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Compensations and contributions under an international carbon treaty

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Abstract

This paper provides a numerical illustration of how an international carbon treaty might work. The simulations in this paper using 2004 data on carbon emissions and per capita GDP from 178 countries suggest that high-income countries might be much better off collectively compensating low-income countries through an international treaty to help reduce carbon emissions rather than reducing carbon emissions without their help.

JEL classification: H23

Keywords: Carbon treaty; Carbon tax; Carbon permits; Compensation; Contributions

1. Introduction

How to make progress with reducing world carbon emissions? Low-income countries rightly point out that high-income countries have been emitting carbon for two centuries in the process of raising their standard of living, so low-income countries have a similar right to raise their standard of living. High-income countries respond that it would be much cheaper for the world if low-income countries participate in carbon reduction. Is there any way to break this impasse?

The simulations in this study suggest there might be. The simulations use actual 2004 data on carbon emissions and per capita GDP from 178 countries to provide a rough estimate

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of how much better off high-income countries might be if they get help from low-income countries in reducing carbon emissions rather than doing it themselves, even if they collectively compensate low-income countries through an international carbon treaty. One purpose of this paper is to provide a numerical illustration of how an international carbon treaty might work.

In this paper we call the administrator of the treaty the "Treaty Board." We will not discuss political and operational aspects of the treaty and the Treaty Board—for example, whether the Treaty Board would be a newly formed agency or a division of a current international agency, how many votes each country would have, and so on. Obviously these aspects of an international carbon treaty would be extremely controversial and would require serious analysis by political scientists.

It must be emphasized that under the treaty each high-income country would make a contribution to the Treaty Board, not to any particular low-income country, according to a formula prescribed by the Treaty Board that applies objectively to all high-income countries; and each low-income country would receive compensation from the Treaty Board, not from any particular high-income country, according to a formula prescribed by the Treaty Board that applies objectively to all low-income countries. Collectively, high-income countries would be compensating low-income countries through the Treaty Board, but there would be no direct transfer from any specific high-income country to any specific low-income country.

In this study we assume that if only a subset of countries undertake emissions reduction, a subset country would have a marginal cost for the last unit it abates that is higher than the marginal cost would be for the first unit of a non-participating country. This assumption implies that it would be possible to reduce the total world cost of reducing emissions by inducing non-participating countries to help. The equations of our simulation model, given in Appendix A, embody this assumption. The importance of obtaining broad international participation in reducing carbon emissions is widely recognized (Aldy, Barrett, & Stavins, 2003; Barrett & Stavins, 2003; Buchner & Carraro, 2005; Frankel, 2007; Olmstead & Stavins, 2006; Onishi, 2007; Pizer, 2006; Weyant, 1999; Zhang, 2004).

This study investigates the quantitative consequences of compensating low-income countries through an international carbon Treaty Board to induce them to help reduce carbon emissions. Within high-income countries, such compensation is often viewed as altruism. This study explores the possibility that, on the contrary, such collective compensation through a Treaty Board might be in the self-interest of high-income countries and provides estimates of how much each high-income country would need to contribute and how much better off it would still be despite its contribution.

The study considers two ways to reduce emissions under the treaty: a harmonized carbon tax or an international permit market (a comparison of the efficiency of a carbon tax, carbon permits, and a hybrid, given uncertainty about compliance costs, is provided by Pizer, 2002). In theory each way would equalize the carbon price facing all emitters and minimize the world cost of achieving a given world emissions reduction target. In practice, the operational and political feasibility of either an internationally harmonized carbon tax or an international permit market is controversial (Liang, Fan, & Wei, 2007).

If emissions are reduced through a harmonized carbon tax (Cooper, 1998, 2000; Nordhaus, 2006; analysis of the design of a carbon tax within each country is given by Goulder, 1992; Metcalf, 2007; Poterba, 1991), a contribution formula would prescribe the contribution from each high-income country government to the Treaty Board, and a compensation formula would prescribe the compensation from the Treaty Board to each low-income country government.

Under the carbon tax treaty, each country that signs the treaty would agree to levy a carbon tax at the uniform magnitude specified by the Treaty Board for all countries (for example, $100 per ton); each country government would levy and administer its carbon tax, collect and keep its carbon tax revenue, and decide how to use the revenue. High-income country governments would make contributions to the Treaty Board which would use this revenue to compensate low-income country governments. Each high-income country government would decide how to finance its contribution to the Treaty Board. Each low-income country government would decide how to use its compensation from the Treaty Board.

If emissions are reduced through marketable permits (permit plans are analyzed in Bradford, 2004; McKibbin and Wilcoxin, 2002; Olmstead and Stavins, 2006; Stavins, 2007), compensations and contributions would be implemented indirectly by a formula used by the Treaty Board to distribute permits to countries under the treaty. Low-income countries would be given more permits than they are expected to use so they would become net sellers of permits and receive compensation through their net sales. High-income countries would be given less permits than they are expected to use so they would become net buyers of permits and would make a contribution through their net purchases. Each country government could sell all its permits, collect and keep its carbon permit revenue, and decide how to use the revenue; or each country government could distribute some or all of its permits for free to its own firms.

The compensation of a participating low-income country under the treaty would be based on a formula for the cost to the country of its emissions reduction under the treaty. This cost formula would be developed by technicians at the Treaty Board. The cost formula used for illustration in this study is given in Appendix A.

In this study, each low-income country's per capita compensation depends on its cost of emission reduction and on its per capita GDP, and each high-income country's per capita contribution depends on the cost saving it achieves from the participation of low-income countries in emission reduction, and/or on its per capita GDP. A formula for the cost saving of a high-income country would be developed by technicians at the Treaty board. The cost-saving formula used for illustration in this study is given in Appendix A.[1]

It should be emphasized at the outset that our illustration assumes that the Treaty Board is able to acquire all the relevant information needed to implement the treaty. First, we assume that the Treaty Board technicians are able to accurately quantify the cost to each low-income country's economy of its emissions reduction under the treaty so that each low-income country can be appropriately compensated. In practice, of course, there would be substantial uncertainty in such cost estimates, and whatever method is used would undoubtedly be politically controversial. Second, we assume that the technicians are able to accurately quantify the cost saving to each high-income country's economy due to the participation of low-income countries so that each high-income country can be assigned a contribution linked to its cost saving. But again, in practice there would be substantial uncertainty in such estimates. Third, we assume per capita GDP, which affects both a low-income country's compensation and a high-income country's contribution, is known and undisputed, but in practice the measure of per capita GDP is controversial both technically and politically. Nevertheless our paper illustrates how a treaty might work and the kind of information

[1] This study does not attempt to vary a country's per capita compensation or contribution with an estimate of the per capita future benefit it might receive from cutting carbon emissions today. It would be difficult to provide estimates of per capita future benefits for individual countries and to get diplomats to accept such estimates, but the feasibility of adjusting compensations and contributions with estimated future benefits might be pursued in further research (benefits as well as costs are weighed in Nordhaus, 2007, and Lewis & Seidman, 1996).

Table 1
100% compensation (billions of dollars).

	46 high-income countries	132 low-income countries	All 178 countries
Cost when 46 participate	\$108.382	\$0	\$108.382
Cost when 178 participate	\$27.670	\$27.093	\$54.763
Cost saving	\$80.712	-\$27.093	\$53.619
Burden after 100% compensation	\$54.763	\$0	\$54.763

required. It also provides initial estimates of the order of magnitude involved in the contributions to and compensations from the Treaty Board.

2. The gains from broader participation

Just how big might the gains be from broader participation?

The IMF World Economic Outlook database (2004) contains 178 countries and provides per capita GDP for each country. According to the Energy Information Administration (EIA, 2004) of the U.S. Department of Energy, emissions for these 178 countries in 2004 were 7.302 billion metric tons of carbon. These 178 countries generated virtually all of world emissions so we will refer to their emissions as "world emissions." Because the most recent data from the EIA for these 178 countries is for 2004,[2] we use 2004 in our study. Consider a dividing point of \$12,000 per capita. The 46 countries with per capita GDP greater than \$12,000 contributed roughly half of world emissions while the 132 countries with per capita GDP less than \$12,000 contributed roughly half.

Suppose the 46 countries with per capita GDP above \$12,000 want to reduce world emissions 15% or 1.095 billion tons of carbon. If they cut their own emissions 1.095 billion, then according to our simulation model the total cost of their emissions reduction would be \$108.382 billion (row 1 of Table 1).[3] But if the 46 high-income countries get optimal help from the 132 low-income countries, then the total cost of reducing emissions 1.095 billion with all 178 countries participating would be only \$54.763 billion (row 2 of Table 1).[4] Thus, the world cost saving from expanding participation from 46 to 178 countries would be \$53.619 billion—the difference between the cost when the 46 do it alone, \$108.382, and the cost when all 178 participate, \$54.763 (row 3 of Table 1).

How much would the cost saving be for just the 46 high-income countries? The cost saving is the difference between the cost of doing it alone, \$108.382, and the cost to the 46 high-income countries only when all countries participate, \$27.670. Thus, the cost saving to the high-income countries would be \$80.712 (row 3 of Table 1).

3. An initial design: 100% compensation, contribution based on cost saving

With all 178 participating, the cost of emissions reduction to the 132 low-income countries would be \$27.093 billion (row 2 of Table 1), while the cost saving to the 46 high-income countries

[2] According to correspondence with Perry Lindstrom of the EIA, after 2004 the EIA switched to publishing regional rather than country data.

[3] Firms in the 46 countries must be faced with a price of \$198 to induce an emissions cut of 1.095 billion.

[4] Firms in the 178 countries must be faced with a price of \$100 to induce an emissions cut of 1.095 billion.

from full participation is \$80.712 billion (row 3 of Table 1). If the high-income countries compensated the low-income countries \$27.093 billion (100% of their cost of emissions reduction), the high-income countries would be \$53.619 billion better off than if they had done it alone.

To implement this design, the Treaty Board ranks countries by GDP per capita (y) and chooses a y^* – in our illustration, \$12,000 – that divides contributors from receivers. Each country with $y < y^*$ is compensated 100% of its cost of emissions reduction. For each country the cost of emissions reduction is given by a formula in Appendix A. Using this formula, the Board technicians calculate the total compensation required for the 132 countries—in our simulation, \$27.093 billion (given in Table 1 for the 132 countries).

The method of implementing this compensation of \$27.093 billion to the 132 low-income countries depends on whether the carbon price is established by a harmonized tax or by an international permit market.

If the price is established by a tax, the Treaty Board estimates the tax that would induce the 178 countries to reduce their aggregate emissions by 15%. For illustration, the simulation model in this study assumes that the tax that would cut aggregate world emissions 15% if all 178 countries participate is \$100 per ton. For each low-income country, the Treaty Board would then estimate the cost of emission reduction and therefore the compensation to be paid. Given the required aggregate compensation, the Treaty Board would use a formula to assign a contribution to each high-income country. Under the tax method, the Board sets the contribution formula to raise just enough funds from the contributor countries with $y > y^*$ to compensate the countries with $y < y^*$.

In the initial design, the *per capita* contribution x from each contributing country ($y > y^*$) is given by $x = h\Delta c$ where h is a parameter and Δc is its *per capita cost saving*; $\Delta c \equiv c_s - c_n$, where c_s is the high-income country's per capita cost of emissions reduction when only s (46) high-income countries participate, and c_n is the high-income country's per capita cost of emissions reduction when all n (178) countries participate. The per capita cost saving Δc is given by a formula in Appendix A. The parameter h is the same for all high-income countries so that each high-income country's per capita contribution x is the same percent, h, of its own per capita cost-saving Δc. A high-income country's total contribution under the treaty would equal its per capita contribution x times its population.

In this initial design, a high-income country's per capita contribution depends *solely* on the cost saving it enjoys when the low-income countries participate; its contribution does *not* depend on its per capita income. The Board technicians determine the value of the parameter h that makes total contributions equal the total required compensation—in this illustration, \$27.093 billion.

If the price is established by a permit market, then the initial distribution of permits to countries would determine each country's compensation or contribution. If the world target is set at 85% of the current emissions of 7.302 billion, then the Treaty Board would distribute 6.206 billion permits.

For each low-income country, the Treaty Board would estimate its emissions under the permit system and give it more permits than it would need to use so it would be a net seller of permits. Suppose the Treaty Board estimates that low-income countries would emit 3.070 billion tons under the permit system (85% of their current emissions). Then the Treaty Board would give low-income countries 3.34093 billion permits so that, if they emitted 3.070 billion, they would be able to sell 0.27093 billion (3.34093 − 3.070). Because the permit price should turn out to be \$100, this sale of permits would yield revenue of \$27.093 billion (\$100 × 0.27093).

For each high-income country, the Treaty Board would estimate its emissions under the permit system and give it less permits than it would need to use so it would be a net buyer of permits. Suppose the Treaty Board estimates that high-income countries would emit 3.136 billion tons

Table 2
Initial design. Dollar amounts in table are per capita.

	c_s	Δc	c_n	x	b
High-income countries					
#1	$161	$120	$41	$40	$81
#2	$79	$59	$20	$20	$40
#3	$84	$63	$21	$21	$42
#4	$77	$57	$20	$19	$39
#5	$67	$50	$17	$17	$34
#6	$53	$40	$13	$13	$26

	c_n	m	b
Low-income countries			
#7	$24	$24	$0
#8	$7	$7	$0
#9	$2	$2	$0

under the permit system (85% of their current emissions). Then the Treaty Board would give high-income countries 2.86507 billion permits so that, if they emitted 3.136 billion, they would have to buy 0.27093 billion (3.136 − 2.86507). Because the permit price should turn out to be $100, this purchase of permits would contribute revenue of $27.093 billion ($100 × 0.27093).

3.1. A country's per capita burden

How big are per capita costs, contributions, and burdens under a carbon treaty?

A high-income country's per capita burden b equals its per capita cost of emission reduction plus its per capita contribution x. A low-income country's per capita burden equals its per capita cost of emission reduction minus its per capita compensation m; in this initial design with 100% compensation, the per capita burden of each low-income country is zero.

The simulation is performed for all 178 countries and Table 2 shows the results for nine large countries. The countries are ranked by per capita income where #1 is highest and #9 is lowest: high-income countries #1 to #6 have per capita income above $12,000, low-income countries #7 to #9 have per capita income below $12,000. Under the treaty, #1 through #6 will be making contributions to the Treaty Board, while #7 through #9 will be receiving compensations from the Treaty Board.

In the top row of Table 2, the per capita cost of emissions reduction for #1 would have been $161 if only the 46 high-income countries had participated (c_s = $161), but is only $41 if all 178 countries participate (c_n = $41), so #1's per capita cost saving Δc is $120.

For the six high-income countries in the table, the per capita contribution x ranges from $40 to $13. Under the treaty the *average* person in high-income country #1 would be asked to contribute $40; if the government of country #1 raises this revenue through an income tax, then each person with above-average income in country #1 would have to contribute more than $40, and each person with below-average income in country #1 would have to contribute less than $40. It is encouraging that our simulation suggests that the contribution for the average person in country #1 under a treaty that reduces world emissions 15% would be $40, not $400 or $4000; and would be less than $40 for the other five high-income countries. For each of the three low-income countries

Table 3
Alternative designs: $y^* = \$12{,}000$, $\underline{y} = \$6000$. Dollar amounts in table are per capita.

	c_s	Δc	c_n	Proportional $v = 1$		Progressive $v = 2$	
				x	b	x	b
$w = 1$							
#1	$161	$120	$41	$42	$83	$50	$91
#2	$79	$59	$20	$13	$33	$10	$30
#3	$84	$63	$21	$13	$34	$10	$31
#4	$77	$57	$20	$12	$32	$9	$29
#5	$67	$50	$17	$10	$27	$7	$24
#6	$53	$40	$13	$8	$21	$5	$18
$w = 0$							
#1	$161	$120	$41	$31	$72	$40	$81
#2	$79	$59	$20	$19	$39	$16	$36
#3	$84	$63	$21	$19	$40	$15	$36
#4	$77	$57	$20	$19	$39	$15	$35
#5	$67	$50	$17	$18	$35	$14	$31
#6	$53	$40	$13	$18	$31	$13	$26

in the table, with 100% compensation the per capita compensation m equals its per capita cost of emissions reduction which ranges from $24 to $2.

For the six high-income countries, the per capita burden b ranges from $81 for #1 ($41 + $40) to $26 for #6 ($13 + $13). For the three low-income countries, with 100% compensation the per capita burden is $0.[5]

3.2. Phasing down the compensation percentage

In practice, the percentage compensation needs to phase down gradually, rather than abruptly, from 100% to 0%. Consider the country that has a per capita income of $12,108. If its per capita income were just $109 less, it would receive 100% compensation, but now it receives none. It is necessary to modify the compensation formula to include a smooth phase-down of the percent of compensation. In the next section, for illustration, we consider 100% compensation for $y < \underline{y} = \$6000$ and a smooth phase-down of the compensation percentage from 100% to 0% as y increases from $6000 to $12,000.[6]

4. A formula with contribution based on income

In the preceding section, the contribution of each high-income country with $y > y^* = \$12{,}000$ depends solely on its cost saving Δc. In this section we consider an expanded contribution formula in which each country's contribution varies with its per capita income so $x = h(\Delta y)^v(\Delta c)^w$, where

[5] For the high-income countries recall that $x = h\Delta c$. According to our simulation model, to raise the required revenue from contributors the Board technicians find that h must be set at 34%, so x as a percent of Δc equals 34% for all contributing countries; thus, each high-income country's contribution is 34% of its cost saving that results from having the low-income countries participate.

[6] Under the formula in the next section, the percent compensation p phases down linearly from 100% to 0% as y rises from $\underline{y}$ to y^*; specifically, $p = (y^* - y)/(y^* - \underline{y})$. Compensation for country i is now p times its cost of emission reduction.

$\Delta y \equiv y - y^*$. In Table 3 we present results for $v = 1$, $v = 2$, $w = 1$, and $w = 0$. If $w = 0$, then x is based solely on Δy. A v of 1 yields a proportional contribution formula while a v of 2 yields a progressive contribution formula.[7] Once again, each year the Board sets the numerical value for h that Board technicians estimate will raise an amount of total funds from the contributor countries equal to the total funds promised to receiver countries.

With this contribution formula, the simulation is performed for all 178 countries and the results for countries #1–#6 are presented in Table 3. Country #1 makes a larger per capita contribution when the formula is progressive ($v = 2$) than when it is proportional ($v = 1$). Conversely, countries #2–#6 each make a smaller per capita contribution when the formula is progressive than when it is proportional. Country #1 makes a larger per capita contribution when cost saving matters ($w = 1$) than when it does not ($w = 0$). Conversely, countries #2–#6 each make a smaller per capita contribution when cost saving matters than when it does not.

5. Conclusions

This paper provides a numerical illustration of how an international carbon treaty might work. The simulations in this paper using 2004 data on carbon emissions and per capita GDP from 178 countries suggest that high-income countries might be much better off collectively compensating low-income countries through an international treaty to help reduce carbon emissions rather than reducing carbon emissions without their help.

We recognize that our illustration assumes that the Treaty Board is able to acquire all the relevant information needed to implement the treaty. In practice, estimating the cost of emissions reduction for each low-income country, the cost saving to each high-income country from the participation of low-income countries, and the per capita GDP of each country, would be technically difficult and politically controversial. Nevertheless our paper illustrates how a treaty might work and the kind of information required. It also provides initial estimates of the order of magnitude involved in the contributions to and compensations from the Treaty Board.

Appendix A. Simulation model equations

(1) $\mathrm{MC} = \alpha(R/E)^{\beta}$.[8] The total cost ($C$) of reducing emissions R units is $C = \int_0^R (\mathrm{MC})\,\mathrm{d}R = \int_0^R \alpha(R/E)^{\beta}\,\mathrm{d}R = (\alpha/E^{\beta})(R^{\beta+1})/(\beta+1) = \alpha(R/E)^{\beta}R/(\beta+1)$, so

(2) $C = (\mathrm{MC})R/(\beta+1)$.[9] Substituting P for MC in (1) yields

(3) $P = \alpha(R/E)^{\beta}$, so in response to price P it chooses

(4) $R/E = (P/\alpha)^{1/\beta}$.[10] Substituting P for MC in (2) yields

[7] Note that setting $v = 0.5$ (not shown in the table) would yield a "regressive" contribution formula which would place less burden than a proportional formula ($v = 1$) on the highest income countries.

[8] The marginal cost MC of reducing emissions is assumed to be an increasing function of the percentage already reduced (R/E). E is emissions in the absence of reductions, R is the emissions reduction relative to E, and R/E is the percentage reduction in emissions. $\mathrm{MC} \equiv \mathrm{d}C/\mathrm{d}R$. Since $\mathrm{d(MC)}/\mathrm{d}R = \beta(\alpha/E^{\beta})R^{\beta-1}$, if $\beta = 1$ then $\mathrm{d(MC)}/\mathrm{d}R$ would be constant as R increases, and doubling R/E would double MC.

[9] If the firm is faced with a price P per ton emitted, then it maximizes profit by reducing emissions until $\mathrm{MC} = P$.

[10] Based on Dinan and Rogers (2002) review of empirical studies for the U.S. and on the articles in Weyant (1999), we choose for our illustrative simulations the simplifying assumption that a $P = \$100$ would induce an $R/E = 15\%$ for each country. For $\beta = 1$, (4) implies that $P = \$100$ induces an $R/E = 15\%$ for $\alpha = 666.667$; we assume α and β are the same for all countries.

(5) $C = PR/(\beta + 1)$. Substituting (4) into (5) yields the *cost formula* for a country:
(6) $C = E(1/\alpha)^{1/\beta} P^{(\beta+1)/\beta}/(\beta + 1)$.

If all n countries face price P_n, from (4) the total emission reduction is

(7) $\sum^n R_i = \sum^n E_i(P_n/\alpha)^{1/\beta} = (P_n/\alpha)^{1/\beta} \sum^n E_i$. If instead only subset s countries (the 46 high-income countries with per capita GDP greater than \$12,000) are subject to price P_s, then the total emission reduction is
(8) $\sum^s R_i = \sum^s E_i(P_s/\alpha)^{1/\beta} = (P_s/\alpha)^{1/\beta} \sum^s E_i$. To make $\sum^s R_i$ in (8) equal $\sum^n R_i$ in (7),
(9) $P_s/P_n = (\sum^n E_i/\sum^s E_i)^\beta$.[11] Setting $P = P_s$ in (5) yields $C_i[P_s]$ for high-income country i; summing over subset s yields
(10) $\sum^s C_i[P_s] = \sum^s P_s R_i/(\beta + 1) = [P_s/(\beta + 1)] \sum^s R_i$.[12] Setting $P = P_n$ in (5) yields $C_i[P_n]$ for any country i; summing over all n countries yields
(11) $\sum^n C_i[P_n] = \sum^n P_n R_i/(\beta + 1) = [P_n/(\beta + 1)] \sum^n R_i$.[13] Because P_s is set so that $\sum^s R_i = \sum^n R_i$, from (10) and (11), and using (9),
(12) $\sum^s C_i[P_s]/\sum^n C_i[P_n] = P_s/P_n = (\sum^n E_i/\sum^s E_i)^\beta > 1$. Thus, the total cost for the subset of s countries is greater than the total cost for the full set of n countries.[14]

For each country i in subset s (the high-income countries with $y > y^*$), if there are only s participants facing price P_s the cost is greater than if there had been n participants facing price P_n. That is, $C_i[P_s] > C_i[P_n]$. From (6) the *cost saving* for i in s is

(13) $C_i[P_s] - C_i[P_n] = E_i[(1/\alpha)^{1/\beta}/(\beta + 1)][P_s^{(\beta+1)/\beta} - P_n^{(\beta+1)/\beta}]$. Dividing (13) by N_i yields the *per capita cost-saving formula* for a high-income country:
(14) $\Delta c_i \equiv c_i[P_s] - c_i[P_n] = (E_i/N_i)[(1/\alpha)^{1/\beta}/(\beta + 1)][P_s^{(\beta+1)/\beta} - P_n^{(\beta+1)/\beta}]$. Summing (13) over all countries in subset s yields the total cost saving that the s countries would experience if the other countries participate,
(15) $\sum^s \{C_i[P_s] - C_i[P_n]\} = [(1/\alpha)^{1/\beta}/(\beta + 1)][P_s^{(\beta+1)/\beta} - P_n^{(\beta+1)/\beta}] \sum^s E_i$.[15]

Compensation for each low-income country depends on its cost C given by (6); compensation is 100% of C if $y < \underline{y}$ and phases down linearly to 0% as y increases from $\underline{y}$ to y^*; summing over all low-income countries yields total compensation M. Each high-income country's per capita contribution $x_i = h(\Delta y_i)^v(\Delta c_i)^w$, so its contribution is

$$N_i x_i = N_i h(\Delta y_i)^v(\Delta c_i)^w$$

[11] With $\sum^s E_i = 3.689$ billion and $\sum^n E_i = 7.302$ billion, the high-income countries have 50.52% of total emissions. With $\beta = 1$, $(P_s/P_n) = 1/.5052 = 1.98$, so if $P_n = \$100$, then $P_s = \$198$. Note that without help from low-income countries, with 50.52% of total emissions the high-income countries must cutback 29.7% to cutback 1.095 billion and P_s would be \$198.

[12] $\sum^s R_i = 1.095$ billion. With $\beta = 1$, $P_s = \$198$ and $\sum^s C_i[P_s] = \$108.382$ billion.

[13] With $\sum^n R_i = 1.095$ billion and $P_n = \$100$, for $\beta = 1$, $\sum^n C_i[P_n] = \$54.763$ billion.

[14] In this example, $\sum^s C_i[P_s]/\sum^n C_i[P_n] = 1.98$ for $\beta = 1$.

[15] With $\sum^s E_i = 3.689$ billion, $\beta = 1$, $\alpha = 666.667$, $P_s = \$198$, and $P_n = \$100$, $\sum^s C_i[P_s] - \sum^s C_i[P_n] = \$108.382$ billion − \$27.670 billion = \$80.712 billion. These three numbers appear in the first column of Table 1.

where N_i is its population; h must be set so $\sum^s N_i h(\Delta c_i)^w(\Delta y_i)^v = M$; hence h must be set equal to $M/\sum^s N_i(\Delta c_i)^w(\Delta y_i)^v$.[16]

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[16] In the simulation, when $w = 1$ we add the constraint that $x_i \leq \Delta c_i$ for all i, it is necessary to solve for h iteratively. There is one country for which x_i generated by this contribution formula exceeds Δc_i for $v = 2$; in this case we set $x_i = \Delta c_i$.