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Conference Paper

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

Beiträge zur Jahrestagung des Vereins für Socialpolitik 2013: Wettbewerbspolitik und Regulierung in einer globalen Wirtschaftsordnung - Session: Climate Policy III, No. E04-V1

Provided in Cooperation with:

Verein für Socialpolitik / German Economic Association

Suggested Citation: Grunewald, Nicole; Jakob, Michael; Mouratiadou, Ioanna (2013) : Decomposing Inequality in CO2 Emissions: the Role of Primary Energy Carriers and Economic Sectors, Beiträge zur Jahrestagung des Vereins für Socialpolitik 2013: Wettbewerbspolitik und Regulierung in einer globalen Wirtschaftsordnung - Session: Climate Policy III, No. E04-V1, ZBW - Deutsche Zentralbibliothek für Wirtschaftswissenschaften, Leibniz-Informationszentrum Wirtschaft, Kiel und Hamburg

This Version is available at:

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Decomposing Inequality in CO₂ 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 CO₂ per capita emissions using both historical data on energy-related CO₂ 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: CO₂ 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 CO₂
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 CO₂ 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 contributions¹. 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 CO₂ 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 CO₂
71 emissions, the cumulative share of global CO₂ emissions is plotted against the cumulative
72 share of the countries from the lowest to the highest per capita emissions. Heil and Wodon,

¹ 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 CO₂ 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 CO₂ emissions for 90
89 countries (which currently account for about 90% of global CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 emissions². 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 Δ 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:

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

² 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 CO₂
 155 emissions from fuel combustion³ over the period of 1971 to 2008 (International Energy
 156 Agency, 2011)⁴ 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 project⁵ (Kriegler et al., submitted).

159 The IEA dataset contains data on CO₂-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

³ Our analysis focuses on energy-related CO₂-emissions; land-use emissions as well as non-CO₂ greenhouse gas emissions (such as CH₄ and N₂O) are not part of the analysis.

⁴ For summary statistics refer to Table A1 and Table A2.

⁵ <http://www.rose-project.org/>

164 on how these emissions should be accounted⁶. 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 emissions⁷ 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 CO₂ emissions on the level of primary energy carriers as well as
176 economic sectors. We further exclude all countries for which CO₂ 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 years⁸. For years prior to 1990, we use
180 emission data for the Former Soviet Union and Former Yugoslavia, respectively, while from

⁶ 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).

⁷ Yet, agriculture is an important source of CH₄, N₂O as well as CO₂-emissions from land use, all of which are not part of our analysis.

⁸ 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 sample⁹. This leaves us
182 with a sample of 90 countries (see Table A3), which accounted for approximately 90% of
183 global CO₂ 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 2005-2100¹⁰.
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 CO₂-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.

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

¹⁰ 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 CO₂ 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 CO₂ per-capita
216 emissions over time.

217

218 Over the entire observation period, the Gini index of per-capita CO₂ 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 CO₂ 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 CO₂
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 CO₂ 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 CO₂
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 CO₂ emissions is explained by the reduced shares of emissions from these
270 energy carriers in total CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 homogeneously and seem to converge faster to
332 more equal per capita CO₂ 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 CO₂ 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 CO₂-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 inequality¹¹. Under the BAU scenario coal is projected to
367 be the major contributor to emission inequality from 2050 onwards. Meanwhile, with the
368 450ppm CO₂-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

¹¹ 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 MtCO₂/yr in BAU and 26640 MtCO₂/yr in POL), reduced to slightly
399 less than one third by 2050 (about 62140 MtCO₂/yr in BAU and 20275 MtCO₂/yr in POL),
400 and characterized by a seven-fold reduction by 2100 (61925 MtCO₂/yr in the BAU scenario
401 to 9200 MtCO₂/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.¹²

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

¹² 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 CO₂ emissions across countries. We analyze past
441 trends using historical data on energy-related CO₂ 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 CO₂ emissions has declined considerably, from about
446 0.6 in 1971 to slightly above 0.4 in 2008. From the perspective of primary energy carries,
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 CO₂ 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 carries, 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 CO₂ 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 CO₂ 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 CO₂ (tCO₂).

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 CO₂ (tCO₂) 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)

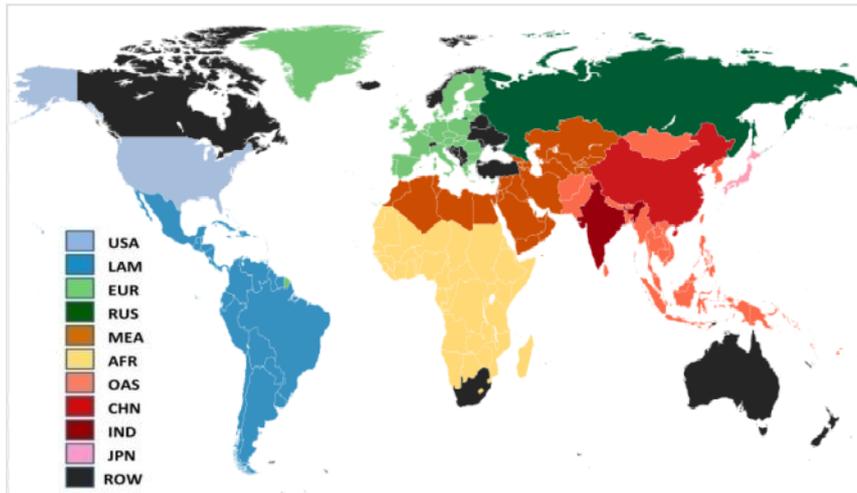
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581 Table A3: Country List

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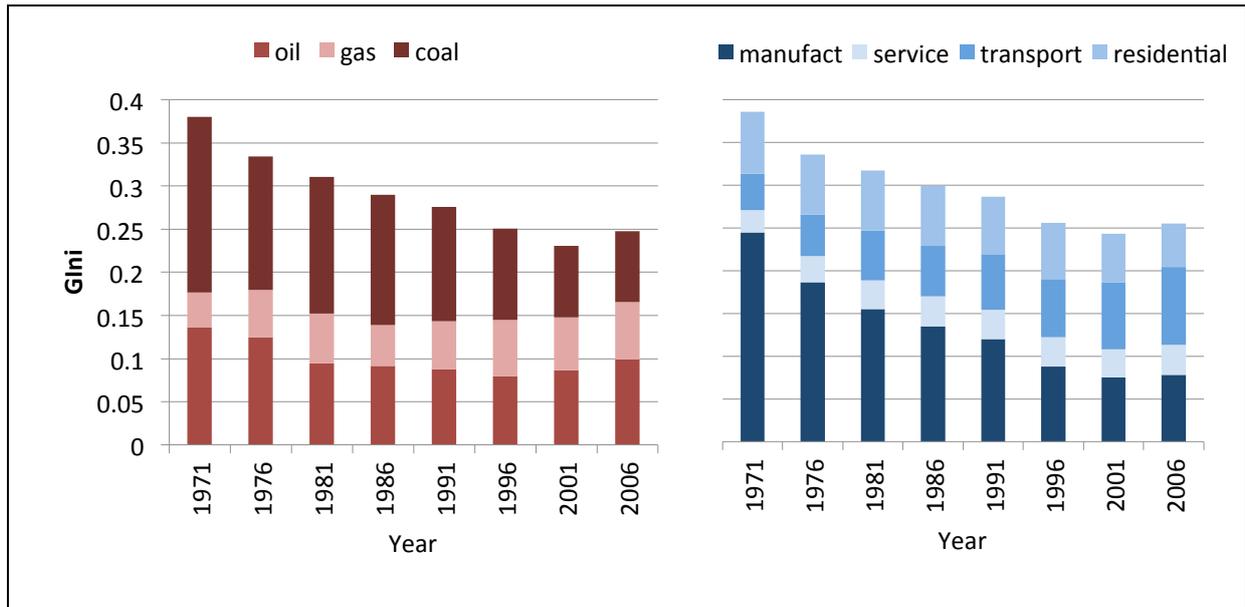
591 Table A4: Contributing factors to changes in the Gini index of total per-capita emissions by
 592 source

	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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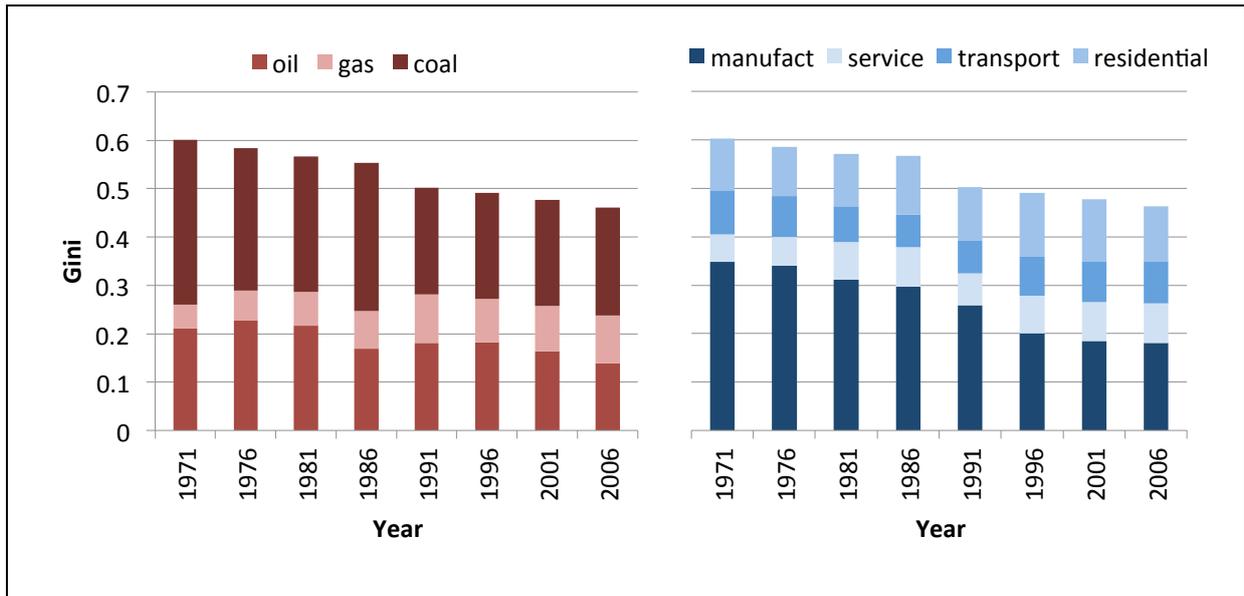
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596 Figure A2: Contribution of emissions from individual primary energy carriers and economic
 597 sectors to total inequality in per-capita CO₂ emissions measured by the Gini index, for OECD
 598 countries only

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601 Figure A3: Contribution of emissions from individual primary energy carriers and economic
 602 sectors to total inequality in per-capita CO₂ emissions measured by the Gini index, for non-
 603 OECD countries only

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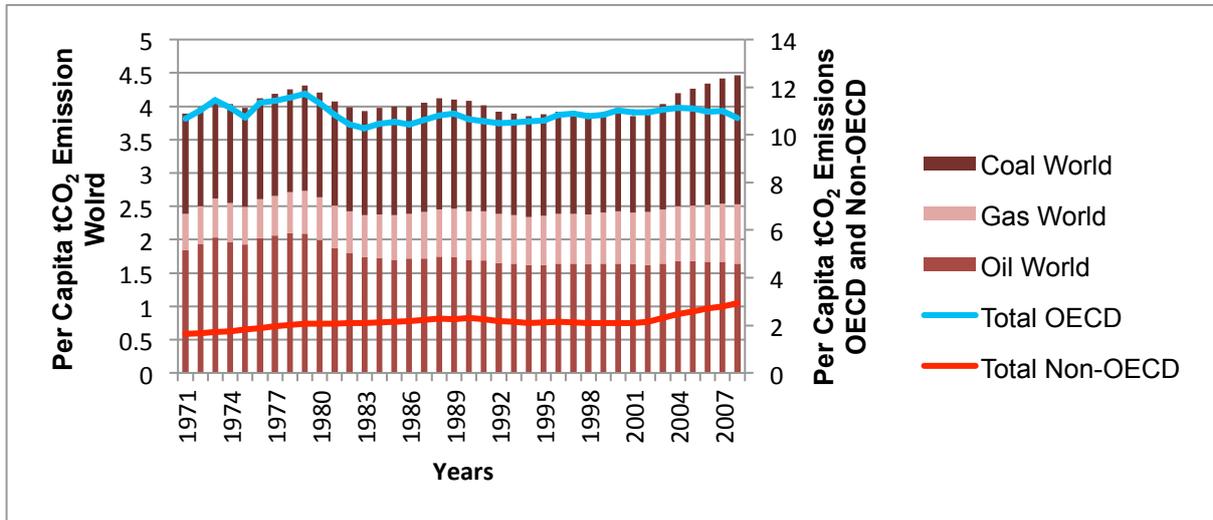
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610 **9 Figures and Tables**

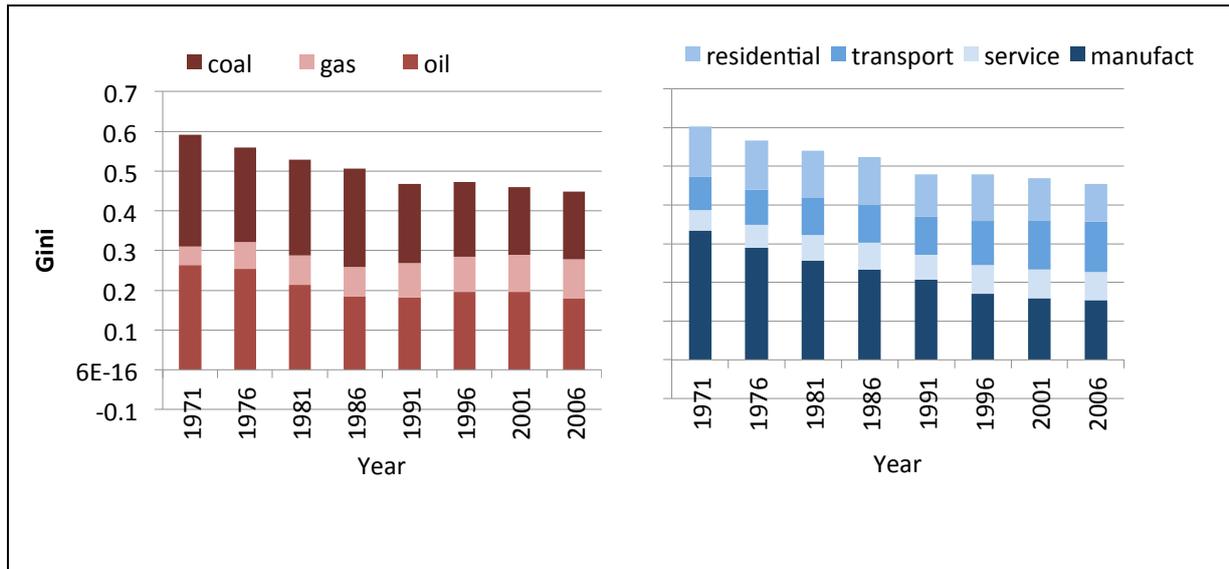
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612 Figure 1: Global, OECD and non-OECD energy-related CO₂ per-capita emissions over time.

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 CO₂ emissions measured by the Gini index

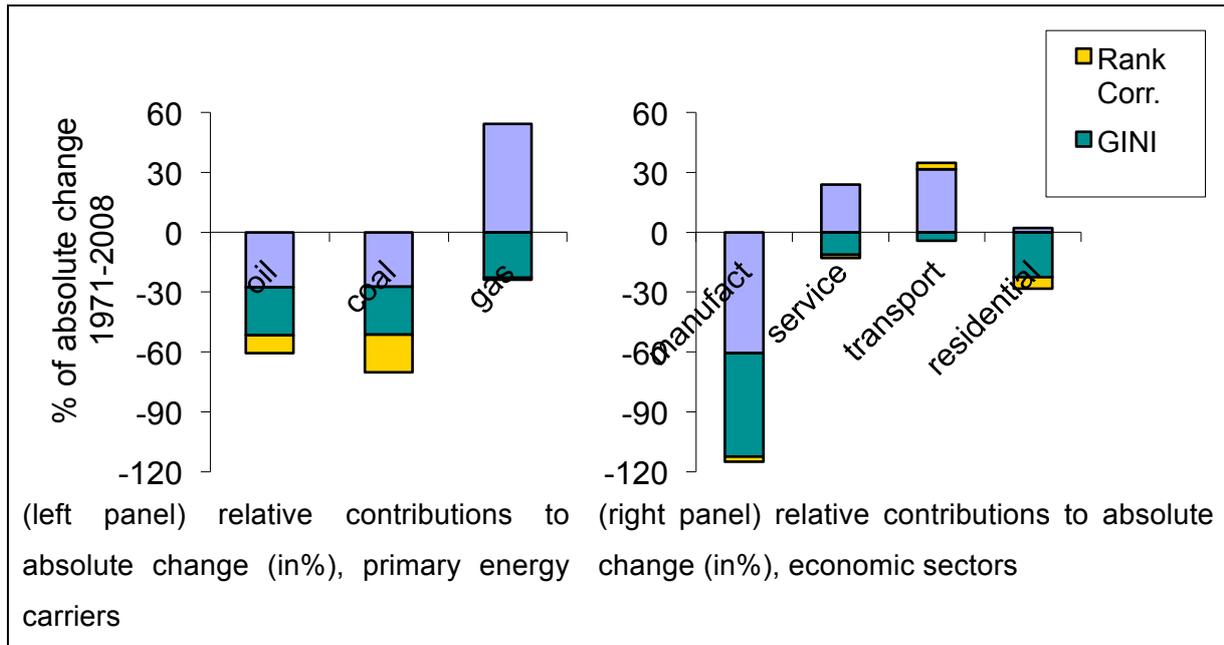
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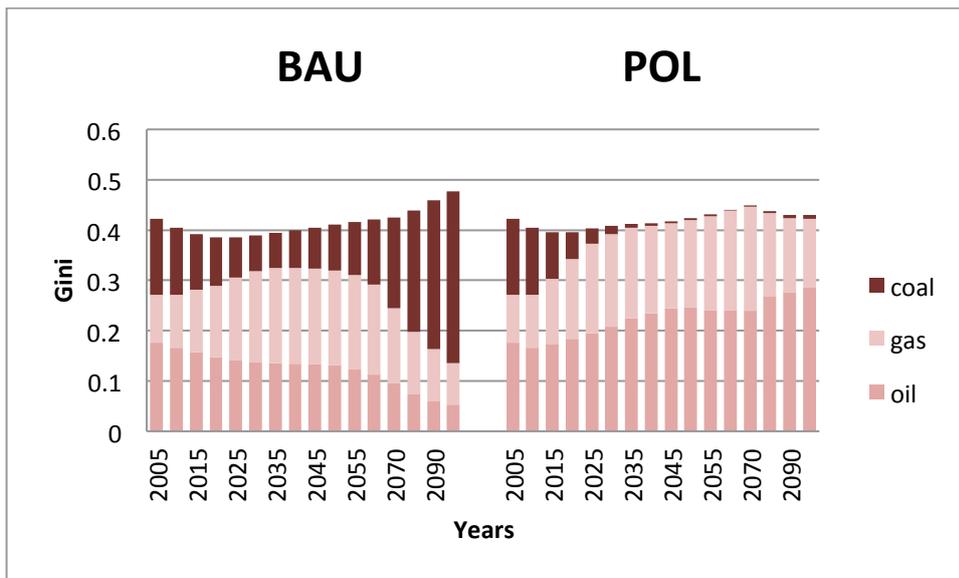
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623 Figure 3: Laspeyres decomposition to determine the source of absolute changes in the Gini
 624 index of total per-capita emissions.

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

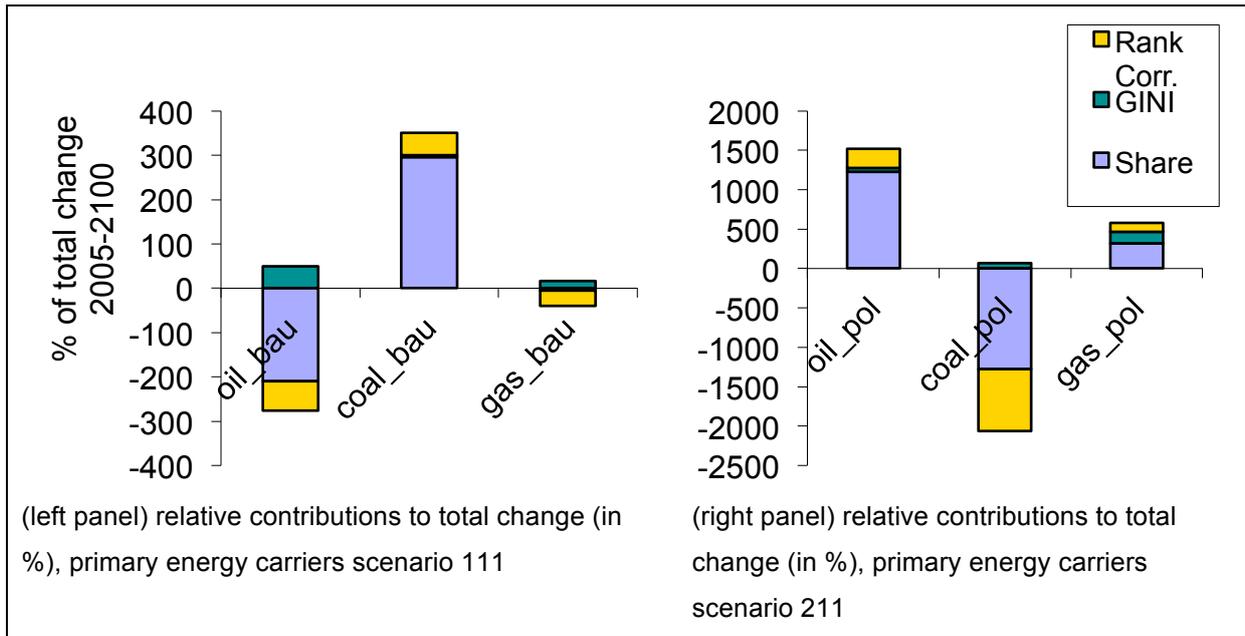
628 CO2 emissions, measured by the Gini index.

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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 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