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From Nash to Lindahl in Climate Change Policy

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Abstract

To reach an international agreement on the cost of abatement of climate change, one needs to specify a fair burden sharing rule. This paper evaluates different burden sharing rules in terms of their redistributive impact and by the extent to which they realize the aim of optimal abatement. It is shown that for all regions and almost all countries, the Lindahl solution, where the burden sharing rule of carbon abatement is determined by each country's willingness to pay, is to be preferred above the noncooperative Nash outcome. Poor countries and regions however would prefer the social planner outcome with a global permit market, because then the burden sharing rule is given a secondary role of income redistribution from rich to poor, on top of its primary role of assigning abatement burdens.

Keywords: Nash; Lindahl; tradable permits; equity; efficiency; burden sharing rule

JEL classification: D610 ; D63 ; H410 ; Q01 ; Q5

1. Introduction

We live in one greenhouse and all of us are global players. Every country, even every citizen, in the world, no matter how rich or poor, contributes to the process of global warming and climate change.[1] Of course, there are large differences within and between countries today – the average American citizen produces about twenty times as much greenhouse gas (GHG) emissions than the average citizen of India – , and also historically – the Annex I countries in the Kyoto protocol are accountable for more than three quarters of all GHG emissions since 1850, while harbouring only one quarter of the world population. Following the reports of the IPCC and the 2006 Stern Review, there has been a flourishing debate among scientists about fair burden sharing and the time path to contain global warming. The timing issue is largely concerned with the choice of appropriate discount rates (Weitzman 2001; Nordhaus 2007) and how to assess the risk of unlikely but potentially disastrous outcomes, e.g. reversal of the 'thermohaline circulation', also known as the 'Great Ocean Conveyor Belt' of the Gulf Stream and the exacerbated release of methane due to global warming from the Arctic permafrost. Here we abstract from the time path and concentrate on how the abatement burdens should be allocated across countries and regions in the world at a given point in time.

Since combatting climate change is a global public good, it requires a global burden sharing rule. The main purpose of this paper is to argue for a burden sharing rule with respect to abatement costs of carbon emissions inspired by the Lindahl equilibrium (hereafter LE). In the burden sharing debate of climate change, surprisingly little attention is paid to the LE.[2] In the LE, each country is assigned an abatement share in such a way that given their assigned share, they all want the same level of the global public good, in this case global carbon emission abatement (for the derivation of Lindahl equilibria in public goods models, see Shitovits and Spiegel 1998, 2003; Mas-Colell 1989; Sandler and Murdoch 1990). In such a LE, each country contributes to the global provision level according to its willingness to pay (WTP). Any International Environmental Agreement (IEA) in which some countries have to contribute less than their WTP is a pity, because they are prepared to abate more, although preferring to abate less and easy ride. At the same time, a country will be reluctant to contribute in excess of its WTP, for instance if it is prescribed to do so

[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 52 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. Burning just one litre gasoline therefore produces $314.7 * 10^{23}$ molecules CO_2, which is, assuming a world population of 6.4 billion, almost 5 million billion (4,916,903 billion) molecules CO_2 per world citizen.

[2] Giersch (2007: 1), comparing Lindahl with the Nash outcome, also mentions that although the Lindahl equilibrium is considered as one of the cornerstones of public finance, it is also “dismissed as unconvincing”.

by invoking the polluter pays principle or ability to pay principle. Therefore, any deviation from the LE would mean that either some countries contribute less than their actual WTP, which is undesirable if we are to realize the aim of mitigating GHG emissions, or that some countries are supposed to contribute more than they are willing to, making an IEA unstable. Therefore, it is important to assess the burden sharing rule according to the LE and to check how it fares compared to other burden sharing rules.

Buchholz and Peters (2007, 2008) have identified the main fairness properties of the LE. They show that the LE is not only efficient (i.e. satisfying the Samuelson condition for the optimal supply of the public good), but also that the benefit principle (described as ‘everyone pays what he gets’), the axiom of proportional contributions (meaning that cost shares are proportional to marginal willingness to pay) and equality of sacrifice (‘everyone bears the same burden’) are satisfied. Despite all these nice properties, the neglect of the LE should not come as a surprise, since in the economic literature on burden sharing to provide a public good, the LE is said to be mainly of theoretical interest, mainly due to the difficulty to assess objectively for each country its WTP and because of the incentives to strategically misrepresent preferences. The best illustration of the practical insignificance of the LE in the debate on climate change is that as far as we know there is no study with an empirical simulation of the abatement burdens across countries or regions in a LE, a lacuna we hope to fill in this paper.

To illustrate the LE by means of a simple example, suppose two persons share a household in which the cleanliness of the house is considered a public good. The problem of burden sharing is how many hours every member of the household has to spend on cleaning. A simple 50-50 split will not do, because one person may prefer to have the kitchen or closet much cleaner than the other, so even an at first glance fair 50-50 split will not solve the question how many hours in total will have to be spent on cleaning, that is, the provision level of the public good. The LE will identify a unique level of the public good with cost shares assigned to each household member in such a way that given the assigned cost share, each member will choose the same (Lindahl) level of public good provision while at the same time the cost shares sum up to unity. However, since cost shares are proportional to marginal WTP, household members have an incentive not to reveal their true preferences in order to easy- or free-ride on the efforts of the other.

Although one may question how plausible it is that people durably living in a household are able and willing to hide true preferences to get an advantage in burden sharing at the expense of the other member, with many agents sharing a public good strategic misrepresentation of preferences can indeed be a serious problem. With respect to an IEA with many states involved, the identified LE from the scientist’ drawing table is therefore only useful as long as the analysis is based on easily observable variables such as GDP, population size, GDP per capita, energy consumption, GHG emissions and to be expected damages from climate changes that are not easy to manipulate. To the extent that some variables can strategically be manipulated, there is the possibility to use a base year for the assignment of cost shares, like the 1997 Kyoto protocol did by specifying abatement efforts to be reached in 2010-12 relative to the emission levels in 1990.

The burden sharing rule inspired by the LE is compared with the actual distribution of emissions in the post-Kyoto era and different hypothetical distributions favoured by a social planner with and without the power to install a global carbon permit market. As limiting cases, we also consider the Nash noncooperative outcome and the outcome of a social planner with the power to redistribute income directly from poor to rich countries. In the empirical section we show that the Lindahl outcomes is preferred by all countries or regions above the Nash outcomes with or with the permit market, but the poor countries prefer the outcome of a social planner, even if it is not endowed with the power to redistribute income but only to assign abatement burdens.

The structure of this paper is as follows. Section 2 briefly presents the suboptimal noncooperating Nash model, without and with cap-and-trade. The problem when countries do not cooperate is easy- or free-riding and consequently climate change is not or insufficiently contained. Section 3 presents the model with a social planner without the instrument of redistribution, which, together with the Nash models are used as benchmarks for the LE. The problem with the optimal outcome chosen by the social planner without a global permit market is that marginal costs of abatement will vary between countries, which is inefficient (as shown earlier by Chichilnisky and Heal 1994; Sandmo 2003; 2007; Eyckmans et al. 1993; Sheeran 2006). A social planner without redistributive powers maximizing world welfare will assign low (high) abatement burdens to poor (rich) countries simply because the welfare cost per dollar of abatement is higher (lower) in poor (rich) countries. Assuming increasing marginal cost of abatement, this translates into low (high) marginal cost of abatement and low (high) abatement efforts for poor (rich) countries, so there is a tradeoff between equity and efficiency (see also Sturm 1995 and Manne and Stephan 2005 for a critical discussion of this so called equity-efficiency puzzle). Section 3 further shows that production efficiency in abatement characterized by uniform marginal costs of abatement can be achieved by a global permit market, which can be advantageous to both rich and poor countries. Section 4 identifies the LE, again with and without cap-and-trade, in the global burden sharing of abatement. The empirical part is presented in section 5. In the first simulation the world is divided into Annex I and Annex II countries, in the second five regions are distinguished. The final section summaries and concludes.

2. Benchmark 1: Noncooperating Nash with and without permit markets

In modeling climate change and abatement, many choices have to be made. Does one take a static or a dynamic perspective, is the externality arising in consumption or production or both, is the approach rooted in welfare economics or game theory, and so on. In general, many of the choices made here are motivated by keeping the model as simply as possible in order to derive burden sharing rules of abatement under different regimes. In the first regime, serving as a benchmark for the models presented in subsequent sections, countries are assumed to follow their self-interest in a noncooperative way. Absent an ambitious climate agreement to which countries have committed themselves, it is not exaggerated to claim that the Nash-Cournot model is an appropriate workhorse and carries a sense of realism. Cramton and Stoft (2010) even go so far to say that “In fact there is no clear evidence that we have done even as well as the public-goods Nash equilibrium”. First we model noncooperative behavior without a permit market.

Noncooperative without a permit market

In the model, utility is a function of per capita income available for consumption (y_i^c) and the level of worldwide abatement (A), the former being a private good and the latter a global public good. The chosen abatement level in some country *i* under Nash behaviour (A_i), taking the abatement effort of others as given ($A_{\_i}$), is simply defined as its emission under a business-as-usual (BAU) scenario minus its actual emission. Country *i* has population size P_i and is endowed with resources R_i, which can be devoted to either consumption ($P_i y_i^c$) or to finance abatement costs ($C_i(A_i)$). The endowment resources R_i can be interpreted as GDP without any cost of abatement, in which case per capita income for consumption equals resources per capita. The Lagrange function for country *i* can be stated as:

$$(1)\ L(y_i^c, A_i) = P_i u_i(y_i^c, A_i + A_{\_i}) - \mu_i [P_i y_i^c + C_i(A_i) - R_i]$$

The first term in the RHS of Eq. 1 is the maximand, the second term is the resource constraint. Differentiating with respect to per capita income and abatement, where variables in subscripts denote derivatives, gives as first order conditions:

(2a) $P_i u_{y_i^c} = \mu_i P_i \Rightarrow u_{y_i^c} = \mu_i$

(2b) $P_i u_A = \mu_i C_{A_i}$

These two optimum conditions can be summarized as:

(2c) $P_i \dfrac{u_{i,A}}{u_{y_i^c}} = C_{A_i}^N \qquad MSB_{i,A} = MC_{A_i}^N MU_{y_i^c}$

Eq. 2c states that the Samuelson rule for the optimal provision of the public good - the sum (P_i) of the marginal rate of substitution ($u_{i,A} / u_{y_i^c}$) between abatement and per capita income must be equal to the marginal cost of abatement ($C_{A_i}^N$) - is only applied at the national level. Expressed differently, each country only abates up to the point at which their marginal social benefits (MSB) are equal to the marginal cost (MC) of abatement times the marginal utility of per capita income (MU). The suboptimality arising under Nash is twofold. First, the positive externalities of abatement in one country imposed on the rest of the world are not taken into account. Second, marginal abatement costs differ between countries, so total abatement is not produced against minimum cost. Overall, abatement levels will be too low and the marginal cost of abatement (hence the abatement level) in a country will be higher the larger its population size and the lower its marginal utility of per capita income.

Nonooperative with a permit market

The second suboptimality can be removed by adopting a worldwide cap-and-trade system - so for each country the optimal actual abatement (A_i) will be determined by where their marginal cost of abatement equals the global permit price (*q*) - while at the same time allowing countries to choose their own target abatement levels (T_i). To see how this works out, the resource constraint changes into:

(3) $R_i = P_i y_i^c + C_i(A_i) + q(T_i - A_i)$

According to Eq. 3, if the actual abatement in a country is lower than its chosen target level of abatement, then it has to buy additional emission permits against a uniform permit price of *q*. Substituting the world abatement constraint $A = T_i + T_{\_i}$ in the utility function and including the new resource constraint of Eq. 3 in the Lagrange function gives:

$$(4)\ L(y_i^c, A_i, T_i) = P_i u_i(y_i^c, T_i + T_{-i}) - \mu_i [P_i y_i^c + C_i(A_i) + q(T_i - A_i) - R_i]$$

Differentiation with respect to per capita income and abatement gives:

$$(5a)\ u_{y_i^c} = \mu_i$$
$$(5b)\ -\mu_i [C_{A_i} - q] = 0 \Rightarrow C_{A_i} = q$$

The optimal abatement level for a country is always where its marginal cost equals the global permit price. For total abatement, which will equal the global sum of the national target abatement levels, the chosen target levels are crucial. Each country will choose its target level according to:

$$(5c)\ \frac{\partial L(y_i^c, A_i, T_i)}{\partial T_i} = P_i u_A \frac{\partial A}{\partial T_i} - \mu_i \left[\frac{\partial C_i}{\partial A_i}\frac{\partial A_i}{\partial T_i} + \frac{\partial q}{\partial T_i}(T_i - A_i) + q(1 - \frac{\partial A_i}{\partial T_i}) \right] = 0$$

Using the optimum condition of Eq. 5a, dividing by $u_{y_i^c}$ and since $\partial A / \partial T_i = 1$,[3] the optimum condition 5c can be rewritten as:

$$(6)\ P_i \frac{u_A}{u_{y_i^c}} = \frac{\partial A_i}{\partial T_i}\left(C_{A_i} - q\right) + q + \frac{\partial q}{\partial T_i}(T_i - A_i)$$

Because of the global permit market, marginal cost will everywhere be equalized to the permit price q (see Eq. 5b), so the first term in brackets will be zero and Eq. 6 reduces to:

$$(7)\ P_i \frac{u_A}{u_{y_i^c}} = q + q_{T_i}(T_i - A_i)$$

Eq. 7 expresses that in choosing the optimal target level each country equates its marginal social benefit (LHS) to the permit price plus the effect of a higher chosen target level on the permit price (q_{T_i}) times the volume of permits bought or sold by

[3] Under the zero Nash conjecture, each country takes the chosen target levels by others as given, so a change in its own target level will lead to an equal change in total abatement.

country *i*. In a global permit market $\partial q/\partial T_i = \partial q/\partial T_j = \partial q/\partial T = q_T$ and summing both sides of Eq. 7 over all countries results in:

(8) $\sum_{i=1}^{n} P_i \frac{u_A}{u_{y_i^c}} = nq + q_T \sum_{i=1}^{n} (T_i - A_i)$

By definition, the last term is zero when the permit market clears, so Eq. 8 boils down to that the global sum of marginal benefits of abatement (the LHS) is equal to the permit price times the number of countries (the RHS). Although the second suboptimality of the noncooperating Nash solution without a global permit market is removed now that the same good abatement is produced at uniform instead of differentiated marginal costs, the first suboptimality is still there: the price of abatement is, from a world point of view, much too low[4] because the LHS of Eq. 7 contains not the global but only the national marginal benefits of abatement.

At first glance, it may seem puzzling that the permit price declines in case a country is artificially split up into two, but this is indeed what would happen according to Eq. 8. The separate governments of the split-up country will both have a lower appetite to abate (because population is halved) and to maintain the optimum condition stated in Eq. 7, the sum of the chosen target levels of abatement of the two countries that have split up will be lower than the chosen target level before separation. Hence, a lower global abatement level results.[5] Put differently, governments acting on behalf of their citizens ensure that at least the interests of their own population are taken into account. Seen from this perspective, absent an IEA the more populous and rich countries bear a higher responsibility since they are able to internalize externalities to a greater extent and their welfare cost of abatement is lower. If governments would not be in charge to (negotiate and) impose domestic abatement levels, then we would have an atomistic world and under Nash everyone would only mitigate its contribution to global warming up to the point where the private marginal benefit equals private marginal costs.[6]

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[4] The social optimum would be that the price of the permit equals the LHS of Eq. 8.

[5] Instead of $MSB_w = nq$, after splitting-up we get $MSB_w^{'} = (n+1)q'$. With *n*+1 countries, there is less internalization of externalities of abatement, so a lower global abatement level, hence the global marginal benefit of abatement is higher. Also under a permit market, the lower the global abatement level, the lower the permit price. Combining both gives $nq/(n+1) < q' < q$.

[6] This can be can be modeled as $L = u_j(y_j, A_{-j} + a_j) - \mu(y_j + c_j(a_j) - r_j)$ where subscript *j* refers to individuals. The optimum condition is $u_{j,A}/u_{y_j} = c_{a_j}^N$ with a_j abatement by *j*. In that case, the private marginal rate of substitution between abatement and consumption is equated against private marginal cost of abatement. Compared with the outcome of Eq. 2 even the positive externalities within one's own country are ignored.

3. Benchmark 2: A social planner without and with a permit market

Now suppose countries agree to install a social planner (labeled S) to redress the suboptimalities of the Nash outcome. If S is given not only the power to set the burden sharing rule for abatement but also the power to redistribute income, the global welfare maximizing outcome will be equality of marginal utilities of income across countries and a single global marginal cost of abatement to ensure production efficiency (see the Appendix). Although equity and efficiency are achieved simultaneously, it is not realistic to assume that to solve the global warming problem, however serious it may be, sovereign rich countries are prepared to equalize their per capita incomes to that of the rest of the world. Therefore, the attention is focused on S without the instrument of income redistribution but acting on behalf of cooperating countries to devise an optimal burden sharing abatement rule. We distinguish between S without and with the power to install a global permit market.

A social planner without a permit market

A distinction can be made whether or not S has to operate under an external global abatement constraint, say that all countries agree that a required level of global abatement (A°), e.g. stipulated by the IPCC relative to BAU-emissions, has to be met. This will add a pollution constraint to the exercise and the only decision by S is to assign the abatement burdens A_i such that their sum equal A°. S maximizes welfare over all countries subject to the global abatement constraint and all national resource constraints:

$$(9)\; L(y_i^c, A_i, A^{\circ}) = \sum_{i=1}^{N} P_i u_i(y_i^c, A^{\circ}) - \lambda[A^{\circ} - \Sigma_i A_i] - \Sigma_i \mu_i [P_i y_i^c + C_i(A_i) - R_i]$$

Note that the only difference of this Lagrange function with the one of S with the power to make cross country lump sum income transfers is that for the former there is a resource constraint for each country *i* (see the last term in Eq. 9), instead of just one world resource constraint ($\mu \Sigma_i [P_i y_i^c + C_i(A_i) - R_i]$) under a social planner with income redistributive powers (see Eq. A1 in the Appendix). Differentiating Eq. 9 with respect to y_i^c, A_i and A° gives:

$(10a)\; u_{y_i^c} = \mu_i$

$(10b)\; \lambda = \mu_i C_{A_i}$

$(10c) \sum_i P_i u_A = \lambda$

According to Eq. 10a, marginal utility of per capita income is country specific. Because there is no income redistribution, marginal utility of per capita income in poor countries will be higher than in rich countries[7] and therefore marginal cost of abatement will be set lower in poor countries (see Eq. 10b). Note that if no external global abatement restraint is imposed, S will maximize Eq. 9 also with respect to global abatement, ensuring the optimal level of total abatement specified by Eq. 10c. The external global abatement level A° may have been set too high, too low or just right and only in the latter case the shadow cost of global abatement (λ) is equal to the global sum of marginal abatement benefits ($\sum_i P_i u_A$), as specified by Eq. 10c. Thus, only if the global abatement level is set at the right level, the optimum conditions of Eqs. 10a-c can be summarized as the following Samuelson rule:

$$(11)\quad \frac{\sum_{j=1}^{N} P_j u_A^j}{u_{y_i^c}} = C_A^{i,S} \qquad MSB_w = MC_A^{i,S} MU_y^i .$$

The numerator in the LHS of Eq. 11, the global sum of marginal benefits of abatement, is a world total and so not country specific. The denominator, marginal utility of per capita income, is country specific. As a consequence, marginal cost of abatement (the RHS) is also country specific. As the alternative expression of Eq. 11 shows, S distributes the burden of abatement in such a way that for each country its marginal cost of abatement times the marginal utility per unit of income - this product can be interpreted as the marginal welfare cost of abatement - is equalized to the global marginal benefits of abatement. All other things equal, poor countries, having a high marginal utility of per capita income, will be assigned a low abatement level so that their (marginal) cost of abatement will be low. Summarizing, compared to the noncooperative case, S is guided by two rules in the maximization of world welfare. First, in allocating abatement burdens to individual countries the global, not the national, abatement benefits are relevant. Second, not national marginal abatement cost are equated to (marginal) benefits of abatement but the marginal welfare cost per unit of abatement is equalized across countries.

Comparing Eqs. 11 and 2c shows that the first Nash suboptimality of not taking positive externalities of abatement in one country to the rest of the world into account is now removed, but the second suboptimality of differentiated, country-

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[7] With lump sum redistribution, $u_{y_i^c} = \mu$, so marginal utility of income per capita is uniform across countries (see the Appendix).

specific, marginal cost of abatement due to the absence of a global permit market is still present. This suboptimality can be removed by empowering S to install a global permit market.

A social planner with a global permit market

To remove the second suboptimality of nonuniform marginal cost of abatement, assume countries allow the social planner to implement a global permit market (labeled as SP)[8] to remove the production inefficiency of abatement produced in different countries against different marginal costs. As before, actual abatement levels will be uniquely determined by the exogenously given abatement cost functions at the national level ($C_i(A_i)$) and the global permit price (*q*), irrespective of the particular choice by SP of the burden sharing rule T_i. The global permit price will be determined by the abatement cost functions at the national level and the chosen level of global abatement by the IPCC or the planner's optimal choice of the global abatement level, again irrespective of the sharing rule T_i. Hence, if the SP can operate without any constraint in setting T_i, to maximize global welfare the planner will choose T_i in such a way that given the optimal domestic abatement levels determined by where marginal abatement costs equals the global permit price, the resulting transfer payments $q(T_i - A_i)$ will equalize marginal utility of per capita incomes, implying uniform per capita income as under the lump sum social planner with unconstrained power to redistribute.[9] Instead of lump sum redistribution, the same redistribution is established by transfer payments following the chosen target abatement levels.[10]

Therefore, a more constrained mandate for SP has to be adopted. For instance, SP can be instructed that the production efficiency gains of adopting the permit market device must be distributed according to some *pro rata* formula, e.g. to target levels of abatement. Since overall abatement becomes cheaper if it is produced against uniform marginal cost compared to differentiated marginal cost, the optimal global abatement level with a permit market can be set higher than without the permit market. Another scheme is one in which the planner deliberately chooses an even higher than optimal global abatement level in such a way that the burden sharing rule

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[8] Alternatively, SP may impose a uniform global carbon tax, with the tax equal to the equilibrium permit price.

[9] SP will assign target abatement levels such that $y_i^c = [R_i - C_i(A_i) - q(T_i - A_i)] / P_i = y_w^c$, while at the same time the global sum of abatement equals the exogenously given or optimal global abatement target, with large negative target levels for poor and large positive target levels for rich countries.

[10] On the same footing, Shiell (2003: 44) notes that "If negative allocations were permitted for some countries, then the system would be equivalent to unrestricted lump sum transfers".

allows a cost break-even for all countries compared to the situation of S without the permit market, or to impose non-negativity of target levels of abatement. For practical reasons (see also the empirical section), we chose to constrain SP in such a way that for each country or region the target abatement level is set equal to the actual abatement level under S. As a consequence, under SP the same global abatement level as under planner S without permit market results. The advantage for the rich countries is that their cost will decline, since the global permit price is below their marginal cost of abatement without emission trading. Poor countries will benefit because their target levels are pitched at the low abatement levels stipulated by Eq. 11 and they become net sellers of permits on the permit market. Switching to a permit market requires that at the country level the consumption constraint is adjusted to include its dealings on the permit market, so each country now faces the Lagrangian:

(12) $L(y_i^c, A_i) = P_i u_i(y_i^c, A) - \mu_i [P_i y_i^c + C_i(A_i) + q(T_i - A_i) - R_i]$

Since the SP is given the authority to set the burden sharing rule T_i, each country takes its assigned burden T_i as given, which gives first order conditions:

(13a) $u_{y_i^c} = \mu_i$

(13b) $C_{A_i} = q$

Thus the SP, although constrained in setting the target level abatements at the actual abatement levels if there would be no permit market, so $T_i^{SP} = A_i^S$, by installing a global permit market 'forces' individual countries to abate up to the point where their marginal cost are equal to the permit price. Both inefficiencies of the noncooperative Nash outcome are then removed. Because of the permit market, the production inefficiency is removed and the IPCC or planner S can choose the optimal global abatement level A°.

4 The Lindahl solution

Given the urgency to reduce GHG emissions worldwide, the most difficult issue is how the burdens 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 vein, the Stern Review (2007, 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". Apparently, both Gardiner and Stern favour a burden sharing rule in which the rich countries bear the lion share of the costs due to their higher ability to pay and to the polluter pays principle. However, combatting climate change is not a morality play. Countries are sovereign and a burden sharing rule based on moral principles such as the polluter pays principle or the ability to pay principle is as strong as the commitment of countries to these same principles.[11] The ability to pay or paying as polluter may not be in line with a countries' willingness to pay.[12] Our preferred burden sharing rule is based on countries' willingness to contribute to combat climate change, which naturally leads to the Lindahl solution to the optimal public good provision level. Admittedly, contributions according to willingness to pay may be squarely at odds with contributions based either on the ability to pay and the polluter pays principle. Suppose that the USA is protected from any consequences of climate change and that only the rest of the world would suffer damages. According to ability to pay and the polluter pays principle, the USA would have to contribute heavily, but its willingness to pay might be low. Analogous, the burden assigned to a poor country at sea level according to ability to pay and polluter pays will be low, but relatively high according to willingness to pay. In theory, countries that would benefit from global warming (e.g. Russia, Canada and Greenland) could have a negative willingness to pay, which implies that they have to be compensated for their participation in an international agreement to abate greenhouse gases.

In the literature, the Lindahl equilibrium is mostly interpreted in terms of cost shares, but here instead each country's share is defined relative to the total abatement level,[13] so willingness to pay has to be interpreted as willingness to contribute.

Lindahl solution without permit market

[11] E.g.., Elzen and Lucas (2003, Chapter 5) provides an overview of ten different burden rules based on four equity principles, namely Egalitarian (equal caps), Sovereignty (grandfathering), Polluter pays and Capability (ability to pay).

[12] In terms of the two person household and the cleanliness as the public good, it might be that one member has a higher ability to clean and is more polluting than the other, but having a much lower preference for a clean house.

[13] Also Giersch (2007: 18) considers this approach, focusing on abatement rather than cost shares, more realistic.

As before, we make a distinction between the Lindahl solution without (labeled L) and with a permit market (LP). Under the former, countries are assigned abatement burdens a_i^L such that these shares sum up to unity:

$$(17)\ a_i^L = \frac{A_i^L}{A^L} \Rightarrow A_i^L = a_i^L A^L \qquad \sum_i a_i^L = 1$$

Given a country's assigned abatement share, to arrive at the Lindahl equilibrium each country chooses the same global abatement level A^L. Each country maximizes:

$$(18)\ L(y_i^c, A^L) = P_i u_i(y_i^c, A^L) - \mu_i [P_i y_i^c + C_i(a_i^L A^L) - R_i]$$

with respect to per capita income and total abatement, giving:

$$(19a)\ u_{y_i^c} = \mu_i$$

$$(19b)\ P_i u_A = \mu_i C_{A_i} a_i^L$$

Combining both gives:

$$(19c)\ P_i u_A = u_{y_i^c} C_{A_i} a_i^L \Rightarrow P_i \frac{u_A}{u_{y_i^c}} = a_i^L C_{A_i}$$

Taking summations on both sides of Eq. 19c results in the global sum of marginal benefits to be equal to the weighted sum of marginal cost of abatement:

$$(19d)\ \sum_{i=1}^{N} P_i \frac{u_A}{u_{y_i^c}} = \sum_i a_i^L C_{A_i}$$

which is akin to the Samuelson condition. Note that without a permit market, marginal cost of abatement may differ between countries.

The Lindahl planner will assign abatement burdens to countries, taking into account that each one maximizes Eq. (18) and that given their assigned abatement shares, they must choose the same global abatement level. In the empirical section, it will be shown that there is a global abatement level compatible with the constraint that the sum of the abatement shares is unity and that given these shares, each country will choose that level of global abatement as being optimal. However, there is a production inefficiency due to the differentiated, country specific, marginal cost of abatement, which can be solved by implementing a global permit market.

Lindahl solution with permit market

A planner that wants to impose a burden rule inspired by Lindahl will simply demand that for each country the willingness to pay equals the marginal burden of abatement. A Lindahl planner also equipped with the power to install a global permit market (LP) will assign target abatement shares t_i^L and given these target shares countries choose the same global abatement level A^L. Given a country's assigned target abatement $t_i A^L = T_i$, each country maximizes:

(20) $L(y_i^c, A_i, A^L) = P_i u_i (y_i^c, A^L) - \mu_i [P_i y_i^c + C_i(A_i) + q(t_i A^L - A_i) - R_i]$

with respect to consumption, domestic abatement and global abatement, giving:

(21a) $u_{y_i^c} = \mu_i$

(21b) $\dfrac{\partial L(y_i^c, A_i, A^L)}{\partial A_i} = -\mu_i [C_{A_i} - q] = 0$

(21c) $\dfrac{\partial L(y_i^c, A_i, A^L)}{\partial A^L} = P_i u_A - \mu_i \left[C_{A_i} \dfrac{\partial A_i}{\partial A^L} + \dfrac{\partial q}{\partial A^L}(t_i A^L - A_i) + q(t_i - \dfrac{\partial A_i}{\partial A^L}) \right] = 0$

Substitution of the first and second into the third first order condition and rearranging gives:

(22) $P_i \dfrac{u_A}{u_{y_i^c}} = \dfrac{\partial A_i}{\partial A^L}(C_{A_i} - q) + q t_i + \dfrac{\partial q}{\partial A^L}(t_i A^L - A_i)$

which is similar to Eq. 7 above. Due to the permit market, the marginal cost of abatement will never be higher than the permit price, so the first term is zero. Therefore, for each country the marginal rate of substitution between consumption and abatement (the LHS of Eq. 22) is proportional to its target 'cost' share (qt_i) plus the price effect of a change in the global abatement level. Taking sums on both sides gives:

(23) $\sum_{i=1}^{n} P_i \dfrac{u_A}{u_{y_i^c}} = q \sum_{i=1}^{n} t_i + \dfrac{\partial q}{\partial A^L} \sum_{i=1}^{n} (t_i A^L - A_i)$

The last summation is zero if the permit market clears, so the Lindahl solution is efficient if the sum of the target shares sum to unity, in which case the population-weighted sum of the marginal rates of substitution between abatement and consumption is equal to the permit price.

Summarizing, the Lindahl solution combines each country's willingness to pay with optimal global abatement, but the price to be paid is that it disregards any reference to polluter pays or ability to pay considerations. To address the question of fairness in terms of contributions of rich and poor, we need to look at the optimum condition for each country, given by Eq. 22. Given that under a permit market the first term is zero and that for countries where actual abatement is close to the assigned target abatement level, the last term will be small and therefore only be of secondary importance, Eq. 22 can approximately be written as:

(22') $P_i u_A \approx t_i q u_{y_i^c} \qquad MSB_i^L \approx MC_{T_i}^L MU_{y_i^C}^L$

The lower per capita income y_i^c, the higher marginal utility of income $u_{y_i^c}$ is, so all other things equal, the lower the marginal cost share $t_i q$ and given the global permit price, the lower the assigned target abatement share $t_i = T_i^L / A^L$. Therefore, poor countries have to abate little, which can be considered fair under the ability to pay principle. Now consider a country with a high marginal social benefit of abatement (e.g. located at sea level), as given by the LHS of Eq. 22'. The higher it is, the higher the assigned target share, again given the permit price and per capita income, so countries more concerned with climate change have to abate more, all other things equal. This is reminiscent of the problem of the Lindahl equilibrium that all countries want to hide their true preferences with respect to abatement if assigned shares are proportional to marginal willingness to pay. This problem however will not arise if the marginal willingness to pay for abatement can be assessed on an objective basis.[14]

In general, with heterogeneous preferences, countries that stand to gain from global warming, so $u_A < 0$, are entitled to a compensation, e.g. arable land benefits forgone if climate change is contained (Canada, Russia). Countries which are particularly vulnerable to climate change (e.g. the Netherlands, Bangladesh and islands in the Pacific ocean all threatened by a sea level rise) and therefore have a higher positive value of u_A, will be assigned a higher target contribution. These country characteristics, which determine the country specific function u_A, should as far as possible be made objective to avoid strategic manipulation of assigned burdens.

5 Empirical specifications and simulation results

Empirical specifications

[14] For instance, Tol (2002) provide estimates of the damage of climate change for nine world regions for the period 2000-2200. Although the negative impacts dominate, for some regions at some intervals the total impact is positive. Also the Stern Review (2007: viii) states that “In higher latitude regions, such as Canada, Russia and Scandinavia, climate change may lead to net benefits for temperature increases of 2 or 3°C, through higher agricultural yields, lower winter mortality, lower heating requirements, and a possible boost to tourism. But these regions will also experience the most rapid rates of warming, damaging infrastructure, human health, local livelihoods and biodiversity.”

In this section, we will compare the outcomes of different regimes or burden sharing rules, especially with respect to global abatement levels and the amount of transfer payments relative to the total cost of abatement. For each regime, we measure the level of abatement relative to the optimal abatement level under Lump Sum (LS, see Appendix). We measure redistribution by the share of the transfer payments made by countries with a higher target abatement level than their actual abatement in total abatement costs. It is measured as:

$$\text{(24a)}\quad TP = \frac{q\sum_{i=1,T_i>A_i}^{n}(T_i - A_i)}{\sum_{i=1}^{n} C_i(A_i)}$$

TP is an indicator of the share of total abatement financed by other countries' payments on the permit market. For regime LS, in which per capita incomes across countries are equalized and where it does not matter who abates, we set TP equal to unity, to express that all costs of abatement are shared. If there is no permit market and every country has to realize its own abatement assignment, this indicator is zero by definition. We also calculate which part of the total cost of abatement is shouldered by the rich countries[15] (e.g. Annex I, or Europe, Oceania and North America in case of the five regions, see below), measured as:

$$\text{(24b)}\quad TC = \frac{\sum_{i=1,T_i>A_i}^{n}[q(T_i - A_i) + C_i(A_i)]}{\sum_{i=1}^{n} C_i(A_i)}$$

Compared to TP, the measure TC also includes actual abatement costs by countries which are buyers on the permit market and if there is no permit market, it simply measures the abatement cost share of rich countries.

Following Nordhaus (1991), Bohm and Larsen (1994), Eyckmans et al. (1993) and Okada (2007), we define the marginal cost function of abatement as:

$$\text{(25)}\quad MC_{USA} = -c\ln(1 - A_{USA}/E_{USA})$$

so marginal cost for the USA are an increasing function of its emission reduction rate A/E .[16]

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[15] Both indicators overestimate in what they purport to measure, because under the assumption of increasing marginal cost of abatement, the average cost will always be below the permit price.

[16] The cost parameter c is estimated by Nordhaus (1991) to be equal to 50.5 per tonne (1,000 kg) carbon dioxide. Without a permit market, the marginal cost for the USA to achieve the Kyoto target to reduce emissions in 2006 to 95% of that in 1990 can be calculated as follows. USA emission in 1990 was equal to 4922 Mt, so its Kyoto emission allocation (ω) for 2006 is 0.95*4922 = 4676. Its actual emission level (E) in 2006 was 5771, so the required emission reduction rate $A/E = (E-\omega)/E$ = (5771-

Other countries or parts of the world may have carbon intensities (*E*/*Y*) higher or lower than the USA. If it is higher, it is reasonable to assume that marginal cost of abatement is lower, but when it is lower, e.g. because in the past already abatement measures were adopted, it is at the margin more costly to reduce emissions further. For a country or region with a carbon intensity different from that in the USA, the marginal cost function relative to the USA is:

$$(26)\quad MC_i = -c\,\ln(1 - \frac{A_i/E_i}{1-r_i}) \qquad r_i = 1 - \frac{e_i}{e_{USA}} \quad if\ e_i < e_{USA}$$
$$r_i = \frac{e_{USA}}{e_i} - 1 \quad if\ e_i > e_{USA}$$

The carbon intensity for the USA in 2006 was 453 ton per million US$, which amounts to slightly less than half a kilo carbon dioxide per US$ production. For Annex I as a whole, it was 404 and for Annex II it was 600, resulting in $r_I = 0.11$ and $r_{II} = -0.24$ (note that r_{USA} is equal to zero).

For the simulation, we assume a quasi-linear utility function of the form

$$(27)\quad u_i(y_i^c, A) = \ln(y_i^c) + \alpha_i A$$

where the parameter α_i denotes the importance of the quality of the atmosphere, measured by global abatement, relative to per capita income for consumption. Differentiation of Eq. 27 gives that the marginal utility of income $u_{y_i^c}$ equals $1/y_i^c$ and marginal utility of abatement $u_{i,A}$ equals α_i.

In what follows, we will highlight the most important equilibrium conditions derived in the previous sections together with the constraints to solve the models.

For the model of Nash without a permit market (denoted by superscript *N*), the condition to be met is Eq. 2*c*, which in combination with Eqs. 25-27 gives:

$$(28)\quad P_i \frac{u_{i,A}}{u_{y_i^c}} = MC_{A_i}^N \Rightarrow \alpha_i Y_i = -c\ln[1 - \frac{A_i^N}{E_i(1-r_i)}] \Rightarrow A_i^N = E_i(1-r_i)(1-\exp(-\alpha_i Y_i / c))$$

using that $P_i y_i^c \equiv Y_i$. Total cost of abatement can be derived from integrating the marginal cost function of abatement (see also Okada 2007: 245 and Bohm and Larsen 1994: 229):

$$(29)\quad C_i(A_i) = \int_0^{A_i} -c\ln[1 - \frac{x}{E_i(1-r_i)}]\,dx = c\{(E_i(1-r_i) - A_i)\ln[1 - \frac{A_i}{E_i(1-r_i)}] + A_i\}$$

4676)/5771 = 0.19, which using Eq. 25 results in a marginal cost of $10.6 per tonne carbon dioxide (equivalently, (44/12)*10.6 = $39 per tonne carbon).

Substituting the abatement cost function and the abatement level derived from the equilibrium condition of Eq. 28 in the resource constraint $R_i = P_i y_i^c + C_i(A_i)$ gives an expression which can be numerically solved for the only unknown, abatement.

For the Nash outcome with a global permit market (denoted by superscript *NP*), the permit price is not dependent on the permit allocation across countries, but only on the relative importance of climate quality versus income and the number of countries, for simplicity assumed to be uniform (so $\alpha_i = \alpha$). Using Eq. 8, it follows that

(8) $$\sum_{i=1}^{n} P_i \frac{u_A}{u_{y_i^c}} = nq^{NP} \Rightarrow \alpha Y_w = nq^{NP}$$

Because of the permit market, marginal cost are uniform:

(30) $$MC_i^{NP} = q^{NP} = -c\ln[1 - \frac{A_i^{NP}}{E_i(1-r_i)}]$$

so for each country the optimal abatement level is[17]

(31) $$A_i^{NP} = E_i(1-r_i)(1-\exp(-q^{NP}/c))$$

and total abatement cost becomes

(32) $$C_i^{NP}(A_i^{NP}) = q(A_i^{NP} - E_i(1-r_i)) + c\,A_i^{NP}$$

Aggregating all country abatements stated by Eq. 31:

(33) $$A^{NP} = \sum_{i=1}^{n} A_i^{NP} = (1-\exp(-q^{NP}/c))\sum_{i=1}^{n}(1-r_i)E_i \Rightarrow q^{NP} = -c\ln[1 - A^{NP}/\sum_{i=1}^{n}(1-r_i)E_i]$$

which indeed shows that the equilibrium permit price is only dependent on the total abatement level. Taking the derivative of Eq. 33 and because a clearing permit market implies $A = T$:

(34) $$q_T^{NP} = q_A^{NP} = \frac{c}{\sum_{i=1}^{n}(1-r_i)E_i - A^{NP}}$$

Rewriting the expression for q^{NP} in Eq. 33 as $A^{NP} = [1-\exp(-q^{NP}/c)]\sum_{i=1}^{n}(1-r_i)E_i$ and substituting in Eq. 34 gives:

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[17] Alternatively, the country-specific abatement levels can be derived from

(30') $$q^{NP} = MC_i = MC_j \Rightarrow \frac{A_i^{NP}/E_i}{(1-r_i)} = \frac{A_j^{NP}/E_j}{(1-r_j)} \Rightarrow A_j^{NP} = \frac{(1-r_j)}{(1-r_i)}\frac{E_j}{E_i}A_i^{NP}$$

Taking sums on both sides and solving for country *i* gives

(31') $$A_i^{NP} = \frac{(1-r_i)E_i}{\sum_{j=1}^{n}(1-r_j)E_j}A^{NP}.$$

(34') $q_A^{NP} = \dfrac{c\exp(q^{NP}/c)}{\sum_{i=1}^{n}(1-r_i)E_i}$

Finally, using Eq. 7,

(7) $P_i \dfrac{u_A}{u_{y_i^c}} = q^{NP} + q_T(T_i^{NP} - A_i^{NP}) \Rightarrow T_i^{NP} = A_i^{NP} + \dfrac{\alpha Y_i - q^{NP}}{q_T^{NP}}$

Turning to the social planner without permit market (denoted by superscript S), the equilibrium condition Eq. 11 translates into

(35) $\dfrac{\sum_{j=1}^{N} P_j u_A^j}{u_{y_i^c}} = MC_i^S \Rightarrow \alpha P_w y_i^c = -c\ln[1-\dfrac{A_i^S}{E_i(1-r_i)}] \Rightarrow A_i^S = E_i(1-r_i)(1-\exp(-\alpha P_w y_i^c/c))$

The system of equations for the social planner with a permit market is easy to solve due to the decision to pitch the target level abatements at the actual abatement levels if there would be no permit market, so $T_i^{SP} = A_i^S$. Doing so ensures that no country will object to install the permit market, because it will never be more expensive under the permit market to meet the same commitment without a permit market. Using that marginal cost will be equal to the permit price, as stated by Eq. 13b, gives each country's abatement according to Eq. 31, except for q^{SP} instead of q^{NP}. Taking the sum on both sides and solving for q^{SP} gives the same expression as the RHS of Eq. 33 and differentiation to q^{SP} gives the same as Eq. 34.

For the Lindahl solution without a permit market, Eq. 19*b* can be expressed as

(36) $P_i u_A = \mu_i C_{A_i} a_i^L \Rightarrow \alpha P_i y_i^c = -a_i^L c\ln[1-\dfrac{a_i^L A^L}{E_i(1-r_i)}]$

The abatement costs as given by Eq. 29 becomes:

(37) $C_i(A_i) = c\{(E_i(1-r_i) - a_i^L A^L)\ln[1-\dfrac{a_i^L A^L}{E_i(1-r_i)}] + a_i^L A^L\}$

Substituting $C_i(A_i)$ into the budget constraint $y_i^c = (R_i - C_i(A_i))/P_i$ and subsequently y_i^c into Eq. (36) gives an expression that can numerically be solved for any global abatement level. The chosen Lindahl solution is that level of global abatement for which the sum of abatement shares sum to unity.

For the Lindahl solution with a permit market, $\sum_{i=1}^{n} t_i = 1$ and $\sum_{i=1}^{n} A_i^{LP} = A^{LP}$. For each country it is optimal to abate up to the point where the cost will be equal to the permit price, so

(38a) $MC_i = q^{LP} = -c\ln[1-\dfrac{A_i^{LP}}{E_i(1-r_i)}] \Rightarrow A_i^{LP} = E_i(1-r_i)(1-\exp(-q^{LP}/c))$

Also, for all countries together it must be the case that

(38b) $q^{LP} = -c\ln[1 - \frac{A^{LP}}{\sum_{i=1}^{n}(1-r_i)E_i}] \Rightarrow A^{LP} = \sum_{i=1}^{n}(1-r_i)E_i(1-\exp(-q^{LP}/c))$

Moreover, each country contributes according to marginal willingness to pay

(39) $P_i \frac{u_A}{u_{y_i^c}} = q^{LP}\, t_i + q_A^{LP}(t_i A^L - A_i)$

with q_A^{LP} similar as in Eq. 34. Finally, the budget constraints to be met are:

(40) $R_i = P_i y_i^c + C_i(A_i) + q(t_i A^{LP} - A_i)$

with cost functions similar to Eq. 32, so $C_i^{LP}(A_i^{LP}) = q^{LP}(A_i^{LP} - E_i(1-r_i)) + c\, A_i^{LP}$. In the simulation where the world is divided into Annex I and Annex II, there are eleven unknowns $\{A_I^{LP}, A_{II}^{LP}, A^{LP}, t_I, t_{II}, q^{LP}, q_A^{LP}, y_I^c, y_{II}^c, C_I, C_{II}\}$ and eleven equations.

Finally, for the lump sum social planner, equalizing per capita incomes for consumption (y_w^c),

(41) $\sum_{i=1}^{n} P_i \frac{u_A}{u_{y_i^c}} = q^{LS} \Rightarrow \alpha P_w y_w^c = q^{LS} \Rightarrow q^{LS} = \alpha Y_w$

and abatement levels can be derived from

(42) $MC_i = q^{LS} = -c\ln[1 - \frac{A_i^{LS}}{E_i(1-r_i)}] \Rightarrow A_i^{LS} = E_i(1-r_i)(1-\exp(-q^{LS}/c))$

Simulation results

We have chosen the parameter for the relative importance of abatement relative to consumption *α* and the cost parameter *c* so that the simulation results simultaneously yields plausible marginal abatement cost (in the range of \$20 to \$80 per tonne CO_2), total abatement cost as a share of GDP and total abatement efforts (e.g. the Stern Review recommends a significant reduction of 60-80% by the rich countries in 2050 relative to 1990).[18] All data are for 2006 and obtained from Climate Analysis Indicators Tool (CAIT), Version 7.0 (Washington DC: World Resources Institute 2010). Table 1 gives an overview of the scores on salient variables if the world is divided into only two blocks, Annex I and Annex II. The Annex I countries comprise

[18] The value for α is set equal to 10^{-5}. The cost parameter *c* is set equal to 0,101, double the value used by Nordhaus (1991) and Bohm and Larsen (1994). They use a value for *c* of 185.2, but since we express emissions in carbon dioxide, where 1 kg carbon corresponds to 3,67 kg CO2, we get 185.2/3.67 = 50.5. Since we measure abatement in Mt and GDP in billions, we have to divide 50.5 by 1000, and doubling (to adjust for inflation since the early nineties and increasing cost of abatement) gives our chosen value of 0,101. More specifically, given the specifications of the utility function in Eq. 27 and the marginal cost function in Eq. 26, the choice of the parameters is such that total cost of abatement will be a small share of GDP, in line with the Stern Review.

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). In Table 2, the results are presented if the world is divided into five regions.

The top panel in Table 1 contains the descriptive statistics: population (in millions), GDP (in billions USD), income per capita, emissions (in Mt), emission per capita (in tonnes), emission intensity and the marginal cost adjustment parameter r (see Eq. 26). Income per capita in Annex I countries is more than six times as high as in Annex II countries and emissions per capita is more than four times as high. In the second panel, (target) levels of abatement and reduction rates are given, where we take the actual emission levels in 2006 as the business-as-usual outcome (which implies that the Nash outcome is the one where Annex I and I operate as blocks). Firstly, total abatement within the same regime is always higher or equal (total abatement under S and SP are set equal by assumption) with a permit market than without. Secondly, in the shift from N to NP, the Annex II target abatement level under Nash with a permit market is below its actual abatement without a permit market. This result can be explained by polarization, also described by Cramton and Stoft (2010: 6), where the country with the higher level of abatement will choose an even higher target level because abatement can be bought more cheaply under a permit market, while the country with the lower abatement level will choose an even lower target level of abatement. Thirdly, total abatement under the social planner, with (SP) or without a permit market (S), is higher than under Lindahl (L or LP) or the lump sum social planner (LS). This is because assigning abatement burdens has a dual role for the social planner SP: not only to mitigate global warming but also to redistribute income. In case of S, Annex I is assigned a very high abatement burden (a reduction rate of 75%, against only 30% for Annex II), because the welfare cost of abatement for the rich countries are relatively small, while the benefits of abatement are global.

The third panel gives information about per capita incomes (y), utility (U), world welfare (W), the permit price (q), average abatement cost (AC), the share of total abatement cost paid for by transfers (TP%) and the share in total cost of buyers on the permit market (TC%). Not surprisingly, global welfare is at maximum in the lump sum case, but it would not be acceptable for Annex I. Departing from regime N, Annex I would even not be in favour to move to regime NP (due to the polarization effect), nor to S or SP. The only moves which would increase utility for Annex I are the Lindahl regimes L and LP. For Annex II, all other regimes than N are better in utility terms, where S and SP are preferred to L and LP. Taken together, departing from N, only L and LP are Pareto improvements and LP Pareto dominates L, so LP would be a viable outcome.[19] The equilibrium permit price under LP is 0.058 billion per Mt CO_2, which corresponds to \$58 per tonne, while average abatement cost per tonne is \$26 (due to increasing marginal costs of abatement, average cost is below marginal cost).

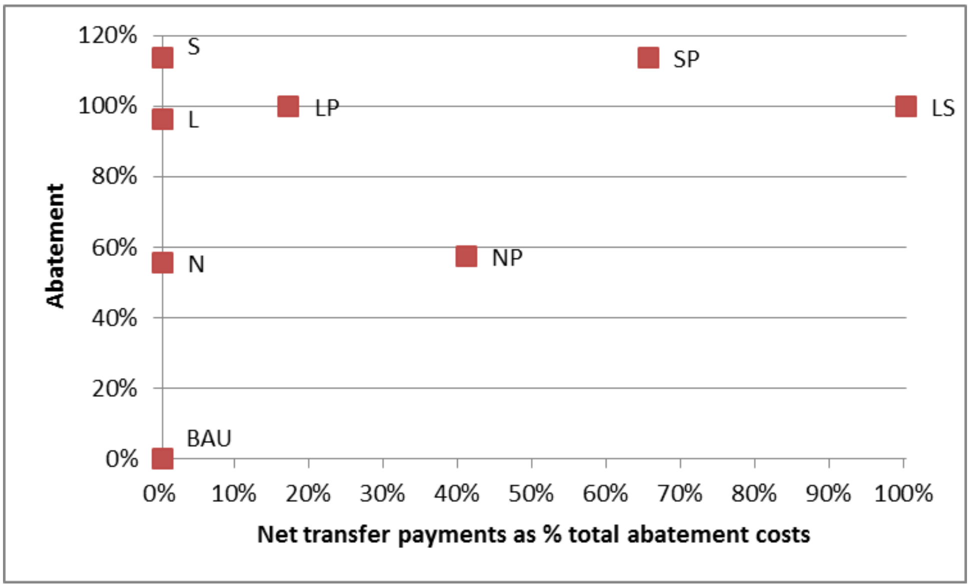
The last panel gives total abatement relative to (optimal) abatement (A%), the share of total abatement cost financed by permits (%TP) and the share of the total cost of abatement taken care of by the rich countries (%TC). The first two of these measures are also illustrated in Figure 1. Apart from LS, there are four regimes that deliver abatement equal or higher than under LS. Production efficiency requires the regimes with permit markets. Among the permit market choice set {NP, SP, LP}, LP combines that abatement is at the optimal level and transfer payments as a share of total costs are at minimum (situated at the left in Figure 1).

Table 1. Annex I and II.

Region	Pop	GDP	yc	E	ec	e	r		
Annex I	1259	35824	28,457	14484	11,505	404	0,108		
Non-Annex	5133	22598	4,403	13558	2,641	600	-0,244		
Total (Avg)	6392	58422	9,140	28042	4,387	480			
	AI	**AII**	**A**	**TI**	**TII**	**RI**	**RII**	**R**	
N	3852	3378	7230			27%	25%	26%	
NP	3240	4231	7471	4693	2777	22%	31%	27%	
S	10711	4094	14805			74%	30%	53%	
SP	6420	8385	14805	10711	4094	44%	62%	53%	
L	6419	6143	12562			44%	45%	45%	
LP	5644	7371	13016	6643	6380	39%	54%	46%	
LS	5651	7381	13032			39%	54%	46%	
	yI	**yII**	**UI**	**UII**	**W**	**q**	**AC**	**TP%**	**TC%**
N	28,405	4,395	3,35380	1,48780	1,85531		0,014	0%	64%
NP	28,387	4,399	3,35341	1,48894	1,85615	0,0292	0,014	41%	84%
S	27,910	4,392	3,34380	1,49457	1,85878		0,050	0%	93%
SP	28,063	4,410	3,34926	1,49876	1,86322	0,0694	0,031	65%	109%
L	28,300	4,377	3,35542	1,48899	1,85659		0,026	0%	60%
LP	28,293	4,376	3,35563	1,48917	1,85677	0,0580	0,026	17%	60%
LS	9,086	9,086	2,21982	2,21982	2,21982	0,0581	0,026	100%	100%
	BAU	**N**	**NP**	**S**	**SP**	**L**	**LP**	**LS**	
A%	0%	55%	57%	114%	114%	96%	100%	100%	
TP%	0%	0%	41%	0%	65%	0%	17%	100%	
TC%	0%	64%	84%	93%	109%	60%	60%	100%	

Figure 1. Abatement versus net transfer payments, Annex I and II.

[19] Buchholz et al. (2006: 33) show that a move from Nash to Lindahl does not necessarily entail a Pareto-improvement because of two countervailing effects. First, all countries will gain in terms of benefits derived from overcoming the suboptimal low Nash provision level of the public good. Second, the move from Nash to Lindahl might however entail higher costs for some (poor) countries, notably if under the Nash outcome they were free-riding on the contributions of others (often manifested in the form of exploitation of the rich by the poor). The second effect may outweigh the first effect, which is more likely the poorer the country is (the more it was easy-riding under Nash) and the higher its marginal preference for abatement (the higher its assigned burden under Lindahl), but as the number of participating countries increase it becomes more likely that the first effect will be dominant.



In Table 2, the world is divided in five blocks. CAIT standardly provides a 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). In Table 2, ME and AFR are merged into AF, CAM and SAM into SA and OC and EUR into EU. In this division, two are rich (North America, and Europe with Oceania) and two are poor (Asia and Africa), with Central and South America in between. Because there are now more players, total abatement levels under Nash are almost halved compared to when Annex I and I operate as blocks. Departing from N, again only L and LP are Pareto-improvements for all regions and LP Pareto dominates L. A striking outcome in Table 2 is that for both Africa and South America it is optimal to choose negative target abatement levels. The extreme polarisation leads here to the situation that under NP total abatement is even lower than under N. Note that under regime NP, each player is free to choose its optimal target level. Net revenues from the permit market equals $q(A_i - T_i)$, so although South America only abates 104 Mt (or 7% of its total abatement), by choosing a target level of -1705 Mt and selling permits for the equilibrium price of \$11.8 per tonne, it receives \$21.4 billion on the permit market, while Africa receives \$20.8 billion. Asia (due to its high population), North American and Europe (due to their high per capita incomes) together pay in total 42 billion (their combined target abatement levels of 6501Mt minus their combined actual abatement of 2938Mt, times \$11.8 per tonne), whereas total abatement cost is only 19.5 billion (total abatement under NP equal to 3361Mt times average cost of \$5.8 per tonne). The main cause of transfer payments under NP outweighing total cost is not so much that the average cost of abatement is below the permit price or marginal cost, but because of polarization.

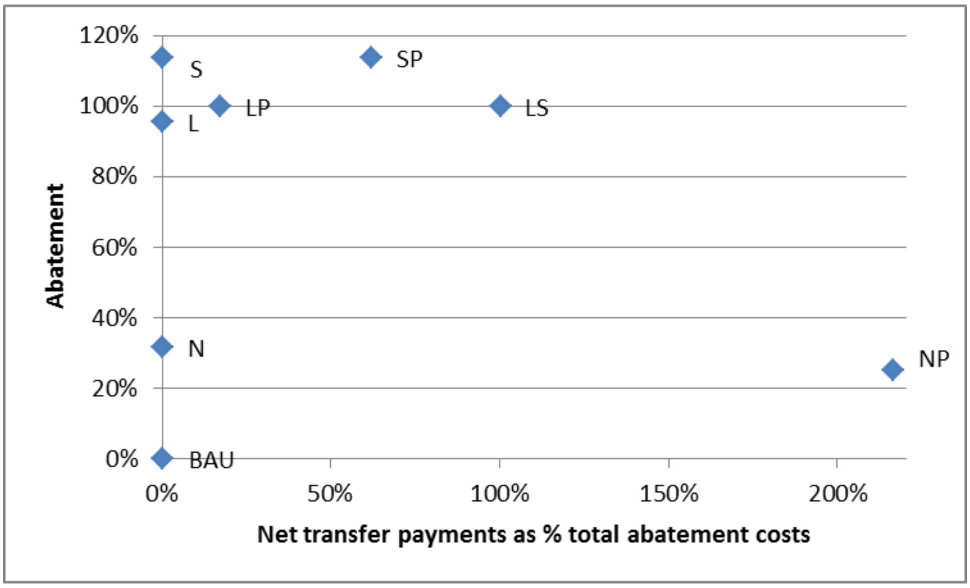
Not surprisingly, total reduction levels (*R*) for the other regimes are almost equal compared to under Annex I and II. Apart from the location of N and NP, Figure 2 therefore gives the same configuration of regimes as in Figure 1, where regime LP combines optimal abatement with modest transfer payments as a percentage of total cost.[20]

Table 2. Five regions (Asia = as; North America = na; Europe & Oceania = eu; Africa and Middle East = af; Central and South America = sa).

[20] Although it is possible to further disaggregate the simulation to the individual country level, under the assumptions made the shift from N to LP will be a Pareto-improvement because the positive effect of the higher abatement level under Lindahl compared to Nash will be even stronger than when the world is divided into two or five regions.

Region	Pop	GDP	yc	E	ec	e	r	
as	3604	17735	4,921	11247	3,1	634	-0,28	
na	329	13896	42,260	6321	19,2	455	0,00	
eu	762	17266	22,649	6755	8,9	391	0,14	
af	1195	5256	4,398	2638	2,2	502	-0,09	
sa	551	5058	9,177	1468	2,7	290	0,36	
All	6441	59210	9,192	28430	4,4	480		
	Aas	**Ana**	**Aeu**	**Aaf**	**Asa**	**A**		
N	2321	812	913	146	46	4238		
NP	1596	699	643	319	104	3361		
S	3876	5853	4412	705	414	15260		
SP	7247	3174	2918	1450	471	15260		
L	5110	2880	2998	1214	608	12810		
LP	6371	2791	2566	1275	414	13417		
LS	6371	2791	2566	1275	414	13417		
	Ras	**Rna**	**Reu**	**Raf**	**Rsa**	**R**		
N	21%	13%	14%	6%	3%	15%		
NP	14%	11%	10%	12%	7%	12%		
S	34%	93%	65%	27%	28%	54%		
SP	64%	50%	43%	55%	32%	54%		
L	45%	50%	44%	46%	41%	45%		
LP	57%	44%	38%	48%	28%	47%		
LS	57%	44%	38%	48%	28%	47%		
	yas	**yna**	**yeu**	**yaf**	**ysa**			
N	4,916	42,243	22,639	4,397	9,176			
NP	4,913	42,228	22,621	4,414	9,214			
S	4,905	40,836	22,328	4,390	9,157			
SP	4,924	41,385	22,391	4,404	9,157			
L	4,892	42,018	22,522	4,372	9,128			
LP	4,890	42,007	22,515	4,371	9,124			
LS	9,137	9,137	9,137	9,137	9,137			
	Uas	**Una**	**Ueu**	**Uaf**	**Usa**	**W**	**TP%**	**TC%**
N	1,597	3,748	3,124	1,485	2,221	1,920	0%	39%
NP	1,595	3,746	3,122	1,488	2,224	1,920	216%	161%
S	1,606	3,725	3,121	1,495	2,230	1,926	0%	90%
SP	1,609	3,738	3,124	1,498	2,230	1,930	62%	102%
L	1,600	3,751	3,127	1,488	2,224	1,923	0%	52%
LP	1,601	3,751	3,128	1,488	2,224	1,924	17%	52%
LS	2,226	2,226	2,226	2,226	2,226	2,226	100%	100%
	q	**AC**	**Tas**	**Tna**	**Teu**	**Taf**	**Tsa**	**T**
N		0,0079						
NP	0,0118	0,0058	3166	1246	2089	-1437	-1705	3358
S		0,0518						
SP	0,0705	0,0312	3876	5853	4412	705	414	15260
L		0,0264						
LP	0,0589	0,0266	5373	2943	3138	1239	725	13417
LS	0,0589	0,0266						
	BAU	**N**	**NP**	**S**	**SP**	**L**	**LP**	**LS**
A%	0%	32%	25%	114%	114%	95%	100%	100%
TP%	0%	0%	216%	0%	62%	0%	17%	100%
TC%	0%	39%	161%	90%	102%	52%	52%	100%

Figure 2. Abatement versus net transfer payments, five regions.



Summary and conclusions

There is a growing consensus that global warming and climate change can cause serious damages worldwide. In this paper the abatement burden sharing rules emerging under different regimes or burden sharing rules, with and without permit markets, were derived. Under Nash, global abatement is too low and under both regimes of the social planner it is too high. The suboptimal level under Nash without permit market is due to both production inefficiency in abatement and not taking global externalities of abatement into account. The first suboptimality can be removed by installing a permit market, but the second requires cooperation or coordination between countries. A social planner without the power to redistribute and without a permit market will impose the rule that the product of the marginal cost of abatement and the marginal utility of income be equalized across countries. This implies high abatement burdens and (marginal) costs for rich and low burdens and costs for poor countries. Also the overall abatement level is higher than optimal, which can be explained by the relatively low welfare cost of abatement in rich countries. The same social planner but equipped with a permit market can organize transfer payments from rich to poor by assigning high target levels to rich and low target levels to poor countries. The burden sharing rule then has a secondary role of redistribution and without any constraint the social planner's outcome will be the same as under an omnipotent social planner with lump sum redistribution.

In the simulations, we showed that the transition to a permit market under Nash can lead to polarization, eventually leading to lower overall abatement as shown for the world divided into five regions. Although poor countries prefer regime SP the most, only the Lindahl regimes Pareto-dominate the Nash regimes, with or without a permit market. Our preferred burden sharing rule can therefore be summarized as that every country or region shares in the burden to combat climate change in proportion to its benefits. The Lindahl solution simultaneously achieves that each country is expected to contribute according to its willingness to pay and an optimal global abatement level, but the price to be paid is to disregard competing principles such as ability to pay and the polluter has to pay. Avenues for further research are to relate the Lindahl solution and the corresponding abatement burdens to country- or region-specific damages from climate change and a more systematic comparison how the Lindahl solution fares compared to other fairness principles governing burden sharing rules for global public goods.

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Key to symbols:

y_i^c	income per capita
A_i^N	abatement in country i under Nash
A	total abatement worldwide
$A_{\_i}$	total abatement except country i
T_i	target abatement level in country i
Y_i	GDP country i
$C_i(A_i)$	Cost of abatement in country i as a function of abatement in i
P_i	population size in country i
R_i	Total resources in country i, to be spent on consumption or abatement
E_i	Greenhouse gas emission in country i
MSB_w	Marginal social benefit of abatement worldwide
MU_y^i	Marginal utility of income in country i
$MC_A^{i,S}$	Marginal cost of abatement in country i under S without permit market
$u_{y_i^c}$	Marginal utility of per capita income in country i
u_A^i	Marginal utility of abatement in country i

Appendix: A social planner with lump sum transfers

A social planner with the instrument of lump sum redistribution (labeled LS) maximizes

(A1) $L(y_i^c, A_i, A) = \sum_{i=1}^{N} P_i u_i(y_i^c, A) - \lambda[A - \sum_i A_i] - \mu \sum_i [P_i y_i^c + C_i(A_i) - R_i]$

The first term is a summation of welfare over all countries and because of the possibility of lump sum transfers, there is only one world resource constraint given by the last term. Differentiating with respect to y_i^c, A_i and A respectively:

$$u_{y_i^c} = \mu$$

$$\lambda = \mu C_{A_i}$$

$$\sum_i P_i u_A = \lambda$$

$$\Rightarrow \sum_i P_i u_A = \mu C_{A_i} = u_{y_i^c} C_{A_i} \Rightarrow \sum_i P_i \frac{u_A}{u_{y_i^c}} = C_{A_i} \qquad \frac{MSB_w}{MU_y} = MC_A^{LS}$$

This SP with the power of lump sum redistribution between countries leads to the result that marginal utility of per capita income is equalized across the world ($u_{y_i^c} = \mu$), which can only occur if per capita income is equal everywhere. Comparing this result with Eq. 2c we find that the only difference is that in 2c we have in the numerator MSB_i (so the marginal social benefit of abatement only in country *i*) and here MSB_w (marginal social benefit of abatement worldwide). Thus, the marginal cost of abatement MC_A^{LS} under a lump sum redistribution scheme exercise is much higher (and therefore the abatement level, assuming increasing marginal cost of abatement) than $MC_A^{i,N}$ under Nash behaviour.

Eq. A1 can be modified to allow for a global permit market, with the additional restriction $\sum_i A_i = \sum_i T_i$:

(A1') $L(y_i^c, A_i, A, T_i) = \sum_{i=1}^{N} P_i u_i(y_i^c, A) - \lambda[A - \sum_i T_i] - \mu \sum_i [P_i y_i^c + C_i(A_i) + q(T_i - A_i) - R_i]$

Which yields

$$u_{y_i^c} = \mu$$

$$\lambda = \mu(C_{A_i} - q) \Rightarrow C_{A_i} = q$$

$$\sum_i P_i u_A = \lambda$$

$$\lambda = \mu q$$

$$\Rightarrow \sum_i P_i u_A = \mu q = u_{y_i^c} C_{A_i} \Rightarrow \sum_i P_i \frac{u_A}{u_{y_i^c}} = C_{A_i} = q \qquad \frac{MSB_w}{MU_y} = MC_A^{LS} = q$$

So the Samuelson condition is met, there is a uniform marginal cost of abatement and marginal utility of income for consumption is equalized.