Burden Sharing Emissions and Climate Change: A Theoretic Welfare Approach

Dritan Osmani [a b *]

[a] International Max Planck Research School on Earth System Modelling (IMPRS-ESM)

[b] Research Unit Sustainability and Global Change, Hamburg University and Center for Marine and Atmospheric Science, Hamburg, Germany

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Abstract

The approximated cost-benefit function of pollution abatement from two integrated assessment models are employed in constructing of social welfare functions (SWF). Following a normative approach and evaluating equally the environmental goods in rich and poor countries, furthermore using distributional weights, a relation between elasticity of marginal utility e and inequality aversion parameter γ is established. By maximizing the global social welfare, the optimal pollution abatement level are found. The relation between the income elasticity of marginal utility e and the inequality aversion parameter γ allow to narrow the variation of e for a particular value of γ. As a consequence, smaller variation for optimal abatement levels are obtained, which allows to inspect if the Kyoto abatement objectives respect the requirement of evaluating equally the environmental goods in rich and poor countries.

Keywords: cost-benefit analysis, distributional weights, global warming, welfare theory, integrated assessment modeling.

JEL: 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 benefit-cost analysis. As per capita income is lower in poor countries, then willingness-to-pay based estimates of 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 criterium that requires that the value of lost lives (also any environmental goods) in rich and poor countries has to be weighted differently. The normative approach is not realistic as it does not respect the WTP estimates which are the base of economic valuation. However, I would like to experiment in order to test the Kyoto emissions reduction targets requiring that the value of life is identical in poor and rich countries.

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 if the Kyoto emissions reduction targets are consistent with the requirement of valuing the life in poor and developed countries by weighting them differently.

Following Ray (1984) and 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 incomes per

*Research Unit Attainability and Global Change, Hamburg University and Center for Atmospheric Science, Bundesstrasse 55 (Pavillion Room 31), 20146 Hamburg, Germany +49 40 42838 6597 (voice) +49 40 42838 7009 (fax) dritan.osmani@zmaw.de

capita, the elasticity of marginal utility e and the inequality aversion parameter γ. The incomes per capita depend on GDP, population and costs and benefits from pollution abatement which are obtained from two different integrated assessment models namely the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model developed by Richard Tol, and the MITs Emissions Prediction and Policy Analysis (EPPA) model developed at MIT. The essential point of the paper is the development of a relation between e and γ by equalizing the value of life in poor and rich regions by following Ray (1984) and Stenman (2000) but allowing for larger range of parameters values that relates e and γ. As e and γ take their values in specific 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 (a global welfare optimization problem is built) 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 test if the abatement targets of Kyoto protocol respect the condition that the value of life is identical in poor and rich countries when equity weights are used. The costs and benefits from pollution abatements are calculated for the year 2010, which is considered as the representative year of the first commitment period of Kyoto protocol that includes the years 2008 through 2012.
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 value of life is equal to rich and poor countries.
The paper is structured as follows. Section two reviews the utility and welfare functions and derive equity weights. The section works with different types of welfare functions, including the utilitarian ($\gamma = 0$), Bernoulli-Nash ($\gamma = 1$), and a special welfare function ($\gamma = 2$)[1]. Section three assumes 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 four presents the optimization global welfare models without permit systems and with permit systems for two different integrated assessment models, FUND and EPPA. The sixth section presents the results. Section seven provide the conclusions. The appendix one contains different tables which present the relation between e and γ, main parameters of FUND and EPPA models, and Figures that illustrate the optimal abatement levels of poor and rich regions. In the appendix two the results of EPPA and FUND model without permits system are compared.

2 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:

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

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[2] to choose for e ? Pearce (2003) suggests a simple way, in case of the classical utilitarian welfare function, for estimating

[1] The reason why I do not use bigger values than 2 for γ is clarified in Footnote (5).

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

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:

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

Y is income, $\bar{Y}$ 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, $\left(\frac{\bar{Y}}{Y_p}\right)^e$, $\left(\frac{\bar{Y}}{Y_r}\right)^e$ 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:

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

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 these simple calculation basis, values even of $e = 2$ are not justified. The apparent consensus in the literature (Clarkson and Deyes, 2002; Pearce and Ulph, 1999; Cowell and Gardiner, 1999; Cline, 1992) on the value of e is $1 < e < 1.5$, although Pearce and Ulph (1994) suggest $e = 0.8$ by using household behavior models. What values can γ take? Firstly, note that γ must be integer in order to make possible for welfare function to take real values and not complex ones. When $e > 1$ utility function takes negative values which implies that γ will be the equality aversion parameter in stead of the inequality aversion one (Azar, 1999). The values for γ will be found by developing in the next subsection a relation between e and γ (Fankhauser et al., 1997; Stenman, 2000).
Equity weights can also be derived by totally differentiating the social welfare function(Ray, 1984; 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.

2.1 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; Stenman, 2000):

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

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:

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

γ has to be integer in order to ensure that welfare function takes real values (and not complex ones). 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). 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[3] $\frac{ln(u_r/u_p)}{ln(Y_p/Y_r)} < 0$. 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 are evidences that the ε can take also values of 0.33. The numerical computations, by letting values of $\gamma = \{0,1,2\}$[4], $Y_r/Y_p = \{3,4,5\}$ and $u_r/u_p = \{1.2, 1.3, 1.4\}$, show that the value of $e \in [0.8, 1.2]$, see Tables 1, 2, 3 and 4 in Appendix[5] one. 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 smaller variation for optimal abatement levels.

3 Allocation Model of Burden Sharing Emissions

The cost (benefit) functions from relative abatements levels for every world region (or region) i are taken from two different models which are: the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model developed by Richard Tol[6];the MITs Emissions Prediction and Policy Analysis (EPPA) model developed at MIT[7]. Two optimization problems are constructed for cost functions specified by different models: one without emissions trading and one with emissions trading. The optimization problems are solved by using the MATLAB Optimization Toolbox[8]. The variables of first optimization problem are: R_i's are relative abatements levels for every world region i; the variables of second optimization problem are again R_i's; the relative permissions levels for every world region i are equal to $(R(i) - R0)$ where $R_0 = 0.2$. The optimization problem without emissions trading is stated below:

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

$$\sum_{i=1:n} R_i \geq R_k{}^9 \tag{10}$$

$$-1 \leq R_i \leq 1 \tag{11}$$

where SWF_i is the social welfare functions for each region i. Let have:

$$(Z_i = GDP_i + B_i - C_i)/POP_i \tag{12}$$

where GDP_i is Gross Domestic Production for every region i, $B_i = f(R_i), C_i = f(R_i)$ are the benefit[10] and cost function for every region i, and they are function of the relative abatement level of region i, R_i. The costs and benefits from pollution abatements are calculated for the year 2010 which is considered as the representative year of the first commitment period of the Kyoto protocol that includes the years

[3] $\frac{ln(u_r/u_p)}{ln(Y_p/Y_r)} < 0$ as $ln(Y_p/Y_r) < 0,\ \ ln(u_p/u_r) > 0$ for $Y_p < Y_r,\ \ u_p < u_r$

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

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

[6] See Yang et al. (1996) for a description of the EPPA model.

[7] See Link and Tol (2004) and http://www.fnu.zmaw.de/FUND.5679.0.html for a description of the FUND model.

[8] Computing programs can be provided on request.

[9] The value of $R_k = 3.2$ is taken. Note that, as the abatement levels of individual regions are finally estimated as fractions of the global abatement levels and not in absolute terms, the selected value for R_k (also for the next optimization problem) is not crucial.

[10] The benefit function from pollution abatement are provided only from the FUND model, while the cost function from pollution abatement are provided from both models FUND and EPPA.

2008 through 2012. The Social Welfare Function (SWF) for each world region i is defined as:

$$SWF_i = POP_i \, \frac{\left(\frac{Z_i}{(1-e)}^{(1-e)}\right)^{(1-\gamma)}}{(1-\gamma)} \qquad \forall\, e \neq 1, \forall\, \gamma \neq 1 \tag{13}$$

$$SWF_i = POP_i \, \frac{\left(logZ_i\right)^{(1-\gamma)}}{(1-\gamma)} \qquad e = 1, \forall\, \gamma \neq 1 \tag{14}$$

$$SWF_i = POP_i \; log\left(\frac{Z_i}{(1-e)}^{(1-e)}\right) \qquad \forall\, e \neq 1, \gamma = 1 \tag{15}$$

$$SWF_i = POP_i \; log\left(logZ_i\right) \qquad e = 1, \gamma = 1 \tag{16}$$

Without constraints on the trading volumes, individually rational countries that maximize their utility of per capita income, will reduce their carbon emissions up to the point where their marginal abatements costs are exactly equal to the market price $C^{'}(R_i) = Pr$. This condition defines the emission reduction supply curve $RSi(Pr) = C^{'-1}(Pr)$. The market clearing price is defined as the price for which total supply is sufficient to achieve the emissions reduction constrain $RSi(Pr) = C^{'-1}(Pr) = 3.2$. The optimization problem with emissions trading is stated below:

$$\max \sum_{i=1:n} SWF_i \tag{17}$$

$$\sum_{i=1:n} R_i = 3.2 \tag{18}$$

$$\sum_{i=1:n} RS_i(Pr) = 3.2 \tag{19}$$

$$lb \leq R_i \leq ub \tag{20}$$

$$0 \leq Pr \leq 1000 \tag{21}$$

The optimization problem 17 has the same welfare function SWF, which is defined in equations (13), (14), (15) and (16), but Z_i is defined differently:

$$Z_i = (GDP_i + B_i - C_i + Pr(R_i - R_0)E_i)/POP_i \tag{22}$$

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 $Pr(Ri - R0)Ei$ (when emission permits are bought or sold), and changes also emissions cost, which is reflected at the cost function C_i.

The FUND model distinguishes 16 major regions of the world, viz. 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 benefit B and the cost C of a country (region) i in the FUND model are given as:

$$B_i - C_i = \beta_i \sum_{j}^{n} R_j E_j - \alpha_i R_i^2 Y_i \tag{23}$$

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 5.

The regions in EPPA model are United States of America (USA), Japan (JPN), European Union (EEC, EC-12 as of 1992), Other OECD Countries (OOE), Eastern Europe (EET), Former Soviet Union (FSU), Energy Exporting Countries (EEX), China (CHN), India (IND), Dynamic Asian Economies (DAE), Brazil (BRA) and Rest Of World (ROW). The cost C of a country (region) i in the EPPA model are given as:

$$C_i = 1/3a_i(R_iE_i)^3 + 1/2b_i(R_iE_i)^2 \tag{24}$$

where R denotes relative emission reduction, a and b are the cost parameters, and E are the unabated emissions, see Table 6.
The world regions for two models FUND and EPPA 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 1, 2, 3 and 4 in Appendix which make 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 emissions reduction levels too.
Four different types of optimization problem are considered, the first two ones are FUND (FUND-1) model and EPPA (EPPA-1) without a permit system. The comparison between the the FUND-1 and EPPA-1 is postponed to Appendix two, as the main purpose of comparing them, is to point out that the results are robust. The upper and low bounds of abatement variables for the first two optimization problem are tightened. If the bounds of variables are not contracted then the optimization for EPPA-1 shifts all the abatement weight to region OOE (Other OECD Countries) as they have a negative parameter (the parameter b) of cost calculation in the equation 24, which makes the results unreliable. The last two models are, the FUND model without permits system (FUND-2), and the FUND model with permits system (FUND-permit). The comparison between the FUND-2 and FUND-permit are presented in the next section.

4 Results, FUND with permits and without permits system

The results of the FUND model without permits system (FUND-2) and with permits system (FUND-permit) are discussed. The abatement levels are estimated as fractions of the global abatement levels. It means that I focus in the fraction of abatement levels that a region (like European Union) is undertaking but not in the absolute amount of it.
The results of FUND-2 are presented in Table 7 and in Figures 1, 3 and 5 while the results of FUND-permit are presented in Table 8 and in Figures 2, 4 and 6. Tables 7 represents all regions and their optimal abatement levels; different values of the elasticity of marginal utility e different values of the inequality aversion parameter γ are taken into account which respect the relation of e and γ originating from equation 8. The Figures[12] introduce the optimal abatement levels for rich and poor regions for γ equal to 0, 1 and 2 and $e \in (0, 1.5)$. The most reliable intervals of e for every specific γ are explained in every figure.
In both models approach (with and without permits system), the abatement levels of poor countries are different from zero as Kyoto protocol assigns. It implies that Kyoto protocol assigns a peculiar value of the elasticity of marginal utility e for every γ which exceeds the value of 1.5 (see Figures from 1 to 6). The peculiar choose of e for every γ leads to a selection of abatement levels which are not optimal.
Former Soviet Union has to abate pollution in large amounts, which is not foreseen in Kyoto protocol. All model approaches (EPPA-1, FUND-1, FUND-2 and FUND-permit) for every combination of parameters e and γ, predict that FSU has to play a central role in abatement policies among non-OECD countries. Therefore, it is considered as a robust result (see Tables 7 and 8).
FUND-permit is highly overestimating the optimal abatement level of Western European Union (by 132%). This result is also not robust as FUND-1 and EPPA-1 estimate the optimal abatement level of WEU similar to USA (EPPA-1 even lower than USA and equal to Japan)). However, seeing beyond

[11]Concerning FUND model, the world regions of United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ) are considered as OECD countries (or rich ones), and the rest of regions as non-OECD ones (or poor ones) while concerning EPPA model, world regions of United States of America (USA), Japan (JPN), European Union (EEC, EC-12 as of 1992), Other OECD Countries (OOE) are considered as OECD countries (or rich ones), and the rest of regions as non-OECD ones (or poor ones)

[12]Numerical instability is experienced for the single point $e = 1$ when $\gamma = 2$, therefore in Figures 5 and 6 a circle is placed in this particular point. However, the optimal abatement levels for the cumbersome point are presented in Tables 7 and 8, and they are consistent with conclusions. I think that the numerical instability is inherited from the shape of the social welfare function because the numerical experiments with the SWF for $e \neq 1$ (when $\gamma = 2$, see equation 13) and, $e = 1$ (when $\gamma = 2$, see equation 14) show that there is discontinuity for both types of functions for the neighborhood of particular point $e = 1$ (which must not be).

simple numbers, it is only a reinforcement that WEU is a key player in global abatement policies. USA has to undertake usually the highest abatement target (sometime WEU has higher abatement target) among all world regions which strengthens the conclusions that there is no successful climate change policy without USA. Japan (JPN) has to abate their pollution levels lower than USA and WEU but higher than any other country (except the FSU which surpass sometimes the abatement levels of Japan). Regions like Canada, Australia, China, India and East European Countries are changing their optimal abatement levels in a wide range from very low (or even negative ones) to some considerable amounts which certify that it is hard based on available information, to assign those countries the "right" abatement level.

5 Conclusions

The paper examines if the abatement targets that 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. Several different global welfare maximization problems with permits system and without permits system are established, which are constrained to the same specific global abatement level. 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 global welfare maximization problems, I make use of benefits and costs of pollution abatement for two different integrated assessment models, the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model developed by Richard Tol, and the MITs Emissions Prediction and Policy Analysis (EPPA) model developed at MIT.
By demanding that environmental goods are evaluated equally in non-OECD (or poor) and OECD (or rich) countries and using equity weights, a relation between the elasticity of marginal utility e and the inequality aversion parameter γ is set up. The relation helps us to contract the intervals of e for particular values of γ. Furthermore, it supports us to tighten the variation of optimal abatement levels when global social welfare is maximized.
It is found that the abatement targets of Kyoto protocol assume only a peculiar value for elasticity of marginal utility e for any possible given value of γ. This peculiar value of e produces no abatement level for developing countries which is not an optimal target. From the other side, the abatement levels for developed countries are correctly assigned. On the opposite the Former Soviet Union has to play a central role among developing countries which is not foreseen in Kyoto protocol. Regions like Canada, Australia, China, India and East European Countries are changing their optimal abatement levels in a wide range which indicates that it is difficult to assign an abatement target to those countries.
As always, further extensions are possible such as the implementation of dynamic framework for a longer time interval, or finding a way of including of political factors in modeling approach.

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Appendix 1

Table 1: 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 2: 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 3: 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 4: 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 5: The FUND data from the year 2010, where α is the abatement cost parameter (unitless), β the marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) E the carbon dioxide emissions (in billion metric tonnes of carbon), Y gross domestic product, in billions US dollars and population in millions people. Source: FUND

	α	β	E	Y	*Population*
USA	0.0152	2.0882	1.7315	11886	295.1
CAN	0.0152	0.0966	0.1315	93	33
WEU	0.0157	3.1036	0.786	14072	39.2
JPK	0.0156	-1.1404	0.5675	9829	185.7
ANZ	0.0151	-0.0257	0.0855	526	25.3
EEU	0.0147	0.1057	0.189	476	122.4
FSU	0.0138	1.1862	0.952	751	291.5
MDE	0.0144	0.1087	0.4875	742	292.2
CAM	0.0149	0.0833	0.126	456	155.5
LAM	0.0151	0.2542	0.2445	1578	390.7
SAS	0.0144	0.3678	0.6575	1064	1585.6
SEA	0.0149	0.7108	0.413	1432	600.8
CHI	0.0145	4.7834	1.6145	3085	1429.7
NAF	0.0147	0.8981	0.1105	261	176.5
SSA	0.0147	0.9469	0.157	374	810.1
SIS	0.0144	0.0627	0.0435	66	49.7

Table 6: The EPPA data from the year 2010, where a, b are the abatement cost parameters (in dollars per tonne of carbon, $a + b$ is the marginal damage costs of first tonne of carbon dioxide emissions), E the carbon dioxide emissions (in billion metric tonnes of carbon), Y gross domestic product, in billions US dollars and population in millions people. Source: EPPA and Weikard et al. (2006)

	a	b	E	Y	*Population*
USA	0.0005	0.0398	2.42	8845	305
JPN	0.0155	1.816	0.56	5584	124
EEC	0.0024	0.1503	1.4	9579	375
OOE	0.0085	-0.0986	0.62	1902	142
EET	0.0079	0.0486	0.51	405	120
FSU	0.0023	0.0042	1	501	287
EEX	0.0032	0.3029	1.22	1650	1602
CHN	0.0001	0.0239	2.36	1021	1340
IND	0.0015	0.0787	0.63	458	1145
DAE	0.0047	0.3774	0.41	972	207
BRA	0.5612	8.4974	0.13	774	190
ROW	0.0021	0.0805	0.7	1119	584

Table 7: Relative abatement levels (as ration of global abatement levels) for different world regions, FUND model without permits system (boundshigh, equal constrains)

	$\gamma = 0, e = 1.2$	$\gamma = 1, e = 0.9$	$\gamma = 2, e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
USA	0.62	0.34	0.62	0.46	1.95	0.25
CAN	-0.48	-0.13	-0.48	-0.28	-2.08	-0.03
WEU	1.52	0.85	1.52	1.19	2.5	0.56
JPK	0.22	0.13	0.22	0.17	1.25	0.1
ANZ	-0.74	-0.28	-0.74	-0.5	-2.18	-0.13
EEU	-0.05	-0.004	-0.05	-0.03	-0.54	0.02
FSU	0.2	0.19	0.2	0.19	0.15	0.19
MDE	0.06	0.07	0.06	0.06	0.31	0.07
CAM	-0.07	-0.03	-0.07	-0.05	-0.32	-0.01
LAM	-0.004	0.01	-0.004	0.002	0.03	0.01
SAS	0.02	0.02	0.02	0.02	0.003	0.02
SEA	0.02	0.02	0.02	0.02	0.03	0.03
CHI	0.07	0.07	0.07	0.07	0.06	0.07
NAF	-0.06	-0.03	-0.06	-0.05	-0.14	-0.01
SSA	-0.01	-0.003	-0.01	-0.01	0.07	0.001
SIS	-0.31	-0.21	-0.31	-0.27	-0.08	-0.15

Table 8: Relative abatement levels (as ration of global abatement levels) for different world regions, FUND model in a permits system (boundshigh, equal constrains)

	$\gamma = 0, e = 1.2$	$\gamma = 1, e = 0.9$	$\gamma = 2, e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
USA	0.6	0.34	0.6	0.45	2	0.23
CAN	-0.84	-0.43	-0.85	-0.63	-2.12	-0.3
WEU	1.32	0.63	1.32	0.96	2.33	0.39
JPK	0.13	0.09	0.13	0.1	0.57	0.07
ANZ	-1.09	-0.65	-1.09	-0.86	-2.12	-0.48
EEU	-0.04	0.01	-0.04	-0.01	-0.56	0.02
FSU	0.53	0.51	0.53	0.52	0.62	0.51
MDE	0.21	0.21	0.21	0.21	0.17	0.21
CAM	-0.07	-0.03	-0.07	-0.05	-0.35	-0.02
LAM	0.01	0.02	0.01	0.01	-0.17	0.02
SAS	0.18	0.19	0.18	0.18	0.18	0.19
SEA	0.08	0.08	0.08	0.08	0.06	0.08
CHI	0.21	0.21	0.21	0.21	0.23	0.2
NAF	-0.01	0.01	-0.01	0.003	0.03	0.02
SSA	0.1	0.1	0.1	0.1	0.08	0.1
SIS	-0.31	-0.26	-0.31	-0.28	0.05	-0.25

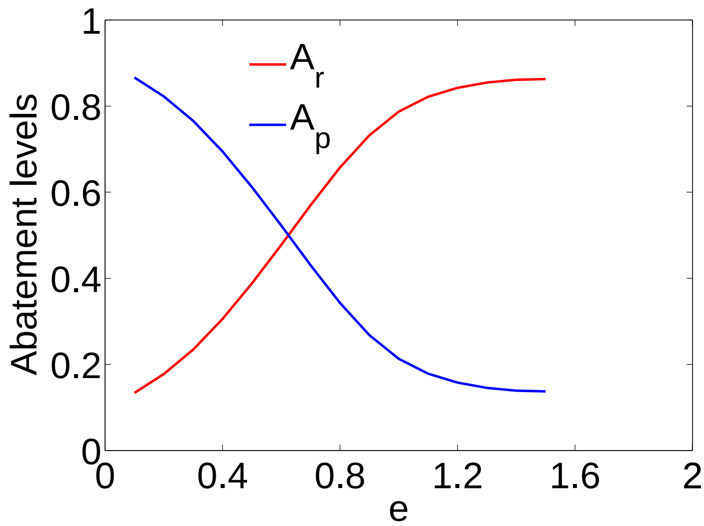

Figure 1: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0$ without permit trading system, FUND model. Note that when $\gamma = 0$, e $= 1.2$ so values of A corresponding to e $= 1.2$ are considered as more realistic.

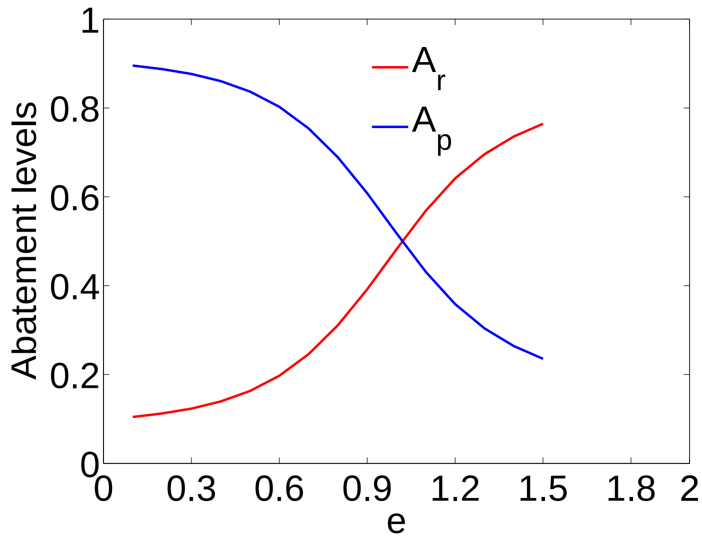

Figure 2: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0$ in permit trading system, FUND model. Note that when $\gamma = 0$, e $= 1.2$ so values of A corresponding to e $= 1.2$ are considered as more realistic.

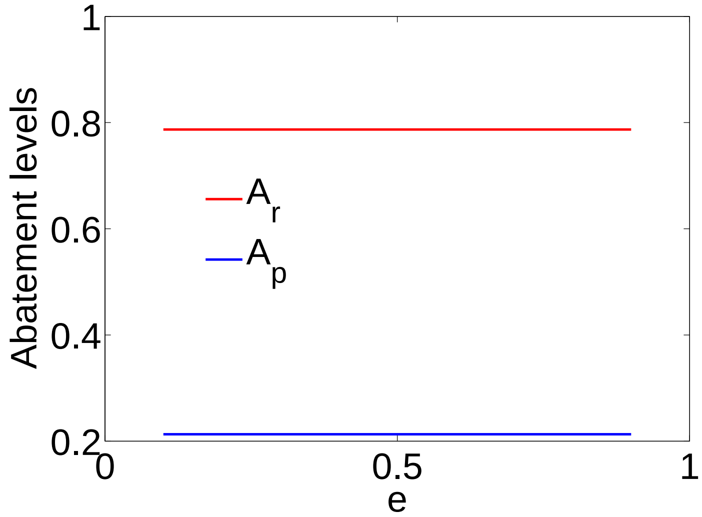

Figure 3: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 1$ without permit trading system, FUND model. Note that when $\gamma = 1$, $e \in (0.99, 1.1)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

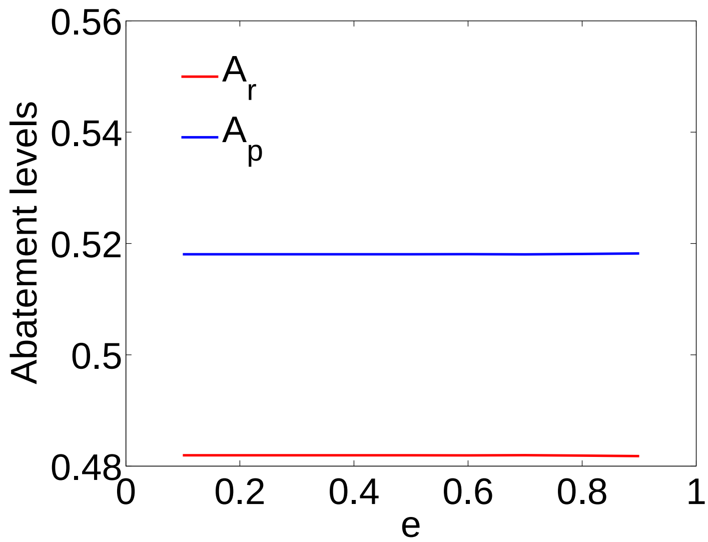

Figure 4: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 1$ in permit trading system, FUND model. Note that when $\gamma = 1$, $e \in (0.99, 1.1)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

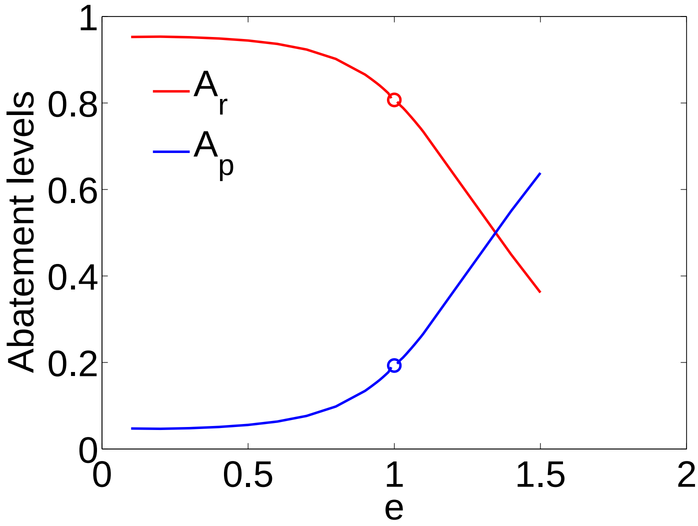

Figure 5: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 2$ without permit trading system, FUND model. Note that when $\gamma = 2$, $e \in (0.78, 1.08)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

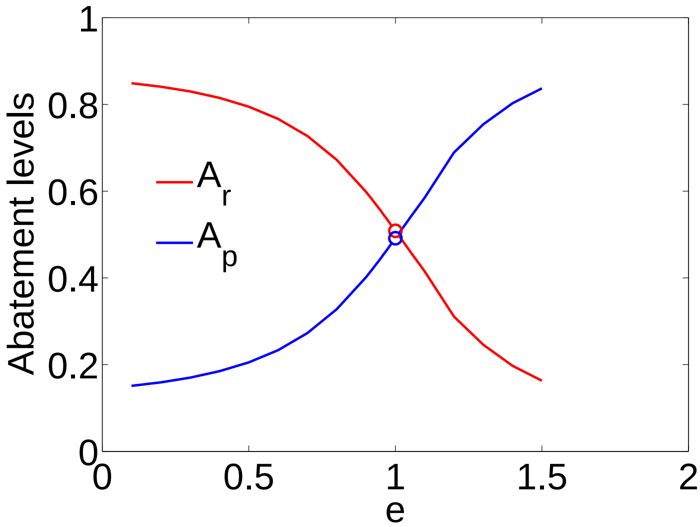

Figure 6: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 2$ in permit trading system, FUND model. Note that when $\gamma = 2$, $e \in (0.78, 1.08)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

Appendix 2

5.1 Comparing results for FUND and EPPA models without permits

The first optimization problem is primarily used in order to make clear that results are robust as estimations from two different models FUND and EPPA display similarities[13].
Table 9, Figures 7, 9 and 11 present the results for FUND model while Table 10, Figures 8 and 10 present the results for EPPA model. Tables 9 represent all regions and their optimal abatement levels (for FUND model) for values of the elasticity of marginal utility e that corresponds to the values of inequality aversion parameter γ (according to relation of e and γ from equation 8). The Figures[14] introduce the optimal abatement levels for rich and poor regions for γ equal to 0, 1 and 2 and $e \in (0, 1.5)$. The most reliable intervals of e for every γ that equals 0, 1 and 2 are given for every figure.
The results demonstrate similar pattern, namely the abatement levels of rich countries are higher than those of poor countries (see Figures from 7 to 10 and Tables 9 and 10). But the abatement levels of poor countries are not zero. The FUND model predicts that the optimal abatement levels of poor countries are in the range of 37 % to 50 % of the total global level, while the EPPA model predicts that the optimal abatement levels of poor countries are in the range from 11 % to 46 % of the total global level. The models affirm that the Kyoto protocol assigns a peculiar value to the marginal elasticity of substitution e for any value of the inequality aversion parameter γ, which advices no abatement efforts for poor countries. Both models also forecast that the Former Soviet Union (FSU) must have a high abatement level which anticipates the Kyoto target for FSU. They assign to China (respectively 2% and 0.2%) and India (respectively 1% and 0.4%) low abatement targets.
The main difference between models is that EPPA assigns to other OECD countries (OOE where Canada and Australia are essential players) a high abatement level of 42%, while FUND assigns to Canada and Australia together only 24%. Other differences, the changes in abatement levels for Western European Union, Japan and Eastern European Countries.

[13] When comparing FUND with EPPA, I use lower bounds equal to -1, while upper bounds equal to 1. Those bounds are used as EPPA models shifts all abatement burdens to region OOE (other OECD countries) as they have partly benefits from pollution abatement (the parameter cost b is negative, see Table 6).

[14] Numerical instability is experienced for the single point $e = 1$ when $\gamma = 2$ for FUND model, and for the interval $e \in (0.8, 1.08)$ when $\gamma = 2$ for EPPA model. Therefore, a circle is placed in the point $e = 1$ in Figures 11. This happens, as already clarified in Footnote 12, because the shape of Social Welfare Function with two parameters (e and γ) behaves inappropriately at the point $e = 1$ (when $gamma = 2$). We experience numerical instability when $\gamma = 2$, which is located in an interval (not in a single point) for EPPA model. The stopping criteria for the optimization problem are sufficiently small (around 10^{-19}), which help to think that the numerical instability occurs because the variation of the optimal abatement levels is very sensible to the variations of elasticity of marginal utility e. There is no Figure for EPPA model when $\gamma = 2$, but the results of optimization problem are shown in the Table 10. Anyway, the variation of the optimal abatement levels stays in an interval that makes possible to claim that the EPPA results have a similar pattern with FUND, and therefore, are still robust.

Table 9: Relative abatement levels (as ration of global abatement levels) for different world regions, FUND model, second optimization problem without permits system (boundslow)

	$\gamma = 0, e = 1.2$	$\gamma = 1, e = 0.9$	$\gamma = 2, e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
USA	0.12	0.13	0.12	0.13	0.1	0.15
CAN	0.12	0.13	0.12	0.13	0.1	0.1
WEU	0.12	0.13	0.12	0.13	0.1	0.17
JPK	0.12	0.1	0.12	0.12	0.1	0.07
ANZ	0.12	0.11	0.12	0.12	0.1	0.09
EEU	0.05	0.05	0.05	0.05	0.1	0.05
FSU	0.11	0.11	0.11	0.11	0.1	0.12
MDE	0.05	0.05	0.05	0.05	0.08	0.06
CAM	0.03	0.03	0.03	0.02	0.05	0.03
LAM	0.02	0.02	0.02	0.02	0.06	0.02
SAS	0.01	0.01	0.01	0.01	0.004	0.02
SEA	0.02	0.02	0.02	0.02	0.03	0.02
CHI	0.04	0.04	0.04	0.03	0.04	0.04
NAF	0.02	0.02	0.02	0.02	0.01	0.02
SSA	0.004	0.01	0.004	0.01	0.01	0.01
SIS	0.02	0.03	0.02	0.03	0.004	0.03

Table 10: Relative abatement levels (as ration of global abatement levels) for different world regions, EPPA model, second optimization problem without permits system (boundslow)

	$\gamma = 0, e = 1.2$	$\gamma = 1, e = 0.9$	$\gamma = 2, e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
USA	0.1	0.1	0.06	0.11	0.07	0.06
JPN	0.06	0.06	0.07	0.06	0.27	0.03
EEC	0.06	0.07	0.08	0.03	0.13	0.04
OOE	0.42	0.31	0.39	0.42	0.42	0.42
EET	0.14	0.17	0.16	0.14	0.05	0.16
FSU	0.15	0.2	0.17	0.18	0.02	0.21
EEX	0.0006	0.001	0.002	0.0004	0	0.001
CHN	0.002	0.002	0.002	-0.003	0	0.003
IND	0.004	0.01	0.001	0.01	0.0002	0.01
DAE	0.04	0.04	0.04	0.02	0.03	0.03
BRA	0.01	0.01	0.01	0.01	0.01	0.01
ROW	0.02	0.03	0.005	0.01	0.005	0.03

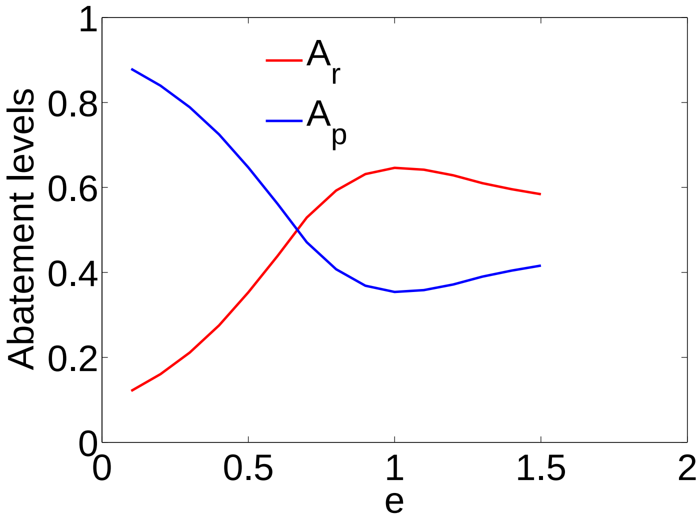

Figure 7: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0$, FUND model. Note that when $\gamma = 0$, e = 1.2 so values of A corresponding to e = 1.2 are considered as more realistic.

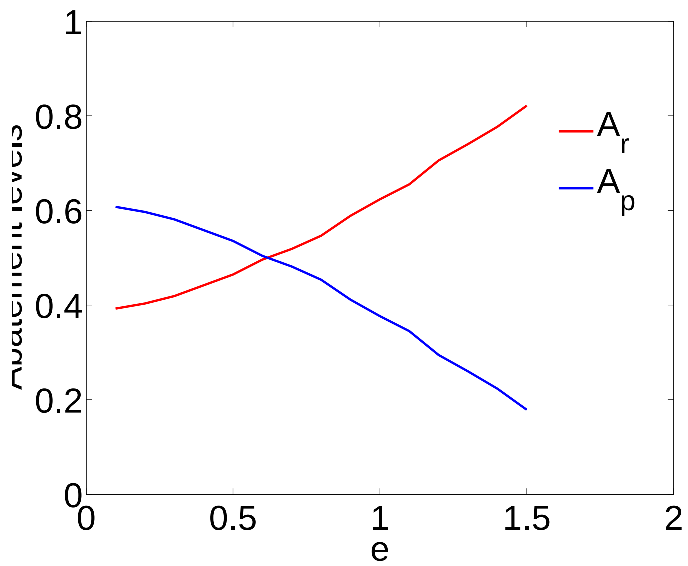

Figure 8: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0$, EPPA model. Note that when $\gamma = 0$, e = 1.2 so values of A corresponding to e = 1.2 are considered as more realistic.

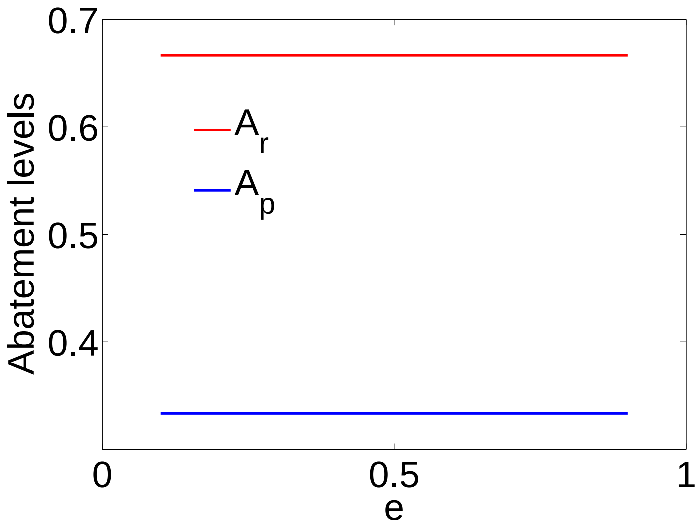

Figure 9: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 1$, FUND model. Note that when $\gamma = 1$, $e \in (0.99, 1.1)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

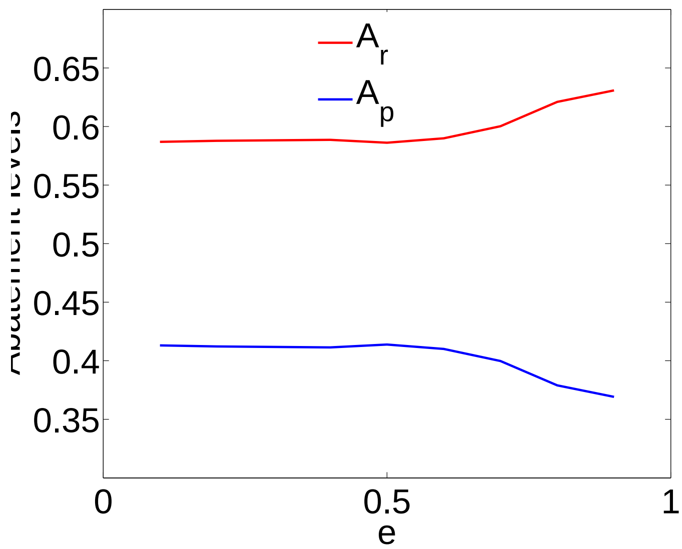

Figure 10: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 1$, EPPA model. Note that when $\gamma = 1$, $e \in (0.99, 1.1)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

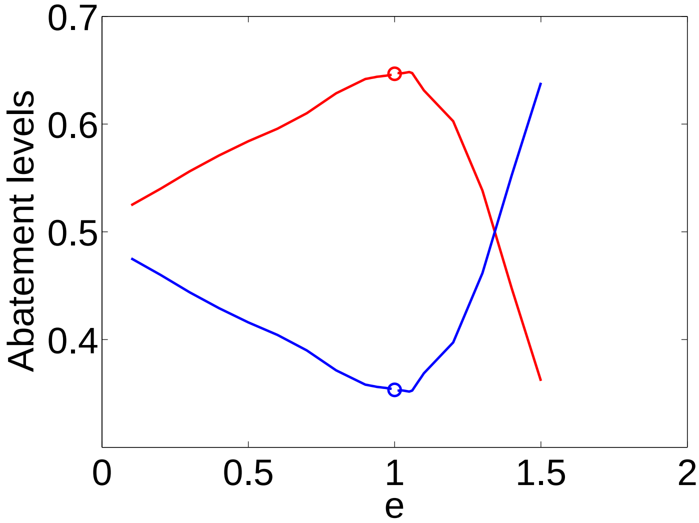

Figure 11: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 2$, FUND model. Note that when $\gamma = 2$, $e \in (0.78, 1.08)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

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