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## Decomposing Inequality in CO2 Emissions: the Role of Primary Energy Carriers and Economic Sectors

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# Decomposing Inequality in CO<sub>2</sub> Emissions: the Role of Primary Energy Carriers and Economic Sectors

## Abstract

Emission inequality across countries and the contribution of the energy mix and the sectoral composition of a country's energy use are of central importance to the climate debate. We analyze the evolution of inequality in global CO<sub>2</sub> per capita emissions using both historical data on energy-related CO<sub>2</sub> emissions and future emission scenarios generated with the integrated assessment model REMIND. Within our sample of 90 countries the results indicate that the Gini index declined from about 0.6 in 1971 to slightly above 0.4 in 2008. A decomposition of the Gini index of total emissions into primary energy carriers and into economic sectors provides additional insights. From the perspective of primary energy carriers, it is indicated that this reduction is mainly attributed to declining shares of emissions from coal/peat and oil in total emissions, and decreasing emission inequality within all fossil primary energy sources. From the perspective of economic sectors, the decline in overall inequality is almost entirely due to a pronounced decline of the contribution of emissions from manufacturing & construction. Our analysis also suggests that an equally spread emission reduction from any one source (i.e. primary energy carrier or economic sector) would not have a major impact on overall emission inequality. The analysis of future scenario data indicates that climate policy reduces absolute emissions inequality, while inducing drastic progressive emission reductions in all regions.

Keywords: CO<sub>2</sub> emission inequality, Gini decomposition by source, economic sectors, climate policy

JEL: O13, D63, Q54, Q58

## 26    **1 Introduction**

27    The question of equity plays a major role in current climate negotiations, involving ethical  
28    considerations and a broader analysis than the utilitarian approach to analyze the costs of  
29    climate change mitigation (Gardiner, 2004). From this perspective, addressing inequality in  
30    per-capita emissions across countries is central for a fair allocation of emission rights, and  
31    hence the responsibility to reduce emissions, in any future climate agreement. Currently,  
32    global emissions are very unequally distributed between countries, with about 1 billion  
33    people living in industrialized countries being responsible for roughly half of the global CO<sub>2</sub>  
34    emissions (WEO, 2010). However, recent growth spurts have caused a sharp increase in  
35    developing countries' emissions, closing part of the gap to richer countries, such that for the  
36    period 2001-2008 the growth of global emission can almost exclusively be attributed to  
37    developing countries (Steckel et al., 2011).

38    Previous literature has highlighted that in the process of economic development countries  
39    undergo characteristic transformations of their energy systems. For instance, while countries  
40    at early stages of industrialization predominantly rely on solid fuels, a large part of these  
41    fuels is replaced by grid-based, high-quality forms of energy - such as natural gas and  
42    electricity - with proceeding industrialization (Grubler, 2008; Marcotullio and Schulz, 2007).  
43    Further, rising per capita income has been found to result in a smaller share of final energy  
44    use for the residential sector but larger ones for transportation and the service sector and a  
45    reversed U-shape pattern for industry (Schäfer, 2005). As convergence in per-capita  
46    incomes is closely related to convergence in energy use patterns (Jakob et al., 2012), one  
47    should expect the spectacular growth performances witnessed in a number of developing  
48    countries to have major impacts on the distribution of CO<sub>2</sub> emissions per-capita across  
49    countries.

Given the pivotal role of emissions inequality for climate negotiations, the issue has been investigated in the literature through a variety of methods. (Hedenus and Azar, 2005) use the Atkinson index (Atkinson, 1970) to find a declining trend in global emission inequality between 1960 and 1999 (from 0.64 to 0.5). This is based on their finding that in 1999 the 20% most emitting countries emitted about 22 times the amount of carbon than the 20% least emitting countries, while in 1960 this gap had been more than twice as large. Various authors use the Theil Index (Theil, 1972) to measure and explain global emission inequality (e.g. Padilla and Duro, 2011). The advantage of the Theil index is that it can be decomposed in inequality within and between country groupings (Shorrocks, 1982). Duro and Padilla, (2006) use the Kaya identity (1989) to decompose emission inequality across countries into the contributions of carbon intensity of energy, energy intensity and affluence. They find that during the period from 1970 to 1999 income differences were the main drivers of emission inequality between countries, while differences in carbon intensity and energy intensity displayed lower contributions<sup>1</sup>. Padilla and Serrano (2006) also show, using the Gini and the Theil index for country-level emissions, that emission inequality is closely correlated with income inequality and that both follow the same path over time. Finally, Duro, (2012) compares a set of inequality measures such as the Gini coefficient, Theil index, the Atkinson measure as well as the coefficient of variation in terms of their sensitivity to changes in the distribution of CO<sub>2</sub> emissions over time. He concludes that different inequality indicators can yield differing results due to differences in their distributive sensitivity.

A further widely employed measure of inequality is the Gini coefficient. In the case of CO<sub>2</sub> emissions, the cumulative share of global CO<sub>2</sub> emissions is plotted against the cumulative share of the countries from the lowest to the highest per capita emissions. Heil and Wodon,

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<sup>1</sup> When Padilla and Duro (2011) apply the Theil index decomposition on emission data from the EU-27, they find that among this more homogeneous group of countries the carbon intensity of energy explains a large share of the emission inequality.

(2000, 1997) follow the methodology of Yitzhaki and Lerman (1991) to decompose the Gini coefficient in a within group and a between group component. The between group component compares rich and poor countries in order to analyze the contribution to the global emission inequality. They find that between group inequality declined slightly, but rich countries would have to reduce emissions by at least 50% to change the ranking of the highest polluting countries.

This paper adds to the existing literature by investigating how the energy mix and the sectoral composition of a country's energy use determine inequality in global CO<sub>2</sub> emissions. Employing the decomposition of the Gini index pioneered by Lerman & Yitzhaki (1985), economy-wide emissions are disaggregated into contributions by primary energy carriers and economic sectors to estimate the contribution of each source of emission (i.e. each primary energy carrier, or economic sector, respectively) to total inequality. While this empirical methodology is well established in the analysis of income inequality between households (Leibbrandt et al., 2000), this is – to our knowledge – the first paper to employ it to analyze inequality in carbon emissions across countries.

We analyze both past trends using historical data on energy-related CO<sub>2</sub> emissions for 90 countries (which currently account for about 90% of global CO<sub>2</sub> emissions) over the period 1971-2008 and, in order to provide an outlook on how climate policy could affect future emission inequality, we also apply the decomposition method on emission scenarios generated with the integrated assessment model REMIND (Kriegler et al., submitted); (Bauer et al., 2012).

The paper proceeds as follows: Section 2 presents the employed empirical method, and Section 3 the used data. Section 4 applies the methodology using both historical data, for a global sample as well as for a sub-sample of OECD and non-OECD countries, and results of the REMIND model. Section 5 presents the outcomes of a sensitivity analysis, while section 6 concludes.

## 99 2 Methodology

100 This study adopts the Gini coefficient as a measure of inequality for two main reasons.  
 101 Firstly, it is arguably the most popular and widely employed inequality measure; for instance,  
 102 it is adopted by the UNDP in its annual Human Development Reports (UNDP, 2010).  
 103 Secondly, it allows for a straightforward decomposition of total CO<sub>2</sub> emission inequality into  
 104 contributions of individual sources and an estimation of the marginal effect of a change in  
 105 any of these sources on overall emission inequality.

106 The Gini index builds on the concept of Lorenz Curves, which plot the cumulative share of  
 107 income earned against the cumulative share of the units from the lowest to the highest  
 108 income (Gini, 1912; Lorenz, 1905). It can range between 0 and 1, where 0 represents total  
 109 equality and 1 represents total inequality. The Gini Index for CO<sub>2</sub> emissions has the  
 110 geometric interpretation as one minus twice the area below the Lorenz Curve for emission  
 111 distribution across countries and the diagonal line, which represents perfect emission  
 112 equality.

113 We apply the decomposition of the Gini index after Lerman and Yitzhaki (1985, 1984) to  
 114 analyze the effects of each source of carbon emissions (i.e. primary energy carrier and  
 115 economic sector) on inequality in per-capita CO<sub>2</sub> emissions across countries. Lerman and  
 116 Yitzhaki (1985, 1984) demonstrate that the Gini coefficient of total emissions can be  
 117 expressed as a function of (i) the inequality within a given source, (ii) the share of this source  
 118 in total emissions, and (iii) its rank correlation with total emission inequality. With this Gini  
 119 decomposition we are able to determine the contribution of each emission source to the Gini  
 120 index of total per-capita emissions ( $G$ ) between countries:

$$121 \quad G = \sum_{k=1}^K G_k S_k R_k \quad (1)$$

122 Here  $k$  is the index denoting the source of emissions (primary energy carrier, or economic  
 123 sector, respectively),  $G_k$  is the Gini of component  $k$ ,  $S_k$  is the share of component  $k$  in total

emissions and  $R_k$  is the rank correlation between emission component  $k$  and total emissions<sup>2</sup>. Consequently, the contribution of each single source  $k$  to overall inequality in per-capita emissions is given by  $G_k S_k R_k$ .

In addition, this methodology allows analyzing the effect of marginal changes in any single source of emissions, which is useful to assess the impact on inequality in carbon emission across countries that are brought about by policies and/or technological advances that equal percentage reduction of emissions from any one source (see section 4.3). This marginal effect of a change  $e$  in any source  $k$  for overall inequality  $G$  can then be written as:

$$\frac{\partial G}{\partial e_k} = S_k (R_k G_k - G) \quad (2)$$

The decomposition method presented above can be applied for any given time period. As we are interested in the evolution of inequality over time, Section 4.1 presents the decomposition of the overall inequality into the contribution of each source of emissions  $k$  (i.e. primary energy carrier, or economic sector, respectively) for 5-year intervals for the period 1971 to 2008.

In order to gain a deeper understanding of the factors driving the evolution of overall inequality, we employ the Laspeyres decomposition method (e.g. Sun and Ang, (2000) see section 4.2). The Laspeyres decomposition allows us to break down changes in overall emission inequality to changes in its single components  $G$ ,  $S$ , and  $R$ . With  $\Delta$  denoting the difference between the year 2008 and 1971, we can decompose the change in the Gini index of total per-capita emissions between two points in time into the joint contribution of three underlying effects  $E$  for every source of emissions:

$$\Delta G = \sum_{k=1}^K (R_k + \Delta R_k)(G_k + \Delta G_k)(S_k + \Delta S_k) - \sum_{k=1}^K R_k G_k S_k \quad (3)$$

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<sup>2</sup> The rank correlation  $R_k$  ranges between +1 and -1. It will approach +1 (-1) if an emission source is an increasing (decreasing) function of total emissions.

146 This can be expressed as:

$$147 \quad \Delta G = \sum_{k=1}^K (E_k^R + E_k^G + E_k^S) \quad (3')$$

148 The individual effects can be derived from carrying out the multiplication in (3) and dividing  
 149 the residuals (i.e. changes of second and third order) evenly across factors. This is  
 150 demonstrated exemplarily for  $E_k^S$ , i.e. the change in inequality that can be attributed to a  
 151 change of the share of source  $k$  in total per-capita emissions, below:

$$152 \quad E_k^S = \Delta S_k G_k R_k + 1/2 \Delta S_k (\Delta G_k R_k + G_k \Delta R_k) + 1/3 \Delta S_k \Delta G_k \Delta R_k \quad (4)$$

### 153 **3 Data**

154 We employ historical data from the International Energy Agency (IEA) on per capita CO<sub>2</sub>  
 155 emissions from fuel combustion<sup>3</sup> over the period of 1971 to 2008 (International Energy  
 156 Agency, 2011)<sup>4</sup> and emission scenario data over the period of 2005 to 2100 generated by  
 157 the version 1.4 of the REMIND model (Kriegler et al., submitted); Bauer et al. 2012;  
 158 Leimbach et al. (2010) under the framework of the RoSE project<sup>5</sup> (Kriegler et al., submitted).

159 The IEA dataset contains data on CO<sub>2</sub>-emissions disaggregated by primary energy carriers  
 160 ('coal/peat', 'oil', 'gas' and 'other') as well as economic sectors ('manufacturing &  
 161 construction', 'transport', 'residential', 'other sectors', and 'agriculture'). We exclude  
 162 emissions specified as coming from 'other' sources, as this source mainly includes  
 163 emissions from the combustion of biomass and waste, and there is currently a lively debate

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<sup>3</sup> Our analysis focuses on energy-related CO<sub>2</sub>-emissions; land-use emissions as well as non-CO<sub>2</sub> greenhouse gas emissions (such as CH<sub>4</sub> and N<sub>2</sub>O) are not part of the analysis.

<sup>4</sup> For summary statistics refer to Table A1 and Table A2.

<sup>5</sup> <http://www.rose-project.org/>



on how these emissions should be accounted<sup>6</sup>. From the sectoral perspective, the data is organized in a way that it attributes emissions produced in transformation sectors (such as electricity generation, or refining) to final use sectors (e.g. transport or residential) according to the latter sector's consumption of energy from each transformation sector. With the aggregate 'other sectors' being the sum of emissions from the residential and the service sector, we are able to derive 'service sector emissions' by subtracting residential emissions from 'other sectors'. Within the IEA dataset we exclude emissions from the agricultural sector due to a lack of available data. As agricultural emissions account for only a small fraction of energy-related emissions<sup>7</sup> for the large majority of countries, we do not expect this exclusion to seriously bias our results.

In our sample, we only include countries for which there is full information (i.e. no values marked as 'missing') for CO<sub>2</sub> emissions on the level of primary energy carriers as well as economic sectors. We further exclude all countries for which CO<sub>2</sub> emissions from any primary energy carrier or economic sector have zero entries over the entire observation period, as we expect that this might indicate erroneous accounting. We do, however, include countries that display zero observations for some years<sup>8</sup>. For years prior to 1990, we use emission data for the Former Soviet Union and Former Yugoslavia, respectively, while from

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<sup>6</sup> For instance, it has been argued that biomass should be regarded as a zero-emission source of energy, as the associated emissions have been sequestered from the atmosphere during plant growth. However, if one regards the entire life-cycle, this picture changes, as also emissions related to land-use have to be taken into account (Farrell et al., 2006; Searchinger et al., 2008).

<sup>7</sup> Yet, agriculture is an important source of CH<sub>4</sub>, N<sub>2</sub>O as well as CO<sub>2</sub>-emissions from land use, all of which are not part of our analysis.

<sup>8</sup> For instance, it seems plausible that some developing countries report zero emissions from services in early periods, with a formalized service sector only beginning to emerge after a certain threshold of economic development.

1990 onwards, we separately include each constituent state in our sample<sup>9</sup>. This leaves us with a sample of 90 countries (see Table A3), which accounted for approximately 90% of global CO<sub>2</sub> emissions in the year 2008.

The REMIND data contain information on emissions per primary energy carrier for a business as usual (BAU) and a climate policy scenario (POL). REMIND is a multi-regional global integrated assessment hybrid model which couples a Ramsey-type optimal growth model with a technology-rich detailed energy system model and a simple climate model. It represents 11 world regions (see Figure A1) and considers the time horizon of 2005-2100<sup>10</sup>. In order to match the regional aggregation of the model to our data, we generate scenarios of future emissions on the country level by means of extrapolation. That is, we apply the changes in emissions from each individual primary energy carrier that are estimated by the model for any of the REMIND regions to each individual country in our dataset that is included in this respective region. As the model's definition of economic sectors does not correspond to the one used in the IEA data, we analyze the inequality of projected future emissions only from the perspective of primary energy carriers. The scenarios analyzed include a BAU scenario that assumes no climate measures and a policy scenario that corresponds to a 450ppm CO<sub>2</sub>-eq. concentration stabilization target by 2100. The policy scenario allows for overshoot and full 'when-where-what flexibility' of emissions reductions after 2010 and accounts for the radiative forcing of all radiative substances including Non-Kyoto gases and aerosols.

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<sup>9</sup> Note that different specifications are explored in the scope of the robustness checks in Section 5.

<sup>10</sup> The spacing of time-steps is flexible: in the default case, there are five-year time steps until 2050 and 10-year time steps until 2100. The period from 2100–2150 is also calculated to avoid distortions due to end effects. Typically, we only use the time span from 2005–2100 for model applications.

## 4 Results

### 4.1 Drivers of Changes in Emission Inequality over Time

This section gives an overview of changes in per-capita emissions and the associated Gini index between 1970 and 2008 for our sample of 90 countries. Further, in order to gain a better understanding of the underlying drivers of the developments, it decomposes overall inequality in per-capita emissions in contributions attributable to emissions from specific primary energy carriers or economic sectors.

In Figure 1, that gives an overview of how per capita CO<sub>2</sub> emissions have developed, we differentiate between emissions from coal/peat, gas or oil combustion. Overall emissions from those three sources are rising, mostly due to an increase in emissions from coal. Additionally, when dividing the sample into OECD and Non-OECD countries we observe a diverging trend between the two groups. Per capita emissions of OECD countries follow a declining trend after 2004, while non-OECD countries show a rising trend after 2002.

Insert Figure 1 here: Global, OECD and non-OECD energy-related CO<sub>2</sub> per-capita emissions over time.

Over the entire observation period, the Gini index of per-capita CO<sub>2</sub> emissions declined from almost 0.6 in 1971 to slightly above 0.4 in 2008, indicating that over time, the distribution has become more equal (Figure 2). Interestingly, and perhaps contrary to what one could expect, the largest part of this reduction is found to take place in years prior to 1990, i.e. before many emerging economies had started the spectacular growth performance witnessed in recent years.

224

225     Insert Figure 2 here: Contribution of individual primary energy carriers and economic sectors  
226     to total inequality in per-capita CO<sub>2</sub> emissions measured by the Gini index

227

228     Analyzing the development of the Gini index disaggregated along primary energy carriers  
229     (Figure 2 left panel) we observe that the decline in total inequality in per-capita CO<sub>2</sub>  
230     emissions can be attributed to (a) a significant reduction in the contribution of emissions from  
231     oil, with the most pronounced drop taking place in the period ranging from the mid-70s to the  
232     mid-80s and (b) a reduction of similar magnitude in the contribution of emissions from  
233     coal/peat, concentrated on the period 1985-2000. Contrary to oil and coal/peat, emissions  
234     from natural gas exert an upward influence on total inequality in most years. Consequently,  
235     the share of total inequality explained by the contribution from natural gas has increased  
236     significantly over the observation period, namely from 8% in 1971 to 23% in 2008.

237     Regarding the evolution of the Gini index of per-capita CO<sub>2</sub> emissions over time along  
238     economic sectors (i.e. residential, transport, services, and manufacturing & construction)  
239     (Figure 2 right panel), the most striking observation is that the declining inequality in CO<sub>2</sub>  
240     emissions observed between 1971 and 2008 is almost entirely explained by the pronounced  
241     drop of the contribution of emissions from the manufacturing & construction sector, which  
242     occurred mainly prior to 2000. While this type of emissions accounted for more than half of  
243     total inequality in 1971, this figure drops to one third in 2008. Likewise, the contribution of  
244     emissions from the residential sector declines by roughly one third from 1971 to 2008. In  
245     contrast, the share of service sector emissions rises from 9 to 16%, and the one for  
246     emissions from transportation from 14 to 28%. The contributions of emissions from the  
247     service, as well as the transport, sector increase each by almost half over the observation  
248     period. However, the effect is quantitatively rather small due to their relatively low initial  
249     shares in total inequality.

These findings are very likely explained by the fact that (a) developing countries are increasingly relying on coal/peat and oil to meet their growing energy needs, while for industrialized countries, natural gas plays an increasing role, and (b) structural economic change has resulted in growth of manufacturing and construction in developing countries, but a relative decline of this sector (i.e. a shrinking share of total economic activity) in industrialized countries.

## 4.2 Laspeyres Decomposition

In this section, in order to give a quantitative assessment of the influence of changes in any single factor on total inequality we employ the Laspeyres decomposition. We investigate the contribution of each of the three factors affecting the value of the Gini index to total inequality (i.e. (i) changes in the Gini index within this source, (ii) changes in the share of this source in total per-capita emissions, and (iii) changes in its rank correlation with total emissions) for every individual source of emissions (i.e. primary energy carrier or economic sector). Table A4 presents the respective values for each of the three factors for the first and the last year included in our sample (i.e. 1971 and 2008). The results of the application of the Laspeyres decomposition are shown in Figure 3 as the percentage of the absolute value of the total observed change in inequality that can be attributed to each individual factor (i.e. computed over all sources  $k$ , the changes attributable to individual factors sum up to 100%).

For emissions from oil as well as coal/peat, the declining contribution to the Gini index of per-capita CO<sub>2</sub> emissions is explained by the reduced shares of emissions from these energy carriers in total CO<sub>2</sub> emissions, lower Gini indices within each of these two sources, and to a lesser extent lower rank correlations with total emissions. For natural gas, on the other hand, the increased contribution to the overall Gini index is almost exclusively due to a higher share of emissions from this source in total emissions, while its declining Gini index works in the opposite direction and the change in the rank correlation is negligible. Consequently, while all three primary energy carriers are characterized by declining 'within'

emissions inequality, it is the shift away from coal and oil and towards natural gas that determines the changes in the relative contribution of the three carriers described in the previous section.

Insert Figure 3 here: Laspeyres decomposition

For emissions from manufacturing & construction, both the sector's reduced share in total emissions and the lower Gini index in 2008 compared to 1971 have comparable impacts on its reduced contribution on overall emission inequality. For emissions from the service as well as the transport sectors, increased shares in total emissions increase inequality in total per-capita CO<sub>2</sub> emissions. On the other hand, decreased Gini indices within both sources work in the opposite direction, without compensating, however, for the previous effect. Finally, for emissions from the residential sector, the reduced inequality of emissions from this sector, and a lower rank correlation with total emissions in 2008 compared to 1971, diminish its contribution of emissions. Its slightly increased share in total emissions causes only a minor increase in the contribution of emissions from this source. Similarly to the decomposition by primary energy carriers, also here we observe that emissions inequality within each of the individual sectors is decreasing over time. However, significant differences are observed between the four sectors, with the Gini coefficient declining more for the manufacturing and residential sector and less for the service and the transport sectors. As a consequence, both diverging changes in the Gini index within each of the four sectors, and changes in the share of each sector in total per-capita emissions, are contributing to differences in overall emissions inequality between countries.

### 4.3 Marginal Effects of Changing Emission Patterns

This section discusses the results of the application of the methodology to determine the marginal effect of an equally spread percentage reduction from any single source of emissions (i.e. primary energy carrier or economic sector) on the Gini index of total per-capita emissions. This kind of analysis could bear importance for the formulation of climate policies, as it allows assessing the impacts of e.g. technological innovations that reduce emissions from one given energy carrier or economic sector (such as more efficient power plants or automobiles), or a global agreement calling for equal percentage reduction of emissions from any particular sector (such as the manufacturing & construction sector).

The results of this exercise (undertaken for 2008 data) are shown in Table 1. The most striking feature is that, regardless of their sign, these marginal effects are relatively small. For instance, an across the board reduction of emissions from coal/peat by 1% would decrease the Gini index of total per-capita CO<sub>2</sub> emissions across countries by no more than 0.07%. For the remaining energy carriers and economic sectors, the respective effects are even less pronounced. Hence, we conclude that an equally spread percentage reduction from any one source of CO<sub>2</sub> emissions would not significantly alter the prevailing pattern of global inequality in per-capita emissions.

Insert Table 1 here: Effects of a 1% decrease of per-capita CO<sub>2</sub> emissions from any particular source on the GINI of total per-capita emissions (in %), using 2008 data.

## 4.4 Emission Inequality for Different Country Groupings

While the focus of this paper is clearly on global inequality, we repeat the above procedure for OECD as well as non-OECD countries, respectively. This allows us to assess whether the trends identified above can also be detected for these individual country groupings.

Compared to the full sample, we find a significantly lower Gini index of overall emissions for OECD countries (Figure A2). In 1971 it lies slightly below 0.4, declining to about 0.25 in 2008. Hence, OECD countries start more homogeneously and seem to converge faster to more equal per capita CO<sub>2</sub> emission than non-OECD countries, which start with an initial Gini of 0.6 and a Gini of 0.45 in 2008 (Figure A3).

The overall pattern in terms of the contribution of each energy carrier is similar between the full sample and the two subsamples (Figure A2 and Figure A3 left panel), but OECD countries display a more pronounced reduction in the contribution of coal/peat to overall emission inequality (which declines by almost one half). Furthermore, both country groups display a slight decrease in the contribution of emissions from oil, and a slight increase in the one from natural gas.

From the perspective of economic sectors (Figure A2 and Figure A3 right panel), the declining contribution of emissions from the manufacturing & construction sector turns out to be the main driving force behind the overall decline in CO<sub>2</sub> emission inequality for both OECD and non-OECD countries. It is more pronounced for the former than for the latter. For non-OECD countries the largest part of the reduction takes place between 1990 and 1998, which is possibly related to economic recession in the countries of Eastern Europe and the former Soviet Union. For OECD countries, this declining contribution is partly counterbalanced by an increasing contribution of transport emissions, while this sector displays only little variation for non-OECD countries. The same holds for emissions from the service as well as the residential sector for both country groups.



This analysis suggests that the observed reductions in overall emission inequality reflect global trends. That is, changing patterns of coal/peat consumption and emissions in the manufacturing & construction sector can to a large extent explain changes in inequality in per-capita emissions across countries. This conclusion not only holds on the global level, as shown in the previous section, but also for OECD and non-OECD countries separately.

## 4.5 Application to Emission Scenarios

In order to provide an outlook on the future development in global emission inequality with and without climate policy, we build on scenario data generated with the integrated assessment model REMIND.

Figure 4 contrasts the results of a BAU scenario (left panel) and a policy scenario (right panel) with a stabilization target of 450ppm CO<sub>2</sub>-eq. by 2100. The BAU scenario indicates that global emission inequality, after an initial slight decline until 2025, is characterized by an increasing trend from then onwards and till the end of the century (slightly above 0.48 in the year 2100). Similarly, in the policy scenario inequality declines until 2020 and then rises again up to 0.46 in 2070 to slightly decline again to 0.44 in 2100. Not surprisingly, a key difference between the two scenarios is the contribution of emissions from the three different primary energy carriers in overall inequality<sup>11</sup>. Under the BAU scenario coal is projected to be the major contributor to emission inequality from 2050 onwards. Meanwhile, with the 450ppm CO<sub>2</sub>-eq. target, emissions from coal contribute a diminishing share to overall inequality after 2035, while emissions from oil play a more important role.

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<sup>11</sup> Note that negative emissions arising from the use of biomass in combination with CCS, which feature in the POL scenario, are not included in this analysis.

Insert Figure 4: Contribution of each primary energy carrier (coal, natural gas, and oil) to total inequality in per-capita CO<sub>2</sub> emissions, measured by the Gini index.

The nature of these results is explained with the use of the Laspeyres decomposition as displayed in Figure 5. For both scenarios we find that the main driver of these changes is changes in the shares of emissions from the different carriers. In the case of the BAU scenario (left panel), an increasing share of emissions from coal is the main cause for the increase in inequality between 2005 and 2100. Inversely, emissions from oil work in the opposite direction, thus leading to a decline in overall emission inequality, which cannot however offset the effect of emissions from coal. The rank correlation with total emissions and the Gini for global coal emissions play a smaller role, and so do gas emissions. For the policy scenario (right panel), the picture is reversed. Here the decreasing share of emissions from coal and its rank correlation with total emissions contribute to a decline in overall emission inequality. This effect is offset mainly by the combined effect of the rise in the share of emissions from oil and its increasing rank correlation with overall emissions, and secondarily gas.

Insert Figure 5: Laspeyres decomposition to determine the influence of changes in individual contributing factors

The above analysis indicates that climate change policies can be expected to result in a more equal distribution compared to the BAU scenario. As we saw under the BAU scenario global emission inequality rises by about 0.05, while under the stabilization scenario it rises by only 0.01. This result is due to both a complete phase out of the most carbon intensive fossil (coal) but also due to the overall gradual dramatic reduction in all fossil fuels

deployment for all regions under the policy scenario. In specific, emissions from fossil fuels at a global level are almost halved by 2030 under the policy scenario in comparison to the BAU case (about 49260 MtCO<sub>2</sub>/yr in BAU and 26640 MtCO<sub>2</sub>/yr in POL), reduced to slightly less than one third by 2050 (about 62140 MtCO<sub>2</sub>/yr in BAU and 20275 MtCO<sub>2</sub>/yr in POL), and characterized by a seven-fold reduction by 2100 (61925 MtCO<sub>2</sub>/yr in the BAU scenario to 9200 MtCO<sub>2</sub>/yr in POL). .

## 5 Sensitivity analysis

In order to assess the robustness of our results with regard to how we select the countries included in our sample, we perform three sensitivity checks.<sup>12</sup>

First, we repeat our estimates excluding the Former Soviet Union and Former Yugoslavia (for years prior to 1990) and its constituent entities (1990 and after) from the overall sample. The results are very similar to those reported above. Therefore we can conclude that the economies in transition do not bias our results for the overall sample.

Second, we include all countries for which data are available, even if zeroes are reported in every single year for a given energy carrier or economic sector. For this enlarged sample of 128 countries, the overall Gini displays a less pronounced decline, from slightly below 0.6 in 1971 to slightly above 0.5 in 2008. This is quite intuitive, as countries reporting zero emissions can be expected to have an upward influence on overall inequality. With regard to primary energy carrier, the general patterns are repeated. Yet, with the larger sample, the decline in the contribution of oil is less pronounced (from 0.21 in 1971 to 0.18 in 2008) and the increase in the contribution of natural gas stronger (from 0.14 to 0.25 in 2008). For economic sectors, we again find that the decline in overall emission inequality is almost

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<sup>12</sup> This section only presents the main conclusions; more detailed information is available on request.

418 exclusively explained by the reduced contribution of the manufacturing & construction  
 419 sector.

420 Third, as observations with a zero value might be considered as a sign of reporting errors,  
 421 we remove all countries that report zero emissions from any single source of emissions in  
 422 any year from our sample. This smaller sample, which includes only 46 countries, produces  
 423 a smaller Gini index for overall emissions (slightly below 0.5 in 1971, and slightly below 0.4  
 424 in 2008). This can very likely be explained by the fact that countries that report zeroes are  
 425 predominantly low emitters. Hence, removing these countries from the sample curtails the  
 426 distribution and decreases overall inequality. For the patterns explaining the observed drop  
 427 in the Gini index, we again find significantly declining contributions from oil and coal/peat  
 428 with the contribution of natural gas working in the opposite direction. With regard to the role  
 429 of economic sectors, the declining contribution of emissions from manufacturing &  
 430 construction is confirmed to be the dominant factor.

431 Hence, even though the choice of methods to construct our sample affects some details of  
 432 the analysis, our overall conclusions appear very robust. For all samples considered, we find  
 433 that the Gini coefficient declines over time, and that this decline can mainly be attributed to  
 434 declining contributions from oil and coal/peat (from the perspective of primary energy  
 435 carriers) or declining contributions of manufacturing & construction (from the perspective of  
 436 economic sectors), respectively.

## 437 **6 Conclusions**

438 This paper uses the decomposition of the Gini index proposed by Lerman and Yitzhaki,  
 439 (1985, 1984) to analyze the contribution of individual primary energy carriers and economic  
 440 sectors on inequality in total per-capita CO<sub>2</sub> emissions across countries. We analyze past  
 441 trends using historical data on energy-related CO<sub>2</sub> emissions and also provide an outlook on

442 how climate policy could affect future emission inequality using scenario data from the  
443 integrated assessment model REMIND.

444 For our sample of 90 countries, which represent about 90% of global emissions in 2008, we  
445 find that the Gini index of per-capita CO<sub>2</sub> emissions has declined considerably, from about  
446 0.6 in 1971 to slightly above 0.4 in 2008. From the perspective of primary energy carriers,  
447 this observation can mainly be explained by a considerable reduction in the contribution of  
448 emissions from oil and coal/peat. A Laspeyres decomposition reveals that declining shares  
449 of emissions from coal/peat and oil in total emissions and the increasing share of emissions  
450 from natural gas work in opposite directions. At the same time, emissions inequality is seen  
451 to decrease similarly within all three individual carriers, and this is also pushing inequality  
452 downwards. From the perspective of economic sectors, decreases in inequality are almost  
453 entirely due to the pronounced decline of the contribution of emissions from the  
454 manufacturing & construction sector. The most relevant explanatory factors are the declining  
455 share of emissions from the manufacturing & construction sector in total emissions, and the  
456 declining Gini index of emission from this sector. These observations highlight the  
457 importance of changing energy use patterns for inequality in per-capita CO<sub>2</sub> emissions  
458 across countries, which had not been analyzed in previous studies.

459 Our results were found to be robust for different country groupings and marginal effects  
460 tests. Firstly, repeating the analysis for OECD and non-OECD countries separately revealed  
461 that, while the results are quantitatively different, a similar pattern emerges. As observed  
462 also for the whole sample, inequality in per-capita emissions decreased for both OECD and  
463 non-OECD countries, and this was mainly due to decreasing contributions from emissions  
464 from coal/peat and oil from a primary energy carrier perspective, and a decreasing  
465 contribution from manufacturing emissions from a sectoral perspective. Evaluating the  
466 marginal effect of an equally spread reduction of emissions from any one source of  
467 emissions (i.e. primary energy carriers, or economic sectors) on the Gini coefficient of total

per-capita emissions, we find that any such reduction would only have minor impacts on overall emission inequality.

Using scenarios of future emissions generated with the integrated assessment model REMIND, we find that climate policy can be expected to result in a more equal distribution of global emissions across countries. The main driver behind this effect is the share of emissions from coal, which under the BAU case is projected to be the major contributor to emission inequality from 2050 onwards, while in the policy case its effect is completely phased out by the end of the century. Changes attributed to oil use are working in the reverse direction, but their effect in overall emissions inequality is not as influential as changes related to coal use. Additionally, notable progressive reductions in global total fossil fuel emissions indicate the considerable diminution in fossil fuel use across all countries. This factor limits the possibility for significant across-country divergence in the level of fossil fuel emissions, in the context of drastic emissions reductions in order to achieve the stabilization target.

Our findings provide a more fine-grained understanding of the underlying drivers of inequality in per-capita CO<sub>2</sub> emissions than previous studies. In particular, they underline the importance of energy system and economic transformations for emissions inequality, by highlighting how changes in the use of primary energy carriers and economic activity between sectors propagates into across-country inequality in per-capita CO<sub>2</sub> emissions.

The issue of inequality in per-capita emissions can be expected to occupy a top spot in the agenda of future climate negotiations. Any future climate agreement faces the challenge of achieving a distribution of emission rights that is recognized as equitable by all participants. Our results indicate that reducing emission inequality is compatible with climate stabilization only if high emitters accept more substantial cuts in their per-capita emissions compared to low emitters. A clear understanding of historical trends and patterns, combined with the

493 integrated assessment of policy scenarios, can form the basis to evaluate the implications of  
494 future climate policies. This is where this paper intends to make a contribution.

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## 8 Appendix

Table A1: Summary Statistics IEA Data: Emissions per capita for primary energy carriers and economic sectors in metric tons of CO<sub>2</sub> (tCO<sub>2</sub>).

Variable	Obs	Mean	Std. Dev.	Min	Max
coal_pc	2935	1.91	3.01	0.00	32.47
gas_pc	2935	0.94	1.26	0.00	6.13
oil_pc	2935	2.62	2.46	0.01	17.09
manufact_pc	2935	1.99	2.60	0.00	38.66
service_pc	2832	0.65	0.74	0.00	3.77
transport_pc	2935	1.12	1.32	0.00	14.73
residential_pc	2935	1.09	1.13	0.00	5.17

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Source: (International Energy Agency, 2011)

576 Table A2: Summary Statistics Scenario Data: Emissions per capita for primary energy  
 577 carriers in metric tons of CO<sub>2</sub> (tCO<sub>2</sub>) and their respective growth rate (in %).

Variable	Scenario	Obs	Mean	Std. Dev.	Min	Max
oil_pc	BAU	1248	2.95	2.94	0.09	22.56
gas_pc	BAU	1248	3.22	3.59	0.00	22.52
coal_pc	BAU	1248	2.86	5.79	0.00	67.65
oil_growth	BAU	1170	0.51	1.65	-0.87	13.09
gas_growth	BAU	1170	4.75	17.29	-0.79	164.46
coal_growth	BAU	1170	4.72	16.61	-0.87	119.56
oil_pc	POL	1248	2.16	2.24	0.06	17.09
gas_pc	POL	1248	1.47	1.74	0.00	13.18
coal_pc	POL	1248	0.48	1.15	0.00	10.49
oil_growth	POL	1170	-0.07	0.55	-0.91	3.26
gas_growth	POL	1170	1.34	5.64	-0.85	39.76
coal_growth	POL	1170	-0.71	0.55	-1.00	5.33

578 Source: Kriegler et al. (submitted)

579

580

581 Table A3: Country List

Country List IEA		
Albania	Georgia	Peru
Algeria	Germany	Philippines
Argentina	Greece	Poland
Armenia	Hong Kong, China	Portugal
Australia	Hungary	Romania
Austria	India	Russian Federation
Azerbaijan	Indonesia	Senegal
Bangladesh	Islamic Republic of Iran	Serbia
Belarus	Ireland	Singapore
Belgium	Israel	Slovak Republic
Bolivia	Italy	Slovenia
Bosnia and Herzegovina	Japan	South Africa
Brazil	Korea	Spain
Bulgaria	Latvia	Sweden
Canada	Lithuania	Switzerland
Chile	Luxembourg	Syrian Arab Republic
People's Republic of China	FYR of Macedonia	Tajikistan
Chinese Taipei	Malaysia	United Republic of Tanzania
Colombia	Mexico	Thailand
Democratic Republic of Congo	Republic of Moldova	Tunisia
Croatia	Mongolia	Turkey
Cuba	Morocco	Ukraine
Czech Republic	Mozambique	United Kingdom
Denmark	Myanmar	United States
Dominican Republic	Netherlands	Uruguay
Egypt	New Zealand	Uzbekistan
Estonia	Nigeria	Venezuela
Finland	Norway	Vietnam
France	Pakistan	

582 Source: IEA (2011)

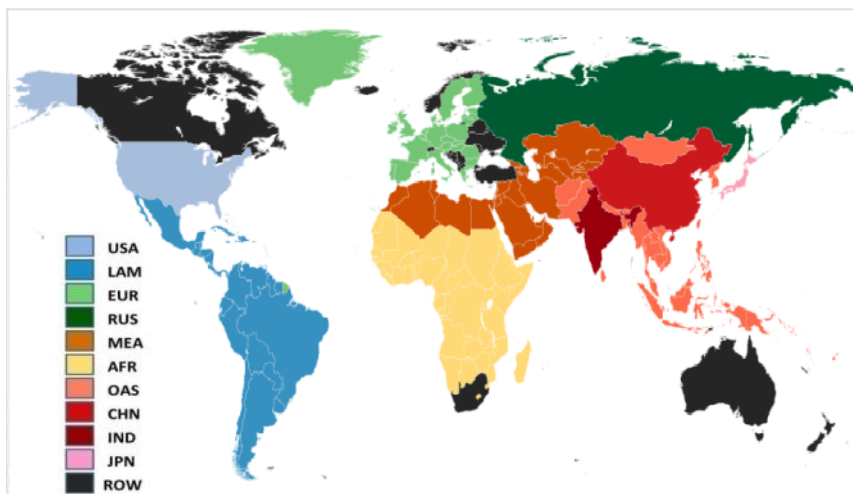


Figure A1: REMIND Regions

Source: Luderer et al. (2013) Note: The regional acronyms are as follows: *USA* – USA; *LAM* – Latin America; *EUR* – Europe; *RUS* – Russia; *MEA* – Middle-East; *AFR* – Africa; *OAS* – other Asia; *CHN* – China; *IND* – India; *JPN* – Japan; *ROW* – rest of the World.

591 Table A4: Contributing factors to changes in the Gini index of total per-capita emissions by  
 592 source

	1971			2008		
	Share	GINI	Rank Corr.	Share	GINI	Rank Corr.
Oil	0.53	0.55	0.90	0.43	0.46	0.85
Coal	0.39	0.77	0.93	0.32	0.65	0.81
Gas	0.08	0.84	0.75	0.25	0.53	0.74
Manufact	0.52	0.65	0.95	0.34	0.45	0.94
Service	0.09	0.69	0.93	0.16	0.54	0.90
Transport	0.17	0.53	0.85	0.28	0.50	0.89
Residential	0.21	0.65	0.98	0.22	0.48	0.91

593 Source: (International Energy Agency, 2011)

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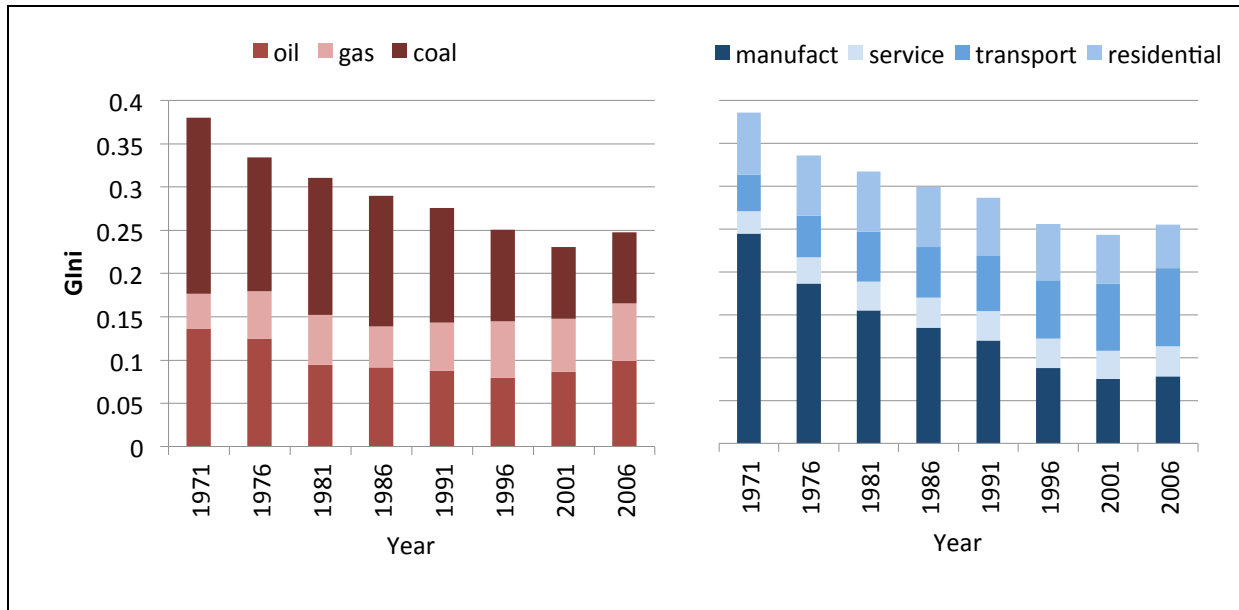


Figure A2: Contribution of emissions from individual primary energy carriers and economic sectors to total inequality in per-capita CO<sub>2</sub> emissions measured by the Gini index, for OECD countries only



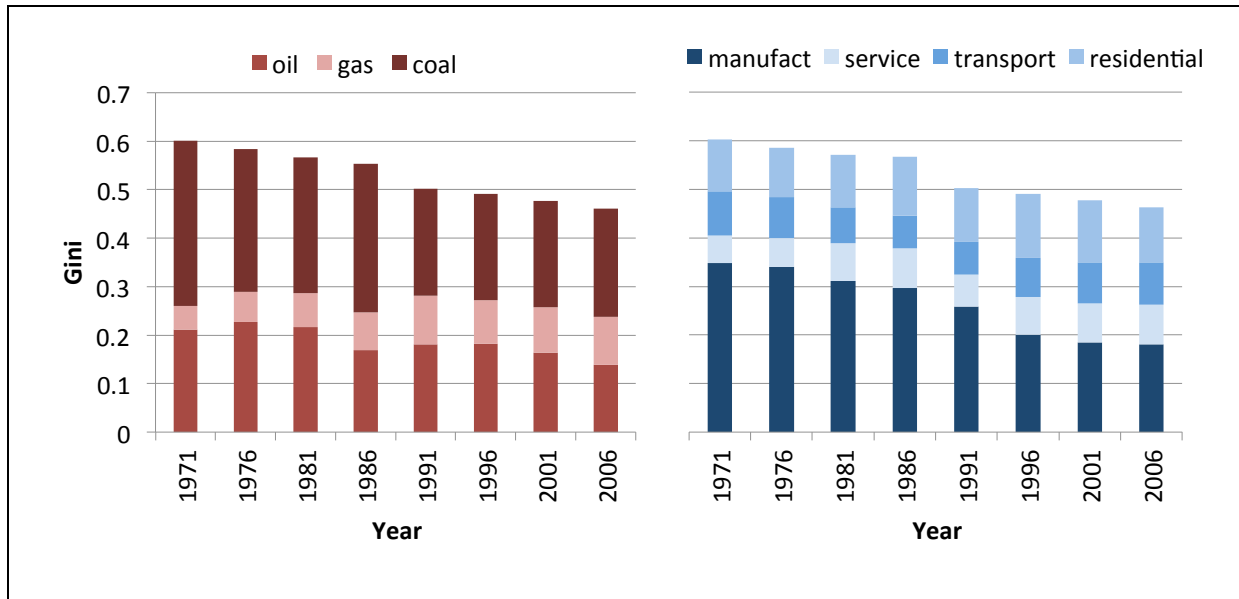


Figure A3: Contribution of emissions from individual primary energy carriers and economic sectors to total inequality in per-capita CO<sub>2</sub> emissions measured by the Gini index, for non-OECD countries only

## 9 Figures and Tables

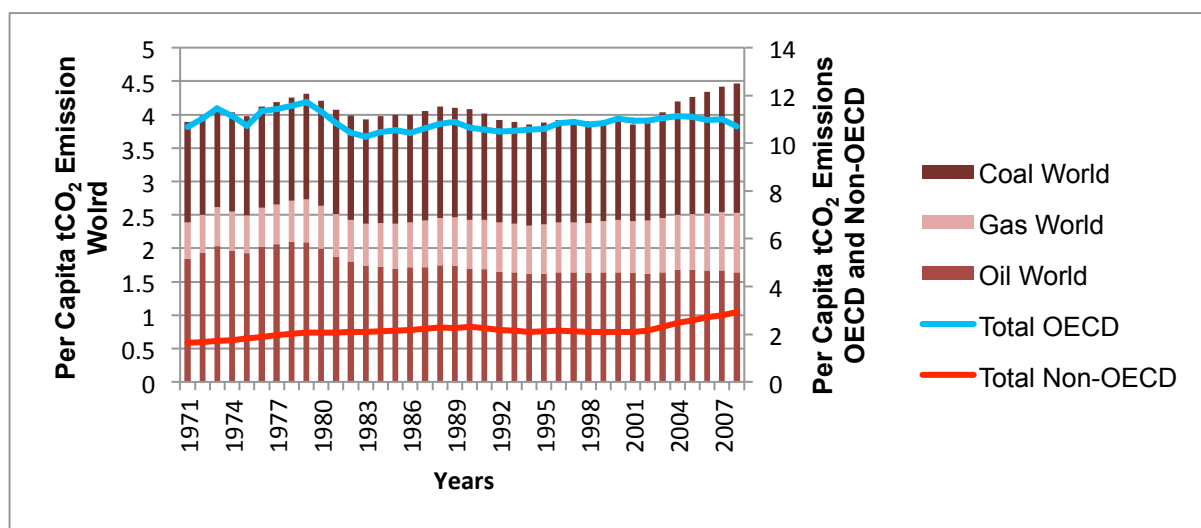
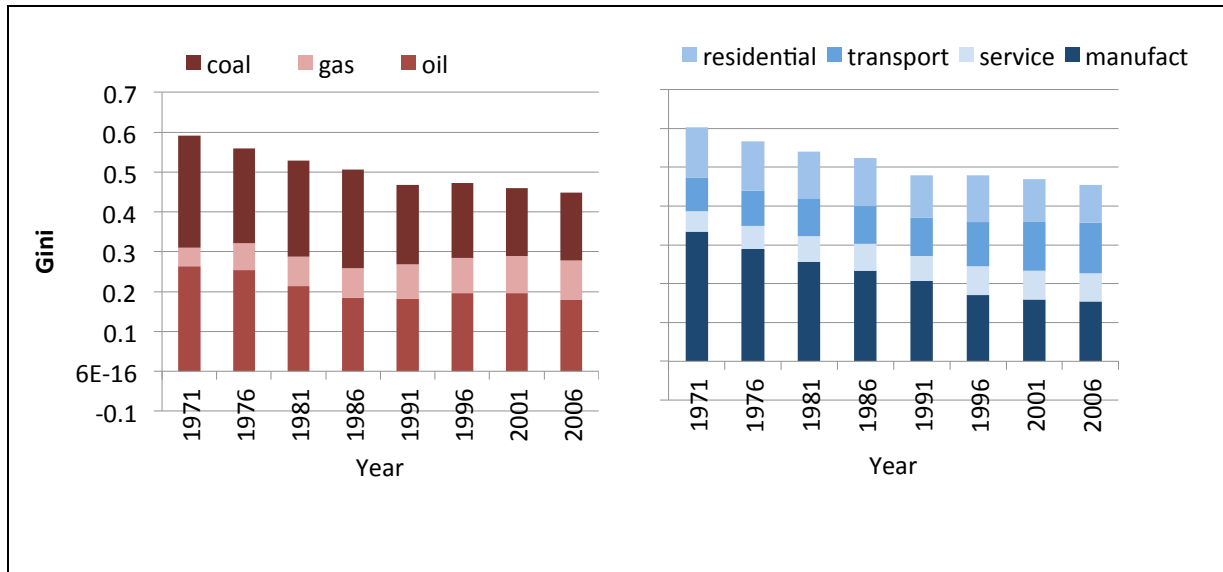
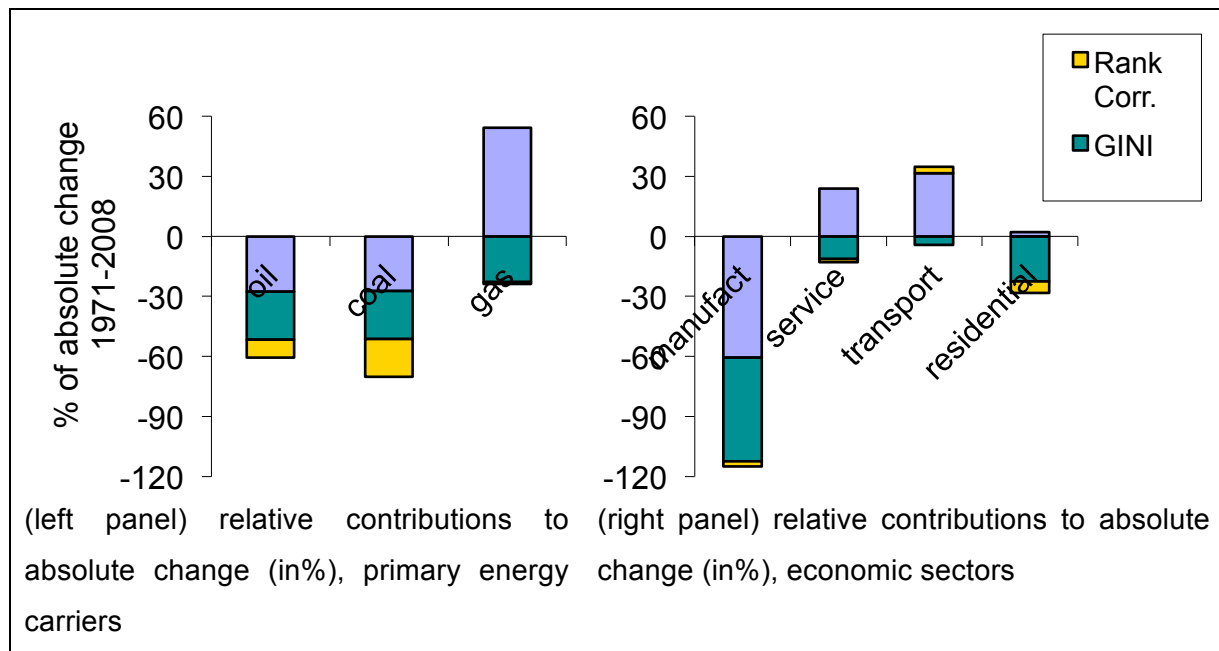


Figure 1: Global, OECD and non-OECD energy-related CO<sub>2</sub> per-capita emissions over time.

Source: IEA (2011)



616 Figure 2: Contribution of individual primary energy carriers and economic sectors to total  
 617 inequality in per-capita CO<sub>2</sub> emissions measured by the Gini index



623 Figure 3: Laspeyres decomposition to determine the source of absolute changes in the Gini  
 624 index of total per-capita emissions.

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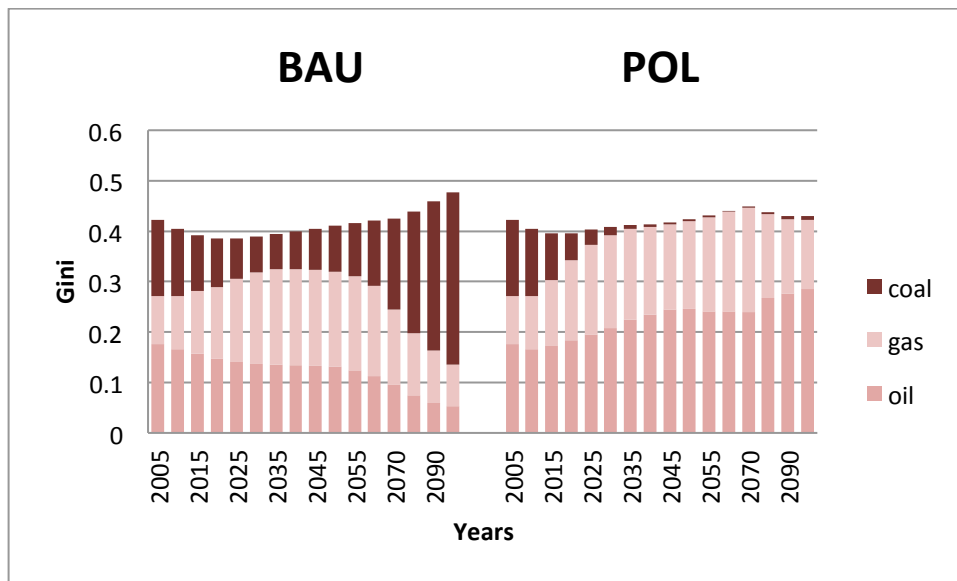


Figure 4: Contribution of individual primary energy carriers to total inequality in per-capita CO2 emissions, measured by the Gini index.

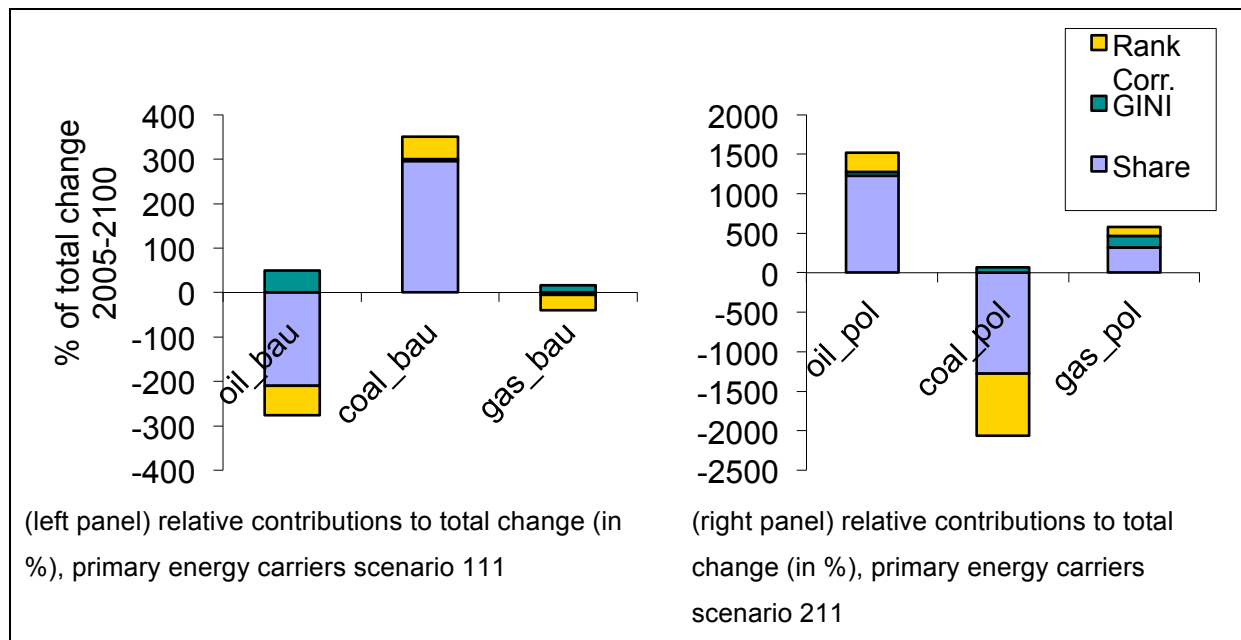


Figure 5: Laspeyres decomposition to determine the source of changes in the GINI index of total per-capita emissions.

639 Table 1: Effects of a 1% decrease of per-capita CO2 emissions from any particular source  
 640 on the Gini of total per-capita emissions (in %), using 2008 data.

Primary Energy Carriers		Economic Sectors	
Oil	0.0465	Manufact.	0.0142
Coal	-0.07	Service	-0.0144
Natural Gas	0.0235	Transport	-0.0014
		Residential	0.0017

641

642