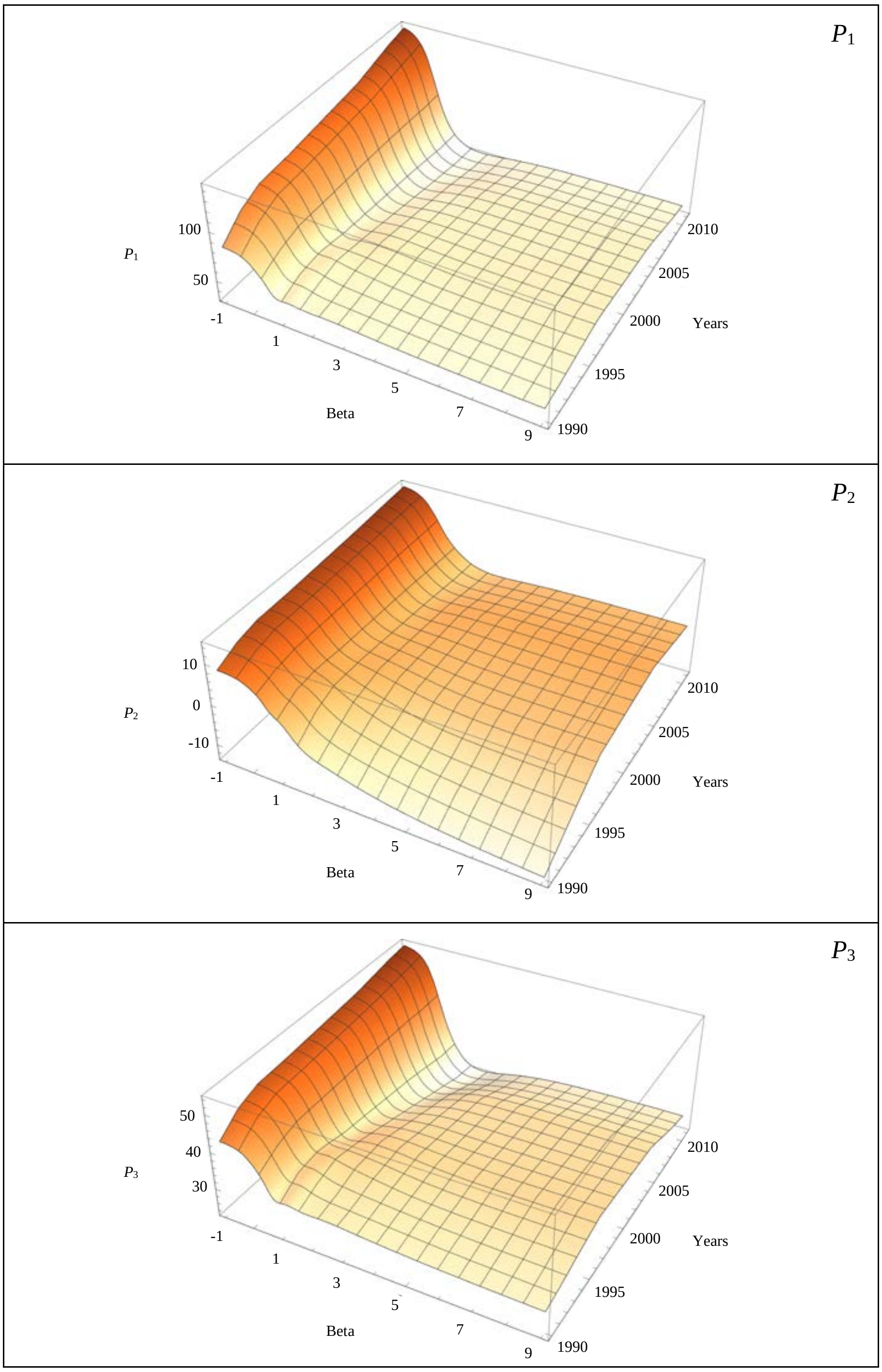


Figure 3.13

Polarization in per capita GHG emissions from 1990 to 2011
assuming different elasticities of substitution among gases
and considering eight groups ($\gamma = 0$)



As for the evolution of the indices, a similar pattern for P_1 and P_3 indices was observed again. When k = 4, polarization was reduced as the degree of substitution among dimensions decreased for the first two years of the study. As the year 2011 was reached, the stabilization of polarization occurred at lower values of the β parameter. For k = 8, the polarization decreased from 1990 to 1994, regardless of the substitution degree among contaminants. For subsequent periods, the behaviour was similar to that observed for the other grouping of countries.

In relation to the evolution of the polarization displayed by P_2, the value of the index decreased in the first three years as the value of the β parameter increased, irrespective of whether the country grouping was around 4 or 8 poles. In the rest of the years considered, the polarization was not stabilized until the degree of substitution among gases was smaller, unlike the behaviour observed for the P_1 and P_3 indices.

3.4 Conclusions and policy implications

In this chapter the inequality and polarization in the distribution of the four main GHG emissions –CO_2, CH_4, N_2O and F-gases– is analysed from a multidimensional perspective in the period 1990-2011. For this purpose, the generalised entropy measures proposed by Maasoumi (1986) which allow us to analyse the between- and within-group inequality components and, the polarization indices developed by Gigliariano and Mosler (2009) –P_1, P_2 and P_3– which are constructed from the decomposition by population sub-groups of the inequality measures mentioned before are used.

The data used in this analysis have been extracted from the Climate Analysis Indicators Tool database, which is updated by the WRI. The per capita emissions of the four main GHGs are expressed in tonnes of CO_2-equivalent using the 100-year GWPs values published in the IPCC's Second Assessment Report of 1996.

The multidimensional inequality analysis shows that the results varied, during the period of study, according to the weight assigned to the different parts of the distribution. When more weight was attached to the emission transfers between the most polluting countries, an increasing inequality trend over the whole period was observed when the substitution degree among gases was perfect or very high. Meanwhile, when the substitution degree among pollutants decreased, a reduction in GHG emissions inequality was perceived. The previous pattern was repeated when all countries were equally weighted.

In contrast, when changes in the least polluting countries prevailed on the rest of the distribution, the results showed a decrease in the concentration of GHG emissions during the period 1990-2011, regardless of the substitution degree among pollutants.

To analyse the decomposition of the generalised entropy measures into their interregional and intraregional components, the countries have been classified into different sub-groups considering the amount of GHG emissions released into the atmosphere by each country in the year 1990. The between-group inequality component showed a declining trend during the period 1990-2011, regardless of the weight given to the different parts of the distribution and the substitution degree among pollutants. The behaviour of the within-group inequality component depended on the substitution degree among gases. Thus, when a low substitution degree among them was assumed, the inequality trend was decreasing; holding the opposite tendency as the β parameter took smaller values.

Analysing jointly both inequality indices, it is observed that, while the interregional component was a predominant factor in the scenarios where the substitution degree among GHGs was perfect or high, inequality within regions received a greater weight when a lower substitution degree among gases was admitted. However, in all cases, the predominant component had been progressively reducing its weight in total inequality in favour of the other element.

Regarding the multidimensional polarization analysis, the creation of groups has been made using the method proposed by Aghevli and Mehran (1981) and Davies and Shorrocks (1989). In particular, this analysis is carried out considering the sample divided into four and eight groups, providing that all countries are equally weighted (γ = 0) and a perfect elasticity of substitution among gases (β = -1).

The multidimensional polarization study gives the following outcomes. Comparing both scenarios, while the P_2 and P_3 indices showed a slightly increasing pattern that was similar regardless of the number of groups considered, the P_1 index experienced an increase that was accentuated when a larger number of groups was considered. In addition, it is observed that the three indices reached the maximum level of polarization in the year 2011 when the elasticity of substitution among pollutants was perfect (β = -1). This result seems to be reasonable since the country grouping has been made taking as a reference that period.

In relation to environmental policies the following can be noted. The compromise reached in the UNFCCC in 1992, to adopt measures to stabilize GHG emissions, may be one of the causes that lies behind the declining inequality trend when it is given more importance to the emission transfers between the most polluting countries. However, there are arguments in the literature to make a distinction between equality and fairness. Because an equal distribution in not necessarily fair, Venkatasubramanian (2010) supports that a fair distribution is the one that maximizes entropy.

It should also be noted that the similarity of the results obtained when the changes in the most polluting countries prevail on the rest of the distribution and when all countries are equally weighted. Thus, although from a point of view of climate policy the first case may seem more interesting, the consistency in the results of both scenarios means that we should give a green light to the use of other inequality measures which do not support assigning a different weight to the different parts of the distribution.

It is expected that the weight of the interregional and intraregional inequality components will be more equal over time as both elements showed a trend in which the predominant component is losing importance in favour of the other one.

As countries refuse to act alone in response to global climate change, international cooperation is needed. Despite the fact that per capita emissions are commonly higher in wealthier countries, there are important exceptions. For instance, some middle-income developing economies have per capita emissions levels close to those of richer developed countries. Given the wide variety of countries with different characteristics and similar per capita emissions profiles, one-size-fits-all strategies are unlikely to be successful in advancing international cooperation on climate change. In this sense, the multidimensional polarization analysis provides a useful framework to understand the potential appearance of conflicts in the global distribution of per capita GHG emissions.

Although climate change became a global matter in the 1990s, climate negotiations are surrounded by conflicts of interests between developed and developing countries. In this line, despite the fact that the Paris Agreement supposed a remarkable step towards the consideration of the different concerns of all Parties, there is still a long path ahead. Thus, in order to balance the two perspectives, political efforts should be made on the basis of the principle “common but differentiated responsibilities”.

Regarding the probability of implementing international agreements, the fact that the P_2 and P_3 indices showed a slightly increasing pattern has to be perceived as positive in terms of advancing towards an international environmental negotiation for two reasons. Firstly, because the polarization degree was similar regardless of the number of groups considered and, secondly, because it suffered a little enlargement despite the fact that the country grouping has been made taking as a reference the year 2011.

It should also be noted that the divergence of the results based on the polarization index confirms that it is necessary to take into account different specifications for these indices in order to project a wide range of possible social and political conflicts and better understand climate negotiations.

In order to reduce the polarization in the global distribution of GHGs, this analysis suggests two policy directions. On the one hand, when the same weight to all countries is attributed and the substitution degree among gases is assumed to be perfect or very high, the attenuation must come from the convergence in the average emissions among the groups of countries given that the heterogeneity between groups is the most important component. On the other hand, for the rest of the combinations of the γ and β parameters, as it is observed a lowest degree of antagonism between groups, the contraction must come from the moderation of the intra-group cohesion.

Chapter 4

Theil's indices for parametric distributions: an application to CO_2 emissions

Introduction

Along the previous chapters it has been explicitly stated that the study of emission inequality has received a huge amount of attention in the literature. The debate about the uneven distributional effects of climate change on the different parts of the world have reinforced the interest in this topic, being still a field of intense ongoing research.

Several inequality measures have been proposed in the literature. Among them, one of the most commonly used is the Gini index whose interpretation, as it was mentioned in Chapter 3, is very intuitive in terms of the area between the egalitarian line and the Lorenz curve. Notwithstanding its popularity, this indicator presents some rigidities with respect to other inequality measures. In particular, it does not allow us to vary the sensitivity of the index to redistributional movements at specific emission ranges, which can point out different evolutions of disparities when no Lorenz dominance can be found. A generalisation of this index was proposed by Yitzhaki

(1983), which includes a parameter to allow for different degrees of aversion to inequality.

In this line, the generalised entropy measures include a sensitivity parameter which varies the importance given to the differences at the upper tail. This index becomes more sensitive to changes at the top of the distribution as the parameter increases. As it was pointed out in Chapter 1, the two limiting cases of this family of inequality measures are obtained when the parameter is set to 0 and 1, corresponding to the *MLD* index and the Theil's entropy index, respectively (hereinafter T_0 and T_1). Although their introduction in the environmental field is still mild, these two measures have been widely used to investigate the evolution of income inequality (see e.g. Bourguignon and Morrisson, 2002; Chotikapanich *et al*., 2007; Warner *et al*., 2014; Jordá *et al*., 2014). The T_1 treats differences in all parts of the distribution equally, while the T_0 is more sensitive to changes at the bottom tail. An appealing feature of the generalised entropy measures is the property of additive decomposability, which makes these indices especially useful for measuring socioeconomic inequalities.

Closed expressions of the generalised entropy measures can be obtained straightforwardly using the theoretical moments of the parametric distributions, but the formulas for Theil indices are not so simple. Thus, in this chapter, a convenient expression for the Theil indices is presented which allows us to obtain these inequality measures for the most relevant families of parametric distributions and to derive closed expressions for multivariate versions of these indices. In particular, these formulas are reviewed for the most common parametric distributions and obtained for those that were not available in the existing literature: the Champernowne (1952) distribution, the generalised gamma and generalised beta of first and second kind distributions (McDonald, 1984), the κ-generalised distribution (Clementi *et* *al*., 2007) and several Pareto and gamma-type distributions. The moments of these families are also included to facilitate the computation of the generalised entropy measures.

Probability models have been successfully applied in many physical phenomena –such as wind speed, rainfall, river discharges and air quality– for predicting purposes (Oguntunde *et al*., 2014). Regarding GHG emissions, the correctly chosen distribution can be used to predict the mean concentration and the probability of exceeding a critical concentration, for instance (Harikrishna and Arun, 2003; Kan and Chen, 2004).

Information concerning the statistical distribution of contaminants can also be used to investigate the level of inequality associated with them. Therefore, the Theil indices developed in this chapter are applied to investigate the inequality in the per capita CO_2 emissions in the year 2012 as they are the major driver of climate change. The emission distribution has been modelled assuming the GB2 distribution (McDonald, 1984) and the goodness of fit has been assessed illustrating the Q-Q plot and the P-P plot. The level of inequality in per capita CO_2 emissions is assessed computing different generalised entropy measures: the T_0, T_1 and $GE(2)$ indices. The analysis points out that the level of inequality depended on the sensitivity of the index to the emissions transfers that may occur in the different parts of the distribution. Thus, the highest inequality value was observed when it was assigned more importance to the transfers at the upper tail of the distribution ($GE(2)$ index).

The contents of this chapter are the following. In Section 4.1 the general expressions for the T_0 and T_1 indices are specified, which are especially convenient to obtain these indicators in a closed form for a battery of parametric distributions. Section 4.2 presents the Theil indices for many classical distributions, including the Champernowne distribution and the three special cases of the generalised beta family. The Pareto hierarchy and recently developed functional forms such as the κ-generalised distribution are also studied. In Section 4.3 the decomposition of the generalised entropy measures is described both by factors and by population sub-groups. Extensions to higher dimensions are displayed in Section 4.4. Next, using the formulas developed in this analysis, the family of generalised entropy measures is applied to study the inequality in per capita CO_2 emissions. Finally, Section 4.6 concludes the chapter.

4.1 Computation of the Theil indices

Let X be an absolutely continuous non-negative random variable with probability density function (pdf) $f(x)$ and support (l, u), where $0 \leq l < u < \infty$. Assume that the mathematical expectation of X is finite and it is given by $E(X) = \mu$.

The class of the generalised entropy measures is given by:

$$GE(\theta) = \frac{1}{\theta(\theta-1)}\left[E\left(\frac{X}{\mu}\right)^{\theta} - 1\right], \quad \theta \neq 0,1, \tag{1}$$

with $E(X^{\theta}) < \infty$. The limiting cases of the generalised entropy measures for $\theta = 0$ and $\theta = 1$ can be obtained as special cases of the following integral:

$$\int_l^u x^r (\log x)^m f(x)\,dx = E[X^r (\log X)^m], \tag{2}$$

with $r = 0$, $m = 1$ and $r = m = 1$, respectively. In order to compute the previous integral (2), the following simple lemma is considered.

Lemma 1 *Let X be an absolutely continuous random variable such that* $E(X^r) < \infty$, *for some positive integer* $r \in \{1, 2, \dots, \infty\}$. *If,*

$$g(r) = E(X^r),$$

then,

$$\frac{d^m}{dr^m} g(r) = E[X^r (\log X)^m], \quad m = 1, 2, ...$$

Proof: The proof is direct using differentiation under the integral sign.

Define,

$$u(r, m) = E[X^r (\log X)^m],$$

then,

$$u(0,1) = E(\log X),$$

and

$$u(1,1) = E(X \log X).$$

Now, the relation of the previous quantities with the Theil indices is direct. If it is considered the two Theil indices,

$$T_0(X) = -E\left(\log \frac{X}{\mu}\right),$$

and

$$T_1(X) = E\left(\frac{X}{\mu} \log \frac{X}{\mu}\right),$$

then,

$$T_0(X) = -u(0,1) + \log\mu, \tag{3}$$

and

$$T_1(X) = \frac{1}{\mu}u(1,1) - \log\mu. \tag{4}$$

These expressions of the Theil indices are especially convenient to obtain these measures in a closed form for different parametric distributions. Equation (2) entails as particular cases the formulas used by Jenkins (2009) to obtain the two limiting generalised entropy measures: $GE(0)$ for $r = 0$ and $m = 1$ and $GE(1)$ for $r = 1$ and $m = 1$. Lemma 1 does not only apply to the one-dimensional case, but also to derive higher order moments which are used in Section 4.4 to obtain the multivariate versions of these indices.

4.2 Parametric distributions

In this section the Theil indices of the main parametric distributions are reported. Tables 4.2 and 4.3 include the T_0 and T_1 indices for a number of classical distributions, which are defined in terms of their pdf or their cumulative distribution function (cdf) as presented in Table 4.1, where the moments are also included.

The T_1 index of the classical Pareto distribution can be found in Kleiber and Kotz (2003). Next, the Pareto's hierarchy of distributions introduced by Arnold (2015) has been incorporated. These indices have been obtained from Table 4.1 and Formulas (3)-(4). For the lognormal distribution both coefficients coincide (Kleiber and Kotz, 2003), while for the Champernowne distribution (Champernowne, 1953) the formulas of these coefficients are new.

Table 4.1

Probability density function or cumulative distribution function and moments of some classical distributions

Distribution	Pdf $f(x)$ or cdf $F(x)$	rth Moment $E(X^r)$
Classical Pareto	$f(x;\alpha,\sigma)=\dfrac{\alpha\sigma^{\alpha}}{x^{\alpha+1}},\quad x\ge\sigma>0$	$\dfrac{\alpha\sigma^{r}}{\alpha-r},\quad \alpha>r$
Pareto II	$f(x;\alpha,\sigma)=\dfrac{\alpha}{\sigma(1+x/\sigma)^{\alpha+1}},\quad x\ge 0$	$\dfrac{\sigma^{r}\Gamma(\alpha-r)\Gamma(r+1)}{\Gamma(\alpha)},\quad \alpha>r$
Pareto III	$F(x)=1-\dfrac{1}{[1+(x/\sigma)^{1/a}]},\quad x\ge 0$	$\sigma^{r}\Gamma(1-ra)\Gamma(1+ra),\quad -1/a<r<1/a$
Pareto IV	$F(x)=1-\dfrac{1}{[1+(x/\sigma)^{1/a}]^{\alpha}},\quad x\ge 0$	$\dfrac{\sigma^{r}\Gamma(\alpha-ra)\Gamma(1+ra)}{\Gamma(\alpha)},\quad -1/a<r<\alpha/a$
Lognormal	$f(x;\mu,\sigma)=\dfrac{1}{\sigma x\sqrt{2\pi}}\exp\left[-\dfrac{1}{2}\left(\dfrac{\log x-\mu}{\sigma}\right)^{2}\right],\quad x\ge 0$	$\exp\left(\mu r+\dfrac{1}{2}r^{2}\sigma^{2}\right)$

Note: $\Gamma(z)$ is the usual gamma function and $\mathrm{B}(x,y)=\dfrac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)}$ is the usual beta function.

Table 4.1 Continued

Probability density function or cumulative distribution function and moments of some classical distributions

Distribution	Pdf $f(x)$ or cdf $F(x)$	rth Moment $E(X^r)$
Gamma	$f(x;b,p)=\dfrac{x^{p-1}e^{-x/b}}{b^p\,\Gamma(p)},\quad x\ge 0$	$\dfrac{b^r\,\Gamma(p+r)}{\Gamma(p)},\quad p+r>0$
Champernowne	$f(x;\alpha,\theta,x_0)=\dfrac{\alpha\sin(\theta)}{2\theta x\{\cosh[\alpha\log(x/x_0)]+\cos(\theta)\}},\quad x\ge 0$	$x_0^r\,\dfrac{\pi}{\theta}\dfrac{\sin(r\theta/\alpha)}{\sin(r\pi/\alpha)},\quad -\alpha<r<\alpha$
GG	$f(x;a,b,p)=\dfrac{ax^{ap-1}e^{-(x/b)^a}}{b^{ap}\,\Gamma(p)},\quad x\ge 0$	$\dfrac{b^r\,\Gamma\left(p+r/a\right)}{\Gamma(p)}$
GB1	$f(x;a,b,p,q)=\dfrac{ax^{ap-1}[1-(x/b)^a]^{q-1}}{b^{ap}B(p,q)},\quad 0\le x\le b$	$\dfrac{b^r\,\Gamma\left(p+r/a\right)\Gamma\left(p+q\right)}{\Gamma(p+q+r/a)\,\Gamma(p)}$
GB2	$f(x;a,b,p,q)=\dfrac{a\,x^{ap-1}}{b^{ap}B(p,q)[1+(x/b)^a]^{p+q}},\quad x\ge 0$	$\dfrac{b^r\,\Gamma\left(p+r/a\right)\Gamma\left(q-r/a\right)}{\Gamma(p)\Gamma(q)},\quad -ap<r<aq$

Note: $\Gamma(z)$ is the usual gamma function and $\mathrm{B}(x,y)=\dfrac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)}$ is the usual beta function.

Table 4.2

T_0 indices of some classical distributions

Distribution	$T_0(X)$
Classical Pareto	$-\frac{1}{\alpha}+\log\frac{\alpha}{\alpha-1}, \quad \alpha>1$
Pareto II	$\gamma+\psi(\alpha)-\log(\alpha-1), \quad \alpha>1$
Pareto III	$\log\left[\Gamma(1-a)\Gamma(1+a)\right], \quad a<1$
Pareto IV	$a[\gamma+\psi(\alpha)]+\log\left[\frac{\Gamma(1+a)\Gamma(\alpha-a)}{\Gamma(\alpha)}\right], \quad \alpha>a$
Lognormal	$\frac{\sigma^2}{2}$
Gamma	$-\psi(p)+\log p$
Champernowne	$\log\left(\frac{\pi}{\theta}\frac{\sin(\theta/\alpha)}{\sin(\pi/\alpha)}\right)$
GG	$-\frac{\psi(p)}{a}+\log\frac{\Gamma(p+1/a)}{\Gamma(p)}$
GB1	$-\frac{\psi(p)-\psi(p+q)}{a}+\log\frac{\Gamma(p+q)\Gamma(p+1/a)}{\Gamma(p)\Gamma(p+q+1/a)}$
GB2	$-\frac{\psi(p)-\psi(q)}{a}+\log\frac{\Gamma(p+1/a)\Gamma(q-1/a)}{\Gamma(p)\Gamma(q)}$

Note: γ = 0.5772156649 is the Euler's constant and $\psi(z)=\frac{d\log\Gamma(z)}{dz}=\frac{\Gamma'(z)}{\Gamma(z)}$ is the digamma function.

Table 4.3

T_1 indices of some classical distributions

Distribution	$\boldsymbol{T_1(X)}$
Classical Pareto	$\frac{1}{\alpha-1}-\log\frac{\alpha}{\alpha-1}, \quad \alpha>1$
Pareto II	$1-\gamma-\psi(\alpha-1)+\log(\alpha-1), \quad \alpha>1$
Pareto III	$a[\psi(1+a)-\psi(1-a)]-\log[\Gamma(1-a)\Gamma(1+a)], \quad a<1$
Pareto IV	$a[\psi(1+a)-\psi(\alpha-a)]-\log\left[\frac{\Gamma(1+a)\Gamma(\alpha-a)}{\Gamma(\alpha)}\right], \quad \alpha>a$
Lognormal	$\frac{\sigma^2}{2}$
Gamma	$\psi(p+1)-\log p$
Champernowne	$-\frac{1}{\alpha}\left[\pi\cot\left(\frac{\pi}{\alpha}\right)-\theta\cot\left(\frac{\theta}{\alpha}\right)-\alpha\log(x_0)\right]-\log(\mu)$
GG	$\frac{\psi(p+1/a)}{a}-\log\frac{\Gamma(p+1/a)}{\Gamma(p)}$
GB1	$\frac{\psi(p+1/a)-\psi(p+q+1/a)}{a}-\log\frac{\Gamma(p+q)\Gamma(p+1/a)}{\Gamma(p)\Gamma(p+q+1/a)}$
GB2	$\frac{\psi(p+1/a)-\psi(q-1/a)}{a}-\log\frac{\Gamma(p+1/a)\Gamma(q-1/a)}{\Gamma(p)\Gamma(q)}, \quad q>1/a$

Notes: γ = 0.5772156649 is the Euler's constant and $\psi(z)=\frac{d\log\Gamma(z)}{dz}=\frac{\Gamma'(z)}{\Gamma(z)}$ is the digamma function. In the Champernowne distribution $\mu=E(X)=\frac{x_0\,\pi}{\theta}\frac{\sin(\theta/\alpha)}{\sin(\pi/\alpha)}$.

The Theil indices for the three McDonald (1984) distributions –the generalised gamma (GG) and the generalised beta of the first and second kind (GB1 and GB2)– have been also added. The Theil indices for the GB2 distribution were obtained by Jenkins (2009). For the GG distribution, the T_1 index was obtained by McDonald and Ransom (2008) for $a = 1$ (the classical gamma distribution). These results were also reported by Salem and Mount (1974) and McDonald (1984). Regarding the GB1 distribution, the formulas for this distribution are also new. For the case of the classical beta distribution ($a = 1$), the formula for T_1 was considered by McDonald (1981) and Pham-Gia and Turkkan (1992).

Tables 4.5 and 4.6 report the Theil indices for other income distributions. The corresponding pdfs or cdfs and moments are given in Table 4.4.

Firstly, the indices for the Pareto-lognormal (Colombi, 1990) and for the double Pareto-lognormal distribution, developed by Reed (2003) and studied further by Reed and Jorgensen (2004), have been included. These indices were obtained by Hajargasht and Griffiths (2013). The single and double Pareto distributions are emerging distributions that are derived from a flexibilisation of the assumptions of the economic model that yields the lognormal distribution. This family has good theoretical properties and some evidence has been found in favour of its performance to fit income data (see Hajargasht and Griffiths, 2013).

The Stoppa (1990) distribution is an extension of the classical Pareto distribution, which is obtained as a power transformation of the cdf of the Pareto distribution. Meanwhile, the log-gamma distribution was proposed by Taguchi *et al*. (1993) and it is also considered as a generalised Pareto distribution since the classical Pareto distribution corresponds to the choice $p = 1$.

Table 4.4

Probability density function or cumulative distribution function and moments of other parametric distributions

Distribution	Pdf $f(x)$ or cdf $F(x)$	rth Moment $E(X^r)$
Pareto-lognormal	$f(x)=\frac{\alpha}{x}\phi\left(\frac{\log x-\mu}{\sigma}\right)R(x_1),\quad x\geq 0$	$\frac{\alpha}{\alpha-r}\exp\left(r\mu+\frac{r^2\sigma^2}{2}\right),\quad \alpha>r$
Double Pareto-lognormal	$f(x)=\frac{\alpha\beta}{(\alpha+\beta)x}\phi\left(\frac{\log x-\mu}{\sigma}\right)[R(x_1)+R(x_2)],\quad x\geq 0$	$\frac{\alpha\beta}{(\alpha-r)(\beta+r)}\exp\left(r\mu+\frac{r^2\sigma^2}{2}\right),\quad \alpha>r$
Stoppa	$F(x)=\left[1-\left(\frac{x}{\sigma}\right)^{-\alpha}\right]^{\theta},\quad x\geq\sigma>0$	$\sigma^r\theta B\left(1-\frac{r}{\alpha},\theta\right),\quad r<\alpha$
Log-Gamma	$f(x;\beta,p)=\frac{\beta^p x^{-(\beta+1)}\left[\log(x)\right]^{p-1}}{\Gamma(p)},\quad x\geq 1$	$\left(\frac{\beta}{\beta-r}\right)^p,\quad \beta>r$

Note: $\varphi(z)$ is the pdf of the standard normal distribution and $R(z)=[1-\Phi(z)]/\Phi(z)$ is the Mill's ratio, where $\Phi(z)$ is the cdf of the standard normal distribution, $x_1=\alpha\sigma-(\log x-\mu)/\sigma$, $x_2=\beta\sigma-(\log x-\mu)/\sigma$, $\exp_k(x)=\left(\sqrt{1+k^2x^2}+kx\right)^{1/k}$ is the deformed exponential function.

Table 4.4 Continued

Probability density function or cumulative distribution function and moments of other parametric distributions

Distribution	Pdf $f(x)$ or cdf $F(x)$	rth Moment $E(X^r)$
Inverse Gamma	$f(x)=\dfrac{\lambda^p}{\Gamma(p)}x^{-p-1}e^{-\lambda/x},\quad x\geq 0$	$\lambda^r\dfrac{\Gamma(p-r)}{\Gamma(p)},\quad p>r$
Log-Gompertz	$F(x;a,b)=\exp[-(x/b)^{-a}],\quad x\geq 0$	$b^r\Gamma\left(1-\dfrac{r}{a}\right),\quad r<a$
κ distribution	$f(x;\alpha,\beta,\kappa)=\dfrac{\alpha}{\beta}\left(\dfrac{x}{\beta}\right)^{\alpha-1}\dfrac{\exp_\kappa[-(x/\beta)^\alpha]}{\sqrt{1+\kappa^2(x/\beta)^{2\alpha}}}$	$\dfrac{\beta^r}{(2\kappa)^{r/\alpha}}\dfrac{\Gamma\left(1+\dfrac{r}{\alpha}\right)}{1+\dfrac{r}{\alpha}\kappa}\dfrac{\Gamma\left(\dfrac{1}{2\kappa}-\dfrac{r}{2\alpha}\right)}{\Gamma\left(\dfrac{1}{2\kappa}+\dfrac{r}{2\alpha}\right)},\quad -\alpha/\kappa<r<\alpha/\kappa$

Note: $\varphi(z)$ is the pdf of the standard normal distribution and $R(z)=[1-\Phi(z)]/\Phi(z)$ is the Mill's ratio, where $\Phi(z)$ is the cdf of the standard normal distribution, $x_1=\alpha\sigma-(\log x-\mu)/\sigma$, $x_2=\beta\sigma-(\log x-\mu)/\sigma$, $\exp_\kappa(x)=\left(\sqrt{1+\kappa^2x^2}+\kappa x\right)^{1/\kappa}$ is the deformed exponential function.

Table 4.5

T_0 indices of other parametric distributions

Distribution	$T_0(X)$
Pareto-lognormal	$-\frac{1}{\alpha}+\frac{\sigma^2}{2}-\log\left(\frac{\alpha-1}{\alpha}\right), \quad \alpha>1$
Double Pareto-lognormal	$-\frac{1}{\alpha}+\frac{1}{\beta}+\frac{\sigma^2}{2}-\log\left(\frac{\alpha-1}{\alpha}\right)-\log\left(\frac{\beta+1}{\beta}\right), \quad \alpha>1$
Stoppa	$-\frac{\gamma+\psi(1+\theta)}{\alpha}+\log\left\{\theta B\left(1-\frac{1}{\alpha},\theta\right)\right\}, \quad \alpha>1$
Log-Gamma	$-\frac{p}{\beta}+p\log\frac{\beta}{\beta-1}, \quad \beta>1$
Inverse Gamma	$\psi(p)-\log(p-1), \quad p>1$
Log-Gompertz	$-\frac{\gamma}{a}+\log\Gamma\left(1-\frac{1}{a}\right), \quad a>1$
κ distribution	$\frac{1}{\alpha}\left[\gamma+\psi\left(\frac{1}{2\kappa}\right)+\log(2\kappa)-\alpha\log\left(\frac{\beta}{m}\right)+\kappa\right], \quad \alpha>\kappa$

Note: In the κ distribution $m=E(X)=\frac{\beta}{(2\kappa)^{1/\alpha}}\frac{\Gamma\left(1+\frac{1}{\alpha}\right)}{1+\frac{1}{\alpha}\kappa}\frac{\Gamma\left(\frac{1}{2\kappa}-\frac{1}{2\alpha}\right)}{\Gamma\left(\frac{1}{2\kappa}+\frac{1}{2\alpha}\right)}$.

Table 4.6

T_1 indices of other parametric distributions

Distribution	$T_1(X)$
Pareto-lognormal	$\frac{1}{\alpha-1}+\frac{\sigma^2}{2}+\log\left(\frac{\alpha-1}{\alpha}\right), \quad \alpha>1$
Double Pareto-lognormal	$\frac{1}{\alpha-1}-\frac{1}{\beta+1}+\frac{\sigma^2}{2}+\log\left(\frac{\alpha-1}{\alpha}\right)+\log\left(\frac{\beta+1}{\beta}\right), \quad \alpha>1$
Stoppa	$\frac{\psi(1-1/\alpha+\theta)-\psi(1-1/\alpha)}{\alpha}-\log\left\{\theta B\left(1-\frac{1}{\alpha},\theta\right)\right\}, \quad \alpha>1$
Log-Gamma	$\frac{p}{\beta-1}-p\log\frac{\beta}{\beta-1}, \quad \beta>1$
Inverse Gamma	$\psi(p-1)+\log(p-1), \quad p>1$
Log-Gompertz	$-\frac{\psi(1-1/a)}{a}-\log\Gamma\left(1-\frac{1}{a}\right), \quad a>1$
κ distribution	$\frac{1}{\alpha}\left[\psi\left(1+\frac{1}{\alpha}\right)-\frac{1}{2}\psi\left(\frac{1}{2\kappa}-\frac{1}{2\alpha}\right)-\frac{1}{2}\psi\left(\frac{1}{2\kappa}+\frac{1}{2\alpha}\right)-\log(2\kappa)+\alpha\log\left(\frac{\beta}{m}\right)-\frac{\alpha\kappa}{\alpha+\kappa}\right], \quad \alpha>\kappa$

Note: In the κ distribution $m=E(X)=\frac{\beta}{(2\kappa)^{1/\alpha}}\frac{\Gamma\left(1+\frac{1}{\alpha}\right)}{1+\frac{1}{\alpha}\kappa}\frac{\Gamma\left(\frac{1}{2\kappa}-\frac{1}{2\alpha}\right)}{\Gamma\left(\frac{1}{2\kappa}+\frac{1}{2\alpha}\right)}$.

The inverse-gamma distribution is used in Bayesian analysis as prior distribution in several problems. Note that Formula (5.69) in Kleiber and Kotz (2003) related to the moments of the inverse gamma distribution is not correct, and hence the right expression is reported in Table 4.4. If $p = 1/2$, the Levy distribution is obtained, which is a special case of the stable distributions and it arises as the first-passage ties in Brownian motion. Formulas for the log-Gompertz distribution are also included.

Finally, the Theil indices for the κ-generalised distribution (see Clementi *et al*., 2007, 2012; Clementi *et al*., 2008) are shown. This distribution has been proposed as a descriptive model for the distribution and dispersion of income within a population based on the deformed exponential and logarithmic functions recently introduced by Kaniadakis (2001). In a reasonably large number of cases, the statistical performance of this model is not considered inferior to those of the Singh-Maddala, the Dagum and the GB2 distributions, whereas its ability of matching the entropy of the data dominates these families. These formulas appear in Clementi *et al*. (2010).

4.3 Decomposition of the generalised entropy measures

In this section the decomposition properties of the Theil index are reviewed. It is considered two kinds of decompositions: by factors and by population sub-groups.

Let X_1, X_2, ..., X_m be independent and positive random variables with finite expectations and consider the new random variable:

$$X = \prod_{i=1}^{m} X_i.$$

Then, it is direct to show that,

$$T_k(X) = \sum_{i=1}^{m} T_k(X_i), \quad k = 0,1. \tag{5}$$

Example 1 *Let X be a Pareto-lognormal distribution with pdf given in the first row, Table 4.4. By construction, $X = X_1 \cdot X_2$, where X_1 is a classical Pareto distribution with parameters α and σ, and X_2 a classical lognormal distribution with parameters μ and σ^2 both independent. Then, using* (5) *for* $T_0(X)$,

$$T_0(X) = T_0(X_1) + T_0(X_2) = -\frac{1}{\alpha} + \log\frac{\alpha}{\alpha - 1} + \frac{\sigma^2}{2},$$

which is the formula for the Pareto-lognormal in Table 4.5. A similar reasoning holds for the computation of $T_1(X)$ *using* (5).

Example 2 *Let X be a GB2 distribution with shape parameters* (*a*, *p*, *q*) *and unit scale. It is well known that X can be written as $X = X_1 / X_2$, where X_1 and X_2 are independent generalised gamma distributions, with unit scale parameters and shape parameters* (*a*, *p*) *and* (*a*, *q*), *respectively* (*see chapter 6 in Kleiber and Kotz, 2003*). *The random variable* X_2^{-1} *is distributed as an inverted generalised gamma distribution with Theil index,*

$$T_0(X_2^{-1}) = \frac{\psi(q)}{a} - \log\frac{\Gamma(q - 1/a)}{\Gamma(q)}, \quad \text{if } q > 1/a.$$

Then,

$$T_0(X) = T_0(X_1) + T_0(X_2^{-1}) = -\frac{\psi(q)}{a} + \log\frac{\Gamma(p + 1/a)}{\Gamma(p)} + \frac{\psi(q)}{a} - \log\frac{\Gamma(q - 1/a)}{\Gamma(q)},$$

which is the formula shown in Table 4.2. In a similar way it is obtained the $T_1(X)$ *index for the GB2 distribution.*

Empirical analyses of the distribution of GHGs frequently require decomposing inequality by population sub-groups to account for different behaviour patterns by country or region, for instance. The generalised entropy measures are of special interest, being the sole indices of relative inequality which are additively decomposable into a component that captures the inequality when the differences between average emissions of each group are only considered (between-group inequality) and another that is calculated as the weighted sum of the inequality values of each group (within-group inequality) (Shorrocks, 1980).

If the world population is divided into K mutually exclusive groups, the GHG distribution can be defined as a mixture of the distributions of those groups weighted by their population shares:

$$f(x) = \sum_{k=1}^{K} \lambda_k f_k(x;\Theta),$$

where λ_k stands for the population weights of the groups. The global cdf would be the integral of the pdf given by the previous equation:

$$F(x) = \sum_{k=1}^{K} \lambda_k F_k(x;\Theta).$$

The mean of this distribution is a weighted sum of the average emissions of each group given by,

$$\mu = \sum_{k=1}^{K} \lambda_k \mu_k,$$

where μ_k is the first moment of the emission distribution in each group, which can be obtained from Tables 4.1 and 4.4.

Overall generalised entropy measures can be expressed in terms of the analytical expression of the decomposition given by:

$$GE(\theta) = \frac{1}{\theta(\theta-1)}\left[\sum_{k=1}^{K}\lambda_k\left(\frac{\mu_k}{\mu}\right)^{\theta} - 1\right] + \sum_{k=1}^{K}\lambda_k^{1-\theta} s_k^{\theta}\, GE_k(\theta), \qquad (6)$$

where λ_k and $GE_k(\theta)$ are the population share and the generalised entropy measure of the group *k*, respectively and s_k stands for the proportion of average emissions of the group *k* in the global average emissions:

$$s_k = \frac{\lambda_k\,\mu_k}{\mu} = \frac{\lambda_k\,\mu_k}{\sum_{k=1}^{K}\lambda_k\,\mu_k}.$$

The first component reflects the level of inequality that would exist if all countries in the group emitted the same quantity of emissions. This is equivalent to removing any differences within the group by replacing each emission level by the mean of the group.

The second component in Equation (6) measures the within-group inequality, given by the weighted sum of disparities in each group. The weights are given by:

$$w_k = \lambda_k^{1-\theta} s_k^{\theta},$$

and they depend on the proportion of population of each group and the share of their per capita emissions in the overall mean. Interestingly, these weights add up to one only for the two limit cases corresponding to the Theil indices, which can be expressed as:

$$T_0 = \sum_{k=1}^{K}\lambda_k T_{0k} + \sum_{k=1}^{K}\lambda_k \log\left(\frac{\mu}{\mu_k}\right),$$

and

$$T_1 = \sum_{k=1}^{K} s_k T_{1k} + \sum_{k=1}^{K} s_k \log\left(\frac{\mu_k}{\mu}\right),$$

where T_{0k} and T_{1k} are, respectively, the T_0 and T_1 indices of the group k, which can be taken from Tables 4.2, 4.3, 4.5 and 4.6.

Interestingly, only the T_1 index is consistent with the concept "emission-weighted decomposability", which defines the decomposition coefficients in terms of the emission shares (Bourguignon, 1979). Alternative candidates for the weights would be population shares, thus resulting in the so-called "population-weighted decomposability" only satisfied by the T_0 index. It should be noted that the within-group component is a weighted average of inequalities within groups only for these two measures. This is an interesting feature from an accounting point of view (Lambert, 1993). Theil (1969) pointed out a relevant advantage of these measures. The term

$$1 - \sum_{k=1}^{K} w_k$$

is proportionate to the between-group component, and hence the decomposition coefficients are independent to differences between groups only for the two special cases T_0 and T_1.

4.4 Extensions to higher dimensions

In this section possible extensions of these indices to higher dimensions are sketched. Let $\boldsymbol{X} = (X_1, ..., X_m)^T$ be an m-dimensional vector with non-negative components. The m-dimensional Theil indices are defined as:

$$T_0^{(m)}(\boldsymbol{X}) = -E\left[\log\left(\frac{X_1 \cdots X_m}{\mu_{12\cdots m}}\right)\right], \tag{7}$$

and

$$T_1^{(m)}(\boldsymbol{X}) = -E\left[\frac{X_1 \cdots X_m}{\mu_{12\cdots m}} \log\left(\frac{X_1 \cdots X_m}{\mu_{12\cdots m}}\right)\right], \tag{8}$$

where

$$\mu_{12\cdots m} = E(X_1 \cdots X_m) < \infty.$$

For the bivariate case m = 2, expression (7) can be written as:

$$T_0^{(2)}(\boldsymbol{X}) = -E(\log X_1) - E(\log X_2) + \log \mu_{12}, \tag{9}$$

and (8) can be expressed as:

$$T_1^{(2)}(\boldsymbol{X}) = \mu_{12}^{-1}[E(X_1 X_2 \log X_1) + E(X_1 X_2 \log X_2) - \mu_{12} \log \mu_{12}], \tag{10}$$

where $\mu_{12} = E(X_1 X_2)$. For computing the terms in (10), it is defined

$$u(r_1, r_2) = E(X_1^{r_1} X_2^{r_2}),$$

then

$$v_1(r_1, r_2) = \frac{\partial u(r_1, r_2)}{\partial r_1} = E(X_1^{r_1} X_2^{r_2} \log X_1), \tag{11}$$

and

$$v_2(r_1, r_2) = \frac{\partial u(r_1, r_2)}{\partial r_2} = E(X_1^{r_1} X_2^{r_2} \log X_2). \tag{12}$$

In consequence:

$$v_1(1,1) = E(X_1 X_2 \log X_1),$$

and

$$v_2(1,1) = E(X_1 X_2 \log X_2).$$

If $\boldsymbol{X} = (X_1, X_2)^T$ is a bivariate lognormal distribution with joint pdf,

$$f_{\boldsymbol{X}}(x_1, x_2) = \frac{1}{2\pi x_1 x_2 \sqrt{|\Sigma|}} \exp\left[-\frac{1}{2} (\log x - \mu)^T \Sigma^{-1} (\log x - \mu) \right].$$

where $x = (x_1, x_2)^T$, $\mu = (\mu_1, \mu_2)^T$. Then:

$$E(X_1^{r_1}, X_2^{r_2}) = \exp\left(r^T \mu + \frac{1}{2} r^T \Sigma r \right),$$

being $r = (r_1, r_2)^T$. Using (9)-(10) and (11)-(12) it is obtained,

$$T_0^{(2)}(\boldsymbol{X}) = T_1^{(2)}(\boldsymbol{X}) = \frac{\sigma_1^2}{2} + \frac{\sigma_2^2}{2} + \sigma_{12},$$

where both bivariate indices are the same, similar to the univariate case.

4.5 Application to CO_2 emissions

In this section, the global inequality in per capita CO_2 emissions in 2012 is studied using the expressions obtained in this chapter for the generalised entropy measures.

The data used in this empirical application have been taken from the Climate Analysis Indicators Tool database (CAIT, 2015), developed by the World Resources Institute[75]. The per capita CO_2 emissions of each country are

[75] Data come from different nongovernmental sources: The Carbon Dioxide Information Analysis Center (Boden *et al.*, 2015), the Food and Agriculture Organization of the United Nations (FAO, 2014), the International Energy Agency (IEA, 2014), the World Bank (World Bank, 2014), the U.S. Energy Information Administration (EIA, 2014) and the U.S. Environmental Protection Agency (U.S. EPA, 2012b).

measured in $MtCO_2e$ using the 100-year GWPs published in the IPCC (1996). This variable is studied across all the countries with available information[76] in the year 2012. Data has been summarized in Table 4.7 showing the mean, the standard deviation, the minimum and maximum values and the number of observations; and it has been represented in Figure 4.1.

Table 4.7

Descriptive statistics of the per capita CO_2 emissions in 2012

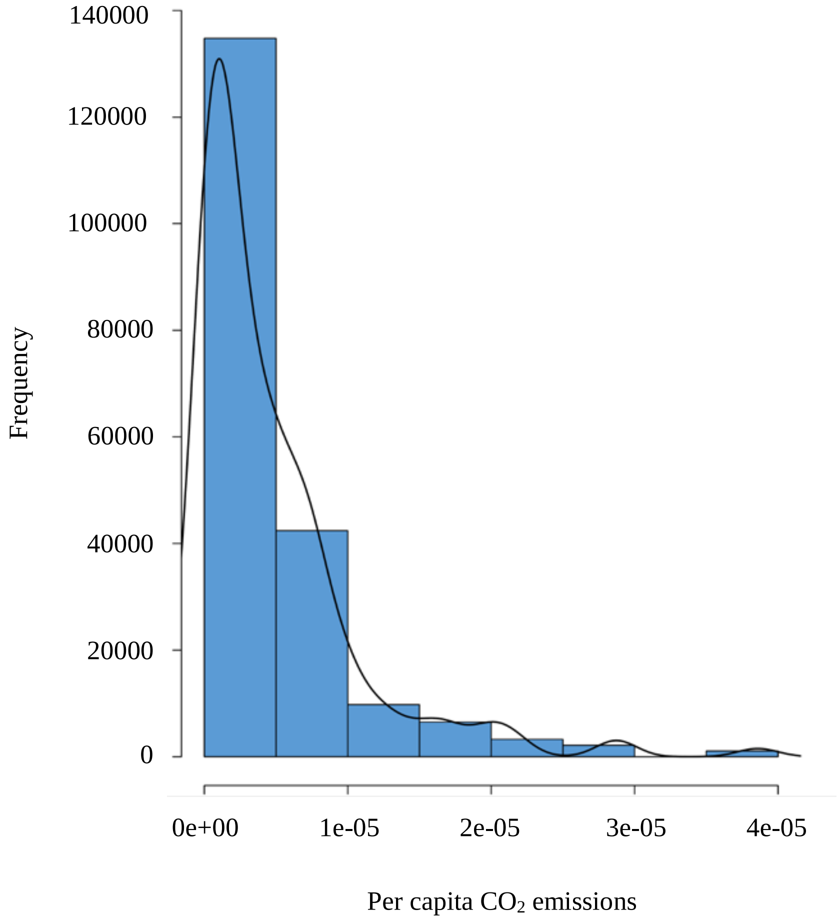
Descriptive statistics	**Value**
Mean	4.6932e-06
Standard deviation	5.8806e-06
Minimum value	2.1232e-08
Maximum value	3.8591e-05
Number of observations	184

It can be deduced from Figure 4.1 that the information on the per capita CO_2 emissions is positively skewed which justifies the use of positively skewed distributions to model the data. The choice of the best distribution to fit the data will depend in large part on the degree of asymmetry observed in the data. Thus, for modelling moderate positive skewness, the lognormal, gamma and Weibull distributions will be usually appropriate. However, when the skewness becomes more severe, as it happens in this case, it will be necessary to consider a distribution with more parameters.

[76] It is studied the year 2012 which is the last year for which the WRI provides information on the variable under study.

Figure 4.1

Distribution of the per capita CO_2 emissions in 2012



Therefore, the GB2 distribution proposed by McDonald (1984) has been considered to model the per capita CO_2 emissions. As the GB2 distribution is widely acknowledged to give an excellent description of income distributions, providing fine goodness-of-fit with relative parsimony[77] (Jenkins, 2009), it is expected that this model will properly characterize the

[77] The GB2 distribution includes the usual second kind beta distribution (a = 1), the Singh-Maddala distribution (p = 1) (Singh and Maddala, 1976), the Dagum (1977) distribution (q = 1), the Lomax or Pareto II distribution (a = p = 1) and the Fisk or log-logistic distribution (p = q = 1) (see Kleiber and Kotz, 2003).

distribution of emissions. The GB2 is a four-parameter distribution where *a*, *b* and *q* are the shape parameters –which control the tail behaviour of the model– and *p* is the scale parameter.

The parameters of the distribution under study (GB2) have been estimated using the method of maximum likelihood estimation as it has many desirable properties[78]. Estimates of the GB2 parameters[79] are shown in Table 4.8.

Table 4.8

Values of the estimated parameters of the GB2 distribution

Estimated parameter	Value
a	1.4472e+00
b	1.5349e-05
p	4.5607e-01
q	2.7251e+00

In order to verify the goodness of fit of the model to the distribution of the per capita CO_2 emissions in the year 2012, the Q-Q plot and the P-P plot[80] are shown in Figure 4.2. It is observed that the distribution of emissions, most notably the right tail, is well-captured by the proposed model.

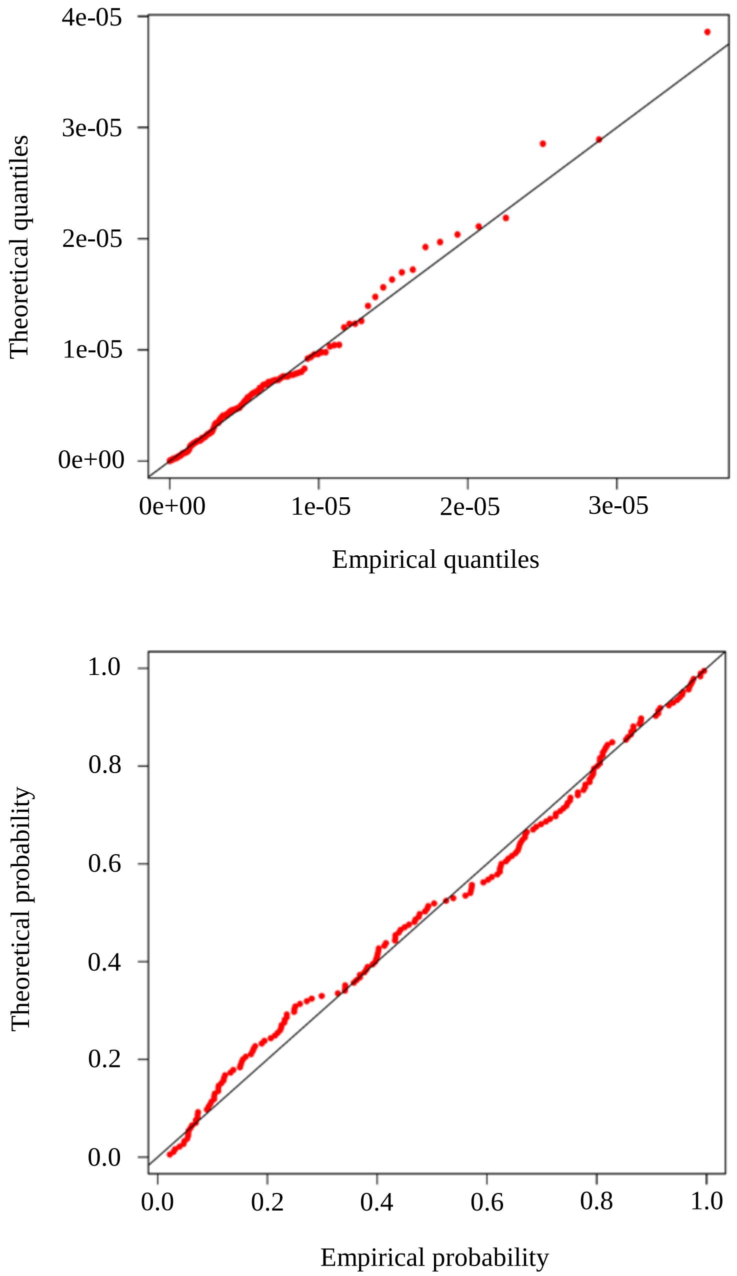
[78] The maximum likelihood estimator is consistent, invariant, asymptotically normal and asymptotically efficient.

[79] It has been used the package GB2 –Generalized Beta Distribution of the Second Kind: Properties, Likelihood, Estimation– in R-program to obtain the parameter estimates (Graf and Nedyalkova, 2015). Moment estimates of the parameters of the Fisk distribution has been used as starting values for the nonlinear optimization of the likelihood of the GB2 distribution (Graf and Nedyalkova, 2014). The system of simultaneous equations used to estimate the parameters of the GB2 distribution is shown in the Appendix 4.1.

[80] The Q-Q plot and P-P plot are two graphical methods used to check the validity of a distributional assumption for a data set. The first (second) displays the empirical quantiles (cumulative distribution function) against the theoretical quantiles (cumulative distribution function) of a GB2 distribution (straight line).

Figure 4.2

Q-Q plot (top panel) and P-P plot (bottom panel) for the per capita CO_2 emissions in 2012



The inequality in the per capita CO_2 emissions in the year 2012 is investigated computing different generalised entropy measures which allow us to vary the sensitivity of the inequality measures to the different parts of the distribution: the T_0, T_1 and $GE(2)$ indices. While the T_0 index corresponds to the GE index when the parameter is equal to 0, being more sensitive to the transfers at the bottom tail of the distribution; the T_1 index is associated with a parameter equal to 1, being equally sensitive to all parts of the distribution. Meanwhile, the $GE(2)$ index gives more weight to the differences at the right tail. In particular, for the GB2 distribution, the expression of the $GE(2)$ measure is given by:

$$GE(2) = -\frac{1}{2} + \frac{\Gamma(p)\Gamma(q)\Gamma\left(p+\frac{2}{a}\right)\Gamma\left(q-\frac{2}{a}\right)}{2\Gamma^2\left(p+\frac{1}{a}\right)\Gamma^2\left(q-\frac{1}{a}\right)}.$$

Table 4.9 presents the T_0, T_1 and $GE(2)$ indices for the GB2 distribution estimated. The influence of the sensitivity parameter on the inequality can be observed. Thus, the highest inequality value was exhibited when the most polluting countries received more weight (0.9308), closely followed by the T_0 index (0.9050). On the contrary, the T_1 index presented a moderate level of inequality (0.6173).

Table 4.9

Inequality in the per capita CO_2 emissions in 2012

Inequality index	**Value**
T_0 index	0.9050
T_1 index	0.6173
GE(2) index	0.9308

4.6 Conclusions

In this chapter some of the existing formulas of the Theil indices for several parametric distributions are reviewed. The *GE* family of inequality measures has been widely used to study concentration and inequality. Its property of decomposability makes these indices particularly useful for studying socioeconomic inequalities. This family includes a sensitivity parameter that varies the weight given to the emission transfers that may occur at the different parts of the distribution. Despite its importance, the expressions of these inequality measures are only available for a few families of distributions. The derivation of closed expressions of the *GE* measures is relatively straightforward using the theoretical moments of the parametric distributions. However, the Theil indices are limiting cases of this family and they cannot be obtained so directly.

Therefore, a convenient general expression for the Theil indices is presented which allows us to obtain these inequality measures for many of the most important parametric distributions and to derive a multivariate extension of these measures. In particular, closed expressions of the T_0 and T_1 indices for the Champernowne (1952) distribution, the generalised gamma and generalised beta of first and second kind distributions (McDonald, 1984), the κ-generalised income distribution (Clementi *et al*., 2007), several Pareto and gamma-type distributions are included. The decomposition of the *GE* measures and the proposed extension of the Theil's indices to higher dimensions is also described.

As an empirical application, the global inequality in the per capita CO_2 emissions in the year 2012 is studied using the expressions obtained in this chapter for the generalised entropy measures. Given that the distribution of the per capita CO_2 emissions is positively skewed and exhibits a right heavy tail, the GB2 distribution (McDonald, 1984) has been considered to model the data. The GB2 distribution can be considered as an appropriate model for fitting the per capita CO_2 emissions as confirmed by the Q-Q plot and the P-P plot. The inequality analysis has been carried out computing different generalised entropy measures –the T_0, T_1 and $GE(2)$ indices–, varying the sensitivity of the inequality measures to the different parts of the distribution. The results indicate that the $GE(2)$ exhibited the highest inequality value, closely followed by the T_0 index. On the contrary, the T_1 index presented the lowest level of inequality.

Conclusiones

Conclusiones

La actual concentración de emisiones de GEI a nivel mundial provocará en las próximas décadas un mayor calentamiento global. Por este motivo, el actual debate sobre cambio climático se focaliza en la limitación del incremento de la temperatura global a 1,5 grados centígrados, con respecto a los niveles registrados en 1990, con el objetivo último de atenuar su impacto. En este sentido, la evidencia de una reducción de la desigualdad en las emisiones de GEI podría alentar a los países a establecer un acuerdo multilateral más ambicioso. Sin embargo, dado que para frenar el cambio climático no es necesaria la igualdad en las emisiones de GEI, sino el control y la reducción de las mismas, será preciso que las políticas ambientales implementadas persigan el siguiente objetivo: disminuir la desigualdad internacional en las emisiones de GEI sin incrementar el nivel global de las mismas.

En este contexto, el objetivo de la presente Tesis Doctoral ha sido analizar la desigualdad en la distribución de las emisiones atmosféricas a través de la familia de índices de entropía generalizada. Este trabajo se estructura en cuatro capítulos que tratan de dar respuesta a distintas cuestiones relacionadas con la desigualdad internacional en las emisiones de GEI.

En esta última sección se presentan los principales resultados e implicaciones en términos de política ambiental, así como las posibles líneas futuras de investigación que se derivan de los cuatro estudios realizados. Para una lectura más detallada de las conclusiones de cada uno de ellos, debe consultarse el capítulo correspondiente.

La actividad llevada a cabo en los distintos sectores origina emisiones atmosféricas que provocan el cambio climático, siendo el CO_2 el GEI más abundante en la atmósfera. Dada la importancia de estabilizar la concentracción atmosférica de sus emisiones, todos los sectores deben ser menos intensivos en CO_2, de acuerdo a sus capacidades y a sus perspectivas de evolución. Por todo ello, en el Capítulo 1 se estudia la desigualdad en las emisiones de CO_2 existente en cada sector en el año 2009, a partir de los datos proporcionados por la AIE y recurriendo al índice de Theil. Asimismo, dicha desigualdad se descompone en sus componentes interregional e intrarregional, tomando como referencia las agrupaciones de países consideradas por el PNUD.

El análisis destaca al sector industrial por sus bajos niveles de desigualdad en lo que a la distribución de las emisiones de CO_2 se refiere; por el contrario, el sector con mayor desigualdad es el aglomerado “otras industrias energéticas”. La componente de desigualdad intrarregional desempeñó, de forma general, un papel muy importante en todos los sectores salvo en el de transporte. La importancia de la componente interregional en el sector transporte y en el sector transporte por carretera pone de manifiesto que en estos sectores los avances tecnológicos se propagan, en un primer momento, dentro de las regiones, para extenderse a continuación de una región a otra. A nivel global, las regiones con menor y mayor desigualdad interna fueron la OECD y África Subsahariana, respectivamente.

Para completar el estudio anterior, se ha analizado también la sensibilidad del índice ante las transferencias de emisiones de CO_2 que puedan tener lugar en las diferentes partes de la distribución, utilizando la familia de índices de entropía generalizada. Con independencia de la sensibilidad de los índices a las diferencias de emisiones en la cola baja o alta de la distribución, los resultados obtenidos muestran que la componente de desigualdad intrarregional sigue siendo el elemento con mayor importancia relativa en todos los sectores y que África Subsahariana fue la zona geográfica con el mayor grado de desigualdad interna. Por el contario, la OCDE mostró un nivel bajo de concentración en ambas partes de la distribución lo cual puede deberse a la existencia de interdependencia sectorial en los países que pertenecen a esta región.

Como se ha puesto de manifiesto, un solo indicador no proporciona la imagen completa del comportamiento de las emisiones de CO_2 de un país. Para continuar con el análisis previo, en el Capítulo 2 se recurre a los factores de Kaya para analizar nuevas fuentes de desigualdad en las emisiones de CO_2 en el periodo 1990-2010. En particular, la desigualdad se descompone en cuatro factores: las emisiones de CO_2 por unidad de electricidad producida, la intensidad de la producción eléctrica en el PIB, la productividad media de la población ocupada y la tasa de ocupación, a partir de los datos facilitados por la AIE y utilizando el índice de Theil. Además, dicha desigualdad se descompone por grupos de población considerando las regiones contempladas por la AIE.

Los resultados revelan una caída de la desigualdad mundial en las emisiones de CO_2 por población activa, cuantificada en un 22 por ciento entre el año 1990 y el año 2010. El grueso de la desigualdad vino originado por la productividad media de la población ocupada. Por tanto, la transferencia de tecnología entre países con diferentes niveles de desigualdad permitirá una mayor convergencia en dicho factor y, por ende, en las emisiones de CO_2. Si bien, para que los países en desarrollo sean capaces de promover sus propios proyectos en el futuro serán necesarias tanto difusiones tecnológicas como transferencias de conocimiento. Por su parte, la reducción de la desigualdad en las emisiones de CO_2 por unidad de electricidad producida puede tener varias explicaciones: los avances tecnológicos en la generación de electricidad, la mejora de la intensidad energética del sector eléctrico o la transición hacia una matriz energética más diversificada que incluya como fuentes de energía, por ejemplo, al gas natural y a las energías renovables.

Por otra parte, la descomposición de la desigualdad en las componentes interregional e intrarregional muestra su contribución a la explicación de la desigualdad global durante el período estudiado. El descenso moderado y leve de la desigualdad asociada a las componentes interregional e intrarregional, respectivamente, evidencia que el conjunto de medidas orientadas a reducir la concentración de emisiones de CO_2 en la atmósfera han logrado su objetivo, en mayor medida, entre las distintas regiones de países que dentro de cada una de las mismas. Por último, mientras que África ha sido la región con el mayor nivel de desigualdad interna durante todo el periodo, seguida de Asia y Oriente Medio; China ha sido el territorio con la menor desigualdad intrarregional.

En términos de política ambiental, el descenso de la desigualdad podría facilitar que los intereses individuales no prevalecieran en las negociaciones internacionales. Dado que las diferencias en el crecimiento económico fueron el factor más relevante para explicar la desigualdad de las emisiones de CO_2, las diferencias en el PIB per cápita deben estar correlacionadas con los esfuerzos exigidos a cada país en la lucha contra el cambio climático.

Además, las desigualdades existentes dentro de las distintas regiones y entre cada una de ellas refuerzan la aplicación del principio del Protocolo de Kyoto de “responsabilidad común pero diferenciada”.

La actividad humana llevada a cabo durante la era industrial ha dado lugar a un incremento drástico tanto de las emisiones de CO_2 como de otros GEI. Estos últimos juegan también un papel importante en el conocimiento del cambio climático global y en la lucha contra el mismo. Sin embargo, las negociaciones para lograr reducir las emisiones se construyen a través de alianzas de grupos de países, siendo necesario, además de los análisis de la desigualdad, llevar a cabo estudios de polarización con el fin de capturar el posible conflicto de intereses inherente a la distribución de GEI. Por este motivo, en el Capítulo 3 se realiza un análisis de desigualdad y polarización desde una perspectiva multidimensional, considerando las emisiones de CO_2, CH_4, N_2O y F-gases durante el período 1990-2011. Para ello, se utilizan las medidas multidimensionales de entropía generalizada propuestas por Maasoumi (1986) –que admiten la descomposición por grupos de población– y los índices multidimensionales de polarización desarrollados por Gigliariano y Mosler (2009).

Los resultados obtenidos en el análisis de desigualdad multidimensional dependen del peso asignado a las diferentes partes de la distribución. Así, cuando se pondera en mayor medida a los países más contaminantes, se observa una tendencia creciente de la desigualdad durante todo el periodo, asumiendo un grado de sustitución entre gases perfecto o muy alto. Por su parte, cuando se supone un menor grado de sustitución entre los contaminantes, se observa una reducción de la desigualdad en la emisión de GEI. Ese mismo patrón de comportamiento se observa cuando todos los países tienen el mismo peso. Por el contrario, en los escenarios en los cuales los cambios producidos en los países menos contaminantes priman sobre el resto de la distribución, la desigualdad en las emisiones de GEI disminuyó durante el periodo 1990-2011, con independencia del grado de sustitución entre los gases.

Los resultados relativos a la descomposición de las medidas de entropía generalizada por grupos de población permiten concluir que, mientras que la desigualdad interregional es un factor dominante cuando el grado de sustitución entre gases es perfecto o muy alto, la desigualdad intrarregional recibe una mayor importancia cuando se admite un menor grado de sustitución entre los contaminantes.

Para llevar a cabo el análisis de polarización multidimensional, la muestra se ha divido en cuatro y ocho grupos, asumiendo que todos los países reciben el mismo peso y que el grado de sustitución entre los gases es perfecto. Mientras que los índices P_2 y P_3 mostraron una tendencia ligeramente creciente con independencia del número de grupos considerados, el índice P_1 experimentó un aumento que se acentuó al considerar un número mayor de grupos.

En términos de política ambiental cabe señalar lo siguiente. Por un lado, el compromiso alcanzado en la CMNUCC en 1992, para adoptar medidas que estabilicen la concentración de emisiones de GEI en la atmósfera, puede ser uno de los factores que han contribuido a la disminución de la desigualdad cuando se da más importancia a las diferencias entre los países más contaminantes. Además, la similitud de estos resultados con los observados cuando todos los países reciben el mismo peso da luz verde al uso de otras medidas de desigualdad que no admitan la asignación de un peso diferente a las diferentes partes de la distribución.

Por otro lado, es probable que la evolución experimentada por los índices de polarización P_2 y P_3 desde 1990 hasta 2011 favorezca la implementación de acuerdos internacionales por dos razones. En primer lugar, porque los niveles de polarización fueron similares, con independencia del número de grupos considerado; y en segundo lugar, porque este fenómeno experimentó un ligero aumento desde 1990 hasta 2011 a pesar de agrupar a los países en base a su nivel de emisiones per cápita en el año 2011.

Con el fin de reducir la polarización en la distribución global de GEI, este análisis sugiere dos direcciones a seguir por las medidas de política ambiental. Por un lado, cuando se atribuye el mismo peso a todos los países y el grado de sustitución entre los gases es perfecto o muy alto, la atenuación debe proceder de la convergencia en las emisiones medias de los distintos grupos de países, dado que la heterogeneidad entre los grupos es la componente más importante. Por otro lado, en el resto de escenarios, ya que la diferencia entre los grupos era menor, la reducción de la desigualdad debe explicarse a través de la moderación de la cohesión intrarregional.

Por último, en el Capítulo 4 se presenta una expresión de los índices de Theil que permite analizar la desigualdad en las emisiones de GEI considerando las distribuciones paramétricas más relevantes –la distribución Champernowne (1952), las distribuciones GG, GB1 y GB2 (McDonald, 1984), la distribución κ-generalizada (Clementi *et al*., 2007) y varias distribuciones de tipo Pareto y gamma– y derivar expresiones cerradas para versiones multivariadas de los mismos. A nivel empírico se analiza la desigualdad en las emisiones de CO_2 en el año 2012 por ser el principal GEI. Dado que la distribución de las emisiones de CO_2 per cápita es asimétrica positiva y presenta una cola derecha pesada, se ha ajustado la distribución GB2 (McDonald, 1984) a los datos de emisiones. Para analizar la desigualdad se han calculado diferentes medidas de la familia de entropía generalizada: la desviación logarítmica media, el índice de entropía de Theil y la medida de entropía generalizada de orden 2. El mayor nivel de desigualdad se observa en el último indicador, seguido de cerca por la desviación logarítmica media. Por el contrario, el índice de entropía de Theil registró el nivel de desigualdad más bajo.

Los cuatro estudios desarrollados en esta Tesis Doctoral analizan diferentes aspectos relativos a la desigualdad en las emisiones de GEI y a partir de ellos se derivan una serie de líneas de investigación que se pueden abordar en futuras investigaciones.

En relación al Capítulo 1, sería muy interesante ampliar el estudio a un mayor número de sectores. La disponibilidad de datos en un futuro próximo permitirá investigar qué actividades humanas son las principales fuentes de emisiones de GEI. Además, el análisis de la evolución temporal de esta desigualdad se convertirá en una herramienta muy útil para diseñar políticas de reducción del nivel global de emisiones.

Como la población es un factor clave a la hora de plantear nuevas y mejores políticas climáticas, los resultados obtenidos en el Capítulo 2 sugieren una extensión del mismo que tenga en cuenta la desagregación de la población en edad de trabajar por tramos de edad (de 20 a 34 años y de 35 a 64 años) de forma que sea posible estudiar el efecto que cada cohorte tiene sobre la desigualdad en las emisiones de CO_2.

Las predicciones sobre las futuras emisiones de CO_2 permiten evaluar cuál será el impacto del cambio climático en el futuro, así como determinar el coste asociado al mismo. Teniendo en cuenta que la futura evolución de las emisiones de CO_2 es muy incierta, diferentes instituciones y grupos de investigación han predicho el futuro nivel de emisiones de CO_2, en base a una serie de supuestos. Por esta razón, además de estudiar las fuentes de la desigualdad en las emisiones históricas de CO_2 tal y como se plantea en el Capítulo 2, sería pertinente examinar los determinantes de la desigualdad de las emisiones futuras bajo diferentes escenarios de emisiones. Esta investigación permitirá establecer una estrategia específica en todas aquellas regiones con un patrón similar en el consumo energía, el crecimiento económico y la distribución de la población.

Por su parte, el análisis realizado en el Capítulo 3 presenta las siguientes limitaciones. En primer lugar, los datos de emisiones de GEI utilizados en este trabajo proceden de los inventarios nacionales de emisiones basados en la producción. Por lo tanto, para analizar la sensibilidad de los resultados, se podría realizar el mismo estudio teniendo en cuenta los datos de emisiones que se derivan de los inventarios nacionales de emisiones basados en el consumo. En segundo lugar, dado que los índices multidimensionales de desigualdad propuestos por Maasoumi (1986) consideran a cada país como una unidad, independientemente del tamaño de su población, sería muy interesante desarrollar su correspondiente versión ponderada que permitiera dar un peso diferente a cada país en base a su participación en la población mundial. En tercer lugar, ya que este estudio no proporciona ningún tipo de información acerca de la desigualdad dentro de cada una de las regiones, la aplicación de este análisis a una región específica podría ser de gran importancia para diseñar políticas regionales efectivas. Por último, llevar a cabo un análisis sobre la evolución de la polarización multidimensional en el que los grupos de países puedan estar constituidos de manera diferente cada año, complementaría en gran medida el análisis presentado en este trabajo.

La futura disponibilidad de datos permitirá asimismo investigar la evolución de la desigualdad mundial en las emisiones de GEI considerando un mayor número de ellos que, sin duda, será una herramienta valiosa para la implementación de políticas climáticas. Además, un estudio similar que abarque un período de tiempo más largo será capaz de mostrar los efectos de los últimos acuerdos internacionales sobre la desigualdad.

Por último, una extensión de las expresiones de los índices de Theil presentadas en el Capítulo 4 consistiría en derivar las expresiones multivariadas de los mismos para las distribuciones paramétricas más relevantes. El desarrollo de estas expresiones permitiría ajustar una distribución a los datos de emisiones de GEI y, por lo tanto, evaluar el nivel de desigualdad asociado a las mismas.

Conclusions

Conclusions

Given the global concentration of GHG emissions in the atmosphere, further warming will unavoidably occur over the next several decades. Then, the current debate on climate change is over whether global warming can be limited to 1.5 degrees Celsius' rise, compared to pre-industrial levels, in order to lessen its impacts. In this sense, evidence of a decrease in the inequality in GHG emissions could encourage countries to establish a stronger multilateral climate change agreement. However, it should be highlighted that to curb climate change the equality in GHG emissions is not necessary but the reduction and control of them. Then, it will be necessary for the environmental policies to meet the following objective: decrease the inequality in GHG emissions without increasing the global level of the same.

In this context, this Doctoral Thesis analyses the global inequality of the distribution of atmospheric emissions using the family of generalised entropy measures. It has been organised into four chapters that, in spite of addressing different research questions, all deal with the international inequality in GHG emissions.

This final section concludes the Thesis including, on the one hand, the principal findings and policy implications derived from the four studies and, on the other hand, the possible future research lines. At the end of each chapter of this work are the specific conclusions obtained in each one; therefore, for a more detailed conclusion of the results one should consult the pertinent chapter.

The activity which takes place in the different sectors originates atmospheric emissions that cause climate change, being the CO_2 the most abundant GHG in the atmosphere. Given the importance of stabilizing the atmospheric concentration of the previous gas, all sectors must be less intensive in CO_2 according to their capabilities and prospects of evolution. Thus, in Chapter 1, the inequality in the global distribution of CO_2 emissions by sector in 2009 is studied, using the data provided by the IEA and the Theil index as inequality tool. To analyse the decomposition of such inequality into their interregional and intraregional components, the regions covered by the UNDP are considered.

The results show that the manufacturing and construction sector was the one with the least inequality in the distribution of CO_2 emissions; on the contrary, the sector with the greatest inequality was the agglomerate “other energy industries”. The within-group inequality component was generally the largest contributor to total inequality but in the transport activities. Thus, the importance of the between-group inequality component in the transport sector points out that technological advances are propagated, firstly, within each region and secondly, from one region to another. As for the regional inequality, it can be seen that, globally, the region with the lowest inequality was the OECD, being Sub-Saharan Africa the one with the greatest internal inequality.

To complete the previous study, the sensitivity of the index to the CO_2 emissions transfers that may occur in the in the upper or lower tail of the distribution has been also studied, using the family of generalised entropy measures. Regardless of the weight assigned to the different parts of the distribution, the results show that the within-group inequality component remained the predominant contributor to global inequality in all the sectors, being Sub-Saharan Africa the geographical area with the highest degree of internal inequality. On the opposite side, the OECD showed a low level of concentration in both tails of the distribution which can be interpreted as a phenomenon of sectoral interdependence in the countries that belong to this geographical area.

As no single indicator can provide a complete picture of a country's CO_2 emissions performance, in Chapter 2, other determinants behind the inequality in CO_2 emissions from 1990 to 2010 are studied, based on the Kaya factors. Using the data provided by the IEA and the Theil index, CO_2 emissions inequality is decomposed into the following factors: carbon intensity of electricity production, electricity intensity of GDP, economic growth in terms of labour production and employment rate. In addition, that inequality is decomposed by population sub-groups considering the regions covered by the IEA.

The results show that global inequality in CO_2 emissions by active population had declined by 22 percent between 1990 and 2010. The bulk of inequality was caused by the economic growth in terms of labour productivity. Thus, technology transfers from developed countries to those that have a lower development will allow a greater convergence in this factor and therefore in the CO_2 emissions. It should be noted that knowledge transfers are as necessary as equipment diffusions so that developing countries will be able to promote their own projects in the future. Meanwhile, the decreasing inequality trend of the electricity intensity of the whole economy may come from technological development within electricity production; changes from high to low energy intensive process in the electricity production or an alteration in the sector structure from industry to services in terms of GDP shares or the use of a diversified energy matrix containing, for example, natural gas and renewable energies.

Furthermore, the between- and within-group inequality components contributed to the explanation of overall inequality during the studied period. The fact that, the between-group inequality component had reduced its concentration of CO_2 emissions by 41 percent while the inequality associated with the within-group inequality component had only been slightly reduced, gives evidence that during the studied period the set of measures to limit the concentration of CO_2 in the atmosphere had reduced the inequality between regions further than the inequality within each one. Finally, whereas Africa had been the region with the highest level of internal inequality during all the period, followed by Asia and Middle East; China had been the territory with the lowest within-group inequality.

From a policy perspective, the observed decreasing inequality trend could facilitate that individual interests do not prevail in international negotiations. Given that differences in the economic growth were more relevant in explaining CO_2 emissions inequality than the carbon intensity of electricity generation or the different production structures, differences in per capita GDP should be nearly correlated to the efforts required to the different countries to improve the fairness of an international agreement to curb climate change. In addition, the considerable inequalities between and within regions observed reinforce the application of the Kyoto Protocol principle “common but differentiated responsibility”.

Human activity which took place during the industrial era has led to a dramatic increase of both CO_2 emissions and non-CO_2 GHG emissions, the last ones playing an important role in understanding and curbing global climate change. However, in the environmental field, global negotiations on reducing emissions are constructed through alliances of groups of countries with conflicting interests, being necessary, apart from the inequality analyses, to carry out polarization studies to understand the potential appearance of conflicts in the global distribution of per capita GHG emissions. Thus, in Chapter 3, the inequality and polarization in the four main GHG emissions – CO_2, CH_4, N_2O and F-gases– from a multidimensional perspective in the period 1990-2011 is analysed. For this purpose, the generalised entropy measures proposed by Maasoumi (1986) which can be decomposed by population sub-groups and, the polarization indices developed by Gigliariano and Mosler (2009) are used.

The results from the multidimensional inequality analysis varied according to the weight assigned to the different parts of the distribution. When more weight was attached to the emission transfers between the most polluting countries, an increasing inequality trend over the whole period was observed when the substitution degree among gases was perfect or very high. Meanwhile, when the substitution degree among pollutants decreased, a reduction in GHG emissions inequality was perceived. The previous pattern was repeated when all countries were equally weighted. In contrast, when changes in the least polluting countries prevailed on the rest of the distribution, the results showed a decrease in the concentration of GHG emissions during the period 1990-2011, regardless of the substitution degree among pollutants.

The decomposition of the generalised entropy measures into their interregional and intraregional components reveals that, while the interregional component was a predominant factor in the scenarios where the substitution degree among GHGs was perfect or high, inequality within regions received a greater weight when a lower substitution degree among gases was admitted.

The multidimensional polarization analysis has been carried out considering the sample divided into four and eight groups, providing that all countries are equally weighted and a perfect elasticity of substitution among gases. Thus, while the P_2 and P_3 indices showed a slightly increasing pattern that was similar regardless of the number of groups considered, the P_1 index experienced an increase that was accentuated when it was considered a larger number of groups.

In relation to environmental policies the following can be noted. The compromise reached in the UNFCCC in 1992, to adopt measures to stabilize GHG emissions, may be one of the causes that lies behind the declining inequality trend when it is given more importance to the emission transfers between the most polluting countries. The similarity of the results obtained when the changes in the most polluting countries prevail on the rest of the distribution and when all countries are equally weighted gives the green light to the use of other inequality measures which do not support assigning a different weight to the different parts of the distribution.

Regarding the probability of implementing international agreements, the evolution of the P_2 and P_3 indices has to be perceived as positive in terms of advancing towards an international environmental negotiation for two reasons. Firstly, because the polarization degree was similar regardless of the number of groups considered and, secondly, because it suffered a little enlargement from 1990 to 2011 despite the fact that the country grouping has been made taking as a reference the year 2011.

In order to reduce the polarization in the global distribution of GHGs, this analysis suggests two policy directions. On the one hand, when the same weight to all countries is attributed and the substitution degree among gases is assumed to be perfect or very high, the attenuation must come from the convergence in the average emissions among the groups of countries given that the heterogeneity between groups is the most important component. On the other hand, for the rest of scenarios, as a lowest degree of antagonism between groups is observed, the contraction must come from the moderation of the intra-group cohesion.

Finally, given that information concerning the statistical distribution of contaminants can be used to investigate the level of inequality associated with them, in Chapter 4 a convenient expression for the Theil indices is presented which allows us to obtain these inequality measures for the most relevant families of parametric distributions –the Champernowne (1952) distribution, the GG and GB1 and GB2 distributions (McDonald, 1984), the κ-generalised distribution (Clementi *et al.*, 2007) and several Pareto and gamma-type distributions– and to derive closed expressions for multivariate versions of them. As an empirical application, inequality in the per capita CO_2 emissions in the year 2012 is investigated as they are the major driver of climate change. Given that the distribution of the per capita CO_2 emissions is positively skewed and exhibits a right heavy tail, the GB2 distribution (McDonald, 1984) has been assumed to model the data. The inequality analysis has been carried out computing different generalised entropy measures –the T_0, T_1 and the $GE(2)$ indices–, varying the sensitivity of the inequality measures to the different parts of the distribution. The results indicate that the $GE(2)$ index exhibited the highest inequality value, closely followed by the T_0 index. On the contrary, the T_1 index presented the lowest level of inequality.

Although the four chapters of this Thesis answer different aspects concerning the inequality in GHG emissions, there are certain lines of research that can be addressed in the future.

Related to Chapter 1, it would be valuable to replicate the same study considering a wide range of sectors. The availability of data in the near future will let us investigate which human activities are the largest sources of GHG emissions. In addition, to study the temporal evolution of such inequality will be a useful tool to implement policies to reduce the emissions.

As different population issues may facilitate the design of better climate policies, the results obtained in Chapter 2 suggest an extension of that analysis taking into account the disaggregation of the working-age population in young (20-34 years) and old workers (35-64 years) to study whether different cohort sizes of the active population have different effects on CO_2 emissions inequality.

Long-term forecasts of CO_2 emissions are crucial inputs to both assessing the future possible impacts of climate change and evaluating the cost of emissions abatement. Given that the future evolution of CO_2 emissions is highly uncertain, different research groups and institutions have proposed different scenarios on future projections of CO_2 emissions based on different assumptions. For this reason, apart from studying the sources of the historical inequality in CO_2 emissions as in Chapter 2, it would be relevant to examine the determinants of the future inequality in CO_2 emissions under different emission scenarios. This research will provide useful insights into establishing a specific strategy in each region, where countries have similar economic and population growth and energy consumption patterns.

Meanwhile, the analysis carried out in Chapter 3 does have some limitations. Firstly, the GHG emissions used in this work are measured using the production-based National Emissions Inventory. Thus, replicating the same study considering the emissions calculated using the consumption-based National Emissions Inventory could be a sensitive analysis of the results. Secondly, as the multidimensional inequality indices proposed by Maasoumi (1986) consider each country as a unit regardless of the size of its population, it would be very interesting to develop their corresponding weighted version to give a different weight to each country based on its share in the world population. Thirdly, as this study does not provide any kind of information about inequality within each region, the application of this analysis to a specific region could be of great importance for policy making. Finally, the assessment of the evolution of the multidimensional polarization for the entire period allowing that the groups of countries might be constituted in a different manner in each year will be a great complement to the presented analysis.

Nevertheless, this work represents one of the first attempts to study the evolution of GHG emissions in a joint manner. Future research should be addressed to expand and complete this work. In this sense, the future data availability will allow us to investigate the evolution of world inequality in GHG emissions considering a greater number of them which, undoubtedly, will be a valuable tool for implementing policies to reduce these emissions. Also, a similar study covering a longer period will be able to show the effects of recent international agreements on inequality.

Finally, a relevant extension of the closed expressions of the Theil indices obtained in Chapter 4 would be to derive their multivariate expressions for the most relevant families of parametric distributions. The development of these expressions would be crucial to model the distribution of per capita GHG emissions and, therefore, assess the level of inequality implied by them.

Appendix

Appendix 1.1

Regions and countries considering the UNDP classification as a reference

Arab States

Algeria, Bahrain, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria, Tunisia, United Arab Emirates, Yemen.

East Asia and Pacific

Cambodia, China, Indonesia, Malaysia, Mongolia, Myanmar, Philippines, Thailand, Vietnam.

Europe and Central Asia

Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Macedonia (Republic of), Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Malta, Moldova (Republic of), Poland, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Tajikistan, Turkey, Turkmenistan, Ukraine, Uzbekistan.

Latin America and the Caribbean

Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela.

South Asia

Iran (Islamic Republic of), Bangladesh, India, Nepal, Pakistan, Sri Lanka.

Sub-Saharan Africa

Angola, Benin, Botswana, Cameroon, Congo (Republic of), Eritrea, Ethiopia, Gabon, Ghana, Ivory Coast, Kenya, Mozambique, Namibia, Nigeria, Senegal, South Africa, Tanzania (United Republic of), Togo, Zambia, Zimbabwe.

OECD

Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Korea (Republic of), Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States.

Appendix 1.2

World CO_2 emissions by sector in 2009

Sector	Emissions
Electricity and heat production	11558.33
Manufacturing and construction	5749.85
Other energy industries	1437.81
Transport	5437.65
Road transport	3251.11
Others	4790.81
Residential	1862.34
Total	27434.75

Note: Emissions are expressed in million tonnes.

Appendix 1.3

Contribution to inequality in per capita CO_2 emissions by sector of the between- and within-group inequality components in 2009

Sector	$T_B(\underline{c}, p)$	$T_W(\underline{c}, p)$
Electricity and heat production	36.55	63.45
Manufacturing and construction	42.70	57.30
Other energy industries	45.93	54.07
Transport	67.86	32.14
Road transport	66.47	33.53
Others	55.30	44.70
Residential	48.90	51.10
Total	49.51	50.49

Note: The contribution is expressed in percentage.

Appendix 1.4

Contribution to inequality in per capita CO_2 emissions by sector of the within-group inequality component in 2009

Sector	θ = -10	θ = -5	θ = -2	θ = -1	θ = 0	θ = 1	θ = 2	θ = 5	θ = 10
Electricity and heat production	100.00	100.00	100.00	99.52	63.45	46.58	51.41	88.55	99.95
Manufacturing and construction	100.00	100.00	99.73	89.12	57.30	50.42	63.41	99.74	100.00
Other energy industries	100.00	100.00	99.93	94.11	54.07	50.87	75.83	99.99	100.00
Transport	100.00	100.00	96.26	66.79	32.14	24.66	34.10	81.03	99.80
Road transport	100.00	100.00	96.02	67.46	33.53	25.06	33.29	81.09	99.93
Others	100.00	100.00	98.41	81.23	44.70	28.51	28.90	68.83	99.13
Residential	100.00	100.00	99.67	89.27	51.10	35.14	36.23	69.95	97.57
Total	100.00	100.00	98.86	83.25	50.49	38.14	41.63	82.21	99.86

Note: The contribution is expressed in percentage.

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Appendix 2.1

Regions and countries considering the IEA classification as a reference

Africa

Algeria, Angola, Benin, Botswana, Cameroon, Congo (Republic of), Congo (Democratic Republic of), Egypt, Ethiopia, Gabon, Ghana, Ivory Coast, Kenya, Libya, Morocco, Mozambique, Nigeria, Senegal, South Africa, Sudan, Tanzania (United Republic of), Togo, Tunisia, Zambia, Zimbabwe.

Asia

Bangladesh, Brunei Darussalam, India, Indonesia, Korea (Democratic People's Republic of), Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam.

China

China, Hong Kong.

Middle East

Bahrain, Iran (Islamic Republic of), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen.

OECD Americas

Canada, Chile, Mexico, United States.

OECD Asia Oceania

Australia, Israel, Japan, Korea (Republic of), New Zealand.

OECD Europe

Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom.

Non-OECD Americas

Argentina, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela.

Non-OECD Europe and Eurasia

Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Macedonia (Republic of), Malta, Moldova (Republic of), Romania, Russian Federation, Serbia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan.

Appendix 2.2

Contribution to inequality in CO_2 emissions by active population of the between- and within-group inequality components from 1990 to 2010

Year	$\boldsymbol{T_B(\underline{c}, p)}$	$\boldsymbol{T_W(\underline{c}, p)}$
1990	48.46	51.54
1995	43.57	56.43
2000	43.49	56.51
2005	40.78	59.22
2010	36.56	63.44

Note: The contribution is expressed in percentage.

Appendix 2.3

Factorial decomposition of regional inequality in CO_2 emissions by active population from 1990 to 2010

	$T_g(\underline{d},e)$	$I_g^w(\underline{d},e)$	$I_g^x(\underline{d},e)$	$I_g^y(\underline{d},e)$	$I_g^z(\underline{d},e)$	$\text{inter}_g(w,xyz)$	$\text{inter}_g(x,yz)$	$\text{inter}_g(y,z)$
Africa								
1990	2.3926	0.1008	0.4447	1.7335	0.0009	-0.5296	0.7042	-0.0619
1995	2.4263	0.0702	0.4415	1.4967	0.0009	-0.2596	0.7185	-0.0418
2000	2.2293	0.1305	0.5166	1.3736	0.0016	-0.3005	0.5831	-0.0756
2005	2.0017	0.1668	0.5468	1.2726	0.0009	-0.3650	0.4296	-0.0501
2010	1.8036	0.2048	0.4056	1.1418	0.0009	-0.2608	0.3469	-0.0356
Asia								
1990	0.9972	0.0965	0.1040	0.7565	0.0001	-0.4470	0.4842	0.0030
1995	0.9914	0.0585	0.0903	0.7654	0.0001	-0.3812	0.4536	0.0047
2000	0.9867	0.0460	0.0714	0.8826	0.0002	-0.3292	0.3159	-0.0002
2005	0.9844	0.0485	0.0811	0.9572	0.0004	-0.2803	0.1703	0.0073
2010	1.0742	0.0497	0.0983	1.0424	0.0001	-0.2107	0.0939	0.0005

Appendix 2.3 Continued

Factorial decomposition of regional inequality in CO_2 emissions by active population from 1990 to 2010

	$T_g(\underline{d},e)$	$I_g^w(\underline{d},e)$	$I_g^x(\underline{d},e)$	$I_g^y(\underline{d},e)$	$I_g^z(\underline{d},e)$	$\mathrm{inter}_g(w,xyz)$	$\mathrm{inter}_g(x,yz)$	$\mathrm{inter}_g(y,z)$
China								
1990	0.0049	0.0021	0.0012	0.0811	0.0000	-0.0277	-0.0546	0.0029
1995	0.0030	0.0012	0.0018	0.0570	0.0000	-0.0128	-0.0451	0.0009
2000	0.0036	0.0006	0.0015	0.0412	0.0000	-0.0078	-0.0316	-0.0002
2005	0.0008	0.0008	0.0020	0.0297	0.0000	-0.0050	-0.0260	-0.0006
2010	0.0001	0.0004	0.0026	0.0180	0.0000	-0.0016	-0.0193	0.0000
Middle East								
1990	0.5898	0.0190	0.0660	0.4874	0.0013	0.0039	0.0158	-0.0036
1995	0.4851	0.0260	0.1383	0.8061	0.0013	-0.1253	-0.3634	0.0021
2000	0.6789	0.0281	0.0614	0.6551	0.0014	-0.0505	-0.0310	0.0143
2005	0.7564	0.0322	0.0574	0.8698	0.0012	-0.1307	-0.0815	0.0080
2010	0.6181	0.0232	0.0616	0.6806	0.0014	-0.0432	-0.1228	0.0174

Appendix 2.3 Continued

Factorial decomposition of regional inequality in CO_2 emissions by active population from 1990 to 2010

	$T_g(\underline{d},e)$	$I_g^w(\underline{d},e)$	$I_g^x(\underline{d},e)$	$I_g^y(\underline{d},e)$	$I_g^z(\underline{d},e)$	$\text{inter}_g(w,xyz)$	$\text{inter}_g(x,yz)$	$\text{inter}_g(y,z)$
OECD Americas								
1990	0.1368	0.0249	0.0837	0.0570	0.0002	-0.0918	0.0661	-0.0033
1995	0.1470	0.0188	0.0691	0.0648	0.0001	-0.0750	0.0677	0.0016
2000	0.1442	0.0112	0.0541	0.0680	0.0001	-0.0487	0.0603	-0.0008
2005	0.1446	0.0092	0.0401	0.0803	0.0001	-0.0370	0.0537	-0.0016
2010	0.1405	0.0094	0.0347	0.0947	0.0002	-0.0486	0.0571	-0.0069
OECD Asia Oceania								
1990	0.0308	0.0287	0.0119	0.0376	0.0004	-0.0603	0.0136	-0.0012
1995	0.0189	0.0266	0.0055	0.0205	0.0002	-0.0365	0.0046	-0.0020
2000	0.0240	0.0126	0.0039	0.0117	0.0000	0.0005	-0.0040	-0.0008
2005	0.0219	0.0079	0.0057	0.0076	0.0000	0.0099	-0.0087	-0.0006
2010	0.0256	0.0117	0.0076	0.0039	0.0000	0.0099	-0.0073	-0.0004

Appendix 2.3 Continued

Factorial decomposition of regional inequality in CO_2 emissions by active population from 1990 to 2010

	$T_g(\underline{d},e)$	$I_g^w(\underline{d},e)$	$I_g^x(\underline{d},e)$	$I_g^y(\underline{d},e)$	$I_g^z(\underline{d},e)$	$\text{inter}_g(w,xyz)$	$\text{inter}_g(x,yz)$	$\text{inter}_g(y,z)$
OECD Europe								
1990	0.0854	0.0729	0.0769	0.0717	0.0006	-0.1407	0.0042	-0.0001
1995	0.0663	0.0717	0.0589	0.0707	0.0012	-0.1317	-0.0023	-0.0022
2000	0.0515	0.0661	0.0429	0.0571	0.0008	-0.1203	0.0025	0.0023
2005	0.0519	0.0501	0.0316	0.0447	0.0007	-0.0957	0.0154	0.0051
2010	0.0590	0.0546	0.0264	0.0425	0.0010	-0.0836	0.0150	0.0033
Non-OECD Americas								
1990	0.2164	0.0999	0.1096	0.0522	0.0007	-0.0495	0.0073	-0.0038
1995	0.1778	0.0792	0.1313	0.0669	0.0012	-0.0743	-0.0165	-0.0099
2000	0.1665	0.0780	0.1453	0.0598	0.0008	-0.0896	-0.0193	-0.0086
2005	0.1753	0.0921	0.1246	0.0517	0.0004	-0.0772	-0.0116	-0.0048
2010	0.1886	0.0991	0.1087	0.0642	0.0003	-0.0720	-0.0091	-0.0026

Appendix 2.3 Continued

Factorial decomposition of regional inequality in CO_2 emissions by active population from 1990 to 2010

	$T_g(\underline{d},e)$	$I_g^w(\underline{d},e)$	$I_g^x(\underline{d},e)$	$I_g^y(\underline{d},e)$	$I_g^z(\underline{d},e)$	$\mathrm{inter}_g(w,xyz)$	$\mathrm{inter}_g(x,yz)$	$\mathrm{inter}_g(y,z)$
Non-OECD Europe and Eurasia								
1990	0.0478	0.0201	0.0784	0.0858	0.0009	-0.0184	-0.1139	-0.0050
1995	0.1294	0.0597	0.0795	0.1192	0.0012	0.0019	-0.1296	-0.0024
2000	0.1371	0.0635	0.0798	0.1201	0.0009	-0.0047	-0.1183	-0.0043
2005	0.1251	0.0642	0.0698	0.1120	0.0014	-0.0056	-0.1153	-0.0014
2010	0.1607	0.0692	0.0608	0.1090	0.0010	0.0052	-0.0856	0.0011

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Appendix 3.1

Groups of countries considering the amount of per capita GHG emissions (tCO_2e) released into the atmosphere by each country in 1990

Group I [0.15 – 0.57)

Bangladesh, Cambodia, El Salvador, Ghana, Guatemala, Kenya, Myanmar, Nepal, Pakistan, Sri Lanka, Vietnam, Yemen.

Group II [0.57 – 1.00)

Congo (Democratic Republic of), Costa Rica, Dominican Republic, Honduras, India, Indonesia, Ivory Coast, Morocco, Nicaragua, Nigeria, Peru, Philippines.

Group III [1.00 – 1.63)

Albania, Bolivia, Brazil, Cameroon, Colombia, Ecuador, Egypt, Panama, Thailand, Tunisia, Zimbabwe.

Group IV [1.63 – 2.57)

Algeria, Angola, Chile, China, Jamaica, Lebanon, Mexico, Syria, Tajikistan, Turkey, Uruguay, Zambia.

Group V [2.57 – 4.36)

Argentina, Bosnia and Herzegovina, Croatia, Cuba, Iran (Islamic Republic of), Iraq, Jordan, Korea (Republic of), Kyrgyzstan, Macedonia (Republic of), Malaysia, Portugal.

Group VI [4.36 – 5.40)

Armenia, Cyprus, France, Hungary, Korea (Democratic People's Republic of), Mongolia, Spain, Sweden, Switzerland, Uzbekistan, Venezuela.

Group VII [5.40 – 6.18)

Austria, Azerbaijan, Georgia, Greece, Iceland, Israel, Italy, Latvia, Norway, Romania, Slovenia, South Africa.

Group VIII [6.18 – 7.84)

Bulgaria, Ireland, Japan, Lithuania, Moldova (Republic of), New Zealand, Oman, Poland, Serbia, Singapore, United Kingdom.

Group IX [7.84 – 11.59)

Belarus, Belgium, Denmark, Finland, Germany, Libya, Netherlands, Saudi Arabia, Slovakia, Trinidad and Tobago, Turkmenistan, Ukraine.

Group X [11.59 – 23.87]

Australia, Bahrain, Brunei Darussalam, Canada, Czech Republic, Estonia, Kazakhstan, Luxembourg, Qatar, Russian Federation, United Arab Emirates, United States.

Appendix 3.2

Decomposition of inequality in per capita GHG emissions by population sub-groups from 1990 to 2011

	***GEM*$_{1.5}$**			***GEM*$_{-1}$**			***GEM*$_{0}$**		
Year \ Beta	**β = -1**	**β = 0.5**	**β = 9**	**β = -1**	**β = 0.5**	**β = 9**	**β = -1**	**β = 0.5**	**β = 9**
Between-group inequality component									
1990	0.4782	0.3080	0.7040	0.2249	0.1633	0.3743	0.1698	0.1241	0.2456
1992	0.4880	0.3056	0.6992	0.2108	0.1547	0.3571	0.1661	0.1211	0.2410
1994	0.4818	0.3015	0.6259	0.2016	0.1444	0.3382	0.1623	0.1166	0.2277
1997	0.4469	0.2770	0.4786	0.1878	0.1272	0.2858	0.1527	0.1061	0.1908
2005	0.4471	0.2453	0.2721	0.1786	0.1053	0.1702	0.1501	0.0925	0.1211
2009	0.3833	0.2186	0.2038	0.1632	0.0942	0.1371	0.1365	0.0834	0.0980
2011	0.3904	0.2222	0.1923	0.1651	0.0945	0.1297	0.1381	0.0840	0.0933
Within-group inequality component									
1990	0.0726	0.1754	4.6037	0.0080	0.0458	0.6132	0.0067	0.0370	0.3825
1992	0.1186	0.1413	4.1165	0.0133	0.0383	0.4657	0.0120	0.0291	0.3330
1994	0.1895	0.1718	3.1554	0.0290	0.0452	0.4145	0.0243	0.0350	0.2976
1997	0.2427	0.1974	1.9349	0.0361	0.0480	0.3127	0.0317	0.0392	0.2364
2005	0.3871	0.1462	0.5453	0.0429	0.0485	0.1826	0.0410	0.0350	0.1166
2009	0.2978	0.1677	0.4159	0.0463	0.0493	0.1746	0.0427	0.0364	0.1040
2011	0.2788	0.1846	0.4099	0.0463	0.0498	0.1771	0.0415	0.0375	0.1053

Appendix 3.3

Endogenous classification of countries into four groups according to their level of per capita GHG emissions (tCO_2e) in 2011

Group I [0.24 – 2.15)

Albania, Armenia, Bangladesh, Bolivia, Brazil, Cambodia, Cameroon, Colombia, Congo (Democratic Republic of), Costa Rica, Dominican Republic, Ecuador, Egypt, El Salvador, Georgia, Ghana, Guatemala, Honduras, India, Indonesia, Ivory Coast, Kenya, Korea (Democratic People's Republic of), Kyrgyzstan, Moldova (Republic of), Morocco, Myanmar, Nepal, Nicaragua, Nigeria, Pakistan, Panama, Peru, Philippines, Sri Lanka, Syria, Tajikistan, Tunisia, Vietnam, Yemen, Zambia, Zimbabwe.

Group II [2.15 – 4.96)

Algeria, Angola, Argentina, Azerbaijan, Bosnia and Herzegovina, Chile, Croatia, Cuba, Cyprus, France, Hungary, Iceland, Iraq, Jamaica, Jordan, Latvia, Lebanon, Lithuania, Macedonia (Republic of), Mexico, Mongolia, Portugal, Romania, Spain, Sweden, Switzerland, Thailand, Turkey, Uruguay, Uzbekistan, Venezuela.

Group III [4.96 – 9.87)

Austria, Belarus, Belgium, Bulgaria, China, Czech Republic, Denmark, Finland, Germany, Greece, Iran (Islamic Republic of), Ireland, Israel, Italy, Japan, Korea (Republic of), Libya, Malaysia, Netherlands, New Zealand, Norway, Poland, Russian Federation, Serbia, Singapore, Slovakia, Slovenia, South Africa, Ukraine, United Kingdom.

Group IV [9.87 – 30.73]

Australia, Bahrain, Brunei Darussalam, Canada, Estonia, Kazakhstan, Luxembourg, Oman, Qatar, Saudi Arabia, Trinidad and Tobago, Turkmenistan, United Arab Emirates, United States.

Appendix 3.4

Endogenous classification of countries into eight groups according to their level of per capita GHG emissions (tCO_2e) in 2011

Group I [0.24 – 1.25)

Albania, Bangladesh, Cambodia, Cameroon, Congo (Democratic Republic of), El Salvador, Georgia, Ghana, Guatemala, Honduras, India, Ivory Coast, Kenya, Kyrgyzstan, Myanmar, Nepal, Nicaragua, Nigeria, Pakistan, Philippines, Sri Lanka, Tajikistan, Yemen, Zambia, Zimbabwe.

Group II [1.25 – 2.73)

Algeria, Angola, Armenia, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, Egypt, Indonesia, Jamaica, Jordan, Korea (Democratic People's Republic of), Moldova (Republic of), Morocco, Panama, Peru, Syria, Tunisia, Uruguay, Vietnam.

Group III [2.73 – 4.22)

Argentina, Azerbaijan, Chile, Croatia, France, Hungary, Iraq, Latvia, Lebanon, Lithuania, Macedonia (Republic of), Mexico, Portugal, Romania, Sweden, Switzerland, Thailand, Turkey, Uzbekistan.

Group IV [4.22 – 5.61)

Bosnia and Herzegovina, Bulgaria, China, Cyprus, Iceland, Italy, Mongolia, Serbia, Slovakia, South Africa, Spain, Ukraine, United Kingdom, Venezuela.

Group V [5.61 – 7.75)

Austria, Belarus, Denmark, Germany, Greece, Iran (Islamic Republic of), Ireland, Israel, Japan, Libya, Malaysia, New Zealand, Norway, Poland, Slovenia.

Group VI [7.75 – 11.05)

Belgium, Czech Republic, Estonia, Finland, Korea (Republic of), Netherlands, Russian Federation, Singapore, Turkmenistan.

Group VII [11.05 – 17.12)

Australia, Bahrain, Canada, Kazakhstan, Luxembourg, Saudi Arabia, United Arab Emirates, United States.

Group VIII [17.12 – 30.73]

Brunei Darussalam, Oman, Qatar, Trinidad and Tobago.

Appendix 3.5

Decomposition of inequality in per capita GHG emissions by population sub-groups from 1990 to 2011 considering four and eight groups (β = -1)

	***k* = 4**			***k* = 8**		
Year	$GEM_0(X)$	$B_0(X)$	$W_0(X)$	$GEM_0(X)$	$B_0(X)$	$W_0(X)$
1990	0.1765	0.1322	0.0443	0.1765	0.1353	0.0413
1992	0.1780	0.1421	0.0359	0.1780	0.1498	0.0282
1994	0.1866	0.1523	0.0343	0.1866	0.1610	0.0256
1997	0.1843	0.1523	0.0321	0.1843	0.1617	0.0226
2005	0.1911	0.1610	0.0301	0.1911	0.1730	0.0180
2009	0.1792	0.1572	0.0220	0.1792	0.1723	0.0069
2011	0.1797	0.1609	0.0188	0.1797	0.1747	0.0050

Appendix 3.6

Polarization in per capita GHG emissions from 1990 to 2011 considering four and eight groups (γ = 0 and β = -1)

	k = 4			k = 8		
Year	P_1	P_2	P_3	P_1	P_2	P_3
1990	0.8412	0.0807	0.4389	0.8327	0.0817	0.4254
1992	0.9601	0.0975	0.4693	1.0158	0.1057	0.4685
1994	1.0411	0.1083	0.4878	1.1153	0.1178	0.4886
1997	1.0582	0.1103	0.4915	1.1467	0.1209	0.4946
2005	1.1363	0.1202	0.5077	1.2750	0.1348	0.5170
2009	1.1831	0.1241	0.5169	1.4013	0.1438	0.5366
2011	1.2425	0.1304	0.5279	1.4476	0.1476	0.5432

Appendix 4.1

System of simultaneous equations used to estimate
the parameters of the GB2 distribution

Using the method of the maximum likelihood, the parameters of the GB2 distribution can be estimated considering that the log-likelihood function is equal to:

$$\log L = n\log\Gamma(p+q) + n\log a + (ap-1)\sum_{i=1}^{n}\log x_i - nap\log b$$
$$- n\log\Gamma(p) - n\log\Gamma(q) - (p+q)\sum_{i=1}^{n}\log\left[1+\left(\frac{x_i}{b}\right)^a\right].$$

and solving the following system of simultaneous equations from the partial derivatives of log L with respect to a, b, p, q, respectively:

$$\frac{n}{a} + p\sum_{i=1}^{n}\log\left(\frac{x_i}{b}\right) = (p+q)\sum_{i=1}^{n}\log\left(\frac{x_i}{b}\right)\left[\left(\frac{b}{x_i}\right)^a + 1\right]^{-1},$$

$$np = (p+q)\sum_{i=1}^{n}\left[1+\left(\frac{b}{x_i}\right)^a\right]^{-1},$$

$$n\psi(p+q) + a\sum_{i=1}^{n}\log\left(\frac{x_i}{b}\right) = n\psi(p) + \sum_{i=1}^{n}\log\left[1+\left(\frac{x_i}{b}\right)^a\right],$$

and

$$n\psi(p+q) = n\psi(q) + \sum_{i=1}^{n}\log\left[1+\left(\frac{x_i}{b}\right)^a\right],$$

where the $\psi(\cdot)$ is the digamma function (Kleiber and Kotz, 2003).

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