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## Conference Paper

# 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.

50 Given the pivotal role of emissions inequality for climate negotiations, the issue has been  
51 investigated in the literature through a variety of methods. (Hedenus and Azar, 2005) use  
52 the Atkinson index (Atkinson, 1970) to find a declining trend in global emission inequality  
53 between 1960 and 1999 (from 0.64 to 0.5). This is based on their finding that in 1999 the  
54 20% most emitting countries emitted about 22 times the amount of carbon than the 20%  
55 least emitting countries, while in 1960 this gap had been more than twice as large. Various  
56 authors use the Theil Index (Theil, 1972) to measure and explain global emission inequality  
57 (e.g. Padilla and Duro, 2011). The advantage of the Theil index is that it can be decomposed  
58 in inequality within and between country groupings (Shorrocks, 1982). Duro and Padilla,  
59 (2006) use the Kaya identity (1989) to decompose emission inequality across countries into  
60 the contributions of carbon intensity of energy, energy intensity and affluence. They find that  
61 during the period from 1970 to 1999 income differences were the main drivers of emission  
62 inequality between countries, while differences in carbon intensity and energy intensity  
63 displayed lower contributions<sup>1</sup>. Padilla and Serrano (2006) also show, using the Gini and the  
64 Theil index for country-level emissions, that emission inequality is closely correlated with  
65 income inequality and that both follow the same path over time. Finally, Duro, (2012)  
66 compares a set of inequality measures such as the Gini coefficient, Theil index, the Atkinson  
67 measure as well as the coefficient of variation in terms of their sensitivity to changes in the  
68 distribution of CO<sub>2</sub> emissions over time. He concludes that different inequality indicators can  
69 yield differing results due to differences in their distributive sensitivity.

70 A further widely employed measure of inequality is the Gini coefficient. In the case of CO<sub>2</sub>  
71 emissions, the cumulative share of global CO<sub>2</sub> emissions is plotted against the cumulative  
72 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.

73 (2000, 1997) follow the methodology of Yitzhaki and Lerman (1991) to decompose the Gini  
74 coefficient in a within group and a between group component. The between group  
75 component compares rich and poor countries in order to analyze the contribution to the  
76 global emission inequality. They find that between group inequality declined slightly, but rich  
77 countries would have to reduce emissions by at least 50% to change the ranking of the  
78 highest polluting countries.

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

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

94 The paper proceeds as follows: Section 2 presents the employed empirical method, and  
95 Section 3 the used data. Section 4 applies the methodology using both historical data, for a  
96 global sample as well as for a sub-sample of OECD and non-OECD countries, and results of  
97 the REMIND model. Section 5 presents the outcomes of a sensitivity analysis, while section  
98 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

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

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

$$132 \quad \frac{\partial G}{\partial e_k} = S_k (R_k G_k - G) \quad (2)$$

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

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

$$145 \quad \Delta G = \sum_{k=1}^K (R_k + \Delta R_k)(G_k + \Delta G_k)(S_k + \Delta S_k) - \sum_{k=1}^K R_k G_k S_k \quad (3)$$

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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/>



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

174 In our sample, we only include countries for which there is full information (i.e. no values  
175 marked as 'missing') for CO<sub>2</sub> emissions on the level of primary energy carriers as well as  
176 economic sectors. We further exclude all countries for which CO<sub>2</sub> emissions from any  
177 primary energy carrier or economic sector have zero entries over the entire observation  
178 period, as we expect that this might indicate erroneous accounting. We do, however, include  
179 countries that display zero observations for some years<sup>8</sup>. For years prior to 1990, we use  
180 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.

181 1990 onwards, we separately include each constituent state in our sample<sup>9</sup>. This leaves us  
182 with a sample of 90 countries (see Table A3), which accounted for approximately 90% of  
183 global CO<sub>2</sub> emissions in the year 2008.

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

---

<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.

## 201 **4 Results**

### 202 **4.1 Drivers of Changes in Emission Inequality over Time**

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

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

214

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

217

218 Over the entire observation period, the Gini index of per-capita CO<sub>2</sub> emissions declined from  
219 almost 0.6 in 1971 to slightly above 0.4 in 2008, indicating that over time, the distribution has  
220 become more equal (Figure 2). Interestingly, and perhaps contrary to what one could  
221 expect, the largest part of this reduction is found to take place in years prior to 1990, i.e.  
222 before many emerging economies had started the spectacular growth performance  
223 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.

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

## 256 **4.2 Laspeyres Decomposition**

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

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

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

279

280 Insert Figure 3 here: Laspeyres decomposition

281

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

299

300

### 301 **4.3 Marginal Effects of Changing Emission Patterns**

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

310 The results of this exercise (undertaken for 2008 data) are shown in Table 1. The most  
311 striking feature is that, regardless of their sign, these marginal effects are relatively small.  
312 For instance, an across the board reduction of emissions from coal/peat by 1% would  
313 decrease the Gini index of total per-capita CO<sub>2</sub> emissions across countries by no more than  
314 0.07%. For the remaining energy carriers and economic sectors, the respective effects are  
315 even less pronounced. Hence, we conclude that an equally spread percentage reduction  
316 from any one source of CO<sub>2</sub> emissions would not significantly alter the prevailing pattern of  
317 global inequality in per-capita emissions.

318

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

321

322

323

324

#### 325 **4.4 Emission Inequality for Different Country Groupings**

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

329 Compared to the full sample, we find a significantly lower Gini index of overall emissions for  
330 OECD countries (Figure A2). In 1971 it lies slightly below 0.4, declining to about 0.25 in  
331 2008. Hence, OECD countries start more homogenously and seem to converge faster to  
332 more equal per capita CO<sub>2</sub> emission than non-OECD countries, which start with an initial  
333 Gini of 0.6 and a Gini of 0.45 in 2008 (Figure A3).

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

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



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

## 355 **4.5 Application to Emission Scenarios**

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

359 Figure 4 contrasts the results of a BAU scenario (left panel) and a policy scenario (right  
360 panel) with a stabilization target of 450ppm CO<sub>2</sub>-eq. by 2100. The BAU scenario indicates  
361 that global emission inequality, after an initial slight decline until 2025, is characterized by an  
362 increasing trend from then onwards and till the end of the century (slightly above 0.48 in the  
363 year 2100). Similarly, in the policy scenario inequality declines until 2020 and then rises  
364 again up to 0.46 in 2070 to slightly decline again to 0.44 in 2100. Not surprisingly, a key  
365 difference between the two scenarios is the contribution of emissions from the three different  
366 primary energy carriers in overall inequality<sup>11</sup>. Under the BAU scenario coal is projected to  
367 be the major contributor to emission inequality from 2050 onwards. Meanwhile, with the  
368 450ppm CO<sub>2</sub>-eq. target, emissions from coal contribute a diminishing share to overall  
369 inequality after 2035, while emissions from oil play a more important role.

370

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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.

371 Insert Figure 4: Contribution of each primary energy carrier (coal, natural gas, and oil) to  
372 total inequality in per-capita CO2 emissions, measured by the Gini index.

373

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

387

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

390

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

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

## 402 **5 Sensitivity analysis**

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

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

409 Second, we include all countries for which data are available, even if zeroes are reported in  
410 every single year for a given energy carrier or economic sector. For this enlarged sample of  
411 128 countries, the overall Gini displays a less pronounced decline, from slightly below 0.6 in  
412 1971 to slightly above 0.5 in 2008. This is quite intuitive, as countries reporting zero  
413 emissions can be expected to have an upward influence on overall inequality. With regard to  
414 primary energy carrier, the general patterns are repeated. Yet, with the larger sample, the  
415 decline in the contribution of oil is less pronounced (from 0.21 in 1971 to 0.18 in 2008) and  
416 the increase in the contribution of natural gas stronger (from 0.14 to 0.25 in 2008). For  
417 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

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

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

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

487 The issue of inequality in per-capita emissions can be expected to occupy a top spot in the  
488 agenda of future climate negotiations. Any future climate agreement faces the challenge of  
489 achieving a distribution of emission rights that is recognized as equitable by all participants.  
490 Our results indicate that reducing emission inequality is compatible with climate stabilization  
491 only if high emitters accept more substantial cuts in their per-capita emissions compared to  
492 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.

495

496

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- 569

570 **8 Appendix**

571 Table A1: Summary Statistics IEA Data: Emissions per capita for primary energy carriers  
 572 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  |

573 Source: (International Energy Agency, 2011)

574

575

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)

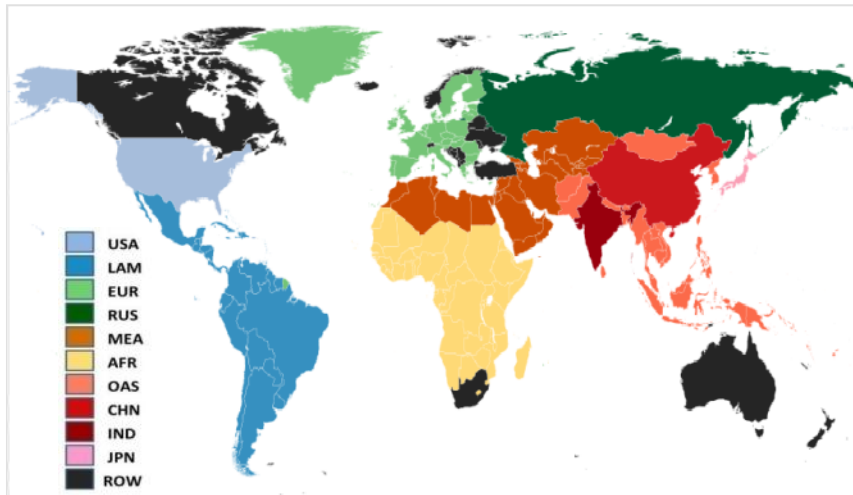
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581 Table A3: Country List

| 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)



583  
584 Figure A1: REMIND Regions

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

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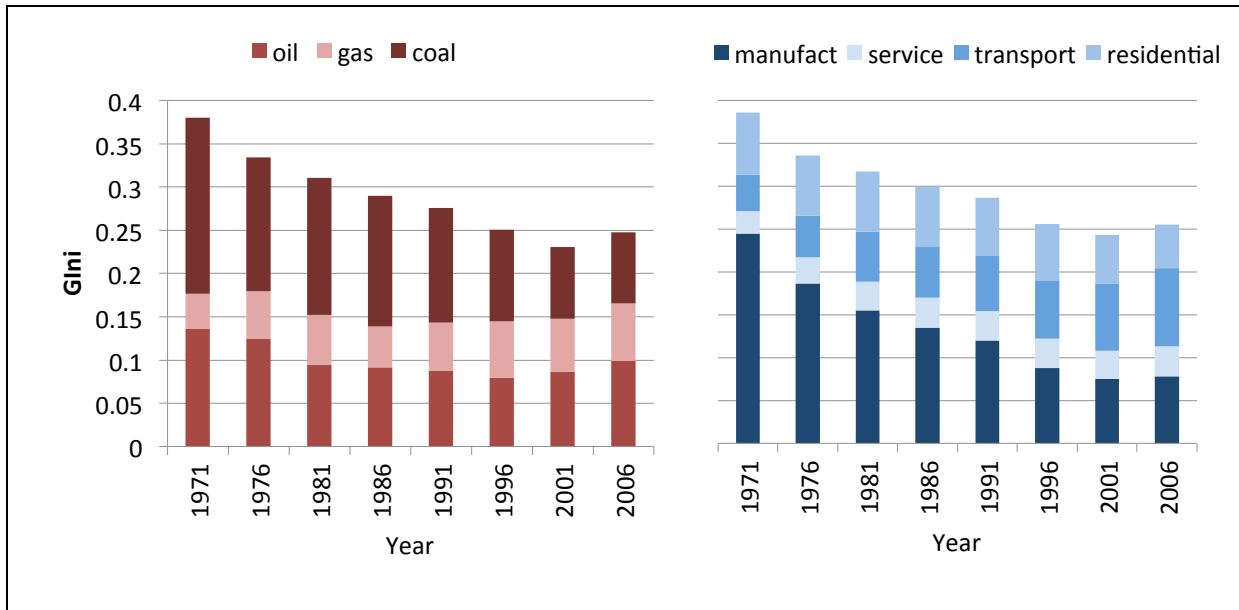
591 Table A4: Contributing factors to changes in the Gini index of total per-capita emissions by  
 592 source

|             | 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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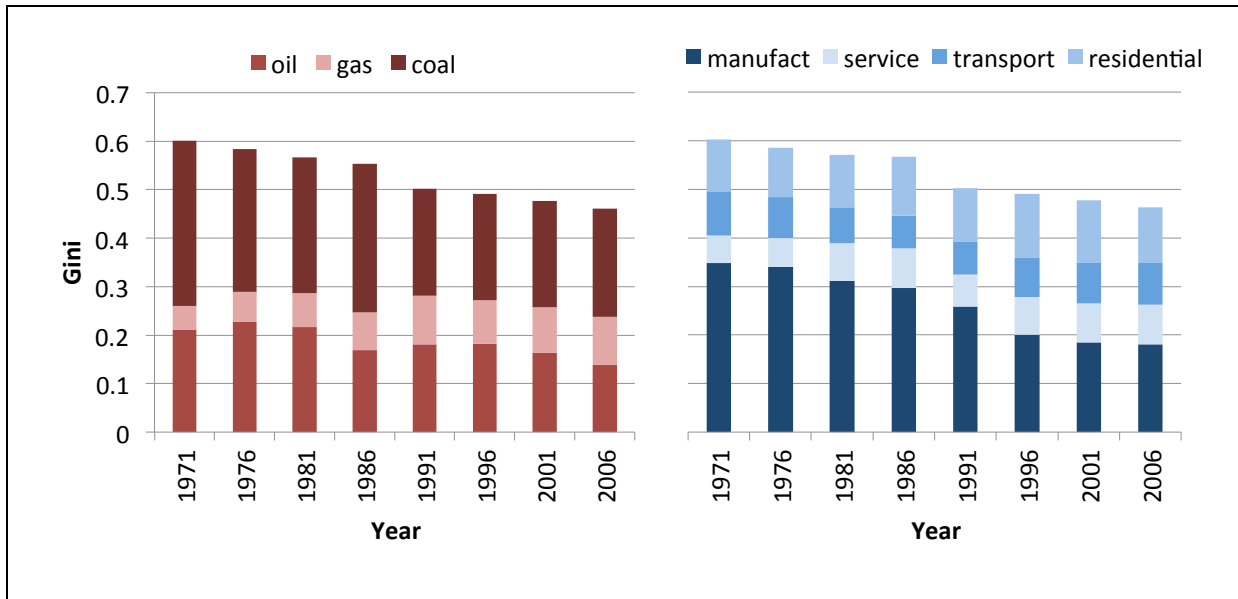


596 Figure A2: Contribution of emissions from individual primary energy carriers and economic  
 597 sectors to total inequality in per-capita CO<sub>2</sub> emissions measured by the Gini index, for OECD  
 598 countries only

599

600





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

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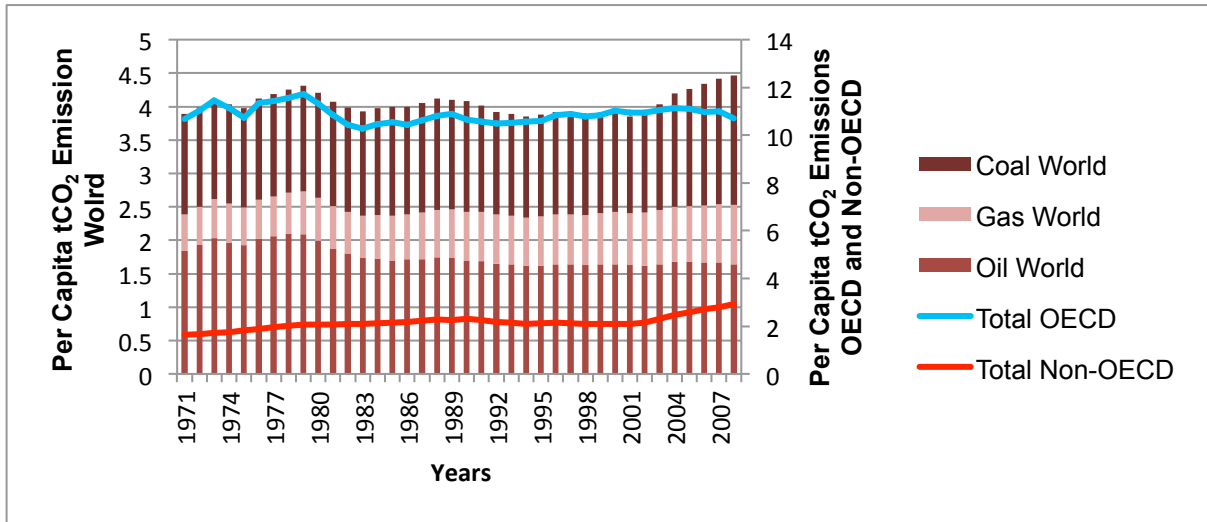
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610 **9 Figures and Tables**

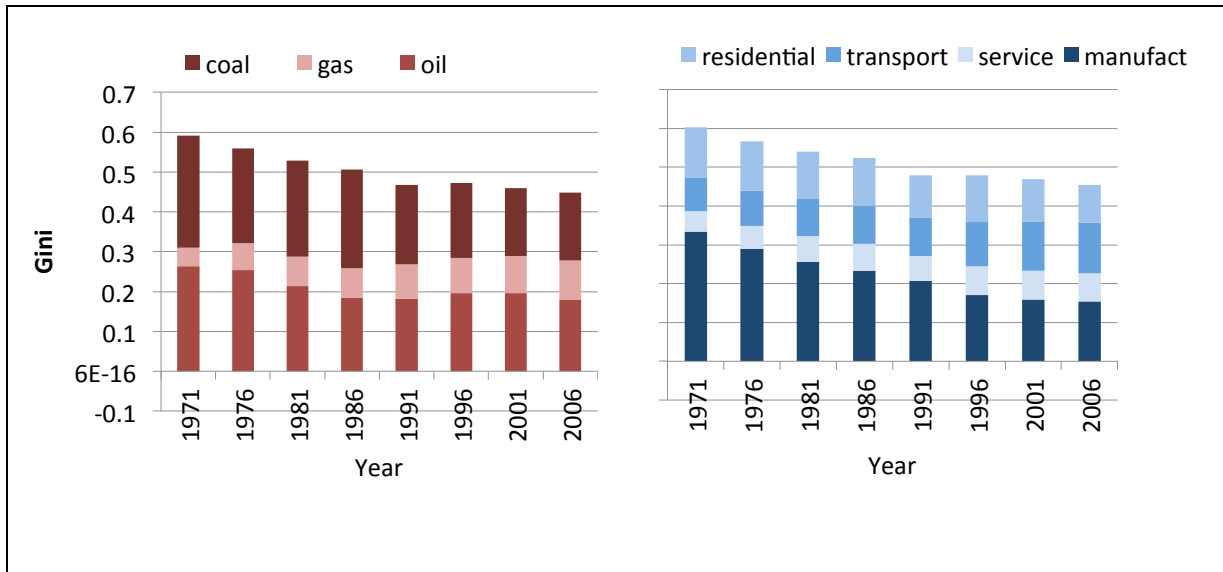
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612 Figure 1: Global, OECD and non-OECD energy-related CO<sub>2</sub> per-capita emissions over time.

613 Source: IEA (2011)

614

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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

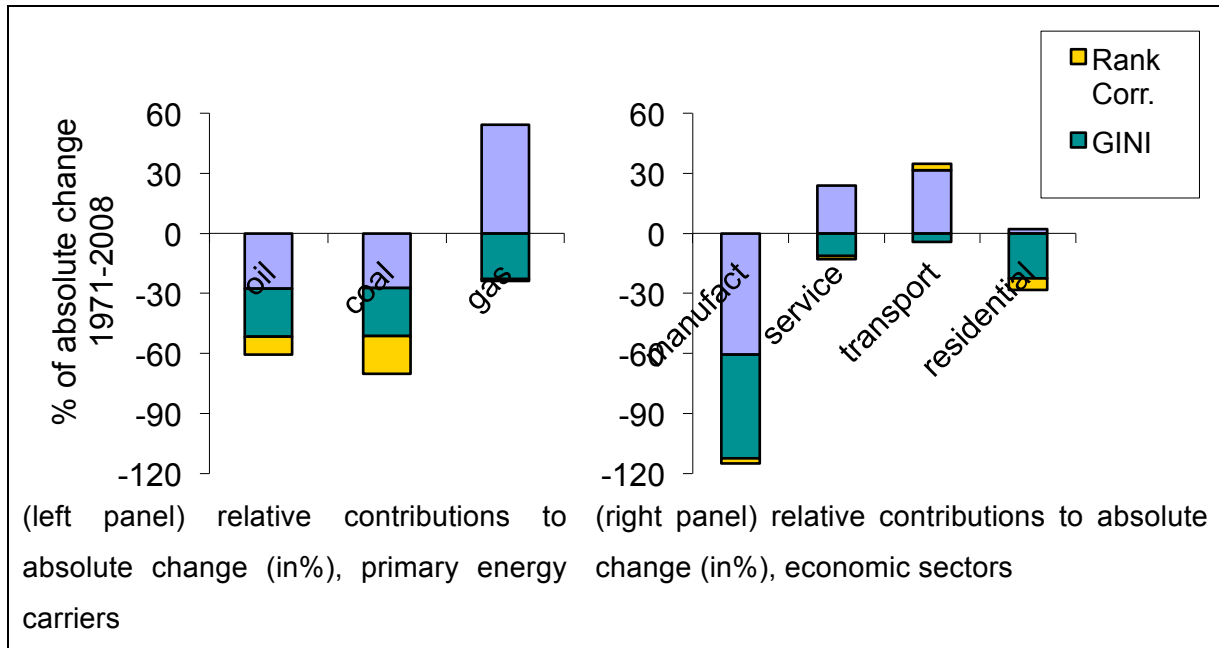
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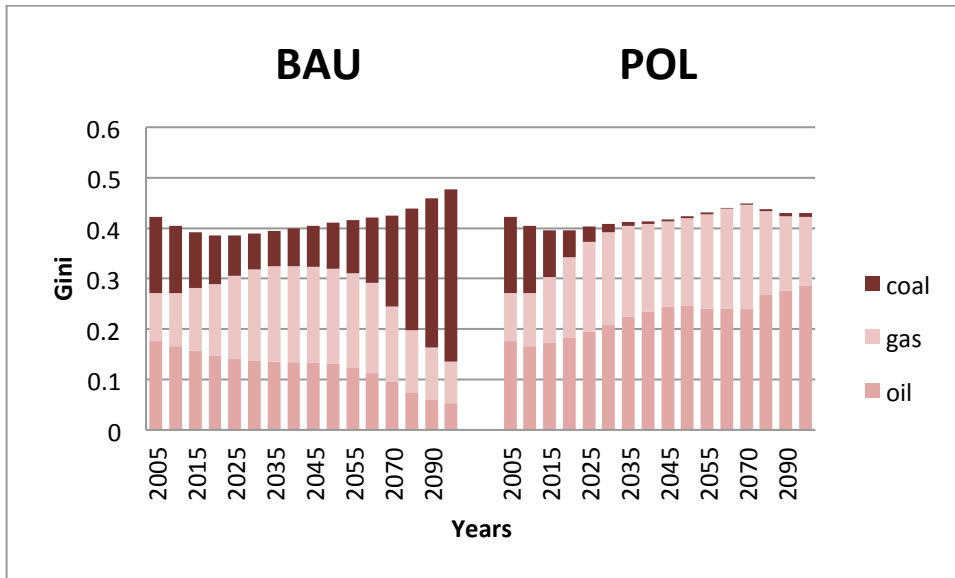
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623 Figure 3: Laspeyres decomposition to determine the source of absolute changes in the Gini  
 624 index of total per-capita emissions.

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627 Figure 4: Contribution of individual primary energy carriers to total inequality in per-capita

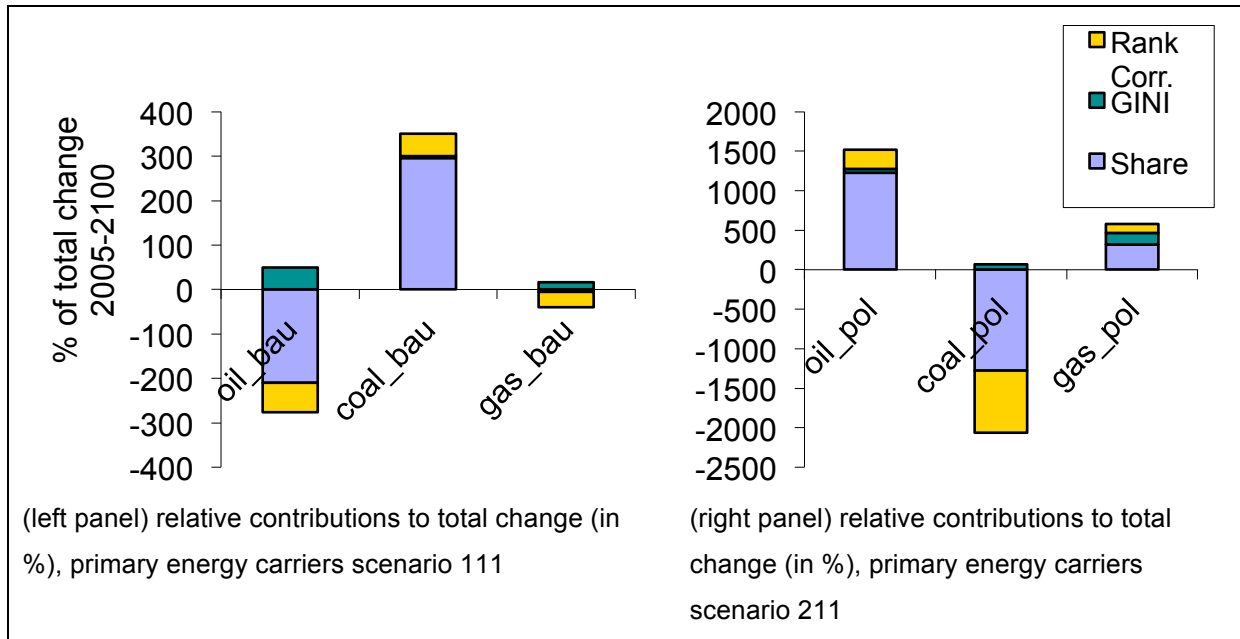
628 CO2 emissions, measured by the Gini index.

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

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639 Table 1: Effects of a 1% decrease of per-capita CO<sub>2</sub> 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