Tjalling C. Koopmans Research Institute

Tjalling C. Koopmans

Discussion Paper Series nr: 08-33

Carbon Lorenz Curves

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November 2008

Abstract

The purpose of this paper is twofold. First, it exhibits that standard tools in the measurement of income inequality, such as the Lorenz curve and the Gini-index, can successfully be applied to the issues of inequality measurement of carbon emissions and the equity of abatement policies across countries. These tools allow policy-makers and the general public to grasp at a single glance the impact of conventional distribution rules such as equal caps or grandfathering, or more sophisticated ones, on the distribution of greenhouse gas emissions. Second, using the Samuelson rule for the optimal provision of a public good, the Pareto-optimal distribution of carbon emissions is compared with the distribution that follows if countries follow Nash-Cournot abatement strategies. It is shown that the Pareto-optimal distribution under the Samuelson rule can be approximated by the equal cap division, represented by the diagonal in the Lorenz curve diagram.

Keywords: carbon emission, climate change, Gini, global warming, Lorenz curve, Samuelson rule

JEL classification: D63, H3, Q01, Q4, Q5

1 INTRODUCTION

The Stern review (2006) regards greenhouse gases emissions (GHG) and the resulting greenhouse effect leading to global warming and climate change as the largest market failure ever experienced. Sinn (2007) speaks of 'The greatest externality ever'. Because diffusion of GHG in the global atmosphere happens quickly, it does not matter where the GHG is emitted. Although the effects of climate change differ per region, all world citizens are affected. It therefore meets the two key conditions of a global public good or bad, nonrivalry and nonexcludability. Without exaggeration we can say that we are all global players now. The atmosphere being the most global of all commons, every citizen in the world, no matter where and no matter how small or large his or her GHG emission, contributes to the process of global warming and climate change.[1]

I concentrate on CO_2 emissions from the combustion of fossil fuels and disregard emissions of non-CO_2 greenhouse gases such as methane (CH_4), nitrous oxide (N_2O) and CO_2 emissions from land use (deforestation). The CO_2 emissions from the combustion of fossil fuels accounts for about two-thirds of the total GHG emission in CO_2 equivalents. CO_2 comprises at about three quarters of the worldwide total, beside methane and nitrous oxide (Baumert et al. 2005: ix). According to the Stern Review, in a business-as-usual (BAU) scenario, the total cost of climate change is "the equivalent of around a 20% reduction in consumption per head, now and into the future" (ibid, x), against only in between 0 and 3% if the Review's recommendations are followed. The current stock of GHG in the atmosphere is equivalent to about 430 parts per million (ppm) CO_2, against 280 ppm before the start of the Industrial Revolution. The Stern Review (Executive Summary, Figure 2) aims at a level for this century stabilizing around 550 ppm, with an expected global temperature increase of almost 3 degrees, with a 95 percent probability range of 1.5 and 4.5 degrees. The social cost of the current emission level in a BAU scenario is estimated to be \$85 per ton of CO_2 (ibid., xvi-xvii), whereas it would only be \$25-30 if the trajectory of stabilizing at 550 ppm advocated by the Stern Review would be accomplished. The challenge for this century is the transition to a low-carbon or even decarbonised world economy.

The main focus of this paper is to spell out how the Lorenz curve can be applied to the distribution of GHG emissions. The structure is as follows. In section 2, the actual inequality

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[1] To illustrate, one litre (gallon) gasoline produces about 2.3 (8.8) kilogram CO_2. Elementary chemistry learns us that 1 mole of CO_2 has a weight of 44 grams, so per litre gasoline about 23 mole CO_2 is produced, which has to be multiplied by the Avogadro constant ($N_A = 6.02 * 10^{23}$) to get the number of molecules CO_2 released in the atmosphere. Just one litre gasoline fueled by one person produces $138.5 * 10^{23}$ molecules CO_2, which is, assuming a world population of 6 billion, more than 2 million billion (2,300,000 billion) molecules CO_2 per world citizen. The logic behind this result is the extraordinary large number of molecules per mole.

in the distribution of GHG emissions across countries is illustrated by means of Lorenz curves and the so called Parade of Dwarfs and Giants, invented by Pen (1977). It is shown that alternative distribution rules, equal caps and grandfathering, correspond to the diagonals against which Lorenz curves are pitched (section 3). In section 4, first a simple model is presented to derive the Nash-Cournot and Pareto optimal levels of abatement efforts across countries and some remarks are made how they can be situated in the Lorenz curve diagrams. The final section summarizes the findings.

2 Inequality measurement of carbon emissions

In what follows, the following symbols are used for the inequality measurement of carbon emissions across countries. Per capita variables have a superscript *c*, the country index is given by the subscript *i* and world totals are given subscript *w*:

$G_i =$ Carbon dioxide emission in country *i*;

$Y_i =$ Gross Domestic Product;

$P_i =$ Population size;

$e_i \equiv \frac{G_i}{Y_i} =$ Carbon dioxide emission per unit GDP;

$y_i^c \equiv \frac{Y_i}{P_i} =$ income per capita;

$g_i^c \equiv \frac{G_i}{P_i} =$ Carbon dioxide emission per capita; (1)

$p_i \equiv \frac{P_i}{P_w} =$ World population share;

$y_i \equiv \frac{Y_i}{Y_w} =$ World income share;

$g_i \equiv \frac{G_i}{G_w} =$ World carbon dioxide emission share.

Table 1 gives an overview of the scores on these variables for the top-25 polluting countries in terms of emission levels. All data are for 2002 and obtained from Climate Analysis Indicators Tool (CAIT), Version 5.0, 2008.

The USA is with almost 6 gigaton[2] the largest polluter in the world (column 3), giving a world share of 24 percent (column 4). Also with respect to emission level per capita (column 5), it is among the top countries, only Bahrain (21.7), Luxembourg (21.8) and Kuwait (26.4) have higher levels. The next three columns give information about GDP, world GDP share and per capita income. Column 9 gives the emission intensity of GDP, which ranges from 16.4 ton CO_2 per million US$ for Chad to over 3,000 for Uzbekistan. The world average is 521 ton per million US$. The two final columns list population size and world population shares.[3]

Table 1. Overview of carbon emission, income and population for the top-25 polluting countries.

1	2	3	4	5	6	7	8	9	10	11
country	**Kyoto Annex I**	**MtCO2**	**% of world total**	**tons CO2 per person**	**total, bill.intl. $**	**% of world**	**intl. $ per person**	**tons/ mill. $**	**mill. of people**	**% world total**
		G	g	g^c	Y	y	y^c	e	P	p
USA	I	5.773	24,0%	20,0	9.929	21,5%	34.430	575	288	4,8%
China		3.783	15,8%	3,0	5.607	12,1%	4.379	616	1.280	21,4%
Russian Fed.	I	1.534	6,4%	10,6	1.127	2,4%	7.821	1370	144	2,4%
Japan	I	1.213	5,1%	9,5	3.315	7,2%	26.021	362	127	2,1%
India		1.106	4,6%	1,1	2.679	5,8%	2.555	399	1.049	17,5%
Germany	I	863	3,6%	10,5	2.108	4,6%	25.546	419	83	1,4%
UK	I	541	2,3%	9,1	1.610	3,5%	27.176	351	59	1,0%
Canada	I	518	2,2%	16,5	883	1,9%	28.155	592	31	0,5%
Korea (South)		499	2,1%	10,5	841	1,8%	17.662	563	48	0,8%
Italy	I	450	1,9%	7,8	1.474	3,2%	25.554	303	58	1,0%
Mexico		396	1,6%	3,9	887	1,9%	8.798	438	101	1,7%
France	I	379	1,6%	6,4	1.583	3,4%	26.613	243	59	1,0%
Iran		370	1,5%	5,6	411	0,9%	6.277	849	66	1,1%
South Africa		364	1,5%	8,0	445	1,0%	9.813	787	45	0,8%
Brazil		343	1,4%	2,0	1.305	2,8%	7.480	263	174	2,9%
Australia	I	337	1,4%	17,2	523	1,1%	26.619	624	20	0,3%
Indonesia		332	1,4%	1,6	651	1,4%	3.074	486	212	3,5%
Spain	I	324	1,3%	7,9	918	2,0%	22.445	335	41	0,7%
Ukraine	I	314	1,3%	6,5	230	0,5%	4.719	1359	49	0,8%
Saudi Arabia		310	1,3%	14,2	266	0,6%	12.151	1101	22	0,4%
Poland	I	298	1,2%	7,8	413	0,9%	10.793	731	38	0,6%
Turkey	I	209	0,9%	3,0	447	1,0%	6.414	451	70	1,2%
Thailand		203	0,8%	3,3	415	0,9%	6.740	454	62	1,0%
Netherlands	I	179	0,7%	11,1	477	1,0%	29.550	374	16	0,3%
Kazakhstan		151	0,6%	10,1	84	0,2%	5.672	1728	15	0,2%
Other countries		3.230	13,4%	1,8	7.609	16,5%	4.173	424	1.824	30,5%
World		24.019	100,0%	4,02	46.238	100,0%	7.732	519	5.980	100,0%

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[2] 1 gigaton (Gt) is thousand megaton (Mt) and 1 Mt is 1 million ton.

[3] A small number of countries, such as Afganistan, Myanmar and Zimbabwe, together comprising 194 million people, are left out because no data are available on income.

All the information contained in Table 1, including the desegregation of 137 countries in the category ‘Other countries’, can be made visible by means of Lorenz curves.[4] The only reference I know that also draws carbon Lorenz curves is Kahrl and Roland-Holst (2008: Figures 1-3, 2-3). Kahrl and Roland-Holst rank countries by per capita income. As a consequence, the ratio of world emission share (measured on the vertical axis) and world population share (on the horizontal axis) is not monotonically increasing, with an awkwardly shaped Lorenz curve as a result. This also makes their Gini index meaningless. Because the correlation between income per capita and GHG emission per capita is high it seems as if it works, but theoretically it is wanting, if not wrong. It will be shown that the criterium to rank countries is fully determined by the variables used on the coordinate axes in a Lorenz diagram.

To start with, we sort countries according to their GHG emission per capita (g_i^c). Let $f(g_i^c)$ be the density function,[5] $F(g_i^c)$ the cumulative density function and $F_1(g_i^c)$ the first moment distribution function. $F(g_i^c)$ gives the cumulative proportion of the world population with per capita GHG emission less than or equal to g_i^c, which can be stated in discrete or continuous forms. In discrete form:

$$F(g_i^c) = \sum\nolimits_{j=1}^{i} p_j \tag{2}$$

The cumulative proportion of world GHG emission is then given by $F_1(g_i^c)$:

$$F_1(g_i^c) = \frac{1}{g_w^c} \sum\nolimits_{j=1}^{i} p_j g_j^c \tag{3}$$

In Eq. (3), the per capita GHG emission of countries is thus weighted by their world population shares. For all countries in the world together, this weighted sum equals the average world per capita GHG emission (g_w^c), so to get for countries $j = 1, 2, \ldots, i$ their cumulative world share, we have to divide by g_w^c. Using the definitions in (1), it follows that:

$$\frac{1}{g_w^c} \sum\nolimits_{j=1}^{i} p_j g_j^c = \frac{P_w}{G_w} \sum\nolimits_{j=1}^{i} \frac{P_j}{P_w} \frac{G_j}{P_j} = \sum\nolimits_{j=1}^{i} \frac{G_j}{G_w} = \sum\nolimits_{j=1}^{i} g_j \, , \tag{4}$$

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[4] For the graphical illustration of Table 1 but now disagregated into world regions and into Annex I versus non-Annex I signatories, see the Appendix.

[5] Because countries are the unit of analysis, the densities are given by the population shares.

so the cumulative proportions of world GHG emission $F_1(g_i^c)$ as given by Eq. (3) can also be expressed simply as the sum of countries' world shares of GHS emissions.

For the continuous forms, by definition:

$$g_w^c \equiv \int_0^{\infty} g^c f(g^c)\, dg^c = \int_0^{\infty} g^c dF(g^c) \tag{5}$$

The cumulative density function is:

$$F(g_i^c) = \int_0^{g_i^c} f(g^c)\, dg^c = \int_0^{g_i^c} dF(g^c) \tag{6}$$

and the first moment distribution function can be expressed as:

$$F_1(g_i^c) = \frac{1}{g_w^c}\int_0^{g_i^c} g^c f(g^c)\, dg^c = \frac{1}{g_w^c}\int_0^{g_i^c} g^c dF(g^c) \tag{7}$$

Analogous to Eq. (4), Eq. (7) can be stated as:

$$\frac{1}{g_w^c}\int_0^{g_i^c} g^c f(g^c)\, dg^c = \int_0^{g_i^c} g\, dg^c \tag{8}$$

The Lorenz curves in Figure 1A now depicts $F_1(g_i^c)$, the cumulative world share in GHG emission on the vertical axis, plotted against $F(g_i^c)$, the cumulative world population share, on the horizontal axis, for two years, 2002 and 1990 (the base year of the Kyoto protocol). As can be seen from the inward shift of the Lorenz curve, the inequality in the distribution of GHG across countries has decreased (the Gini coefficient decreases from 63 to 57 percent). Since the distributions over time are so close to each other, I will concentrate on the distribution in 2002, the last year for which CAIT gives data. The Parade, similar to the Parade of Dwarfs and Giants for the income distribution invented by Jan Pen (1971), in Figure 1B plots per capita emission (g_i^c) against $F(g_i^c)$. In both figures countries are sorted in ascending order according to GHG per capita.

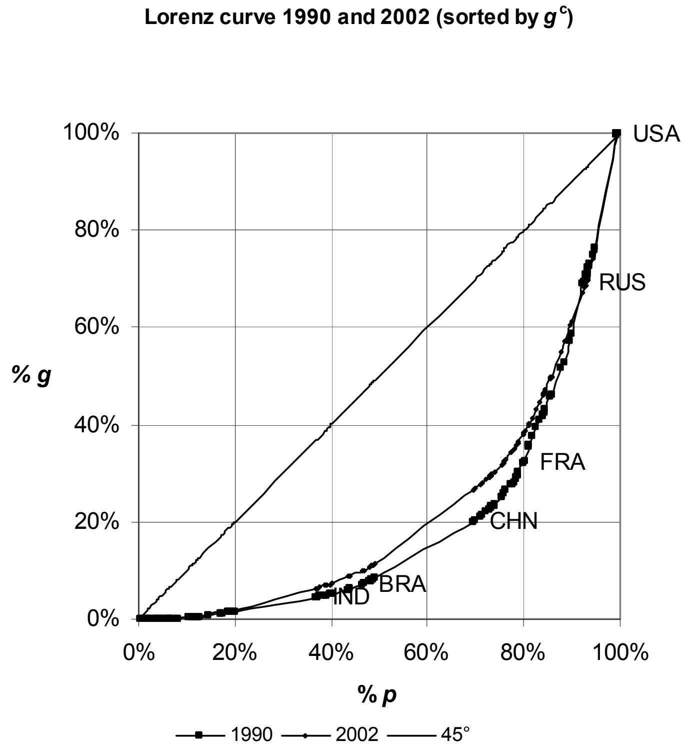

Figure 1A. The Lorenz curve in 1990 and 2002 for countries sorted by per capita emission (g^c), cumulative world emission shares (%g) on the vertical and cumulative world population shares (%p) on the horizontal axis.

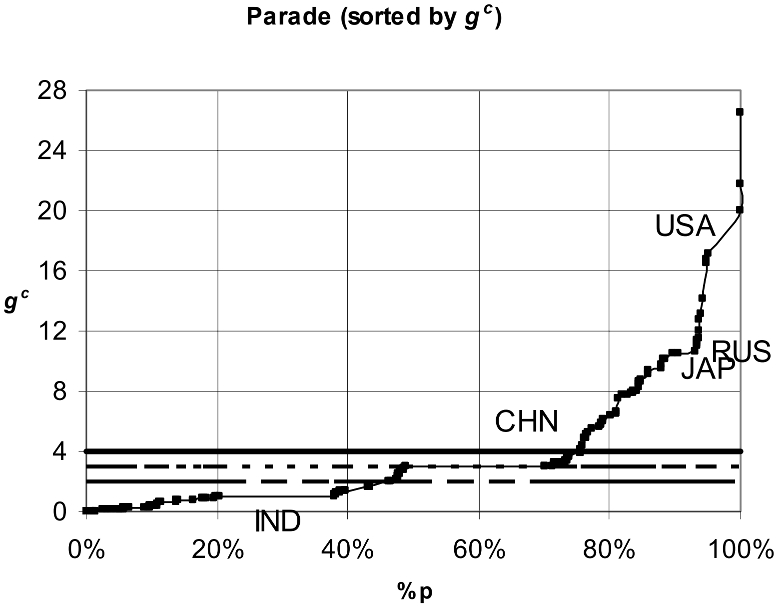

Figure 1B. Parade for countries sorted per capita emissions (g^c), per capita emissions on the vertical and cumulative world population shares (%p) on the horizontal axis.

India and China are situated on the left: they harbour 17.5 and 21.4 percent of the world population, but only emit 4.6 and 15.8 percent of world GHG. On the very far left are poor countries as Chad, Congo and Burundi. The USA is located on the far right (only Luxembourg and the Gulf states Kuwait and Bahrain have even higher emissions per capita, but their share of the world population is so small that they virtually coincide with the USA in Figure 1A). The USA accounts for nearly five percent of the world population, but for about a quarter of world GHG emission. Not surprisingly, since there is a strong correlation between income per capita and GHG per capita, all rich countries are situated on the right, whereas all developing countries are situated on the left of the point where the Lorenz curve is parallel with the diagonal.

Using the continuous forms of Eqs. (6) and (7), the slope of the Lorenz curve at any point can be represented as:

$$\frac{dF_1(g_i^c)}{dF(g_i^c)} = \frac{d\left(\frac{1}{g_w^c}\int_0^{g_i^c} g^c dF(g^c)\right)}{d\left(\int_0^{g_i^c} dF(g^c)\right)} = \frac{g_i^c}{g_w^c}, \tag{9}$$

so the slope of the Lorenz curve is simply the ratio of a country's emission level per capita relative to the world's emission level per capita. That is, if the slope of the Lorenz curve (multiplied by the constant g_w^c) is plotted against the cumulative world population shares, we have produced the Parade of Dwarfs and Giants of Figure 1B. Where the Lorenz curve runs parallel with the diagonal, a country's share in world emission is equal to its share in the world population. At that point the GHG emission per capita is equal to the mean of the distribution, the world average GHG per capita, just above 4 ton per capita and represented by the horizontal line in Figure 1B.[6] This is approximately the case for Mexico, Jamaica and Macedonia. Note that the carbon Lorenz curve and the associated Parade are not only very useful tools for policy-makers, but also for educational purposes and for informing the general public about inequalities in GHG emission and abatement policies. At a single glance, Figure 1A tells us that countries with the lowest per capita levels of GHG emission harbouring half of the world population produce only 10 percent of world's GHG emissions. In the same way, Figure 1B shows that one US citizen emits on average as much as 20 citizens from India.

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[6] The global GHG in 2002 is equal to 24.7 gigaton, corresponding to 4.02 ton per world citizen, which is approximately equal to the GHG emission per capita of Macedonia.

The diagonal, with a slope equal to unity, represents the hypothetical situation of equal GHG emission per capita across countries. Using Eq. (1), the following relationships obtain for the diagonal:

$$\frac{g_i}{p_i} = \frac{G_i/G_w}{P_i/P_w} = 1 \Rightarrow \frac{G_i}{P_i} = \frac{G_w}{P_w} \Rightarrow g_i^c = g_w^c \Rightarrow \frac{G_i}{Y_i} = \frac{G_w P_i}{P_w Y_i} \Rightarrow e_i = \frac{g_w^c}{y_i^c} \tag{10}$$

Eq. (10) shows that if each country's share in world GHG emission equals its share in the world population ($g_i/p_i = 1$), then GHG emission per capita must be equalized across countries and equal to the world GHG emission per capita ($g_i^c = g_w^c$), which in turn is equivalent to the situation that given the GHG emission per capita in the world (g_w^c), the GHG intensity per unit of GDP in a country may be higher, the lower one's per capita income ($e_i = g_w^c / y_i^c$). From this it can already be seen that any distribution rule in the direction of equal GHG per capita implies that developed rich countries have to decarbonise their economies – that is to reduce e_i - at a far higher rate than developing poor countries.

To get a properly shaped Lorenz curve, and a well defined Gini-index, it must have a monotonically increasing slope. This means that the criterium to rank countries is fully determined by which variables are put on the abscissa. Since in Figure 1A we have put the (cumulative) share of GHG emission (g_i) and world population share (p_i) on the abscissa, we must rank countries according to the ratio g_i/p_i, which is equivalent to rank them according to GHG per capita (g_i^c). However, we may also rank countries according to another criterium. For instance, it can be expected that GHG emissions across countries are closely correlated with population size and GDP per capita, whose product equals GDP. Suppose we want a Lorenz curve, see Figure 2A, that plots as before the cumulative share in world GHG emission on the vertical axis but now against the cumulative shares in world GDP, instead of cumulative shares in world population, on the horizontal axis. In discrete form, the vertical axis measures as before $F_1(o) = \sum_{j=1}^{i} g_j$, but the horizontal axis now measures $F(o) = \sum_{j=1}^{i} y_j$. The question is, how do we line up the countries, that is, what criterion must be used to rank countries? Obviously, if we were to rank countries according to emission levels per capita (g_i^c) as before, an awkwardly shaped Lorenz curve would result. The reason is that for a properly shaped Lorenz curve, the ratio of the variable on the vertical axis and the variable on the horizontal axis must be monotonically increasing. Because of the equalities stated in Eqs. (4) and (8), when countries are sorted according to GHG emission per capita, this condition was met for the Lorenz curve depicted in Figure 1A. Given that in Figure 2A the variable 'share in world GHG emission' is used for the vertical axis and 'share in world GDP' for the horizontal axis, countries must be sorted according to the ratio of the former and the latter (g_i/y_i). As a consequence, countries that have a far higher (lower) share in world GHG emission than their world GDP share 'justifies' are located on the far right (left) side of the Lorenz curve. Using the definitions of Eq. (1), ranking countries according to g_i/y_i is equivalent to rank them according their GHG intensity (e_i):

$$\frac{g_i}{y_i} = \frac{G_i/G_w}{Y_i/Y_w} = \frac{G_i/Y_i}{G_w/Y_w} = \frac{e_i}{e_w} \tag{11}$$

For individual countries, e_w can be taken as given, so to rank them according to g_i/y_i is the same as to rank them according to e_i . Therefore, we can use e_i as the argument for the continuous form functions, so the horizontal axes of Figure 2A and B measures $F(e_i) = \int_0^{e_i} y de$, the vertical axis of Figure 2A measures $F_1(e_i) = \frac{1}{e_w}\int_0^{e_i} e_i y_i de = \int_0^{e_i} g de$ and the vertical axis of Figure 2B measures $e_w\, F_1(e_i)$. The corresponding Lorenz curve and the Parade are depicted in Figure 2A and B.

First, note that inequality as measured by the divergence of the Lorenz curve from the diagonal by the Gini coefficient[7] is much lower when greenhouse emissions shares are pitched against world GDP shares rather than world population shares. The Gini coefficient of the former is 0.23, against 0.56 for the latter. Second, the giant leap in the middle of the Lorenz curve is accounted for by the USA: its share in world output is 26.2 percent and its share in world GHG emission is almost of the same order of magnitude, 24.7 percent. Countries to the right (left) are those that emit relatively much (little) GHG per unit of GDP. This may have various causes, e.g. a high energy use because of extreme climate conditions (heaters in cold climates and air conditioners in hot climates), energy inefficiencies in production and consumption or international specialization in the production of energy-intensive products (e.g. steel). Beside China and Russia, almost all other formerly communist countries are located on the right, probably because their GDP production is highly energy

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[7] Heil and Wodon (2000) perform a group decomposition of the Gini coefficient to measure the impact of different abatement proposals on the future inequality in GHG emissions.

inefficient and hence GHG intense. Ukraine, Kazakhstan, Uzbekistan and Russia have emission intensities well above twice the world average. At the other side are France (due to a high share of nuclear energy) and Scandinavian countries like Norway and Sweden, with a relatively low GHG emission intensity.

For the diagonal in Figure 2A, the following equalities hold:

$$\frac{g_i}{y_i} = \frac{G_i/G_w}{Y_i/Y_w} = 1 \Rightarrow \frac{G_i}{Y_i} = \frac{G_w}{Y_w} \Rightarrow e_i = e_w \Rightarrow \frac{G_i}{Y_i P_i} = \frac{e_w}{P_i} \Rightarrow g_i^c = e_w y_i^c \qquad (12)$$

On the diagonal, each country's share in global GHG emission equals its share in world income ($g_i = y_i$); also, its GHG intensity is equal to the global GHG intensity ($e_i = e_w$) and finally, given the global GHG intensity (e_w), a country's GHG emission per capita (g_i^c) is proportional to its per capita income ($g_i^c = e_w y_i^c$). Obviously, the relationships set out in Eq. (12) are relevant to the grandfathering rule that allocates emission rights proportional to world income shares, so that emission rights per capita are proportional to income per capita. It is also compatible with a policy aiming at convergence of emission intensities in the long term. In the next section, it will be illustrated how a definite global ceiling on GHG emission combined with particular distribution rules can be incorporated in the Lorenz diagrams.

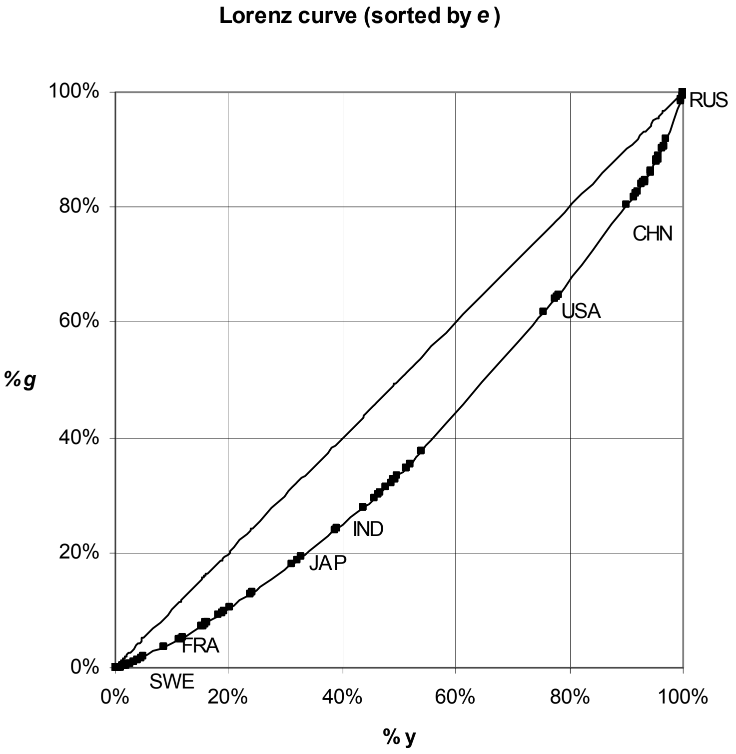

Figure 2A. The Lorenz curve for countries sorted by emission intensity (e), cumulative world emission shares (%g) on the vertical and cumulative world income shares (%y) on the horizontal axis.

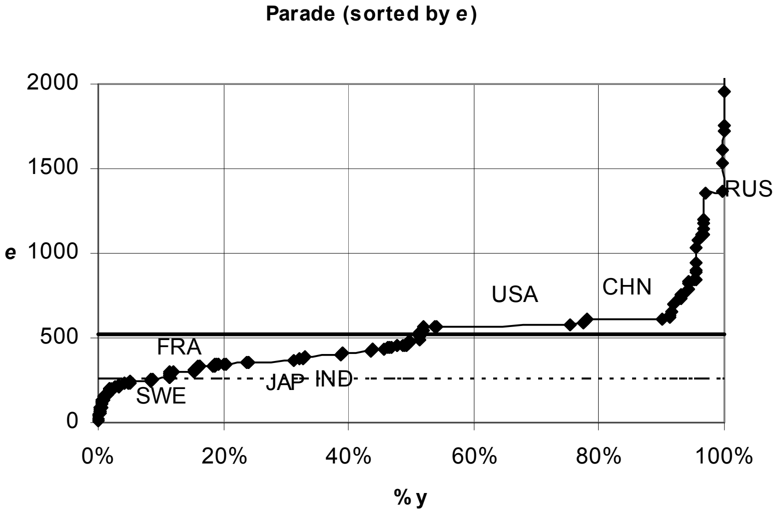

Figure 2B. The Parade of Dwarfs and Giants, with countries sorted by emission intensity (e), emission intensities on the vertical and cumulative world income shares (%y) on the horizontal axis.

3 Distribution rules: equal caps versus grandfathering

In the literature on the equity of different distributions of GHG levels across countries, several distribution rules are proposed (see e.g. Elzen and Lucas 2003, chapter 5 for an overview of ten different emission allocation models based on four equity principles). I will only discuss the two most simple and familiar rules and show how they can be fitted in in the Lorenz curves and associated Parades. One of them, favourable to China, India and most other LDCs, is the egalitarian rule, stipulating equalized per capita emission entitlements; the other, favourable to most developed countries, is the grandfathering rule.[8]

3.1 Equal caps

Given the urgency to reduce GHG emissions worldwide, a difficult issue is how the burdens of the transition are distributed across countries. Gardiner (2004: 590) concludes that "… there is a great deal of convergence on the issue of who has primary responsibility to act on climate change. The most defensible accounts of fairness and climate change suggest that the rich countries should bear the brunt, and perhaps even the entirety, of the costs". In the same vain, the Stern Review (2006, xxiii) states that "Securing broad-based and sustained co-operation requires an equitable distribution of effort across both developed and developing countries. There is no single formula that captures all dimensions of equity, but calculations based on income, historic responsibility and per capita emissions all point to rich countries taking responsibility for emissions reductions of 60-80% from 1990 levels by 2050". The distribution rule of equal caps is probably the most straightforward way of allocating a greater burden on the rich countries.

Global per capita GHG emission in 2002 equals about 4 ton per world citizen (24 gigaton divided by 6 billion persons). Of course, the target level of the equal cap depends on the future population growth and the desired long term stabilization level of carbon dioxide concentration in the atmosphere. For simplicity, it is assumed that world population shares remain constant and that the global emission level, taking 2002 as the base year, must roughly be halved, corresponding to a yearly world fossil fuel carbon dioxide emission of about 12 gigaton. In the absence of population growth, the global per capita GHG emission has to be

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[8] In principle, the Lorenz curve analysis can further be extended by focussing on the distribution rule of an equalized *cumulative* cap that also takes historical emissions from 1850 onwards into account and projecting future emissions into the distant future as far as 2050 or 2100. The Lorenz curve would then depict the distribution of historical emission and the resulting future emission quotas. This rule can be contrasted with allocating emission allowances based on cumulative emission in the past, known as grandfathering inherited quotas.

reduced from 4 to 2 ton per capita to meet the target of 12 gigaton.[9] How can these figures be linked to the Lorenz curves above? First, an equalized per capita emission limit suggests that the diagonal of Figure 1 is the relevant yardstick. On the diagonal, each country's share in the world GHG emission is equal to its world population share ($g_i = p_i$, see Eq. (10)). India will get a 17.5 percent share of the grand total of 12 gigaton, corresponding to an emission cap of 2.1 gigaton, China will get a 21.4 percent share worth 2.6 gigaton and the USA gets a 4.8 percent share or 0.58 gigaton, one tenth of its 2002 level of GHG emission. However, if trading of emissions permits is allowed, this strict proportional relationship only holds for the emission permits *allocated* to countries, but not necessarily for their actual emissions.

What kind of shift is involved if a nontradable equal cap of 2.01 ton (12 gigaton divided by about 6 billion people) is imposed? To show the shift relative to the 2002 distribution, we have to transform the normal Lorenz curve into a *Generalized* Lorenz curve. On a Generalized Lorenz curve, the variable on the vertical axis is the cumulative *population weighted* per capita emission (equal to $\sum_{j=1}^{i} g_j^c p_j$ in discrete form, see Eq. (3), or $\int_0^{g_i^c} g^c f(g^c) dg^c$ in continuous form, see Eq. (7)). The Generalized Lorenz curve (labelled A) in Figure 3 in fact reproduces Figure 1A, with the only difference that the vertical axis now measures the cumulative population share weighted per capita emission, instead of the cumulative global emission share. In Figure 3 India has coordinates (38%, 0.28), which means that 38 percent of the world population including India are responsible for only 0.28 ton per capita. Therefore their GHG emission per capita is on average 0.28/0.38 = 0.73 ton per capita. Now we add the Generalized Lorenz curve (with label NT) belonging to a nontradable equalized per capita emission cap of 2.01 ton (see also the bottom horizontal line in the Parade of Figure 1B).

If no permit trading is allowed, countries will either use up their GHG emission permit if the present level is higher than the permitted level and implement abatement measures to reduce their excess emissions, or they simple continue to produce the actual level if it is below the permitted level. Therefore, the Generalized Lorenz curve NT coincides with the Generalized Lorenz curve A only for that part of the segment where countries are located for which the cap has no bite. For all other countries for which the cap has a bite, the NT curve is below the A curve. As the Parade in Figure 1B shows, for nearly half (47 percent) of the world population, in fact the poorest half, the uniform per capita GHG cap of half the 2002

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[9] If the world population increases to a projected level of 9 billion in 2050, the emission cap is 1.33 ton per world citizen (12 gigaton/9 billion), about a third of the level in 2002.

level has no real bite and for them it is business as usual, at least for the near future. As a consequence, they will use less than their allocated emission cap: e.g. India has a cap of 2.1 gigaton, but only produces 1.1 gigaton, but the surplus cannot be transferred or traded to countries which want to use more than their allotted cap. In total, about 8.9 gigaton instead of the grand total of 12 gigaton results, corresponding to 1.495 ton per capita, which is where the NT curve in Figure 3 cuts the vertical axis on the right side. Because of the non-tradability, not all caps are used in full, which results in an extra emission reduction of about 3.1 gigaton, on top of the 12 gigaton reduction already accounted for. The Parade in Figure 1B also shows that the other half of the world is in serious problems: the USA confronts a ceiling of about 0.58 gigaton against an actual GHG emission of 5.8 gigaton; for Japan it is 0.26 against 1.21, for Germany 0.17 against 0.86 and for the UK 0.12 against 0.54. In sum, without trading and a distribution rule of equalized per capita emissions, the big polluters would have to cut emission levels by at least 70 percent.[10]

However, given the goal of a global emission cap of 12 gigaton, the nontradable per capita emission allowance can be increased up to 3.01 ton per capita (corresponding to the middle horizontal line in Figure 1B). Now for up to 70 percent of the world population, including China, it is business as usual and the countries for which this higher cap has a bite still have to reduce their emission by 70 percent.[11] Allowing such a higher cap results in the Generalized Lorenz Curve T, which cuts the vertical axis on the right at 2.01 ton per capita. This will of course also be the end point of the Generalized Lorenz Curve under tradable permit rights, since countries that are situated on the left of the Generalized Lorenz curve NT (based on a permit of 2.01 ton per capita) will sell their surplus emission permits to countries located on the right. On top of that, GHG abatement policies have to be adopted to bring down the world average of 4.02 ton per capita down to 2.01 per capita. Although under tradable permit rights, opposed to non-tradability, it is unclear which countries will adopt abatement measures,[12] it must be the case that the area under the curve but above the horizontal line at a level of 2.01 ton per capita (on the right in Figure 3) must be equal to the area under the same line but above the curve (on the left in Figure 3). This exercise learns us that the Generalized Lorenz and the associated Parade allows us to amalgate into one simple

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[10] The countries with actual emission levels above 2.01 per capita together produce 21.5 gigaton and are only granted 6.4 gigaton permit rights.

[11] The countries with actual emission levels above 3.01 per capita together produce 17.4 gigaton and are only granted 5.4 gigaton permit rights.

[12] For instance, although the equal cap has no bite for India, it might still be profitable for India to adopt abatement policies if the price per tradable unit GHG is higher than its marginal abatement cost.

diagram the inequality in the distribution of actual (2002) emissions, a particular distribution rule governing the distribution of permitted emissions and the global emission cap. Admittedly, for the distribution of *actual* emissions under an (equal) cap-and-trade system much more information is required, such as the marginal abatement costs in different countries, the equilibrium permit price of emission, future GDP and population growth by country, etc. If the data are available and the modelling is done, then in principle the resulting distribution can be projected in the Lorenz diagram in the same way as is done here for nontradable caps.

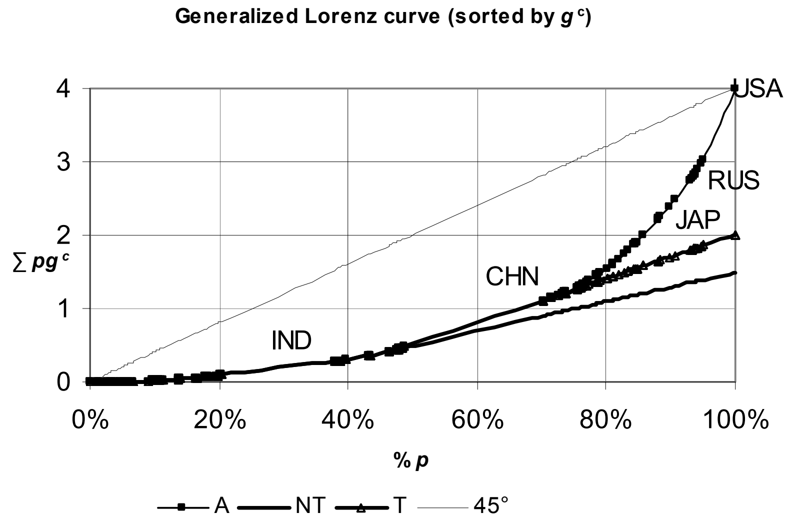

Figure 3. Generalized Lorenz curve for countries sorted by per capita emissions (g^c), cumulative population weighted per capita emissions ($\sum pg^c$) on the vertical and cumulative world population shares (%p) on the horizontal axis.

3.2 Grandfathering

Usually, the grandfathering method takes as point of departure the actual or historic levels of emissions, so endowing countries with caps or quotas based on their emission level in some base year (e.g. 1990 as in the Kyoto protocol). It thus maintains the relative levels of GHG emissions in the base year. Of course, then for all countries in the world the cap has a serious bite: all countries have to reduce their emissions by the fraction of one minus the ratio of the global cap and the actual global emission, even if some of them are now at an extremely low level of GHG emission per capita (e.g. Chad, with a recorded GHG emission per capita of 0.02 against 4 for the world average). This is not only to the disadvantage of the LDCs with low levels of GHG emissions per capita, but also to developed countries which already have taken measures in the recent past to curtail their GHG emissions.[13] This inequity towards the LDCs cannot be removed if one sticks to a grandfathering rule, but the inequity towards the developing countries with a relatively low carbon dioxide emission per unit of GDP is eliminated by grandfathering according to world GDP shares, instead of emission levels, in some base year. This suggests that the diagonal of Figure 2A is the relevant yardstick. As before, we reproduce Figure 2A, but transformed into a Generalized Lorenz curves, giving Figure 4. The horizontal axis measures $F(e_i) = \int_0^{e_i} y\,de$ and the vertical axis $e_w F_1(e_i) = \int_0^{e_i} e_i y_i de$.

The aim is again to halve the world aggregate GHG emission to 12 gigaton, divided across countries according to the actual world GDP shares in 2002 (or alternatively, that in any future year a country gets a GHG permit equal to its world GDP share times the at that time yearly allowable global GHG emission). Confronting India and France shows that this grandfathering rule is indeed rather harsh on the developing countries: India's share in world output is 5.8 percent, so its get a permit of 0.7 gigaton, against an actual level of 1.1 gigaton, so the cap has a bite; France has a GDP share of 3.4 percent and gets 0.41 gigaton, against an actual level of 0.38 gigaton, so the cap has no bite. As Figure 4 and the corresponding Parade of Figure 2B shows, for only 15 percent of the world population, comprised of the countries with an emission intensity (*e*) of less than half the 2002 world average emission intensity of 520 ton CO_2 per million of US$ produced,[14] the grandfathering cap has no immediate bite. The other 85 percent have to reduce their emission level by on average 53 percent.[15] Probably there will not be so much difference between the case of allowing trade versus no trade of permits, since even under the no trade regime the resulting global emission level is 11.8 gigaton, only 0.2 gigaton short of the global ceiling of 12 gigaton due to unused permit rights.

Under the grandfathering method, the position of countries in Figures 4 and 2B is determined by their GDP emission intensities (*e*). Figure 4 shows that Sweden and France are located on the left, whereas USA and China, with much higher levels of *e*, are located on the right of the Generalized Lorenz curve. In the Parade of Figure 2B, the bold horizontal line

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[13] For instance, the carbon dioxide emission per unit of GDP in Sweden (202), Norway (236) and France (243) is far lower than in the USA (575).

[14] Given the distribution according to world GDP shares and the aim of halving the global emissions, it follows that for all countries with an emission intensity of less than half the global average emission intensity the cap is not biting. Among these countries are many LDCs as Chad, Costa Rica and Ghana, but also some developed countries, like Sweden, Norway, Switzerland and France.

[15] These countries together produce 23.2 gigaton and hold permit rights for only 11.0 gigaton.

represents the 2002 world average emission intensity and the horizontal dashed line the stated objective to roughly half emission intensities across the board. It can be clearly seen that the grandfathering cap does not have a bite for Sweden and France, opposed to India and China.

It is possible to have the same vertical axis as in Figure 3, while maintaining the cumulative share of world output on the horizontal axis. This is illustrated on the vertical axis on the right of Figure 4, where this secondary vertical axis measures the cumulative population weighted per capita emission ($\int_0^{e_i} p_i g_i^c de$). To see why still a properly shaped Lorenz curve results, recall that the right criterium to rank countries is the ratio of the variables on the vertical and the horizontal axis. With the cumulative population weighted per capita emission on the (secondary) vertical and the cumulative world output share on the horizontal axis, this ratio is equal to:

$$\frac{p_i g_i^c}{y_i} = \frac{P_i}{P_w}\frac{G_i}{P_i}\frac{Y_w}{Y_i} = \frac{G_i}{Y_i}\frac{Y_w}{P_w} = e_i y_w^c \tag{13}$$

Because y_w^c is given for individual countries, the ranking is indeed again according to emission intensities. Using Eq. (1), it also follows that $p_i g_i^c = y_w^c y_i e_i$, so the population share weighted per capita emission is equal to world output share weighted emission intensity times a constant. Since the sequence in which countries are lined up is the same and the variable on the left vertical axis ($y_i e_i$) is strictly proportional to the variable on the right vertical axis ($p_i g_i^c$), the corresponding (generalized) Lorenz curves must coincide, provided that the primary and secondary vertical axes are scaled properly.

Comparing the equal per capita distribution rule with the grandfathering rule, both giving the same grand total of 12 gigaton, learns us that under the equal cap rule it is for a much higher share of the world population business as usual (47 percent under no trade, and even 70 percent under cap-and-trade), but as a consequence the countries which face the bite have to cut their emission levels much more (up to 70 percent) than under the grandfathering rule. Under the grandfathering rule, more than 80 percent of the world population faces the cap as a bite, but they only have to reduce their emission levels by about 50 percent. Another major difference is that under the equal per capita rule the burden of abatement is entirely on the developed countries, whereas all LDCs are not constrained in GHG emission (at least not in the short term). Under the grandfathering rule the picture is more mixed: even some developed countries are not constrained, whereas many LDCs, among them China and India, have to adopt abatement policies or buy permits to stay under their GHG allowances, despite their still low (and well below world average) GHG emission per capita.

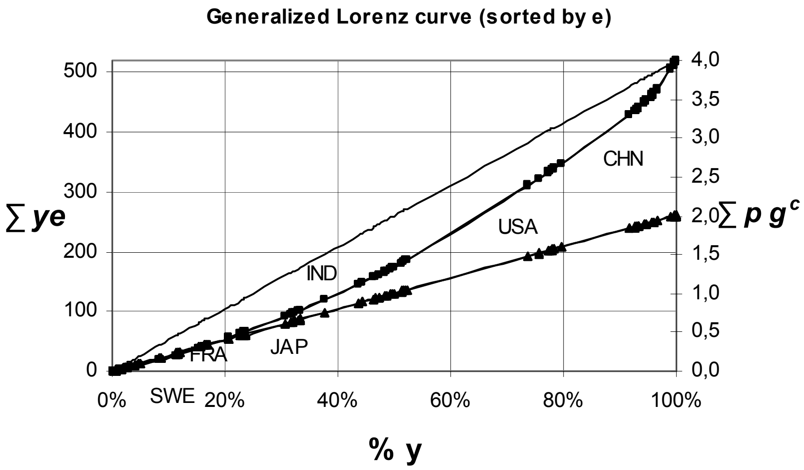

Figure 4. Generalized Lorenz curve for countries sorted by emission intensity (e), cumulative world income share weighted emission intensity (∑ye) on the left vertical axis, cumulative population weighted per capita emission on the right vertical axis (∑pg^c) and cumulative world income shares (%y) on the horizontal axis.

4 The optimal distribution under the Samuelson rule

In this section, a simple formal model will be developed.[16] The representative citizen in a country has a utility function with two arguments, per capita income y_i^c and the global public good *A,* which stands for abatement. Formally, $u_i(y_i^c, A)$ is a continuous, concave function with

$$\partial u_i / \partial y_i^c = u_{y^c} > 0; \partial^2 u_i / (\partial y_i^c)^2 < 0; \partial u_i / \partial A = u_A > 0; \partial^2 u_i / (\partial A)^2 = u_{AA} < 0 \tag{14}$$

Because of the rapid diffusion of carbon dioxide in the global atmosphere, GHG emission is a global public bad and abatement a global public good. Therefore, abatement efforts of individual countries can be added up:

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[16] The model in this paper is inspired by similar models in Chichilnisky and Heal 1994, Eyckmans and Coenen 2004 and Eyckmans, Proost and Schokkaert 1993.

$$A = \sum_{i=1}^{N} A_i = A_i + A_{\_i} \tag{15}$$

Assuming no transfers between countries, total resources in a country can either be spend on consumption or on investment in abatement:

$$R_i = P_i y_i^c + C_i(A_i) \tag{16}$$

When countries follow a noncooperative Nash-Cournot strategy, they maximize $W_i = P_i u(y_i^c, A_i + A_{\_i})$ subject to the resource constraint given by Eq. (16), so the Lagrangian becomes:

$$L^N(y_i^c, A_i, \lambda) = P_i u(y_i^c, A_i - A_{\_i}) - \lambda[P_i y_i^c - C_i(A_i) - R_i] \tag{17}$$

with first-order conditions:

$$u_{y_i^c} - \lambda = 0 \tag{18}$$

$$P_i u_A - \lambda C_{A_i} = 0 \tag{19}$$

Solving Eqs. (18) and (19) results in the famous Samuelson rule for the optimal provision of abatement at the *national level*:

$$C_{A_i}^N = P_i \frac{u_A}{u_{y_i^c}} \tag{20}$$

According to Eq. (20), marginal cost of abatement in a country, the LHS of Eq. (20), will be equal to the sum (P_i) of the marginal rate of substitution between the public good abatement and private consumption $(u_A / u_{y_i^c})$. Note that all other things equal, the marginal abatement cost and therefore also the total abatement effort in a rich country will be higher than in a poor country (see also Sandmo 2007: 12 for a similar result).

The Nash-Cournot levels of abatement can be compared with the Pareto-optimal levels of abatement chosen by a hypothetical social planner. Assume this social planner maximizes the utilitarian global welfare function:

$$L^P(y_1^c,...,y_n^c,A_1,...,A_n,\lambda_1,...\lambda_n)=\sum_{j=1}^n P_j u(y_j^c,\sum_{j=1}^n A_j)-\sum_{j=1}^n \lambda_j[P_j y_j^c - C_j(A_j)-R_j] \quad (21)$$

Differentiating with respect to per capita income in country *i* gives an expression similar to Eq. (18),

$$u_{y_i^c}-\lambda_i=0 \quad (18)$$

but with respect to the optimal abatement effort of country *i*, Eq. (19) changes into:

$$\sum_{j=1}^n P_j u_A-\lambda_i C_{A_i}=0 \quad (23)$$

which leads to a Samuelson rule for the optimal provision of abatement at the *global level*:

$$C_{A_i}^P=\frac{\sum_{j=1}^n P_j u_A}{u_{y_i^c}} \quad (24)$$

Comparing the Nash-Cournot equilibrium outcome, denoted by superscript *N*, with the Pareto-optimal outcome, denoted by superscript *P*, shows that given per capita income in a country, $C_{A_i}^P$ is way higher than $C_{A_i}^N$, which implies that abatement levels under Pareto are much higher than under Nash-Cournot. Note also that under the Pareto outcome the optimal level of abatement is determined by per capita income in a country and the global sum of positive externalities of abatement, but is independent of the population size of the country. This is natural, because under the Pareto outcome the population size for a country is of no concern since GHG emission is taken as a public bad at world scale and henceforth abatement as a global public good. Under the Nash-Cournot outcome, however, the optimal abatement level is determined by both population size and per capita income on the country level, but is independent of the global sum of positive externalities of abatement, because the benefits of abatement as a public good is only taken into account in so far as it affects the own population. These outcome are well-known in the environmental economics literature (for similar results, see). The result that the Pareto optimal outcome does not require equalization of marginal costs across countries, but that they are inversely related to marginal utility of income (see Eq. 24) leading to higher marginal cost of abatement for rich countries, is in line with Chichilnisky and Heal (1994) and largely due to the fact that abatement enters as a consumption externality and the use of a social welfare function (see Sturm 1995, Manne and Stephan 2005 and Sheeran 2006).

However, within the confines of this paper, it is interesting to find out where the Nash-Cournot and Pareto outcomes situate themselves in the carbon Lorenz curve framework presented in the previous sections. Obviously, the Nash-Cournot outcomes coincides with what is commonly called business-as-usual. It is the level of GHG emission and abatement in the absence of any international coordination. The 1997 Kyoto protocol is so far the only international agreement, which came into effect in February 2005 (after the ratification by the Russian Doema the requirement that at least 55 countries together responsible for at least 55 percent of the world GHG emission must ratify the agreement was met). The specified target level is a reduction of on average 5.2 percent in 2012 relative to the base year 1990. By and large, the Annex I countries (see the second column of Table I) still have to implement the abatement effort to realize their Kyoto commitments. Therefore, it will not be very much off the mark if we assume that the actual (2002) distribution as given by the Lorenz curves and Parades in section 2 are taken as the Nash-Cournot outcomes.

To get a clue how the Pareto optimal outcome situate in the Lorenz curve diagram, we have to make some further assumptions. First, assume that marginal utility of income is inversely relate to per capita income, so the richer a country, the lower its marginal utility of more consumption. Second, assume that the marginal costs of abatement varies inversely with the GHG intensity of production in a country ($e_i = G_i / Y_i$), so the more GHG per unit of GDP produced in a country, the lower its marginal cost of abatement. This second assumption therefore implies that countries with the highest emissions per unit of GDP, such as the countries of the former Soviet Union and the formerly communist countries in Eastern Europe, have to incur the lowest per unit abatement cost, apparently because there is still much room to make production more clean in terms of GHG emission. Substituting both assumptions into the Samuelson rule for the Pareto optimal provision of abatement and making use of the identity that GDP is population times income per capita ($Y_i = P_i y_i^c$) gives:

$$C_{A_i}^{P} = \frac{a}{G_i / Y_i} = y_i^c \sum_{j=1}^{n} P_j u_A \Rightarrow \frac{G_i}{P_i} = g_i^c = \frac{a}{\sum_{j=1}^{n} P_j u_A} \tag{25}$$

The denominator in the RHS of Eq. (25) represents the global sum of abatement benefits and expresses that the higher this global sum of benefits is, the lower the GHG emissions per capita must be. Since this sum is determined on the global level, dependent only on the aggregate abatement effort due to abatement being a global public good, the level of the per capita emissions across countries under these assumptions have to be uniform. Together with the global pollution constraint $\sum_{j=1}^{n} P_j g_j^c \leq G_w^*$, Eq. (25) determines the per capita allowance. Clearly, the diagonal of the Lorenz curve depicted in Figure 1A is relevant here, as can be seen from Eq. 10, where it was derived that along the diagonal it must be the case that $g_i^c = g_w^c$. Since the latter is equivalent with $e_i = g_w^c / y_i^c$, and given uniform per capita emission entitlement, rich countries have to decarbonise their economies to a greater extent than poor countries.[17]

Conclusion

The income inequality literature offers a broad array of indicators, concepts and graphical tools to characterize the distribution of income or to compare the distribution over time or between countries. In principle, all of them can also be applied to the distribution of GHG, provided appropriate adjustments are made. In this paper, I have chosen to apply the Lorenz curve, the Parade and the Gini coefficient to the distribution of GHG, because each of them allows a very natural and easy to grasp interpretation, which may be of great help not only to policy-makers but also the general public to be informed about the problems surrounding global warming and climate change.

By way of illustration, two well-known distribution rules, equal caps and grandfathering, are discussed. The (generalized) Lorenz curves and the associated Parades show the impact of these rules on the distribution of (future) GHG entitlements across countries compared to the actual distribution and the distribution in the past. Not surprisingly, under the equal (cumulative) cap rule, the rich countries have to carry the brunt of the burden to curtail GHG emissions. For a large majority of the world population, an equal cap would allow them to pursue a BAU-policy, while the rich minority have to cut emissions (or buy permits, implying others to cut their emissions instead) by about 70 percent. Under the grandfathering rule, also developing countries, no matter how low their present or past GHG emission per capita or income per capita, have to adopt abatement policies. Only a small minority of the world population, composed of countries with rather low GHG intensities of GDP, among them some rich countries, would not face a bite, but all other countries have to

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[17] Of course, under permit trading, rich countries may buy emission permits from poor countries. Although the issue of permit trading goes beyond the scope of this paper, the uniform permit price reestablishes the equality of marginal costs of abatement and consequently the production efficiency of abatement efforts world wide.

cut emissions by on average 50 percent. It would be nice if in the future every serious emission allocation proposal discussed during meetings of the IPCC or other supranational gremia is accompanied with the corresponding (generalized) Lorenz curves and Parades to allow both policy-makes and the general public to quickly grasp what is actually on the table. Finally, it was shown that under specific simplifying assumptions the Nash-Cournot and Pareto distribution of GHG emission as expressed in the Samuelson rule for the optimal production of abatement on the national and the global level can be approximated by the actual distribution as given by the Lorenz curve and the corresponding diagonal, respectively.

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Appendix The Distribution between Regions

The world can be divided in several ways. One distinction is between Annex I and Non-annex I countries. Another is the CAIT division into the eight geographical regions Asia (AS), Europe (EUR), Middle East & North Africa (ME), Sub-Saharan Africa (AFR), North America (NA), Central America & Caribbean (CAM), South America (SAM) and Oceania (OC). Heil and Wodon (2000) divide countries according to income per capita into four groups (Lower, Lower-middle, Upper-middle and High). In the figures included in this appendix, I have merged ME and AFR into AF, CAM and SAM into SA and OC and EUR into EU. The Annex I countries comprise the regions Europe and Oceania (EU) and North America (NA). The non-Annex I countries comprise the regions Sub-Saharan Africa and Middle East & North Africa (AF), South America and Central America & Caribbean (SA) and Asia (AS). The table and figures below are the counterparts of Table 1 and Figures 1-4 in the main text, but now based on regions instead of countries.

Table A1. Overview of carbon emission, income and population for a broad classification into Annex I versus non-Annex I signatories and into five regions.

	G	g	g^c	y^c	Y	y	e	P	p	%p	%y	%g
NAI	10.588,4	42,9%	2,1	3.717	18,3	39,7%	578	4,932	79,9%	79,9%	39,7%	42,9%
AI	14.116,8	57,1%	11,4	22.466	27,9	60,3%	506	1,242	20,1%	100,0%	100,0%	100,0%
AF	2.272,0	9,2%	2,1	2.934	3,2	6,9%	708	1,095	17,7%	17,7%	6,9%	9,2%
AS	8.328,3	33,7%	2,4	4.359	15,2	32,8%	549	3,479	56,3%	74,1%	39,7%	42,9%
SA	1.320,3	5,3%	2,5	6.914	3,6	7,9%	363	0,527	8,5%	82,6%	47,6%	48,3%
EU	6.493,5	26,3%	8,6	17.779	13,4	29,0%	484	0,754	12,2%	94,8%	76,6%	74,5%
NA	6.291,1	25,5%	19,7	33.815	10,8	23,4%	582	0,320	5,2%	100,0%	100,0%	100,0%
World	24.705,2	100,0%	4,0	7.489	46,2	100,0%	534	6,174	100,0%			

Figure A.1A shows how close the dichotomy between Annex I (abbreviated as AI) signatories versus the non-Annex I (NAI) countries matches the division between Europe, Oceania and North America on the one hand and the NAI regions on the other hand. The dashed line in Figure A.1A shows that the 80 percent of the world population belonging to NAI countries only produces slightly above 40 percent of the GHG emission, so AI countries together comprising only one fifth of the world population emit nearly 60 percent of the world GHG. Figure A.1B shows that the per capita emission of North America is more than twice that of Europe, and that of Europe is four times that of Africa, Asia and South America.

Figures A.2A and B shows that on a high level of aggregation, GHG emissions are almost proportional to GDP. The Lorenz curves almost coincide with the diagonal, which only occurs when emission intensities are equal, or equivalently, that per capita emission are proportional to per capita income. To some extent, this is an artefact (compare Figure A.2A with Figure 2A in the main text) resulting from merging countries with high and low emission intensities into the same region, for instance the Baltic and Scandinavian states into Europe.

In Figure A.3, the coordinates of the point labelled AS is (74,1%, 1.7) which means that three quarter of the world population, composed of Africa and Asia, together are accountable for 1.7 out of 4 ton GHG per capita world wide, so the remaining quarter of the world population is accountable for 2.3 out of the world average of 4 ton GHG per capita. Finally, Figure A.4 shows that except for SA (with an emission intensity far below the world average) and AF (far higher), the variation in emission intensities on a region level is rather modest.

Figure A.1A Lorenz curve, 2002 emission (sorted by g^c)

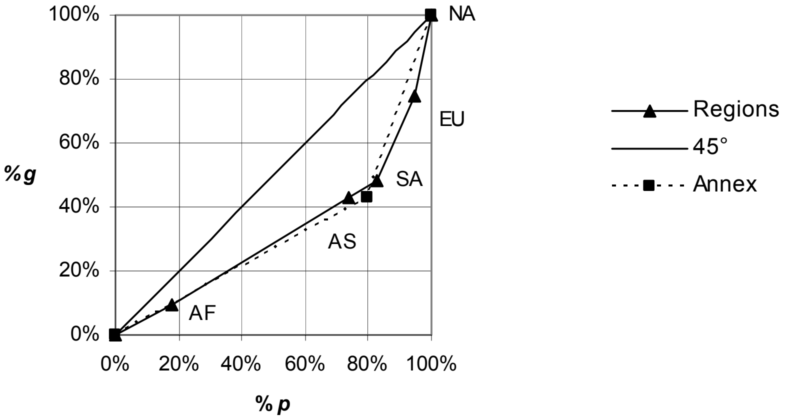

Figure A.1B Parade (sorted by g^c)

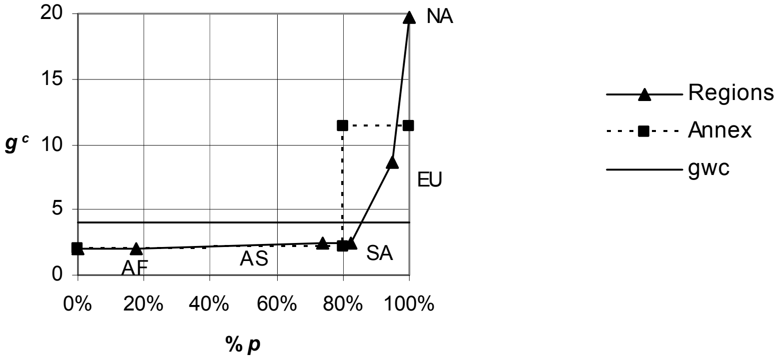

Figure A.2A Lorenz curve (sorted by *e*)

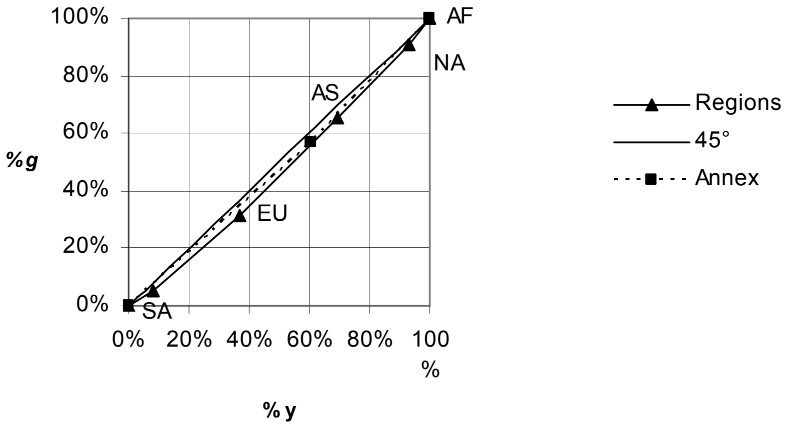

Figure A.2B Parade (sorted by *e*)

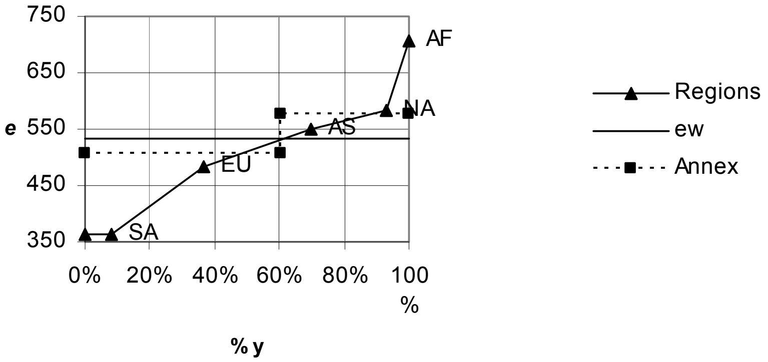

Figure A.3 Generalized Lorenz curve (sorted by g^c)

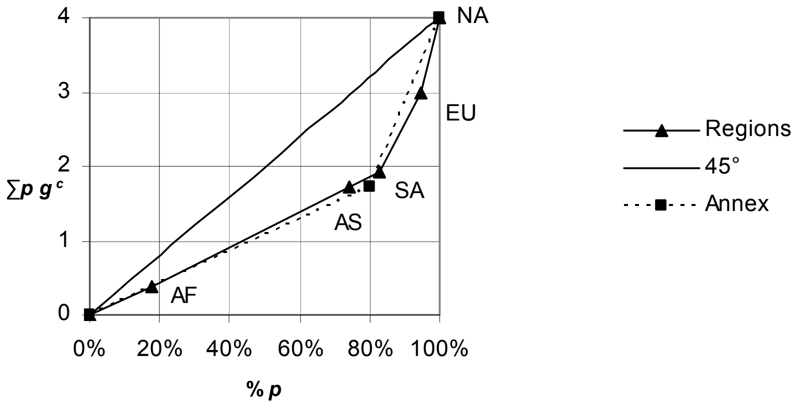

Figure 4 Generalized Lorenz curve (sorted by e)