Czech Economic Review 7 (2013) 73–99
Acta Universitatis Carolinae Oeconomica

Valuing Equally the Environmental Goods in Rich and Poor Countries in a Post-Kyoto World

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Received 24 August 2012; Accepted 18 April 2013

Abstract The optimal pollution abatement levels are found by maximizing global social welfare in a permits trade system under the constraint that environmental goods are evaluated equally in rich and poor countries. Evaluating equally environmental goods in poor and rich countries makes possible to build a relation between the income elasticity of marginal utility e and the inequality aversion parameter γ (Fankhauser et al. 1997; Johansson-Stenman 2000), which narrows the variation of e for a particular value of γ. As a result, smaller variation for optimal abatement levels is obtained, which allows to inspect what Post-Kyoto abatement levels for poor and rich countries respect the requirement of evaluating equally the environmental goods in rich and poor countries. One finding is that in a Post-Kyoto world, the optimal abatement levels of poor countries are always different from zero, if we aim to evaluate equally the environmental goods in poor and rich countries. Furthermore, in a permits trade system, if we increase abatement levels continually, it can happen that poor countries have to carry out higher emission reductions than rich ones.

Keywords Cost-benefit analysis, distributional weights, global warming, welfare theory, integrated assessment modeling
JEL classification D61, D62, D63

1. Introduction

Environmental equity is a sensible concept in global warming debates. It addresses the distributional issue which is the cumbersome point of cost-benefit analysis. The capita income is lower in poor countries in comparison to rich ones. Consequently, the willingness-to-pay (WTP) in order to avoid climate damages in poor countries are lower than in the developed countries even though the impact is identical in human, physical or ecological terms. One way of managing this would be to use a normative approach by introducing weight factors based on the different marginal value of money in the different regions of the world. This would give higher weight to costs in the poor countries. Environmental equity can be understood as assuming a new decision criterion that requires that the value of lost lives (also any environmental goods) in rich and poor countries has to be weighted differently. I would like to test when Post-Kyoto emissions reduction targets respect that the value of life is identical in poor and rich

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countries when distributional weights (or equity weights) are used.

There are different views in favor and against of using weight factors. I do not plan to review this discussion. I simply assume that weight factors are considered appropriate from a normative point of view, and then examine when Post-Kyoto emission's reduction targets are consistent with the requirement of valuing the life in poor and developed countries by weighting them differently.

Following Ray (1984) and Johansson-Stenman (2000), I obtain the equity weights by totally differentiating the social welfare function. The social welfare function depends on three parameters, which are the income per capita, the elasticity of marginal utility e and the inequality aversion parameter γ. The income per capita depends on GDP, population and pollution abatement costs and benefits, which are obtained from integrated assessment model FUND (Climate Framework for Uncertainty, Negotiation and Distribution) developed by Richard Tol (see Section 2).

The essential point of the paper is investigating the consequences of abatement policies when global welfare is maximized under the constraint that environmental goods are evaluated equally in rich and poor countries. Following Johansson-Stenman (2000), using weights and equalizing the value of life (or any environmental good) in poor and rich regions, we develop a relation between e and γ. However, I consider a larger range of parameter values that relates e and γ compared to Johansson-Stenman (2000). As e and γ take their values in intervals, there is a significant advantage to have a relation between them, as it is possible to restrict the intervals for e and γ when the world regions are approximated in only two types, namely poor and rich. That is, when the world social welfare for different e and γ is maximized (under the constraint that environmental goods are evaluated equally in rich and poor countries), and pollution abatements levels are found, one focuses on smaller intervals for e and γ which are going to give smaller variation for abatement levels.

Finally, it is possible to inspect if the abatement targets of a Post-Kyoto protocol respect the condition that the value of life is identical in poor and rich countries when equity weights are used, which is the main contribution of this research. The costs and benefits from pollution abatements are calculated for the year 2015, which is considered as the representative year of a selected commitment period of Post-Kyoto protocol that includes the years 2013 through 2017.

The optimization global welfare models are similar to Eyckmans et al. (2002), Rose et al. (1998) and Rose and Stevens (1993). Eyckmans et al. (2002) maximize a social welfare function (only for EU) with only one parameter, namely e, which is less general that our social welfare function with two parameters (namely e and γ). Rose et al. (1998) minimize cost of pollution abatement (or maximize benefits in Rose and Stevens 1993) and use different international equity criteria, while in this paper a social welfare function is maximized when the value of life is equal in rich and poor countries.[1]

The paper is structured as follows. Section 2 introduce the FUND model. Sec-

[1] Anthoff et al. (2009) and Anthoff and Tol (2010) use the full integrated model FUND, so have a more sophisticated approach than me which allows for broad conclusions. Here the advantage of having a relations between e and γ is exploited in order to find out where is excepted more abatement in rich or poor countries if we increase continually the abatement levels.

tion 3 reviews the utility and welfare functions and derives the distributional weights. Different types of welfare functions, are considered, including the utilitarian ($\gamma = 0$), Bernoulli-Nash ($\gamma = 1$), and a special welfare function ($\gamma = 2$).[2] In this section, I assume that the value of life in poor and developed countries is the same by weighting them differently in order to derive a relation between the elasticity of marginal utility e and the inequality aversion parameter γ. Section 4 presents the optimization global welfare models with permits system for the integrated assessment model FUND. Section 5 presents the results. Section 6 provides the conclusions.

Appendix 1 contains different tables, which present the results, and parameters intervals that produce the relation between e and γ, main parameters of the FUND model, and Figures that illustrate the optimal abatement levels of poor and rich regions for the optimization global welfare model with permits system. Appendix 2 introduces the optimization global welfare model without permits system, and discusses the results originating from it.

2. FUND model

This paper uses version 2.8 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.8 of FUND corresponds to version 1.6, described and applied by Tol (1999a,b, 2001, 2002c), except for the impact module, which is described by Tol (2002a,b) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. Finally, the model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by Tol (2006).

Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world: the United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Central and Eastern Europe (EEU), the former Soviet Union (FSU), the Middle East (MDE), Central America (CAM), South America (LAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA), and Small Island States (SIS). The model runs from 1950 to 2300 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. In FUND, the impacts of climate change are assumed to depend on the impact of the previous year, in this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be poorly represented in the first few decades of the model runs. The period of 1950–1990 is used for the calibration of the model, which is based on the IMAGE 100-year database (Batjes and Goldewijk 1997). The period 1990–2000 is based on observations of the World Resources Databases (W.R.I. 2001). The climate scenarios for the period 2010–2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al. 1992). The

[2] The reason why I do not use bigger values than 2 for γ is clarified in Footnote (7).

2000–2010 period is interpolated from the immediate past, and the period 2100–2300 extrapolated.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (W.R.I. 2001). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The market impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time.

The endogenous parts of FUND consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean surface temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt et al. (1992). The model also contains sulphur emissions (Tol 2006).

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine et al. (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case (business as usual), the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn et al. 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996).

3. Utility, welfare function and equity weights

It is common to use a conventional iso-elastic utility function that depends solely on consumption:

$$u = \begin{cases} \dfrac{Y^{(1-e)}}{1-e} + u_0 \ , & e \neq 1 \\ \ln(Y) + u_0 \ , & e = 1 \end{cases} \tag{1}$$

where $e = -[du'/dY]Y/u' = -Yu''/u'$ is the income elasticity of marginal utility, which shows that e is a measure of the curvature of $u(Y)$.

The class of welfare functions for which inequality parameter γ is constant is given by the Bergson-Samuelson form:

$$W = \begin{cases} \displaystyle\sum_{i=1}^{n} \frac{u_i^{(1-\gamma)}}{1-\gamma} \ , & \gamma \neq 1 \\ \displaystyle\sum_{i=1}^{n} \ln(u_i) \ , & \gamma = 1 \end{cases} \tag{2}$$

where γ is the parameter of inequality aversion. The smaller is γ, the smaller is the worry about equality. For $\gamma = 0$, equation implies the classical utilitarian welfare function and $\gamma = 1$ is associated with the Bernoulli-Nash function, while $\gamma \to \infty$ represents the maximin case. However, what value to choose for e? Pearce (2003) suggests a simple way, in case of the classical utilitarian welfare function, for estimating the value of e. He judges the value of e by employing equity weights in order to evaluate the climate damages between poor and rich regions:

$$D_{WORLD} = D_p \left(\frac{\overline{Y}}{Y_p}\right)^e + D_r \left(\frac{\overline{Y}}{Y_r}\right)^e , \tag{3}$$

where Y is income, $\overline{Y}$ is the average world per-capita income, P and R refers to poor and rich regions, D is damage, and e is the elasticity of the marginal utility of income, $\left(\overline{Y}/Y_p\right)^e$ and $\left(\overline{Y}/Y_r\right)^e$ are the equity weights for evaluating the damage in poor and rich regions. In equation (3) all damages are considered but the damage happened to developing countries (with incomes lower than world average) attracts higher weights than the damages in developed countries (with incomes higher than world average). One can judge the value of e by estimating the ratio of weights between poor and rich in equation (3) (that equals the ratio of the marginal utilities between poor and rich if the utility function of rich and poor are expressed by equation (1)) which is given by:

$$\left(\frac{\overline{Y}}{Y_p}\right)^e / \left(\frac{\overline{Y}}{Y_r}\right)^e = \left(\frac{Y_r}{Y_p}\right)^e$$

Assume $Y_R = 10Y_P$ is the case for international real-income comparisons between high income countries and low income countries. At $e = 1$, unit damage to the poor (or a marginal unit of income) is valued ten times the unit damage of the rich; if $e = 2$, the relative valuation is 100 times. On this simple calculation basis, values even of $e = 2$ are not justified. Clarkson and Deyes (2002), Pearce and Ulph (1999), Cowell and Gardiner (1999) and Cline (1992) consider the value of e is $1 < e < 1.5$, Pearce and Ulph (1994) suggest $e = 0.8$, while Dasgupta (2008) proposes the value of e between 2 and 3.

Evans (2005) also calculates the values of elasticity of marginal utility e for 20 OECD countries based on a tax-model. However, we are going to focus on a relation between e and γ in stead of merely the value of e.

However, what values can γ take? Firstly, *as we assume* $u_0 = 0$ note that γ must be an integer in order to make possible for welfare function to take real values and not complex ones.[3] The values for γ will be found by developing in the next subsection a relation between e and γ (Fankhauser et al. 1997; Johansson-Stenman 2000).

Equity weights can also be derived by totally differentiating the social welfare function(Ray 1984; Johansson-Stenman 2000):

$$dW = \sum_{i=1}^{n} \frac{\partial W}{\partial u_i} \frac{du_i}{dy_i} dY_i = \sum_{i=1}^{n} q_i \, dY_i, \tag{4}$$

where equity weights q_i are:

$$q_i = \frac{\partial W}{\partial u_i} \frac{du_i}{dY_i} = \begin{cases} u_i^{-\gamma} Y_i^{-e}, & e \neq 1 \quad \forall i \\ u_i^{-\gamma} Y_i^{-1}, & e = 1 \quad \forall i \end{cases} \tag{5}$$

Equity weights must be used as the utility function can be concave in income, so that for the same income variation, utility changes more for a poor than for a rich person; alternatively, the social welfare function may be concave in utilities, so that the same utility variation from a low level, changes the social welfare more than the same utility variation from a high level.

3.1 Monetary evaluation for environmental quality

One of the most debated issues related to the cost-benefit analysis (CBA) is the fact that the economic value of the environmental quality can be lower in poorer countries in comparison to richer ones due to positive income elasticity for risk reductions, if one does not apply any distributional weights. The condition for an equal monetary value of environment between poor and rich regions (or any other good like value of statistical life (VOSL)) to be used in a CBA can be written as follows (Fankhauser et al. 1997; Johansson-Stenman 2000):

$$\frac{\partial W}{\partial u_r} \frac{du_r}{dY_r} V_r = \frac{\partial W}{\partial u_p} \frac{du_p}{dY_p} V_p \Longleftrightarrow q_r V_r = q_p V_p, \tag{6}$$

[3] Azar (1999) already noted that when $e > 1$ utility function takes negative values, which imply that γ will be the equality aversion parameter in stead of the inequality aversion one.

where V_r, V_p are values of environmental quality in rich and poor regions, and q_r, q_p are equity weights for rich and poor regions. After replacing in the equation (6), the derivative from equation (1) and equation (2), and noting that $V_r/V_p = (Y_r/Y_p)^{\varepsilon}$ where ε is the income elasticity of demand for environmental equality, it results:

$$\gamma = \frac{(e-\varepsilon)\ \ln(Y_p/Y_r)}{\ln(u_r/u_p)} \tag{7}$$

It implies that it makes sense to have e as a function of γ:

$$e = \gamma\, \frac{\ln(u_r/u_p)}{\ln(Y_p/Y_r)} + \varepsilon \tag{8}$$

I am going to perform a simple sensible analysis of equation (8).[4] The income elasticity of demand ε in equation (8) is upper bound for e; when $\gamma = 0 \Longrightarrow e = \varepsilon$; when γ increases (keeping other parameters unchanged), e decreases as[5] $\ln(u_r/u_p)/\ln(Y_p/Y_r) < 0$. Therefore, it makes sense to support values of $\varepsilon = 1.2$, which gives γ a chance of being bigger than 1 in spite of, there is evidence that the ε can take also values of 0.33.

The numerical computations, by letting values of $\gamma = \{0,1,2\}$,[6] $Y_r/Y_p = \{3,4,5\}$ and $u_r/u_p = \{1.2, 1.3, 1.4\}$, show that the value of $e \in [0.8, 1.2]$, see Tables A1, A2, A3 and A4 in Appendix 1.[7] The advantages of the numerical experiment above arise when there are only two types of countries, rich and poor. As the same social welfare function is used for both types of countries, then it is possible to find which values (or intervals) to use for e and γ in order to obtain a smaller variation for optimal abatement levels.

Numerical computation with the equation (6) allows us to inspect if, *the normative requirement* that environmental goods are valued equally in non-OECD (or poor) and OECD (or rich) countries, *is respected*. This is a crucial advantage; therefore, we build the equation (6), and perform some simple numerical computation with it. However, there are also disadvantages, as the values of elasticity of marginal utility higher than 1.2 are not supported, for any values of inequality aversion γ. Anyway, it is worthwhile to mention that *all our conclusions hold also for values of elasticity of marginal utility e in the interval 1.2–1.8*, and the values of the inequality aversion γ corresponded to the given values of e.

[4] Czajkowski and Ščasný (2010) and Flores and Carson (1997) point out that the relation between the income elasticity of marginal utility e and the income elasticity of demand for environmental equality ε is not straightforward, but we claim that can be approximated by equation (8) when we assume having two types of countries.

[5] $\ln(u_r/u_p)/\ln(Y_p/Y_r) < 0$ as $\ln(Y_p/Y_r) < 0$, $\ln(u_p/u_r) > 0$ for $Y_p < Y_r$, $u_p < u_r$.

[6] $\gamma = \{0,1,2\}$ means $\gamma = 0$, $\gamma = 1$, $\gamma = 2$.

[7] When $\gamma = \{3,4\}$, the value of e goes down to 0.58. Therefore, those values of γ are considered as too high.

4. Allocation model of burden sharing emissions

The cost-benefit functions for every world region (or region) i are taken from integrated assessment model FUND (Climate Framework for Uncertainty, Negotiation and Distribution) model. The optimization problem with emissions trading system is constructed for cost-benefit functions specified by FUND model. The optimization problem is solved by using the MATLAB Optimization Toolbox.[8] The variables of the optimization problem are: R_i's which are relative abatements levels for every world region i, and Pr which is price of carbon emissions in dollars per metric ton of carbon, while the relative permissions trading levels for every world region i are equal to $(R_i - R_0)$ where initial emission allocation for every region i are $R_0 = 0.2$. R_k is the total relative abatement level, we simulate results for R_k equal to 1.6, 3.2, 4.8 and 6. The optimization problem is stated below:

$$\max \sum_{i=1}^{n} SWF_i \tag{9}$$

$$\text{s.t.} \quad \textstyle\sum_{i=1}^{n} R_i = R_k \tag{10}$$

$$\textstyle\sum_{i=1}^{n} RS_i(Pr) = \sum_{i=1}^{n} (1/(2\,\alpha_i Y_i)\, E_i^2)\, Pr = R_k \tag{11}$$

$$lb \leq R_i \leq ub \tag{12}$$

$$0 \leq Pr \leq 1000, \tag{13}$$

where SWF_i is the social welfare function for each region i.

Let define

$$Z_i = (GDP_i + B_i - C_i + Pr(R_i - R_0)E_i)/POP_i, \tag{14}$$

where GDP_i is gross domestic production for every region i, $B_i = f(R_i), C_i = f(R_i)$ is the benefit[9] and cost functions for every region i, and they are functions of the relative abatement level of region i, R_i. The costs and benefits from pollution abatements are calculated for the year 2015 which is considered as the representative year of the commitment period of the Post-Kyoto protocol that includes the years 2013 through 2017. The price of selling (when selling $R_i < R_0$, when buying $R_i > R_0$) of 1 ton emissions equals Pr Dollars, which changes income by $Pr(Ri - R_0)Ei$ (when emission permits are bought or sold), and changes also emissions cost, which is reflected at the cost function C_i.

A very simple sketch of our main optimization problem can be:

The FUND model distinguishes 16 major regions of the world: the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The benefit B and the cost C of a country

[8] The computation programs can be provided on request.

[9] The benefit and cost functions from pollution abatement are provided from the FUND model.

Table 1. A sketch of main optimization problem

Objective function: Maximize the social welfare function in (9)
Variables: Abatement levels R_k
Constraints:
Under different carbon emissions target in (10)
Under a permit emissions market in (11)
Under the conditions that the environment is valued equally in poor and rich countries in (8)
Output: Optimal abatement levels when the environment is valued equally in poor and rich countries

(region) i in the FUND model are given as:

$$B_i - C_i = \beta_i \sum_j^n R_j E_j - \alpha_i R_i^2 Y_i, \tag{15}$$

where R denotes relative emission reduction, β marginal damage costs of carbon dioxide emissions, E unabated emissions, Y gross domestic product, indexes i denote regions and α is the cost parameter, see Table A5. The social welfare function (*SWF*) for each world region i is defined as:

$$SWF_i = POP_i \frac{\left(\frac{Z_i}{1-e}\right)^{(1-e)(1-\gamma)}}{(1-\gamma)} \quad \forall e \neq 1, \forall \gamma \neq 1 \tag{16}$$

$$SWF_i = POP_i \frac{\left(\log Z_i\right)^{(1-\gamma)}}{(1-\gamma)} \quad e = 1, \forall\, \gamma \neq 1 \tag{17}$$

$$SWF_i = POP_i \log \left(\frac{Z_i}{1-e}\right)^{(1-e)} \quad \forall\, e \neq 1, \gamma = 1 \tag{18}$$

$$SWF_i = POP_i \log\left(\log Z_i\right) \quad e = 1, \gamma = 1 \tag{19}$$

The using of social welfare function, presented in equations (16)–(19), has clearly advantages, but also disadvantages. One advantage is the effect of elasticity of marginal utility, and inequality aversion are separated, but the main advantage is the developing of the equation (6) which controls if the environmental goods are equally evaluated in rich and poor countries. One disadvantage is that when inequality aversion $\gamma = 1$ the social welfare function cannot support values of $e > 1$ as the expression under the logarithm in equation (18) becomes negative.[10]

[10] Numerical instability is experienced for the single point $e = 1$ when $\gamma = 2$. I think that the numerical instability is inherited from the shape of the social welfare function because our numerical experiments with the *SWF* for $e \neq 1$ (when $\gamma = 2$, see (16)), and $e = 1$ (when $\gamma = 2$, see (17)) show that there is a discontinuity for both types of functions for the neighborhood of particular point $e = 1$ (which must not be) .

One crucial point is the explanation of equation (11) in our optimization problem. Without constraints on the trading volumes, individually rational countries (which maximize their utility of per capita income) will reduce their carbon emissions up to the point where their marginal abatement costs are exactly equal to the market price $C_i^{'}(R_i) = Pr$. This condition defines the emission reduction supply curve $RS_i(Pr) = C_i^{'-1}(Pr)$ (Eyckmans et al. 2002). The emission reduction supply curve (or equivalently the inverse cost curve) is a linear function of the market price, see (15) for the shape of abatement cost function. The market clearing price is defined as the price for which total supply is sufficient to achieve the emissions reduction constraint:

$$\sum_{i=1}^{n} RS_i(Pr) = \sum_{i=1}^{n} C_i^{'-1}(Pr) = \sum_{i=1}^{n} (1/(2\,\alpha_i Y_i)\, E_i^2)\, Pr = R_k, \tag{20}$$

where α is the abatement cost parameter, which is unitless; E is the carbon dioxide emissions in billion metric tonnes of carbon; Y is gross domestic product in billions US dollars, see Table A5. Finally, $n = 16$ as there are 16 world regions in FUND.

The world regions for model FUND can be fairly approximated by two types, OECD countries (or rich ones) and non-OECD countries (or poor ones).[11] The social welfare function of the same shape is used for both types of countries. The values (or intervals) of the elasticity of marginal utility e and the inequality aversion parameter γ are taken from Tables A1, A2, A3 and A4 in Appendix 1, which makes use of the equation (8). The relation between e and γ allows to narrow the variation of e for a specific value of γ. As a consequence it is possible to attain smaller variation for the optimal emission reduction levels too.

5. Results

The results of the FUND model with a permits system (FUND-permit) are discussed. The results of FUND model (FUND-nonpermit) without a permits system are postponed in Appendix 2, as we mainly build FUND-nonpermit for comparison purposes with FUND-permit. The emission's reductions (or abatement levels) are estimated as *fractions of the total world emissions*. Let me explain:

$$R_i = \frac{Er_i}{Eb_i} = \frac{\text{Emissions reduction in absolute terms for region } i}{\text{Total emissions for region } i} \tag{21}$$

$R_i \rightarrow$ Emissions reduction of region i as fractions of its own total emissions,

where Eb_i is the total emission budget *for the country (or world region) i* in absolute terms, before the abatement takes place; Er_i is the amount of emissions reduction *for the country i* in absolute terms; and R_i is the emission's reduction *for the country i* in

[11] Concerning FUND model, the world regions of United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand are considered as OECD countries (or rich ones), and the rest of regions as non-OECD ones (or poor ones).

relative terms (or relative emission's reduction).

$$Rf_i = \frac{R_i Eb_i}{\sum_{j=1}^{16} R_j Eb_j} = \frac{\text{Emissions reduction in absolute terms for region } i}{\text{Total world emissions}} \tag{22}$$

$Rf_i \rightarrow$ Emissions reduction of region i as fractions of the total world emissions,

where $R_i Eb_i = Er_i$ is the amount of emission reductions in absolute terms *for the country* i; $\sum_{j=1}^{16} R_j Eb_j = \sum_{j=1}^{16} Er_j$ is the total emission's reduction *for all the world*, and there are 16 world regions; and Rf_i is the emission's reduction *for the country i* as *fraction of the total world emission's reduction*.

We calculate Rf_i for each world region. For FUND-permit model see Table A6. Clearly $\sum_{i=1}^{16} Rf_i = 1$, and $Rf_i < 0$ indicates that the country i can *increase its emissions*. This occurs as it is expensive to reduce emissions in country i. Instead, emissions are decreased in other regions of the world where it is cheaper.

Furthermore, emission's reductions for rich (A_r) and poor regions (A_p) are estimated as *fractions of the total world emissions*. See Figures A1, A2 and A3 for FUND-permit.

$$A_r = \frac{\sum_{l=1}^{5} R_l Eb_l}{\sum_{j=1}^{16} R_j Eb_j} = \frac{\text{Emissions reduction in absolute terms for all rich regions}}{\text{Total world emissions}} \tag{23}$$

$A_p \rightarrow$ Emissions reduction for rich regions as fractions of the total world emissions,

where $\sum_{l=1}^{5} R_l Eb_l = \sum_{l=1}^{5} Er_l$ is the amount of emission's reduction in absolute terms *for rich countries*. The FUND model has 5 rich world regions (or countries), which are United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand. The $Ewr = \sum_{j=1}^{16} R_j Eb_j = \sum_{j=1}^{16} Er_j$ is the total emission's reduction *for all the world* (we have 16 world regions), and A_r is the abatement level (or emissions reduction) *for rich countries* as *fraction of the total world emissions Ewr*.

$$A_p = \frac{\sum_{t=1}^{11} R_t Er_t}{\sum_{j=1}^{16} R_j Eb_j} = \frac{\text{Emissions reduction in absolute terms for all poor regions}}{\text{Total world emissions}} \tag{24}$$

$A_p \rightarrow$ Emissions reduction for poor regions as fractions of the total world emissions,

where $\sum_{t=1}^{11} R_t Eb_t = \sum_{t=1}^{11} Er_t$ is the amount of emission reductions in absolute terms *for poor countries*. The FUND model has 11 poor world regions, which are Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States; $\sum_{j=1}^{16} R_j Eb_j = \sum_{j=1}^{16} Er_j = Ewr$ is the total emission's reduction *for all the world* (we have 16 world regions); and A_p is the abatement level (or emissions reduction) *for poor countries* as *fraction of the total world emissions Ewr*.

It is trivial to see that $A_r + A_p = 1$.

Table A6 represents all regions and their optimal abatement levels for FUND-permit, where:

- different values of the elasticity of marginal utility e, and different values of the inequality aversion parameter γ are considered;
- different values of total relative abatement levels R_k are taken into account;
- the values of e and γ respect the relation of e and γ originates from equation (8).

The Figures[12] A1 to A3 for FUND-permit introduce the optimal abatement levels for rich and poor regions for γ equal to 0, 1 and 2 and $e \in [0, 1.5]$. *Optimal abatement levels mean that the world global welfare is maximized, and environmental goods are equally evaluated in poor and rich countries.* The intervals of e for every specific γ, which respect the requirement that environmental goods are equally evaluated in rich and poor countries, are shown in every figure. Different values of total relative abatement levels R_k are taken into account.

In all simulations for FUND-permit and FUND-nopermit (for different value of γ, e and R_k), the abatement levels of poor countries are different from zero. It implies that in a Post-Kyoto world, the abatement levels of poor countries have to be different from zero, if we aim to evaluate equally the environmental goods in poor and rich countries. See Figures A1, A2 and A3 for FUND-permit.

If the global abatement level R_k increases, then the relative abatement levels of poor countries A_p increase (or the relative abatement levels of rich countries A_r decrease, as $A_p + A_r = 1$) for all value of γ and e, which respect the requirement that environmental goods are valued equally in poor and rich countries. The optimization process analysis and Figures A1 to A3 show that:

- We claim that abatements levels of poor and rich countries depend on two factors; firstly, as inequality aversion γ gets bigger the abatement is shifted to the developed countries, as the welfare devoted to abatement policies receive higher weights in developing countries. *This we call the first factor.* secondly as the abatement levels are increased the cost increase more in the developed countries as the productions there is more efficient; as a consequence when the abatement level are increased, then it can reach point where it is more beneficial to increase abatement in the developing countries. *This we will call the second factor.*
- For $\gamma = 0$ and $\gamma = 1$, for any of relative abatement levels we have $A_p > A_r$; the abatement is cheaper in developing countries than the developed ones when environmental goods are valued equally in developed and developing countries, see Tables A1 and A2. *As inequality aversion is small, only the second factor determinants the abatement levels.*
- Nevertheless when $\gamma = 2$, when $R_k = 1.6$ or $R_k = 3.2$, it is possible that $A_r > A_p$; different from the previous cases when $\gamma = 0$ or $\gamma = 1$, the abatement is cheaper

[12] Numerical instability is experienced for the single point $e = 1$ when $\gamma = 2$, (for FUND-nopermit also) therefore, in Figure A3 and A4 when $\gamma = 2$, a circle is placed in this particular point. However, the optimal abatement levels for the cumbersome point are presented in Table A6, and it is consistent with conclusions. I think that the numerical instability is inherited from the shape of the social welfare function because our numerical experiments with the SWF for $e \neq 1$ (when $\gamma = 2$, see (16)), and $e = 1$ (when $\gamma = 2$, see (17)) show that there is a discontinuity for both types of functions for the neighborhood of particular point $e = 1$ (which must not be).

in developed countries in comparison to the developed ones when environmental goods are valued equally in developed and developing countries, see Table A3. *The first factor dominates the second one here.*

But as the abatement levels are increased ($R_k = 4.8$ or $R_k = 6$), then it reaches a point when the opposite is true, namely the abatement is cheaper in developing countries in comparison to the developed ones. A straightforward explanations can be derived from Table A6 where it is clearly seen that the sum abatement levels of crucial player of OECD countries (USA and Europe have the highest abatement levels) are higher than abatement levels of crucial players of non-OECD countries (Former Soviet Union and China have the highest abatement levels); at the beginning (when $R_k = 1.6$ or $R_k = 3.2$) the abatement levels of crucial OECD countries are higher than crucial non-OECD countries, but as the abatement increase the profits from abatement reduce significantly in the OECD countries but it stays almost constant for crucial non-OECD countries. *Here occurs the opposite namely, the second factor dominates the first one.*

The intuition behind is that if for the highest global abatement targets ($R_k = 4.8$ or $R_k = 6$) in our modeling when $\gamma = 2$, it is more profitable for developing countries to sell their emissions permits (and to abate themselves) to developed countries than to use them by themselves.

– It follows that, in a Post-Kyoto world in a permit system, if the abatements levels are continuously increased, it can happen that we reach a point where poor countries have to carry out higher emissions reductions than rich ones.

No wonder that regions like USA, Western European Union and Japan have the biggest optimal abatement levels. It is necessary to mention that Former Soviet Union has to abate pollution in large amounts. All simulations for every combination of parameters e, γ and R_k suggests that Former Soviet Union has to play a central role in abatement policies among non-OECD countries (see Table A6). Canada and Australia have negative or low optimal abatement levels. This shows that it is very expensive for Canada and Australia to reduce their emissions. By other sides China, India and East European Countries are changing their optimal abatement levels from low to significant as the global abatement level is increased.

6. Conclusions

The paper examines if the abatement targets that a Post-Kyoto protocol assigns to different countries, are consistent with the normative requirement that environmental goods are valued equally in non-OECD (or poor) and OECD (or rich) countries. A global welfare maximization problems with a permits system is established, which is constrained to different global abatement levels. The global welfare optimization problem can find regional optimal abatement targets, which maximize the world global welfare, and respect the requirement that environmental goods are equally evaluated in poor and rich countries. A wide range of social welfare functions is used such as the utilitarian ($\gamma = 0$), Bernoulli-Nash ($\gamma = 1$), and a special welfare function ($\gamma = 2$). In the global welfare maximization problems, I use the costs and benefits from pollution abatements of integrated assessment model FUND (Climate Framework for Uncertainty, Negotiation and Distribution) developed by Richard Tol.

One finding is that in a Post-Kyoto world, the optimal abatement levels of poor countries is different from zero; this is independent of how big abatement targets are, while one evaluates equally the environmental goods in poor and rich countries. Furthermore, if the global abatement targets are increased further, it always reaches a point where it is more profitable for developing countries to sell their emissions permits to developed countries than to use them by themselves. It follows that, in a Post-Kyoto world in a permits trade system, if we increase abatement levels continuously, it can happen that poor countries have to carry out higher emission reductions than rich ones.

No surprise that USA, Western European Union and Japan have the biggest optimal abatement levels. It is necessary to mention that Former Soviet Union has to abate pollution in large amounts. Canada and Australia have negative or low optimal abatement levels, while China, India and East European Countries are changing their optimal abatement levels from low to significant as the global abatement level is increased.

As always, further extensions are possible such as the implementation of a dynamic framework for a longer time interval, or finding a way of including of political factors in modeling approach.

Acknowledgment I am specially grateful to Richard Tol for his comments and suggestions. I am also thankful to the participants of Adam Smith seminar at University of Hamburg, especially to Anke Gerber and Andreas Lange for their useful comments. All remaining errors are mine.

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Appendix 1

Table A1. The values of elasticity of marginal utility e for different values of γ, when $u_r/u_p = 1.2$, $Y_r/Y_p = 5$, $\varepsilon = 1.2$.

$\gamma = 0$	$\gamma = 1$	$\gamma = 2$
1.2	1.1408	1.0816

Table A2. The values of elasticity of marginal utility e for different values of γ and u_r/u_p, when $Y_r/Y_p = 5$, $\varepsilon = 1.2$.

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$
$u_r/u_p = 1.2$	1.2	1.0867	0.9734
$u_r/u_p = 1.3$	1.2	1.037	0.874
$u_r/u_p = 1.4$	1.2	0.9909	0.7819

Table A3. The values of elasticity of marginal utility e for different values of γ and Y_r/Y_p, when $u_r/u_p = 1.2$, $\varepsilon = 1.2$.

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$
$Z_r/Z_p = 3$	1.2	1.0685	0.937	0.8054	0.6739
$Z_r/Z_p = 4$	1.2	1.0982	0.9965	0.8947	0.793
$Z_r/Z_p = 5$	1.2	1.117	1.034	0.9511	0.8681

Table A4. The values of elasticity of marginal utility e for different values of γ, Z_r/Z_p and u_r/u_p, when $\varepsilon = 1.2$.

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$	
$Z_r/Z_p = 3$	1.2	1.0685	0.937	0.8054	0.6739	$u_r/u_p = 1.2$
$Z_r/Z_p = 4$	1.2	1.0536	0.9071	0.7607	0.6143	$u_r/u_p = 1.3$
$Z_r/Z_p = 5$	1.2	1.0469	0.8937	0.7406	0.5875	$u_r/u_p = 1.4$

Table A5. The FUND data for the year 2015

	α	β	E	Y	Population
United States of America	0.015194	1.98	1.816	13372	296.5
Canada	0.015205	0.10	0.139	1054	33.3
Western Europe	0.015680	3.05	0.81	15569	394.4
Japan and South Korea	0.015591	−0.86	0.610	11130	193.5
Australia and New Zealand	0.015149	0	0.092	606	26.2
Central and Eastern Europe	0.014733	0.11	0.201	544	122.4
Former Soviet Union	0.013839	1.10	1.093	872	293.0
Middle East	0.014400	0.17	0.551	871	320.7
Central America	0.014911	0.10	0.137	524	162.9
South America	0.015161	0.24	0.266	1804	409.7
South Asia	0.014455	0.38	0.756	1296	1681.3
South East Asia	0.014881	0.69	0.492	1770	637.4
China	0.014589	5.21	1.798	3795	1475.6
North Africa	0.014706	0.83	0.120	309	195.9
Sub-Saharan Africa	0.014718	0.82	0.169	445	899.4
Small Island States	0.014387	0.07	0.049	76	51.9

Notes: α is the abatement cost parameter (unitless), β the marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon), E is the carbon dioxide emissions (in billion metric tonnes of carbon), Y is gross domestic product (in billions US dollars and population in millions people).

Source: FUND

Table A6. Relative abatement levels (as fraction of global abatement levels) for different world regions, FUND model in a permits system, different values of R_k

$R_k = 1.6$	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	1.1647	0.6249	1.1646	0.8561	1.8750	0.4582
Canada	−0.8530	−0.4529	−0.8530	−0.6197	−1.8750	−0.3329
Western Europe	0.3054	0.1629	0.3052	0.2218	1.8750	0.1210
Japan and South Korea	0.4136	0.2049	0.4139	0.2904	1.8750	0.1462
Australia and New Zealand	−1.3084	−0.7755	−1.3082	−1.0099	−1.8750	−0.5955
Central and Eastern Europe	−0.0033	0.0174	−0.0034	0.0082	−1.4045	0.0241
Former Soviet Union	0.7543	0.6957	0.7543	0.7225	1.2085	0.6723
Middle East	0.2838	0.2693	0.2837	0.2765	0.2282	0.2628
Central America	−0.0567	−0.0374	−0.0570	−0.0449	−0.8692	−0.0314
South America	0.0315	0.0327	0.0316	0.0324	−0.3696	0.0328
South Asia	0.1833	0.1871	0.1833	0.1850	0.1563	0.1895
South East Asia	0.1157	0.1099	0.1156	0.1127	0.0691	0.1076
China	0.2642	0.2473	0.2642	0.2550	0.4084	0.2409
North Africa	−0.0027	0.0010	−0.0024	−0.0002	−0.0611	0.0007
Sub-Saharan Africa	0.0854	0.0827	0.0854	0.0843	0.0381	0.0807
Small Island States	−0.3778	−0.3702	−0.3777	−0.3702	−0.2792	−0.3769

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Table A6 – *Continued from previous page*

$R_k = 3.2$	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.5887	0.3216	0.5887	0.4359	0.9375	0.2395
Canada	−0.4850	−0.2725	−0.4851	−0.3630	−0.9375	−0.2061
Western Europe	0.1511	0.0823	0.1511	0.1105	0.9375	0.0622
Japan and South Korea	0.1967	0.0980	0.1969	0.1383	0.9231	0.0705
Australia and New Zealand	−0.7116	−0.4434	−0.7115	−0.5626	−0.9375	−0.3483
Central and Eastern Europe	0.0295	0.0382	0.0293	0.0346	−0.7131	0.0402
Former Soviet Union	0.5437	0.5126	0.5437	0.5268	0.7664	0.4998
Middle East	0.2191	0.2105	0.2191	0.2150	0.1787	0.2065
Central America	−0.0064	0.0014	−0.0065	−0.0015	−0.4385	0.0027
South America	0.0294	0.0295	0.0294	0.0297	−0.1957	0.0292
South Asia	0.1671	0.1686	0.1671	0.1678	0.1543	0.1694
South East Asia	0.0903	0.0869	0.0903	0.0885	0.0603	0.0853
China	0.1923	0.1836	0.1923	0.1876	0.2632	0.1802
North Africa	0.0400	0.0387	0.0401	0.0397	0.0106	0.0368
Sub-Saharan Africa	0.0901	0.0877	0.0901	0.0891	0.0649	0.0859
Small Island States	−0.1349	−0.1435	−0.1349	−0.1363	−0.0743	−0.1537
$R_k = 4.8$	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.3960	0.2200	0.3960	0.2950	0.6250	0.1662
Canada	−0.3614	−0.2114	−0.3612	−0.2762	−0.6250	−0.1633
Western Europe	0.0994	0.0552	0.0994	0.0735	0.6250	0.0424
Japan and South Korea	0.1237	0.0620	0.1238	0.0870	0.5394	0.0452
Australia and New Zealand	−0.5107	−0.3319	−0.5106	−0.4122	−0.6250	−0.2648
Central and Eastern Europe	0.0400	0.0449	0.0399	0.0431	−0.4628	0.0454
Former Soviet Union	0.4743	0.4519	0.4743	0.4624	0.6250	0.4426
Middle East	0.1974	0.1909	0.1974	0.1941	0.1690	0.1877
Central America	0.0101	0.0141	0.0101	0.0126	−0.2828	0.0141
South America	0.0286	0.0283	0.0286	0.0286	−0.1277	0.0279
South Asia	0.1617	0.1623	0.1617	0.1620	0.1537	0.1626
South East Asia	0.0817	0.0790	0.0817	0.0804	0.0608	0.0777
China	0.1682	0.1623	0.1682	0.1650	0.2169	0.1599
North Africa	0.0540	0.0513	0.0540	0.0530	0.0366	0.0486
Sub-Saharan Africa	0.0916	0.0893	0.0916	0.0906	0.0749	0.0876
Small Island States	−0.0548	−0.0682	−0.0549	−0.0590	−0.0030	−0.0798

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Table A6 – *Continued from previous page*

$R_k = 6$	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.3186	0.1793	0.3186	0.2386	0.5000	0.1370
Canada	−0.3114	−0.1866	−0.3113	−0.2414	−0.5000	−0.1458
Western Europe	0.0785	0.0443	0.0785	0.0584	0.5000	0.0344
Japan and South Korea	0.0943	0.0477	0.0943	0.0666	0.4302	0.0351
Australia and New Zealand	−0.4292	−0.2862	−0.4291	−0.3512	−0.5000	−0.2316
Central and Eastern Europe	0.0441	0.0473	0.0439	0.0463	−0.3554	0.0474
Former Soviet Union	0.4469	0.4278	0.4469	0.4368	0.5000	0.4199
Middle East	0.1887	0.1829	0.1887	0.1859	0.1681	0.1801
Central America	0.0166	0.0188	0.0166	0.0184	−0.2157	0.0187
South America	0.0282	0.0278	0.0282	0.0282	−0.0963	0.0275
South Asia	0.1595	0.1598	0.1595	0.1597	0.1535	0.1599
South East Asia	0.0783	0.0759	0.0782	0.0771	0.0625	0.0746
China	0.1586	0.1537	0.1586	0.1560	0.1992	0.1517
North Africa	0.0595	0.0562	0.0594	0.0581	0.0480	0.0533
Sub-Saharan Africa	0.0922	0.0899	0.0922	0.0912	0.0793	0.0882
Small Island States	−0.0233	−0.0386	−0.0232	−0.0287	0.0266	−0.0505

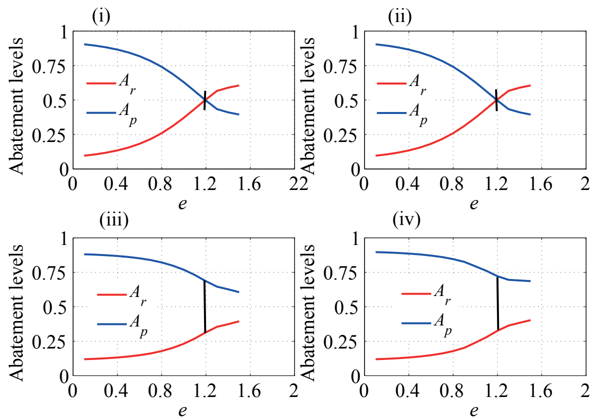

Figure A1. The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0$ in a permit trading system, FUND model. $\gamma = 0$, $e = 1.2$ respect the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore a straight line is placed on $e = 1.2$ that connect A_r and A_p. In part (i) $R_k = 1.6$; (ii) $R_k = 3.2$; (iii) $R_k = 4.8$; (iv) $R_k = 6$.

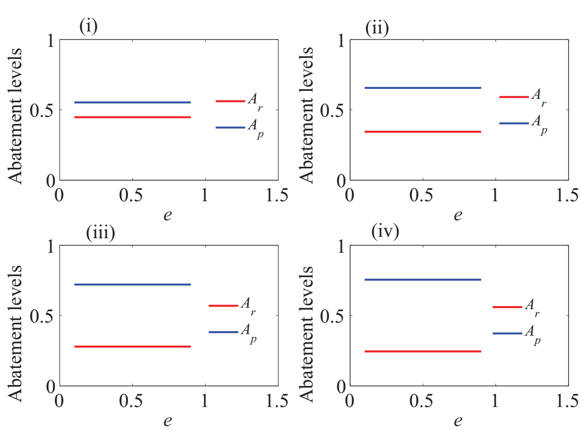

Figure A2. The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 1$ in a permit trading system, FUND model. $\gamma = 1$, $e \in [0.99, 1.14]$ are values that respect the requirement that environmental goods are equally evaluated in poor and rich countries. The social welfare function take complex values for $e > 0.9$, as the logarithm of negative number is met. $\gamma = 1, e = 0.9$ satisfy the most appropriately the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore the graph of A_r and A_p are presented for value of $e \in [0, 0.9]$. In part (i) $R_k = 1.6$; (ii) $R_k = 3.2$; (iii) $R_k = 4.8$; (iv) $R_k = 6$.

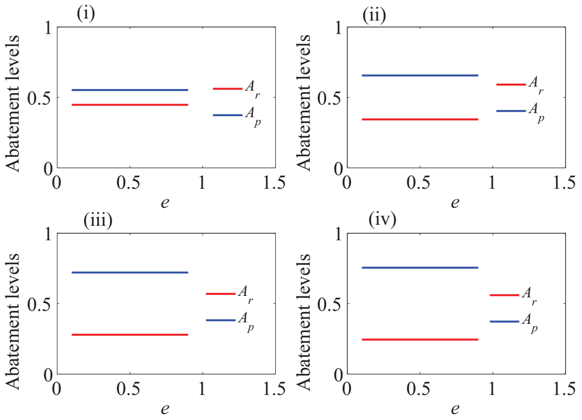

Figure A3. The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 2$ in a permit trading system, FUND model. $\gamma = 2$, $e \in [0.78, 1.08]$ respect the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore a straight line is placed on $e = 0.8$ and $e = 1.1$ that connect A_r and A_p. In part (i) $R_k = 1.6$; (ii) $R_k = 3.2$; (iii) $R_k = 4.8$; (iv) $R_k = 6$.

Appendix 2

Here we present the FUND model without a permit system (FUND-nopermit), and discuss its results. The variables of the optimization problem without permit trade system are: R_i's which are *relative abatements levels* for every world region i; R_k is the total relative abatement level. We simulate results for R_k equal to 1.6, 3.2, 4.8 and 6. The optimization problem without emission trading is stated below:

$$\max \sum_{i=1}^{n} SWF_i \tag{25}$$

$$\text{s.t.} \quad \textstyle\sum_{i=1}^{n} R_i \geq R_k \tag{26}$$

$$-1 \leq R_i \leq 1 \tag{27}$$

where SWF_i is the social welfare function for each region i.

Let define

$$Z_i = (GDP_i + B_i - C_i)/POP_i, \tag{28}$$

where GDP_i is gross domestic production for every region i, $B_i = f(R_i), C_i = f(R_i)$ is the benefit[13] and cost functions for every region i, and they are functions of the relative abatement level of region i, R_i. The costs and benefits from pollution abatements are calculated for the year 2015 which is considered as the representative year of the commitment period of the Post-Kyoto protocol that includes the years 2013 through 2017. The Social Welfare Function (SWF) for each world region i is defined as in equations (16)-(19).

The explanation of R_i, Rf_i, A_r and A_p:

$$R_i = \frac{Er_i}{Eb_i}, \quad Rf_i = \frac{R_i Eb_i}{\sum_{j=1}^{16} R_j Eb_j}, \quad A_r = \frac{\sum_{l=1}^{5} R_l Eb_l}{\sum_{j=1}^{16} R_j Eb_j}, \quad A_p = \frac{\sum_{t=1}^{11} R_t Er_t}{\sum_{j=1}^{16} R_j Eb_j} \tag{29}$$

is found in the Section 5. We calculate Rf_i's for each world region. For FUND-nopermit model see Table A7. Furthermore, emission's reductions for rich (A_r) and poor regions (A_p) are presented in the Figure A4.

Table A7 represents all regions and their optimal abatement levels for FUND-nopermit; different values of the elasticity of marginal utility e, different values of the inequality aversion parameter γ and different values of total relative abatement levels R_k are taken into account (the values of e and γ respect the relation of e and γ originating from equation (8)). The Figure[14] A4 introduces the optimal abatement levels for rich and poor regions for γ equal to 0, 1 and 2 and $e \in [0, 1.5]$. *Optimal abatement levels mean that the world global welfare is maximized, and environmental goods are equally evaluated in poor and rich countries.* The intervals of e for every specific

[13] The benefit and cost functions from pollution abatement are provided from the FUND model.

[14] Numerical instability is experienced for the single point $e = 1$ when $\gamma = 2$, (for FUND-permit also) therefore, in Figure A4 when $\gamma = 2$, a circle is placed in this particular point. However, the optimal abatement levels for the cumbersome point are presented in Table A7 and it is consistent with conclusions.

γ, which respect the requirement that environmental goods are equally evaluated in rich and poor countries, are shown in every figure. Different values of total relative abatement levels R_k are taken into account.

In all simulations for FUND-permit and FUND-nopermit (for different value of γ, e and R_k), the abatement levels of poor countries are different from zero. It implies that in a Post-Kyoto world, the abatement levels of poor countries have to be different from zero, if we aim to evaluate equally the environmental goods in poor and rich countries; see Figure A4.[15]

FUND-nopermit predicts that the optimal abatement levels of poor countries A_p are always higher than abatement levels of rich countries A_r. The abatement levels of poor countries A_p increase from 25 % (for $\gamma = 0$, $e = 1.2$) to more than 45 % (for $\gamma = 2$, $e = 1.1$); see Figure A4. As a consequence in a Post-Kyoto world without a permits system, if we plan huge amount emissions reductions then, poor countries have to carry out a significant part of it.

Similarly, to FUND-permit, it follows that, in a Post-Kyoto world in a permits system, if we plan big amount emissions reduction then, it can happen that poor countries have to carry out higher emissions reduction than rich ones.

No wonder that regions like USA, Western European Union and Japan have the biggest optimal abatement levels. It is necessary to mention that Former Soviet Union has to abate pollution in large amounts. All simulations for every combination of parameters e, γ and R_k suggests that Former Soviet Union has to play a central role in abatement policies among non-OECD countries (see Table A7). Canada and Australia have negative or low optimal abatement levels, while China, India and East European Countries are changing their optimal abatement levels from low to significant as the global abatement level is increased.

[15] In Figure A4, when $\gamma = 0$ and R_k equals 1.6, 3.2, 4.8 or 6, the values of A_r and A_p differ by less than 10^{-2} for all R_k, so the graph looks identical with different R_k. Therefore, one graph is presented for $\gamma = 0$ and all R_k. The same is true for $\gamma = 1$ and $\gamma = 2$, so one graph is presented for $\gamma = 1$ (and $\gamma = 2$) and all R_k.

Table A7. Relative abatement levels (as fraction of global abatement levels) for different world regions, FUND model without permits system, different values of R_k

$R_k = 1.6$	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	1.1785	0.1868	0.2245	0.2082	1.8750	0.1641
Canada	−0.4544	0.1284	0.1492	0.1437	−1.8750	0.1161
Western Europe	0.3322	0.0617	0.0762	0.0690	1.8750	0.0544
Japan and South Korea	0.4858	0.0950	0.1249	0.1096	1.8750	0.0808
Australia and New Zealand	−0.8838	0.1086	0.1197	0.1076	−1.8750	0.1014
Central and Eastern Europe	−0.0107	0.0524	0.0417	0.0493	−1.0463	0.0576
Former Soviet Union	0.4463	0.1270	0.0945	0.1106	0.9968	0.1449
Middle East	0.1488	0.0563	0.0410	0.0483	0.1843	0.0648
Central America	−0.0623	0.0267	0.0200	0.0233	−0.6770	0.0301
South America	0.0201	0.0203	0.0164	0.0187	−0.2123	0.0222
South Asia	0.0352	0.0147	0.0083	0.0111	0.0052	0.0192
South East Asia	0.0603	0.0246	0.0180	0.0209	0.0613	0.0282
China	0.1480	0.0396	0.0287	0.0341	0.3095	0.0458
North Africa	−0.0572	0.0199	0.0132	0.0165	−0.1131	0.0241
Sub-Saharan Africa	−0.0045	0.0060	0.0032	0.0044	−0.0394	0.0083
Small Island States	−0.3823	0.0319	0.0205	0.0246	−0.3439	0.0380
$R_k = 3.2$	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.6030	0.1868	0.2245	0.2082	0.9375	0.1641
Canada	−0.0871	0.1284	0.1492	0.1437	−0.9375	0.1161
Western Europe	0.1780	0.0617	0.0762	0.0690	0.9375	0.0544
Japan and South Korea	0.2685	0.0950	0.1249	0.1096	0.9375	0.0808
Australia and New Zealand	−0.2833	0.1086	0.1197	0.1076	−0.9375	0.1015
Central and Eastern Europe	0.0216	0.0524	0.0417	0.0493	−0.3408	0.0576
Former Soviet Union	0.2340	0.1270	0.0945	0.1106	0.5392	0.1449
Middle East	0.0838	0.0563	0.0410	0.0483	0.1305	0.0648
Central America	−0.0124	0.0267	0.0200	0.0233	−0.2474	0.0301
South America	0.0179	0.0203	0.0164	0.0187	−0.0429	0.0222
South Asia	0.0190	0.0147	0.0083	0.0111	0.0031	0.0192
South East Asia	0.0348	0.0246	0.0180	0.0209	0.0506	0.0282
China	0.0760	0.0396	0.0287	0.0341	0.1626	0.0458
North Africa	−0.0146	0.0199	0.0132	0.0165	−0.0418	0.0241
Sub-Saharan Africa	0.0002	0.0060	0.0032	0.0044	−0.0132	0.0083
Small Island States	−0.1394	0.0319	0.0205	0.0246	−0.1374	0.0380

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Table A7 – *Continued from previous page*

$R_k = 4.8$	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.4109	0.1867	0.2245	0.2093	0.6250	0.1641
Canada	0.0347	0.1292	0.1505	0.1401	−0.6250	0.1161
Western Europe	0.1264	0.0617	0.0765	0.0698	0.6250	0.0545
Japan and South Korea	0.1957	0.0949	0.1249	0.1097	0.6250	0.0808
Australia and New Zealand	−0.0800	0.1088	0.1174	0.1120	−0.6250	0.1014
Central and Eastern Europe	0.0320	0.0526	0.0425	0.0485	−0.0963	0.0576
Former Soviet Union	0.1631	0.1269	0.0944	0.1103	0.3840	0.1449
Middle East	0.0621	0.0563	0.0409	0.0489	0.1108	0.0648
Central America	0.0040	0.0265	0.0200	0.0240	−0.1045	0.0301
South America	0.0170	0.0202	0.0164	0.0183	0.0114	0.0222
South Asia	0.0136	0.0147	0.0083	0.0113	0.0023	0.0192
South East Asia	0.0262	0.0245	0.0180	0.0212	0.0462	0.0282
China	0.0520	0.0396	0.0288	0.0341	0.1133	0.0458
North Africa	−0.0006	0.0199	0.0133	0.0156	−0.0184	0.0241
Sub-Saharan Africa	0.0017	0.0061	0.0032	0.0045	−0.0047	0.0083
Small Island States	−0.0589	0.0315	0.0204	0.0224	−0.0693	0.0380
$R_k = 6$	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.3340	0.1856	0.2245	0.2095	0.5000	0.1376
Canada	0.0828	0.1296	0.1503	0.1398	−0.5000	0.1312
Western Europe	0.1057	0.0615	0.0765	0.0698	0.5000	0.0473
Japan and South Korea	0.1664	0.0945	0.1249	0.1099	0.5000	0.0716
Australia and New Zealand	0.0024	0.1101	0.1179	0.1118	−0.5000	0.131
Central and Eastern Europe	0.0361	0.0526	0.0425	0.0484	0.0040	0.0597
Former Soviet Union	0.1347	0.1262	0.0944	0.1104	0.3211	0.1238
Middle East	0.0533	0.0561	0.0409	0.0489	0.1024	0.0580
Central America	0.0105	0.0269	0.0199	0.0240	−0.0471	0.0343
South America	0.0166	0.0202	0.0164	0.0183	0.0324	0.0218
South Asia	0.0114	0.0146	0.0083	0.0113	0.0021	0.0168
South East Asia	0.0228	0.0244	0.0180	0.0212	0.0443	0.0255
China	0.0424	0.0394	0.0288	0.0341	0.0936	0.0385
North Africa	0.0050	0.0201	0.0133	0.0157	−0.0092	0.0286
Sub-Saharan Africa	0.0023	0.0061	0.0032	0.0044	−0.0014	0.0089
Small Island States	−0.0267	0.032	0.0202	0.0224	−0.0421	0.0654

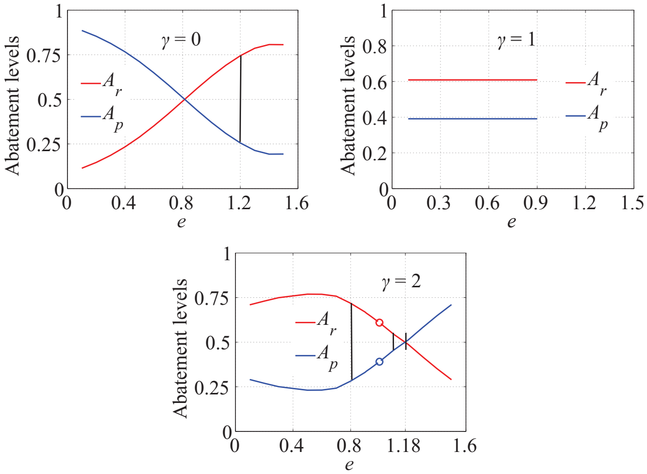

Figure A4. The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0, \gamma = 1$ and $\gamma = 2$ in the FUND model without permit trading system. When $\gamma = 0$ and R_k equals 1.6, 3.2, 4.8 or 6, the values of A_r and A_p differ by less than 10^{-2} for all R_k, so the graph looks identical for different R_k. Therefore one graph is presented for $\gamma = 0$ and all R_k. The same is true for $\gamma = 1$ and $\gamma = 2$, so one graph is presented for $\gamma = 1$ (and $\gamma = 2$) and all R_k. $\gamma = 0$, $e = 1.2$ respect the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore a straight line is placed on $e = 1.2$ that connect A_r and A_p. As social welfare take complex values for $e > 0.9$. $\gamma = 1$, $e = 0.9$ satisfy the most appropriately the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore the graph of A_r and A_p are presented for value of $e \in [0, 0.9]$. $\gamma = 2$, $e \in [0.78, 1.08]$ respect the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore a straight line is placed on $e = 0.8$ and $e = 1.1$ that connect A_r and A_p.