# Green Growth and Sustainability:
# Analyzing Trade-offs in Climate Change Policy Options

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**Abstract**

We investigate the trade-offs between economic growth and low carbon targets for developing and developed countries in the period up to 2035. Policy options are evaluated with an original version of the dynamic CGE model GDynE. Abatement costs appear to be strongly detrimental to economic growth for developing countries. We investigate options for reducing these costs that are consistent with a green growth strategy. We show that Green Climate Fund financed through a levy on carbon taxation can benefit all parties, and larger benefits are associated with investment of the Green Climate Fund to foster energy efficiency in developing countries.

**Keywords:** Climate Change Policies, Green Growth, Developing Countries, Dynamic CGE Energy Model, Green Climate Fund

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## 1. Introduction

One of the politically most controversial climate change questions is how much will it cost to meet the greenhouse gas emissions reduction targets that are consistent with a reasonable probability of avoiding major upheavals in the world's climate in the medium to long term. There has been a huge amount of work on this over the last twenty years or more (Clarke *et al*., 2009). The issues under debate cover several aspects, ranging from the quantification of abatement costs to the distribution of these costs across countries. The uncertainty characterizing the assessment exercises is one source of difficulty in reaching a global consensus on the effective actions to be taken by the bargaining parties in international negotiations.

The main purpose of this paper is to analyze a specific aspect of the difficulty regarding the assessment of alternative policy options aimed at reducing abatement costs for developing countries in order to facilitate the achievement of a global consensus. The principle of Common But Differentiated Responsibilities (CBDR), introduced in the general framework adopted by the United Nations Convention on Climate Change (UNFCCC) and fully adopted by the Kyoto Protocol (KP), has acknowledged different capacities and needs of developed and developing countries, and has proposed a differentiated approach to computing emission reduction efforts. It takes the view that, although addressing climate change is a global challenge, national responsibilities should be differentiated, with developed countries bearing a heavier burden in both reducing emissions and providing resources for adaptation measures than developing countries.

The issue of CBDR is currently being debated as a crucial point in Post-Kyoto negotiations. Developing countries consider it as being based on historical responsibility for Greenhouse Gas (GHG) emissions whereas developed countries emphasize the role of current and future emissions trends. Developing countries are now responsible for more than half of global GHG emissions (IEA, 2013a) and the projected emissions trend reveals that the share of GHG assigned to developing countries by 2035 will reach almost 70% of global emissions (Oliver *et al*., 2012). These figures explain why these countries are asked to participate actively in abatement actions by the developed nations.

Starting with the Copenhagen Agreement (UNFCCC, 2009), the interpretation of CBDR has begun to be softer, reflecting both the developed countries' position which demands a more stringent abatement effort for major developing economies and the developing countries' demand for maintaining differentiation in burden sharing. It is clear that positive outcomes in terms of reducing global warming are likely only if global efforts are undertaken by all parties (Brunnée and Streck, 2013).

At the same time, several concerns about potential abatement costs in terms of economic growth expectations and equity within and between countries reduce the propensity of developing countries accepting binding constraints on GHG emissions since they consider them a strong limit to their development prospects (Golub *et al.*, 2006; Markandya, 2011).

While no clear agreement on such negative impacts has been reached at the international level by the scientific community, assessment models have nonetheless emphasized that the potential costs of undertaking emissions reductions would affect the whole economy. The models used to estimate the costs of different low carbon trajectories over periods up to 2100 and beyond differ in many respects. Looking so far into the future requires a number of assumptions to be made about how the economic systems will evolve and, especially, about what technologies will be available, at what cost, and how the burden of decarbonizing will be shared across the different nations. Hence, it is not surprising that the results across the models have some variations (Edenhofer *et al*., 2010; Nordhaus, 2013).

Together with the uncertainty about the overall abatement costs assessment, another concern that has been expressed is that economic losses (usually expressed in terms of GDP reduction) vary according to region. In the majority of models currently available, China has costs that are consistently higher than the world average and the US has the highest costs among developed countries.

One of the most used physical scenarios refers to an energy pathway consistent with the goal of limiting the global increase in temperature to 2°C by limiting concentration of greenhouse gases in the atmosphere to around 450 parts per million (PPM) of $CO_2$ by 2050.

Research on possible impacts of not meeting the 450 PPM target indicates these could be very significant and destabilizing for the world. Yet, with the exception of the European Union (EU), practically no country or region is currently following policies that will lead to a 450 PPM stabilization target along the paths identified in the mitigation research. There are a number of reasons that explain this behaviour.

The first point is that even though the global costs of meeting the target are small, they are significant in the short term, and the benefits in terms of avoided damages, while potentially large, will occur further in the future (2050 and beyond). (Nordhaus, 2007; Stern, 2007; Tavoni and Tol, 2010; Tol and Yohe, 2006).

This question of the time profile of costs is perhaps the most important factor. Estimates are based on discounted values for 2011, using discount rates of 3 to 5 per cent. Decisions to act, however, are much more influenced by the costs to be borne in the immediate future. The pressing imperative of current budgets and impacts on the living standards of people today play a role that is much greater than can be captured by the 2100 net present value costs. This is something that exercises the minds of politicians much more than the discounted present value cost to 2100. If we can throw some light on the reasons for the differences and possible implications for other key macroeconomic indicators, we will have more influence on policy. This will be even more useful if we can find ways to keep the short term costs as low as possible, perhaps even if it means a slightly higher cost in the distant future. The issue of short term costs is especially important for developing countries.

Although several different approaches and models have been developed (Anandarajah *et al.*, 2011; Andersen and Ekins, 2009; Barker *et al.*, 2011; Criqui *et al.,* 1999; Kreiser *et al.*, 2011; Lutz and Meyer, 2009, 2010), there is still no clear answer to the question of what will happen in the short to medium term if we impose taxes or take other measures to make much bigger reductions in GHGs, in line with the 450 PPM target.

It is in this vein that the present paper wishes to contribute to the discussion by developing a dynamic economic-energy model that can simulate alternative and feasible policy options and that focuses on the relatively short and medium term costs of climate policies in a global setting in order to facilitate the current international negotiation debate.

In particular, since developing countries are considered crucial to reaching effective abatement measures, we have specifically developed modeling choices in this direction. Since assessing alternative policy options is the core issue examined here, our model should be as close as possible to those developed and currently used by the international scientific community in order to provide comparable results by making assumptions that are widely acceptable.

Most importantly, to the best of our knowledge, there is no scientific contribution assessing the potential role played by the new and highly debated Green Climate Fund (GCF), which seems to represent the climate instrument that most developing countries are focusing on in order to reach a consensus in the Post Kyoto negotiations. The GCF, when operational, would channel significant financial resources into adaptation and mitigation, potentially enhancing the development of low-emission technologies in developing countries. The fund tries to solve a number of problems clearly summarized in Cantore *et al*. (2009), constituted not only by the level of finance provided by developed countries to developing countries for mitigation and adaptation, but also the mechanisms for raising such finance, the financial instrument used to distribute it and its governance.

During recent Conferences of the Parties (COPs), and specifically those held in Cancun (2010), Durban (2011), and Warsaw (2013), the GCF has been discussed and envisaged as a unique global fund financed by all nations in different ways to implement climate change mitigation and adaptation measures in those countries in which climate change is expected to have the greatest impact. The GCF (which is part of the UNFCCC) represents the main multilateral financing mechanisms to support climate action in developing countries. It will channel a significant share of financing for adaptation and mitigation, including activities to reduce emissions from deforestation and degradation, and it was expected to be fully operational by 2014. Regarding the status of the contributions, at the Cancun conference (2010), following the Copenhagen track, a target of 100 billion US dollars by 2020 was established, with an initial allocation of 30 billion in the first three years. As of March 31, 2014, the total amount of pledges and contributions to the GCF Trust Fund amounted to only around USD 55 million, managed by the World Bank as the interim trustee.

Although the size of contribution is still unclear, it is widely considered that it will be significantly greater than existing climate funds. These resources will support cost-efficient mitigation and adaptation initiatives in a balanced way, putting an emphasis on potential environmental and social and development co-benefits. It is worth noting that both developed and developing countries have equal representation in the GCF board where Least Developed Countries (LDCs) and Small Island Developing States (SIDS) are expected to be the largest beneficiaries. (Grießhaber *et al*. 2012).

Some aspects of the fund's operation require further discussion, such as the observers participation regime (and its financial support), the inclusion of other stakeholders (i.e. the development of finance institutions) and countries, the relationship with the COP (currently guiding on eligibility criteria and priorities) and, most importantly, the criteria for allocating resources (Schalatek *et al*., 2012).

Such an initiative will of course help to face the detrimental climate change impacts, but another important issue, the growth of developing countries (hopefully, in qualitative terms, via "green growth"), remains unaddressed. This constitutes an important shortcoming in such a global initiative and is also  a lost opportunity to address the important issue of growth in this context.

We consider this gap in the scientific literature as crucial to depicting a clear assessment of alternative policy options and thus driving negotiations. Hence, we propose an original modeling approach in order to partially fill this gap. The following additional aspects have therefore been introduced:

i) We analyze the effects of starting on a path that does not allow the world to exceed 450 PPM equivalent concentrations of GHGs by 2050 and compare it with the impacts of such policies as are necessary to be on track for this target over the period up to 2035.  This focus on the medium term horizon is more useful for current policy design.

ii) We develop a specific version of the CGE dynamic GTAP model with an energy module, known as GDynE (Golub, 2013), which include the implementation of the GCF discussed in the Post Kyoto negotiations among the climate policy options.

iii) We explore how the GCF could be reasonably financed and what would b the costs for developed countries to create and sustain GCF.

iv) We model alternative options in terms of how the GCF can be used in developing countries in order to understand if some win-win solutions may help in solving the negotiation deadlock and lead to a reduction in abatement costs for both developed and developing economies through promoting technological innovation, which will make participation in an agreement more attractive for developing countries.

The rest of the paper is structured as follows: Section 2 lays out a description of the model used, Section 3 presents the simulation design, Section 4 describes the main results, and Section 5 outlines conclusions and policy implications.

## 2. The model

### *2.1 The GDynE: an energy version of the dynamic GTAP*

The energy version of the well-known GTAP (Global Trade Analysis Project) developed in Purdue University and available in a static setting (Burniaux and Truong, 2002; McDougall and Golub, 2007) is now also available in a dynamic setting (GDynE) as described in Golub (2013).

The standard version of GDyn (Lanchovichina and McDougall, 2000) is a recursive-dynamic extension of the standard GTAP (Hertel, 1997), developed for better treatment of long term simulations. While preserving, on the one hand, all the standard features of the GTAP model – perfect competition, Armington elasticities for trade flows, disaggregated imports by activity, non-homothetic consumer demands and explicit modeling of international trade and transport – it enhances the investment side of the framework to allow for international capital mobility and ownership. A more sophisticated theory of investments based on adaptive expectations allows for a disequilibrium approach to model international capital mobility endogenously (for a theoretical review, see Lancovichina and Walmsley, 2012). The GDyn model uses the standard GTAP database supplemented with additional foreign income data provided by the International Monetary Fund (IMF) Balance of Payments Statistics in order to track international capital mobility.

The energy version of the GDyn, here referred to as GDynE, results from the merging of the static version of GTAP-E with GDyn, maintaining all the policy modeling choices developed for the static version. In particular, it includes an explicit treatment of energy demand, the possibility of inter-factor and inter-fuel substitution, data on carbon dioxide emission accounting at sector and regional level, and the possibility of introducing market-based policy instruments such as carbon taxes or emission trading.

The GDynE developed by the authors and adopted here uses the latest version of the GTAP-Database (GTAP-Database 8.1, updated to 2007), together with the latest version of the additional GTAP-Energy data on $CO_2$ emissions along with the arrays in the standard GTAP-Database 8.1.

With regard to the GDynE version developed by Golub (2013), we have made several changes to the behavioral parameters in order to improve the reliability of simulations in terms of abatement costs and growth effects.

The first and most significant improvement regards the elasticities of substitution between energy and capital which are crucial in determining how the output in different sectors is affected by energy price changes. According to Antimiani *et al*. (2013), the impact in terms of different reaction behaviors for abating countries with substantially different reduction targets related to alternative substitution values is quite large and it requires greater modeling accuracy. The key elasticities that have been modified are given in Table 1. In the first column (GTAP Standard), we report the substitution elasticity values provided in the standard version of GTAP (Golub, 2013) which have been criticized for not being empirically based. In this respect, Beckman *et al*. (2011) proposed alternative values (second column in Table 1) on the basis of a review of recent empirical estimates. Such values, however, are considered by many too restrictive.

Other meta-analysis include Koetse *et al*. (2008) for energy-capital substitution elasticity (ELKEN in GTAP nomenclature) and Stern (2012) for inter-fuel elasticities. In this model we have adopted the figures from the last two studies as representing the base case (the third column in Table 1). The elasticities we have chosen give results closer to those from models in the Edenhofer *et al*. (2010) where other modelling approaches have been compared.

**Table 1**

With regard to the other behavioral parameters adopted in GTAP models that are exogenously given, the following further adjustments have been made to the standard model.

The Armington elasticities for energy commodities have been changed as suggested in Hertel *et al*. (2007) in order to improve the coherence of the geographical pattern of emissions when unilateral climate policies are simulated.

An autonomous energy efficiency improvement parameter (AEEI) has been modeled in the baseline as an exogenously given input augmenting technical change. This is a common parameter in bottom-up energy-technology models (de Beer, 2000).[1]

[1] The use of a single parameter to capture all the latent non-price technology developments has been subject to criticism (Grubb *et al*., 1993; Mabey, 1997 among others). Dowlatabadi (1998) and Dowlatabadi and Oravetz (1997) note for example that there are at least two other transmission channels able to capture the potential of technical change in decoupling energy consumption and economic growth: the price-induced elasticity of substitution between energy and other factors and the price elasticity of demand of energy. Therefore, the AEEI is able to explain non-price factors as well as structural changes only partially (for a recent contribution, see Webster *et al*. 2008). On the other hand, the AEEI approach is simple and reduces the risk of model non-linearities, multiple equilibria and permits ready sensitivity analysis using different AEEI values (Popp et al., 2010). This ease of use, together with the rich empirical documentation on the value of this parameter, makes it a common feature in several environmental-energy economy models (E3) as well as in the Global 2100 models (Manne and Richels, 1992; Manne *et al*., 1994), GREEN

## *2.2 The modeling specification of the Green Climate Fund*

A key novelty of the modeling approach adopted here is represented by explicit equations which allow for the introduction of a GCF.

The assumption here is that a percentage of total carbon related revenue gathered by governments of developed countries, either through a carbon tax or an emissions trading scheme is collected by the GCF. This share can be treated as an exogenous parameter according to a potential international agreement in the sense that all developed countries participating in a Post-Kyoto agreement commit to providing a x% from their carbon tax revenue (CTR). This payment by developed countries is subtracted from their equivalent variation (EV), resulting in an additional cost to abatement efforts and a reduction in domestic welfare.

The x% of CTR is uniformly applied to all developed economies, meaning that it is set during international negotiations. Further interesting issues may arise when the x% is endogenously given by different criteria that should be negotiated (this could be an interesting future research issue to investigate). Given that x% is exogenous, the higher the CTR value for one country, the higher its contribution to GCF.

In mathematical terms, the formation of the GCF is built as follows.

We have modeled the contribution that all countries may make to the GCF as a share of the total CTR.[2] In formulas, total revenue from $CO_2$ abatement is computed as:

$$CTR(r) = CO2(r) \cdot CTAX(r) \qquad (1)$$

where $CTR(r)$ is the revenue in country $r$ resulting from a tax on a target level for $CO_2$ emissions and $CTAX(r)$ is the domestic level of carbon tax or alternatively the permit equilibrium price if emission trading is allowed in that country. Finally $CO2(r)$ is the amount of taxable emissions in country r. The value of $CTR$ which is devolved towards the GCF is modeled as:

$$CTRF(r) = \alpha(r) \cdot CTR(r) \qquad (2)$$

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(OECD, Burniaux *et al*., 1992), ERB (Edmonds and Reilly, 1985), and also in the more recent models using GTAP database such as ENVISAGE used by the World Bank (van der Mensbrugghe, 2008) or EPPA version 3 and 4 (Babiker et al., 2001 and Paltsev et al., 2005, respectively) developed at the Massachusetts Institute of Technology. Well conscious of its limitations and aforementioned drawbacks, we decided to incorporate such a parameter in the GDynE model since this still represents a standard modeling approach in this literature.

[2] In the GDYnE carbon taxation is modelled as a standard lump sum in welfare computation.

where $\alpha(r)$ represents the national contribution to $GCF$. $CTRF$ corresponds to a reduction in the total $CTR$ which must in turn be deducted from a measure of a country's welfare (taken to be its equivalent variation (EV)) since it is to be considered a net cost (tax payers are less than compensated by the lump sum). The GCF is thus given by the sum of all regional contributions:

$$GCF = \sum_{r=1}^{N} CTRF(r) \tag{3}$$

According to the Post Kyoto negotiations, the GCF should only be funded by developed economies, hence $\alpha(r)$ will be equal to zero for developing countries and equal to x% which can be equal across developed countries or differentiated on the basis of the international negotiations outcome.

The GCF is then distributed to all developing countries according to a parameter that can change according to the scenario under scrutiny. The contribution of GCF to each region ($RGCF(r)$) is computed by applying a distribution parameter $\beta(r)$, representing the share of the GCF going to each country ($r$). This means that it is not possible to bank anything in this formulation and the whole fund is used completely in each period resulting in $\sum_{r=1}^{n} \beta(r) = 1$ with $\beta(r) = 0$ if $r$ is a developed country.[3]

$$RGCF(r) = GCF \cdot \beta(r) \tag{4}$$

In this paper we have set the distribution parameters at the regional contribution to world economy in terms of GDP in 2010. This means that countries with larger GDP shares receive a proportionally greater share of GCF. Further efforts in terms of assessing distributive impacts of GCF will be analyzed in the future.

As already mentioned, in our scenarios we modeled the contribution of GCF going solely to developing countries. This means that GCF is funded by developed economies and used by developing ones with no overlapping cases. This is a modeling choice that can be changed and GDynE can be used for all possible combinations with a full overlapping option.

In terms of how to use $RGCF(r)$, we hypothesized three alternative solutions that can also be combined in a sort of policy mix strategy.

The first one is to use GCF for redistributive purposes only, so it is distributed to developing countries according to some exogenous criteria ( $RGCF(r)$ in eq. (4)), as a lump sum thus increasing only the welfare level as an additional factor to the EV of the receiving country:

[3] Further analysis on banking solutions would be possible in the future.

$$EVGCF(r) = RGCF(r) \tag{5}$$

In this way, the total contribution of GCF to receiving regions is modeled as a direct contribution to welfare levels as a positive term of the equivalent variation (6a) and the reduction due to funding contribution influences the EV formula for the funding regions (6b) as follows:

$$EVnew(r) = EV(r) + EVGCF(r) \tag{6a}$$

$$EVnew(r) = EV(r) - CTRF(r) \tag{6b}$$

The alternative options explored here refer to using part or total $RGCF(r)$ to improve technological options in receiving countries. In particular, we consider two technological options: improving energy efficiency or improving the production of renewable energy in receiving countries. The portion of total $RGCF(r)$ directed to technological option is modeled as:

$$TGCF(r) = \left(1 - \gamma(r)\right)RGCF(r) \tag{7}$$

where $\gamma(r)$ represents the share of $RGCF(r)$ devoted to a lump sum. If $\gamma(r) = 1$ we are in the case described in eq. (5) whereas for $\gamma(r) < 1$ we are in the case where part of the GCF is used for enlarging technological options in receiving countries. We explore the first technology policy option where $\gamma(r) < 1$ and a part of $RGCF(r)$ is used for improving energy efficiency. The relationship between technical change in energy efficiency and GCF is modeled in a very simple way. An elasticity parameter ($R_{EE}(i,r)$) is taken in order to transform research and development (R&D) efforts (millions of US$) into technical progress in energy efficiency by using an average (and rather low) elasticity value based on the literature on this topic (Adams and Jaffe, 1996; Griffith *et al*., 2006; Griliches and Lichtenberg, 1984; Hall and Mairesse, 1995; Lichtenberg and Siegel, 1991). In this case, we adopted an identical value for $R_{EE}$ for all energy inputs and all produced commodities. Such an approach represents a standard modeling choice when sectoral empirical estimates are not given. The final equation for translating R&D efforts into technical progress in energy efficiency is thus given by

$$t_{EE}(i,r) = R_{EE}(i,r) \cdot TGCF(r) \tag{8}$$

where $i$ stands for inputs, and $t_{EE}(i,r)$ is the technical energy efficiency gain in sector $i$ in country or region *r* as a result of funds allocated to R&D in that country or region. In this paper we have assumed that all R&D efforts from the fund are directed towards improvements in energy efficiency in the production function, but specific gains in input efficiency or a generalized improvement in efficiency across all commodities or across specific ones can also be modeled.

The second technology option is to use GCF to finance the increasing production of renewable energies. In this case, a share of $RGCF(r)$ devoted to technology options is directed toward financing the production of renewable energies. Here, from a pure modeling approach, what is affected is not an input augmenting technical change parameter as $t_{EE}(i,r)$ in energy efficiency, but an output augmenting measure in the electricity sector given by $el_{RW}(j,r)$ (we ignore biofuels and other non-electricity renewable sources):

$$el_{RW}(j,r) = [R_{RW}(j,r)] \cdot TGCF(r) \quad (8)$$

where $R_{RW}(j,r)$ represents the reactivity of the electricity sector to R&D investments. In this specific case, the reactivity parameter is calibrated with regard to the last ten years of investment in R&D activities in renewable energies and the corresponding increase in installed capacity in renewable electricity in OECD countries (IEA energy Balance dataset available online).

The option related to pure lump sum transfer to EV does not modify the structure of the global markets since no impacts on prices arise and it represents a mere redistribution in EV terms. On the other hand, the other two options produce several impacts in terms of market prices for energy commodities, as well as resource efficiency in the production function and energy availability and mix. Even though all these changes occur only in developing countries, by working with a CGE, there are also indirect impacts on developed countries. In particularan active policy adopted in developing countries thanks to financial assistance by GCF funded by developed economies may also offer benefits to developed countries. It is in this vein that alternative policy options simulated in a dynamic CGE context may provide interesting insights and pave the way to new political arguments to be discussed on the international agenda.

## 3. Simulation Design

### *3.1 The baseline scenario*

The baseline scenario corresponds to a Business as Usual Scenario (BAU) built upon the $CO_2$ projections provided by IEA in the World Energy Outlook (WEO) 2013 (IEA, 2013b).

In terms of country coverage we include in our simulation 17 regions with 7 developed regions (Canada, European Union, Former Soviet Union, Japan, Norway, United States, Rest of OECD), and 10 developing regions (Brazil, China, India, Indonesia, Mexico, Energy Exporters, Rest of Africa, Rest of America, Rest of Asia, Rest of Europe). The basis for the classification adopted follows the rationale that we consider as developed those economies included in the Annex I list in the Kyoto Protocol where countries are aggregated if they have the same bargaining position (European Union countries) or if they are residual rich economies with small specific weight in terms of abatement efforts (Rest of OECD, which includes Australia, Israel, New Zealand, South Korea, Switzerland).

With regard to developing regions, we considered as single countries the main emerging economies which have a potential for distinguishing their bargaining positions since they are considered as those regions excluded by commitments in the Kyoto Protocol but which should be included in active abatement efforts in the Post Kyoto negotiations. We also considered the Energy Exporters as an aggregate since they will face similar impacts due to $CO_2$ emissions reduction policies even if they are geographically and economically divergent countries. We then modeled residual regions according to a geographical criterion bearing in mind that most Least Developed Countries (LDC) are in the two aggregates Rest of Africa and Rest of Asia.

In terms of sector coverage, the rationale behind the sector aggregation is to divide energy commodities from the rest of the economy as a first step and to disentangle energy intensive industries from the rest of the economy as a second step, resulting in 10 sectors: Agriculture, Energy Intensive Industries, Other Industries, Transport, Services, as a group of non-energy commodities; Coal, Oil, Natural gas, Oil products, Electricity as energy commodities.

In terms of the temporal dimension, a temporal horizon going from 2010 to 2035 has been considered, with a temporal structure based on 5-year periods. The starting date is set at 2010 because data on $CO_2$ emission levels based on energy balances calculated within the CORINAIR framework ($CO_2$ emissions related to combustion of fossil fuels according to the existing technologies) are available at historical level only until 2010 (IEA, 2013a). Since GDynE is a top-down model where international economic relationships are very well designed whereas technology is exogenously given, we decided to stop our simulation in 2035, where $CO_2$ projections are given on the road to 450 PPM concentration according to WEO 2013, meaning that we trace the path towards the achievement of the 2050 abatement goal.

The AEEI is modeled here as an input augmenting technical change with an approximate value corresponding to an increase in energy efficiency per year of 1%. This is an average value within the feasible range indicated by the literature where AEEI estimations vary from 0% to 2% per annum (Grubb *et al*., 1993; IPCC, 2013; Löschel, 2002; Weyant, 1999).

GDP projections are taken from the comparison of the reference case for four main sources, the OECD Long Run Economic Outlook, the GTAP Macro projections, the IIASA projections used for the OECD EnvLink model, and the CEPII macroeconomic projections used in the GINFORS model. Population projections are taken from the UN Statistics (UNDESA). Projections for the labor force (modeled here as skilled and unskilled) are taken by comparing labor force projections provided by ILO (which result as aggregate) with those provided by the GTAP Macro projections (where skilled and unskilled labor force are disentangled).

Starting from 2010 $CO_2$ emissions, we then recursively adjusted the baseline scenario obtained over the period 2010-2035 by retaining macro projections while working on forecast fossil fuels resource availability. In the GTAP framework all energy commodities are modeled as traded goods and not as resources. This means that in a demand driven context, when GDP and population grow, if no constraints are explicitly modeled, fossil fuels supply also continue to growth, resulting in increasing $CO_2$ emissions well above the projections included in the BAU scenario provided by WEO 2013. By giving output (supply) constraints to fossil fuels, we automatically reduced emissions.

### *3.2 The 450 PPM scenario*

The emissions quota assigned to each region is a proportion of the baseline values. Since calibration for the period 2010-2035 mostly reproduces $CO_2$ emission trends in WEO 2013 but figures are not exactly coincident, our 450 PPM scenario reproduces the same shocks given to emissions in the baseline (hence the % change in emissions level is the same in our model as it is in the WEO 2013 but the final $CO_2$ emissions level may be slightly different). This modeling choice is also necessary since regional aggregation is not exactly the same in the two models, hence only changes over time can be compared.[4] It is worth mentioning that the 450 PPM $CO_2$ projection considers a reduction or stabilization of $CO_2$ emissions for the whole world, meaning that both developed and developing countries should positively contribute to reaching the abatement target. For this purpose we take in this simulation exercise the burden sharing as exogenously given by WEO 2013. Further work needs to be done to analyze cases with an endogenous burden sharing and that is an important future research task.

The standard market-based policy options available for reaching this emissions path are a domestic carbon tax (GCTAX simulation as in Figure 1), where each country/region should reduce its own emissions, or the functioning of an international emission trading (IET) system (IET in Figure 1). In this paper we model the two market-based policy options as alternatives, considering as a standard result that the option of domestic carbon taxation represents the upper bound of abatement costs for reaching the road to the 450 PPM scenario whereas IET is the cost-effective option giving the lower bound to the costs.

For IET, we adopt the same abatement commitments as in the GCTAX scenario, but in this case countries may trade permits in order to reach higher policy efficiency (same environmental target at lower costs). Since nothing has yet been decided at international level, in this paper we have hypothesized that all countries actively participate in the achievement of the 450 PPM pattern, and all countries participate in the emission trading market.[5]

[4] Geographical regions resulting from country aggregates are in some cases largely distant from WEO 2013 (as for instance with regard to Energy Exporters) so that only percentage changes are applied.

[5] We are aware of all the technical and institutional barriers related to the implementation of an IET where all countries participate. Hence, our IET case must be considered a benchmark case where the final goal is to reach the most effective scenario in terms of lowering abatement costs and where no binding constrains are settled in terms of the permit quantity assigned to each country.

### *3.3 The 450 PPM scenario with IET and GCF used as a lump sum in EV (GCF-EV)*

This scenario has been implemented with the aim of allocating a percentage of CTR to the GCF (eq. 2) in line with ongoing negotiations. For this purpose, we first set the percentage value ($\alpha(r)$) able to ensure a financial flow comparable with the $100 billion flow by 2020 recommended by the XVI COP in Cancun in 2010. It is worth noting that the resulting GFC amount is positively correlated with the carbon tax level (or in the case of permit trading, with the equilibrium permit price). This means that, at a practical level, when abatement targets begin to be more stringent, the permit price rises and, consequently, the size of the GCF also increases. In this sense, a potential bargaining theme could be to set the percentage values of CTR in dynamic terms in order to ensure a constant 100 billion USD amount. While this is a valid option to be investigated when practical policy implications need to be derived from the analysis, in this case we are only interested in understanding the mechanism behind the convenience of different policy options. Hence, for the sake of simplicity, we set a uniform and constant percentage value of 8%, which is the required amount of CTR by developed countries to reach an average annual value of around 100 billion USD over the period 2015-2035.

It is also worth noting that this percentage of the tax was set for the scenario in which GCF is used only for redistributive purposes from developed to developing countries in the form of a lump sum going directly into the EV, without changing the international market price system (eq. 6a and eq. 6b for developing and developed countries, respectively). In other simulations this tax rate will generate different revenues to the fund for reasons that are explained below.

The final issue to be considered for this scenario is the criterion used for distributing GCF between developing countries ($\beta(r)$ in eq. 4). In this paper we have considered the allocation to be based on the cumulated GDP losses over the period 2010-2035 in the 450 PPM scenario with IET, so that the higher the GDP loss, the higher the share of GCF obtained. The justification is clearly to compensate developing countries that participate in proportion to any losses they may suffer.

### *3.4 The 450 PPM scenario with IET and GCF used for financing technical change in energy efficiency (GCF-EE)*

In this scenario the percentage value of CTR to finance GCF is fixed at 8% but, considering that the permit price is endogenously determined in IET and that the investment of GCF in energy efficient technologies in developing countries will contribute to reduce the equilibrium carbon tax level (we must bear in mind that carbon tax is built as an ad valorem on energy commodities, and when energy efficiency reduces energy prices, the carbon tax level is also reduced), the global available amount of GCF will be reduced by energy efficiency gains. This means that on one side the global amount of GCF will be lower (and this could be a negative factor for developing countries, *ceteris paribus*), but the effectiveness of the GCF in reducing mitigation costs for developing countries in this scenario compared with the lump sum option in EV terms may compensate for that.

In order to transform GCF in monetary terms into energy efficiency technical improvement, we used several calibration benchmarks. The first is the paper by Verdolini *et al*. (2011) which uses econometric methods (for the electricity sector only) to estimate that a 1% increase in knowledge stock determines an increase in fuel combustion efficiency of 0.12%. Since this is a result valid for one specific sector, we also calculated the reaction function of energy intensity to public R&D efforts in energy efficiency in OECD countries over the period 2000-2008 (IEA R&D Energy Statistics, online database). An average elasticity value equal to 0.39 (a 1% increase in R&D equals to a reduction of 0.39% in energy intensity calculated over the whole economic system) is estimated. We then took a conversion parameter to obtain as an intermediate elasticity value equal to 0.25% derived from the average elasticity calculated over the whole period 2010-2035.

We also considered the energy-efficient scenario provided by the WEO 2013 (Efficiency World Scenario – EWS), and calibrated the reaction function in order to have a reduction in energy intensity which is similar to that shown in the WEO 2013. Taking the EWS as a benchmark in terms of energy intensity reduction, we obtain a reduction in the energy intensity indicator in the period 2010-2035 of -45%, which is comparable with the reduction in energy intensity obtained in our GCF-EE scenario (where energy intensity indicator is reduced by -48% in the same period). Finally, primary energy demand by 2035 in the WEO EWS is reduced by -18% compared with 2010 at world level whereas in our scenario we obtain a reduction of -16.5%.

### *3.5 The 450 PPM scenario with IET and GCF used for financing production of renewable energies (GCF-RW)*

In this case capital investments go to the electricity sector in order to increase the production of renewable energies. Apart from directing capital flows toward the electricity sector, we also relaxed the substitution elasticity constraint by shocking $ELFKEN$ up to 1.00 only for the electricity sector (see Table 1 for a benchmark), thus reducing the technical constrain and allowing the system to produce electric power only by using capital as an input (e.g. from wind and solar power which are by definition available with virtually no energy input).

Also in this case the reaction parameters are calibrated to allow the energy system to meet three driving criteria: 1) over the period 2000-2008 a 1% increase in public R&D in renewable energies produces an increase by 0.35% in renewable production (in volume terms); 2) the increase in renewable production by developing countries in our GCF-RW scenario reaches a total volume of renewable energy almost equal to half of total value in Mtoe for the whole world by 2035 according to the Renewable Energies Scenario described in WEO 2013; 3) according to EIA-DOE projections provided for two specific sources (wind and solar, which are the only sources which do not have natural constraints and are valid and feasible with current state of technology) the growth rate in production during the period 2010-2035 is 5-7% per year in a high oil price scenario (in our case the average growth rate amounts to about 5% per year).

**Figure 1**

### *3.6 The 450 PPM scenario with IET and GCF used for financing both technical change in energy efficiency and production of renewable energies (GCF-MIX)*

The final scenario we consider is simply a combination of energy efficiency (GCF-EE) and renewable energy (GCF-RW), with an equal share of the GCF going to the two alternatives (GCF-MIX). This scenario is implemented with the specific purpose of assessing different economic impacts to developed and developing countries and comparing how much the two different GCF options influence the global market price systems. More specifically, this is a benchmark case that is valid for understanding the feasibility of alternative policy options in terms of convenience for the financing of the program and in terms of providing useful information for future policy design. Also in this case, the choice of an equal distribution of the $TechGCF(r)$ to energy efficiency and renewable energies is an exogenous assumption in order to compare it with the two opposite options, but further endogenous modeling features could be implemented in the future.

## 4. Results with GDynE

### *4.1 Baseline*

Table 2 gives the predicted evolution of GDP across 17 regions and the world as a whole from 2010 to 2035, in the absence of further measures to reduce $CO_2$ emissions except for those currently adopted. Global GDP nearly doubles over the period, with an average annual growth rate of 3.8%.

**Table 2**

Table 3 shows $CO_2$ emissions in the baseline for the same regions and globally. In the absence of further measures, there will be an increase of 56% in annual global emissions by 2035 compared with 2010. What is more important, however, is the huge variation in the changes by region over the period. At the bottom of the list is the EU27, which achieves a 1% increase only.[6] At the other end is India, which has a projected increase of 196%. Even among the OECD countries, there is a lot of variation and some, such as Canada and Mexico, envisage increases of 19% and 70% respectively. These differences are important because they imply that any measures to impose reductions to meet a climate target will have very different costs for different regions.

**Table 3**

### *4.2 The 450 PPM scenario*

The climate scenario examined here is the one consistent with stabilizing concentrations of $CO_2$ at 450 PPM by 2050. The WEO 2013 has developed a scenario in which the main regions have reduction targets so that the world as a whole is on track in 2035 to meet the 450 PPM target by 2050.

The emissions along that track and the implied reduction for each region relative to the baseline are given in Table 4. Globally, emissions are now 49% lower than the baseline, with most regions reducing their emissions compared with 2035 baseline levels by between 39% (India) and 68% (Norway). As a first remarkable result, it is noticeable that developing countries are generally expected to make major contributions during this period which may be difficult to achieve politically without some form of support. This is exactly the reason behind the deadlock in international negotiations and the very heart of the debate surrounding the CBDR. It appears therefore that developed countries acting alone will be ineffective in stabilising the global temperature but an active role played by developing countries will bring them unacceptable abatement costs, affecting substantially their economic development perspectives. It clearly emerges therefore that the implementation of climate finance support mechanisms such as the Green Climate Fund constitutes a key policy strategy.

Figure 2 shows the path for global emissions in the baseline and the two options analyzed in this paper.

**Table 4**

**Figure 2**

[6] The baseline case is not consistent with the EU's stated objective of a 50% reduction by 2050 but is what emerges from the WEO 2013 baseline scenarios, assuming current policies and trends.

As mentioned earlier in the simulation design description, in order to achieve this target, we first assume a domestic carbon tax that is collected nationally (GCTAX). The GDynE model is then run to calculate endogenously the carbon tax (Table 5) and the implied change in GDP (Table 6) relative to the baseline.

The rates start low but rise quite sharply, from around $15/ton on average in 2015 to $384/ton in 2035.[7] It is well established that different tax rates in different countries for the same commodity are inefficient: the cost of meeting the same target reduction would be lower if the same tax were applied across all countries. A measure of the degree of inefficiency is the coefficient of variation (the standard deviation divided by the mean) of the rates. This is around 0.6 in 2015 and declines to 0.4 in 2025 but increases again to 0.6 in 2035 indicating no real change in the degree of inefficiency which remains considerable.

The next question is how much would such taxes impose in terms of welfare reduction, as measured as a loss of GDP in constant prices.

The answer is shown in Table 6. Two important remarks follow on from these results. First, the overall losses are small to start with but grow substantially over time. In 2015, the policies cost about 0.1% (in terms of GDP loss) but by the end of the period, losses go up to 4.6%. Second, there is a considerable variation in the losses, with major producers of fossil fuels (the Energy Exporters region) losing more than average and developing countries that are not energy exporters suffering smaller losses. Losses for China are also exceptionally high by the end of the period. In both cases, however, these results are in some contrast to the figures obtained by some of the other models discussed in the introduction. The models considered in Edenhofer *et al*. (2010) for example, have losses in 2040 of at most 2% whereas we get a loss of around 4-5%. This partly results from GDynE being a top-down model that is not able to take into account the entire arena of energy technologies explicitly and partly by the fact that we are pursuing an inefficient solution with 17 national/regional carbon taxes and no carbon trading between the regions. However, one could argue that our “inefficient” solution is more realistic.

**Table 5**

**Table 6**

Next we consider a single carbon market, which can take the form of a single global carbon tax or a single emissions trading scheme, with a unique price for emissions.

[7] The regional rates are weighted by the regional emissions to calculate the weighted average, which is reported.

As expected, the price of a ton of emissions with a global market is lower than in the case of domestic tax, and by 2035 a ton of $CO_2$ in IET scenario costs about 13% less than in GCTAX. Nevertheless, it is still a high price that will demand major adjustments in the use of fossil fuels.

We modeled the case of a global carbon market as one with emissions trading, where emissions rights are allocated in proportion to 2010 emissions (a grandfathering system). This means that there are some regions/countries that end up as sellers and some as buyers. The impacts of these purchases or sales have been taken into account in calculating the GDP changes. Of course with a different allocation of permits, the impacts of the global carbon market would be different and this alternative will be part of future research.

The results in terms of GDP effects are shown in Table 7, where we find the losses are about 0.7% lower than with separate carbon markets. This result is in line with the theoretical result that international emission trading is cost effective. Nevertheless, this higher effectiveness in terms of a reduction in abatement costs is always assessed in global terms whereas few analyses devote attention to inter-regional cost effectiveness and economic impacts.

In this respect, it is important to note that not all parties gain as a result of such a market in a GCTAX scenario. In particular, the Energy Exporters face bigger losses in this case: by 2035, for example, this region is 17% worse off than the baseline with a global carbon market whereas they were only 7% worse off with a separate regional/national target. This specific result strongly depends on the energy market mechanism: although the overall demand for fossil fuels remains the same in the two scenarios by construction (the global $CO_2$ emissions in the time span 2010-2035 are exactly the same), the different reduction efforts played in different regions will produce a reduction in the reactivity of energy prices to carbon taxation. In particular, in the IET scenario, while fossil fuels quantity remains unchanged, the energy prices are lower, thus reducing the overall export revenue for Energy Exporters. This is just an example of how it could be useful to analyze climate change options from a CGE point of view as well, since several aspects related to inter-country relationships are not modeled by partial equilibrium or bottom-up models.

Going into further detail at regional level, it is also worth noting that while China will face substantial gains from implementing a common carbon market, India and Indonesia will face a further reduction in GDP growth when the emission targets are achieved by an IET system. More importantly, the three regional aggregates where most LDCs are grouped (i.e., Rest of Africa, Rest of America, Rest of Asia) have a further reduction in GDP levels compared with the baseline.

This means that a global carbon market as the sole climate policy option leads to a deadlock in negotiations: while developed countries will surely gain from implementing such flexible mechanisms, developing economies, and especially the most vulnerable, will be far from being favored by the policy. If cost effectiveness is to remain a guiding criterion in order to settle climate reduction policies, further complementary measures are strongly required to achieve global agreement.

**Table 7**

### *4.3 The Green Climate Fund scenario: potential benefits for green growth in developing countries*

The results for the three GCF scenarios, along with the non-GCF scenarios discussed above, are given in Tables 8-10 and Figures 3 and 4.

The prices of permits are considerably lower with GCF than without (about 43% less at the start of the period, going down to 37% less by 2035 for the mixed allocation of GCF funds to renewable energy and energy efficiency) as shown in Table 8 and Figure 3. The reason is simply that the increased allocation to energy efficiency and renewable energy reduces costs for low carbon options, thus reducing the price of $CO_2$ needed to achieve a given reduction in emissions.

Of the GCF options considered, the reduction in permit prices is greatest for mixed allocation, followed by the renewable energy program and last by the energy efficiency program. Mixed allocation produces lower permit prices than the other two GCF options mainly due to the synergistic effect of increased energy efficiency working to reduce renewable energy costs as well.

The cumulative loss of welfare resulting from the measures is given in Table 9 for both developing and developed countries and the world as a whole. Developing countries face reduced losses in all GCF cases examined compared to a tax (GCTAX) or a permit scenario (IET) without GCF, and they are actually better off in absolute terms in the case of the GCF with energy efficiency (GCF-EE). Developed countries are slightly worse off in the energy efficiency and renewable energy cases but they are better off in the case of the mixed program (GCF-MIX).

When comparing EV in the GCF-EV scenario with the one in the IET scenario, it is worth noting that at while global level losses are equal (5,600 billion USD over the period 2010-2035) their distribution favors developing countries in the GCF-EV. The GCF-RW scenario softens the negative impacts on EV compared with the GCF-EV scenario, but not in a significant way. By contrast, the GCF-EE scenario gives the lowest loss at the global level, with positive benefits for developing countries as an aggregate compared with the baseline and a smaller increase in losses for developed economies compared with the standard IET scenario. On the other hand, the mixed option (GCF-MIX) provides a robust reduction in welfare losses for developing countries but also a reduction in losses for the developed countries in aggregate.

In Table 10 the size of a fund with different allocations is compared with a fund that makes no allocations to energy efficiency or renewable energy (GCF-EV), which is modeled according to the ongoing negotiations of a constant year flow of 100 million USD by 2020. In all cases, the fund declines in size as the GCF starts to operate to allocate resources to energy efficiency. This is because the amount of revenues raised from a tax of permit scheme declines (prices of permits or tax rates become lower) and the scheme works on the basis that a fixed share ($\alpha(r) = 8\%$) of the carbon tax revenues goes to the GCF fund. The decline in the extreme case is about 17% in cumulative terms.

**Table 8**

**Table 9**

**Table 10**

The larger reduction in abatement costs at the global level in the GCF-EE scenario is mainly driven by the resource efficiency effect in the production function for the whole economy. By considering that GDynE is a CGE model based on market price mechanisms and increasing the technical efficiency of energy consumption, the $CO_2$ abatement efforts are feasible at a lower economic impact in terms of resource constraints. For the GCF-RW scenario, the amount of renewable energy available by investing the GCF has not the same (positive) economic impact with regard to improving energy efficiency.

**Figure 3**

**Figure 4**

In our view this last outcome offers a crucial insight since it provides the rationale for a potential final international climate agreement over the next decades which could represent the first best solution in terms of reducing global abatement costs, but would ensure a higher likelihood of being signed and respected by all Parties.

## 5. Conclusions

In this paper we have examined the options for a low carbon mitigation strategy from a global as well as a regional perspective using a new top-down model (GDynE). The aim is to use a model that has a general equilibrium structure with a well-developed trade database that tracks bilateral relationships accurately and to apply it to look at the cost of meeting desired carbon reduction targets in the short to medium term. The model comes up with costs that are a little higher than the consensus of the existing models; moreover, it shows that these costs vary more across regions than most of the current models. This last point is important and means that any negotiations for a global scheme will need further bilateral negotiations.

We have examined two options in detail: (a) a scenario for meeting the 450 PPM target with national/regional sub-targets that have to be met individually, with no international trading and

(b) the same overall target to be met with a global carbon market. The latter is more efficient and reduces costs by about 1 per cent of GDP compared with the former. The global carbon market can, however, involve inter-country transfers that need further investigation but this analysis identifies possible gainers and losers relative to option (a).

The paper suggests that there are some reasons why the current consensus of low costs of mitigation to 450 PPM is not being taken up more enthusiastically by policy makers. The implied taxes or permit prices by 2035 are high and would entail considerable courage on the part of governments to impose them. They also imply losses in GDP that would be hard to sell to a skeptical public, especially in the face of other pressing challenges such as youth unemployment, ageing of the population and the like. These concerns would apply, to a different extent and with different consequences, both to developed and developing countries, showing how the debate on CBDR is far from being solved.

This paper suggests that one way of solving this negotiation impasse is to lower the costs of mitigation for developing countries. If carbon taxes can be used to fund a major low carbon program in developing countries this will have benefits for both recipients and funders. In particular, a GCF, financed from 8% of the carbon tax receipts in developed countries and invested to increase energy efficiency in developing countries can have major benefits. It reduces the costs of meeting the global target of 450 PPM for both groups of countries and can even result in a small gain for developing countries. This option is therefore worth more careful consideration.

Although these first results are food for thought for policy makers, the paper also traces the path to further developments which should be followed in the very near future in order to help international negotiations escape the deadlock. First, negative economic impacts on energy exporting countries due to low carbon strategies should be carefully considered and possible complementary measures reducing such losses should be included in the global climate policy mix. Second, other measures that also allocate resources to R&D in developed countries, thereby lowering the cost of substituting fossil fuels over the next two decades, should be examined. Third, actual values of total costs will decline if long term benefits from reducing climate change are accounted for in the welfare computation and the distribution of costs may be substantially different over a long term horizon.

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**Table 1 – Comparison of alternative substitution elasticity values in energy nests**

| Elasticity | GTAP Standard | Beckman *et al.* (2011) | Koetse *et al.* (2008) / Stern (2012) |
|---|---|---|---|
| Capital and energy (ELKEN) | 0.50 | 0.33 | 0.38 |
| Electricity and non-electricity (ELFENY) | 1.00 | 0.16 | 0.81 |
| Non-electricity energy sources (ELFNELY) | 0.50 | 0.07 | 0.57 |
| Non-coal energy sources (ELNCOAL) | 1.00 | 0.25 | 0.41 |

**Table 2 - Baseline GDP projections to 2035 (billion constant USD)**

| **Regions** | **2010** | **2015** | **2020** | **2025** | **2030** | **2035** | **Growth p.a.** |
|---|---|---|---|---|---|---|---|
| Canada | 916 | 1,022 | 1,125 | 1,221 | 1,321 | 1,447 | 2.2% |
| European Union | 12,619 | 13,705 | 14,760 | 15,852 | 17,013 | 18,374 | 1.8% |
| Former Soviet Union | 809 | 988 | 1,154 | 1,336 | 1,500 | 1,696 | 4.2% |
| Japan | 5,019 | 5,341 | 5,617 | 5,902 | 6,169 | 6,369 | 1.0% |
| Norway | 212 | 229 | 246 | 257 | 269 | 281 | 1.3% |
| United States | 12,293 | 13,946 | 15,574 | 17,026 | 18,495 | 19,887 | 2.4% |
| Rest of OECD | 2,255 | 2,692 | 3,132 | 3,534 | 3,938 | 4,331 | 3.5% |
| *Developed countries* | *34,122* | *37,923* | *41,609* | *45,129* | *48,704* | *52,385* | *2.1%* |
| Brazil | 896 | 1,109 | 1,324 | 1,526 | 1,723 | 1,959 | 4.6% |
| China | 3,714 | 6,047 | 8,430 | 10,150 | 12,656 | 15,108 | 11.8% |
| India | 366 | 529 | 697 | 835 | 1,051 | 1,267 | 9.5% |
| Indonesia | 1,140 | 1,759 | 2,387 | 2,883 | 3,566 | 4,281 | 10.6% |
| Mexico | 791 | 950 | 1,110 | 1,322 | 1,499 | 1,749 | 4.7% |
| Energy Exporters | 2,367 | 2,980 | 3,604 | 4,416 | 5,224 | 6,289 | 6.4% |
| Rest of Africa | 436 | 597 | 761 | 957 | 1,187 | 1,489 | 9.3% |
| Rest of America | 570 | 730 | 893 | 1,102 | 1,308 | 1,576 | 6.8% |
| Rest of Asia | 1,317 | 1,744 | 2,178 | 2,737 | 3,354 | 4,029 | 7.9% |
| Rest of Europe | 548 | 673 | 797 | 944 | 1,085 | 1,248 | 4.9% |
| *Developing countries* | *12,146* | *17,117* | *22,180* | *26,872* | *32,653* | *38,996* | *8.5%* |
| *World* | *46,268* | *55,040* | *63,790* | *72,002* | *81,357* | *91,381* | *3.8%* |

*Source: own elaboration on GDynE results calibrated with WEO Current Policies Scenario (IEA, 2013b)*

**Table 3 - Baseline $CO_2$ projections to 2035 according to WEO 2013 Current Policy Scenario (Gt $CO_2$)**

| Regions | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | Change 2010-2035 |
|---|---|---|---|---|---|---|---|
| Canada | 0.55 | 0.54 | 0.55 | 0.55 | 0.64 | 0.65 | 19.2% |
| European Union | 3.68 | 3.67 | 3.73 | 3.58 | 3.70 | 3.72 | 1.2% |
| Former Soviet Union | 1.65 | 2.00 | 2.11 | 2.45 | 2.41 | 2.51 | 52.1% |
| Japan | 1.14 | 1.16 | 1.24 | 1.32 | 1.41 | 1.35 | 17.7% |
| Norway | 0.05 | 0.05 | 0.06 | 0.07 | 0.07 | 0.07 | 39.7% |
| United States | 5.39 | 5.50 | 5.72 | 5.10 | 5.24 | 5.13 | -4.9% |
| Rest of OECD | 1.08 | 1.22 | 1.37 | 1.38 | 1.48 | 1.52 | 40.5% |
| *Developed countries* | *13.54* | *14.13* | *14.78* | *14.45* | *14.95* | *14.94* | *10.4%* |
| Brazil | 0.38 | 0.46 | 0.59 | 0.61 | 0.69 | 0.79 | 105.7% |
| China | 7.13 | 9.06 | 10.24 | 11.03 | 11.85 | 12.43 | 74.2% |
| India | 0.40 | 0.55 | 0.71 | 0.88 | 1.02 | 1.19 | 196.2% |
| Indonesia | 1.60 | 2.07 | 2.45 | 2.96 | 3.41 | 3.79 | 136.0% |
| Mexico | 0.41 | 0.47 | 0.52 | 0.56 | 0.62 | 0.69 | 70.3% |
| Energy Exporters | 3.17 | 3.70 | 4.27 | 4.77 | 5.39 | 6.42 | 102.3% |
| Rest of Africa | 0.27 | 0.37 | 0.45 | 0.49 | 0.63 | 0.84 | 207.2% |
| Rest of America | 0.29 | 0.34 | 0.39 | 0.45 | 0.50 | 0.53 | 84.2% |
| Rest of Asia | 1.13 | 1.35 | 1.60 | 1.96 | 2.29 | 2.58 | 127.8% |
| Rest of Europe | 0.66 | 0.70 | 0.76 | 0.85 | 0.92 | 0.93 | 41.5% |
| *Developing countries* | *15.46* | *19.06* | *21.98* | *24.55* | *27.31* | *30.19* | *95.3%* |
| *World* | *29.00* | *33.20* | *36.76* | *39.00* | *42.27* | *45.14* | *55.6%* |

*Source: own elaboration on GDyn-E results calibrated with WEO Current Policies Scenario (IEA, 2013b)*

**Table 4 - $CO_2$ emissions along the 450 PPM Target (Gt $CO_2$)**

| Regions | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | Change 2010-2035 | % Decline w.r.t Baseline |
|---|---|---|---|---|---|---|---|---|
| Canada | 0.55 | 0.49 | 0.41 | 0.35 | 0.34 | 0.29 | -48% | -56% |
| European Union | 3.68 | 3.42 | 3.21 | 2.67 | 2.33 | 1.98 | -46% | -47% |
| Former Soviet Union | 1.65 | 1.88 | 1.86 | 1.85 | 1.54 | 1.35 | -18% | -46% |
| Japan | 1.14 | 1.08 | 1.09 | 1.00 | 0.90 | 0.73 | -36% | -46% |
| Norway | 0.05 | 0.05 | 0.04 | 0.03 | 0.03 | 0.02 | -56% | -68% |
| United States | 5.39 | 5.26 | 5.23 | 3.75 | 2.90 | 2.19 | -59% | -57% |
| Rest of OECD | 1.08 | 1.12 | 1.05 | 0.88 | 0.75 | 0.58 | -46% | -62% |
| *Developed countries* | *13.54* | *13.30* | *12.89* | *10.53* | *8.78* | *7.15* | *-47%* | *-52%* |
| Brazil | 0.38 | 0.43 | 0.51 | 0.45 | 0.43 | 0.42 | 9% | -47% |
| China | 7.13 | 8.11 | 8.41 | 7.26 | 6.14 | 4.83 | -32% | -61% |
| India | 0.40 | 0.53 | 0.63 | 0.66 | 0.69 | 0.73 | 81% | -39% |
| Indonesia | 1.60 | 1.85 | 2.02 | 1.97 | 1.91 | 1.82 | 13% | -52% |
| Mexico | 0.41 | 0.44 | 0.42 | 0.40 | 0.39 | 0.39 | -5% | -44% |
| Energy Exporters | 3.17 | 3.57 | 3.80 | 3.81 | 3.82 | 4.00 | 26% | -38% |
| Rest of Africa | 0.27 | 0.35 | 0.39 | 0.39 | 0.43 | 0.50 | 83% | -40% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Rest of America | 0.29 | 0.33 | 0.35 | 0.35 | 0.35 | 0.32 | 12% | -39% |
| Rest of Asia | 1.13 | 1.31 | 1.42 | 1.60 | 1.73 | 1.78 | 57% | -31% |
| Rest of Europe | 0.66 | 0.66 | 0.61 | 0.59 | 0.55 | 0.49 | -26% | -48% |
| *Developing countries* | *15.46* | *17.57* | *18.55* | *17.49* | *16.46* | *15.28* | *-1%* | *-49%* |
| *World* | *29.00* | *30.87* | *31.44* | *28.02* | *25.24* | *22.43* | *-23%* | *-50%* |

*Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario(IEA, 2013b)*

**Table 5 - Carbon tax required for each region to be on 450 PPM track (USD/Ton $CO_2$) (GCTAX scenario)**

| **Country** | **2010** | **2015** | **2020** | **2025** | **2030** | **2035** |
|---|---|---|---|---|---|---|
| Canada | - | 18.0 | 59.8 | 113.7 | 128.4 | 279.4 |
| European Union | - | 21.9 | 48.0 | 145.6 | 263.9 | 470.8 |
| Former Soviet Union | - | 12.8 | 18.1 | 74.8 | 109.3 | 209.2 |
| Japan | - | 24.2 | 44.2 | 136.6 | 196.1 | 355.0 |
| Norway | - | 37.5 | 97.0 | 162.2 | 221.4 | 523.5 |
| United States | - | 7.0 | 13.3 | 104.8 | 229.6 | 416.8 |
| Rest of OECD | - | 19.1 | 77.7 | 168.5 | 291.3 | 630.9 |
| *Developed countries* | - | *16.2* | *41.1* | *121.4* | *219.7* | *413.1* |
| Brazil | - | 33.4 | 39.5 | 130.2 | 174.6 | 271.9 |
| China | - | 17.4 | 26.4 | 119.8 | 247.1 | 565.1 |
| India | - | 10.6 | 27.1 | 74.0 | 70.3 | 88.4 |
| Indonesia | - | 8.4 | 14.2 | 58.3 | 113.4 | 176.0 |
| Mexico | - | 15.3 | 63.7 | 111.6 | 153.1 | 266.9 |
| Energy Exporters | - | 5.5 | 22.5 | 58.1 | 82.2 | 118.7 |
| Rest of Africa | - | 16.5 | 34.1 | 84.8 | 103.9 | 121.4 |
| Rest of America | - | 4.2 | 46.4 | 103.9 | 153.8 | 311.2 |
| Rest of Asia | - | 11.2 | 37.8 | 70.7 | 84.4 | 138.4 |
| Rest of Europe | - | 11.7 | 58.1 | 118.2 | 169.9 | 300.7 |
| *Developing countries* | - | *14.9* | *28.1* | *98.2* | *180.9* | *368.8* |
| *World* | - | *15.3* | *32.7* | *106.5* | *195.0* | *384.0* |

*Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario (IEA, 2013b)*

*Note: values for the aggregate regions (including World, Developed and Developing countries), are given by weighted average of carbon tax on total abatement efforts.*

**Table 6 - Change in GDP (%) in implementing domestic carbon taxes required for 450 PPM (GCTAX scenario)**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Canada | - | -0.2% | -1.0% | -2.0% | -3.6% | -5.0% |
| European Union | - | 0.0% | 0.1% | 0.3% | 0.4% | 0.0% |
| Former Soviet Union | - | -0.6% | -2.0% | -5.1% | -8.7% | -13.5% |
| Japan | - | 0.0% | 0.0% | -0.1% | -0.7% | -1.6% |
| Norway | - | -0.7% | -2.3% | -5.8% | -10.8% | -14.4% |
| United States | - | 0.0% | 0.3% | 0.4% | -0.4% | -2.0% |
| Rest of OECD | - | 0.0% | -0.6% | -2.0% | -3.9% | -6.9% |
| *Developed countries* | - | *0.0%* | *0.0%* | *-0.2%* | *-0.8%* | *-2.2%* |
| Brazil | - | -0.1% | 0.0% | 0.1% | 0.5% | 0.4% |
| China | - | -0.5% | -1.1% | -2.9% | -6.9% | -13.7% |
| India | - | -0.1% | -1.2% | -1.4% | -4.0% | -7.6% |
| Indonesia | - | 0.2% | 0.7% | 0.4% | -1.6% | -4.3% |
| Mexico | - | -0.1% | -0.9% | -2.4% | -3.8% | -6.0% |
| Energy Exporters | - | -0.2% | -1.1% | -3.4% | -6.0% | -7.2% |
| Rest of Africa | - | 0.0% | -0.1% | -0.2% | 0.1% | 1.0% |
| Rest of America | - | 0.2% | 0.3% | 0.1% | -0.2% | -1.2% |
| Rest of Asia | - | 0.1% | -0.2% | -0.5% | -0.2% | 0.1% |
| Rest of Europe | - | 0.0% | -0.9% | -3.2% | -6.5% | -10.6% |
| *Developing countries* | - | *-0.2%* | *-0.7%* | *-2.0%* | *-4.3%* | *-7.8%* |
| *World* | - | *-0.1%* | *-0.2%* | *-0.8%* | *-2.2%* | *-4.6%* |

*Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario (IEA, 2013b).*

**Table 7 - Change in GDP (%) with a global carbon market that achieves 450 PPM reduction in emissions (IET scenario)**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Canada | - | -0.1% | -0.3% | -1.0% | -3.0% | -4.7% |
| European Union | - | 0.1% | 0.4% | 1.0% | 1.7% | 2.2% |
| Former Soviet Union | - | -0.6% | -2.6% | -7.7% | -13.2% | -18.1% |
| Japan | - | 0.1% | 0.5% | 0.8% | 0.6% | 0.0% |
| Norway | - | -0.4% | -1.4% | -4.5% | -9.0% | -12.0% |
| United States | - | 0.0% | 0.0% | 0.0% | -0.4% | -1.2% |
| Rest of OECD | - | 0.1% | 0.3% | 0.2% | -0.1% | -0.8% |
| *Developed countries* | - | *0.1%* | *0.2%* | *0.0%* | *-0.5%* | *-0.1%* |
| Brazil | - | 0.1% | 0.5% | 1.0% | 1.4% | 0.9% |
| China | - | -0.3% | -1.0% | -2.3% | -4.5% | -7.8% |
| India | - | -0.2% | -1.5% | -2.6% | -7.9% | -13.8% |
| Indonesia | - | -0.1% | -0.4% | -2.0% | -4.6% | -7.5% |

| | | | | | | |
|---|---|---|---|---|---|---|
| Mexico | - | -0.1% | -0.1% | -0.7% | -2.4% | -5.8% |
| Energy Exporters | - | -0.4% | -1.8% | -5.8% | -11.4% | -17.0% |
| Rest of Africa | - | 0.0% | 0.0% | -0.4% | -1.3% | -2.8% |
| Rest of America | - | 0.0% | 0.2% | 0.4% | 0.1% | -0.8% |
| Rest of Asia | - | 0.0% | -0.1% | -1.0% | -3.3% | -6.3% |
| Rest of Europe | - | -0.1% | -0.1% | -1.1% | -4.0% | -8.5% |
| *Developing countries* | - | *-0.2%* | *-0.7%* | *-2.2%* | *-4.9%* | *-8.3%* |
| *World* | - | *-0.1%* | *-0.2%* | *-0.7%* | *-2.0%* | *-3.9%* |

*Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario (IEA, 2013b).*

## Table 8 - Prices of permits under different scenarios

| Scenarios | 2015 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|
| GCTAX | 15.34 | 32.74 | 106.51 | 194.98 | 383.99 |
| IET | 12.68 | 25.79 | 101.43 | 169.21 | 294.31 |
| GCF-EV | 12.68 | 25.79 | 101.43 | 169.21 | 294.31 |
| GCF-EE | 12.38 | 24.78 | 94.11 | 146.49 | 240.55 |
| GCF-RW | 8.80 | 20.62 | 84.03 | 148.13 | 261.22 |
| GCF-MIX | 8.75 | 20.41 | 82.34 | 140.83 | 242.58 |

*Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario (IEA, 2013b).*

## Table 9 - Cumulative EV under different scenarios (US$Bn 2010-2035)

| Regions | GCTAX | IET | GCF-EV | GCF-EE | GCF-RW | GCF-MIX |
|---|---|---|---|---|---|---|
| Developed countries | -3,125 | -2,644 | -3,096 | -2,749 | -2,758 | -2,623 |
| Developing countries | -3,668 | -2,956 | -2,504 | 870 | -2,279 | -541 |
| World | -6,793 | -5,600 | -5,600 | -1,879 | -5,038 | -3,163 |

*Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario (IEA, 2013b).*

## Table 10 - GCF values under different scenarios (US$Bn)

| Scenarios | 2015 | 2020 | 2025 | 2030 | 2035 | Average value 2015-2035 | Cumulated value 2015-2035 |
|---|---|---|---|---|---|---|---|
| GCF-EV | 14.57 | 28.60 | 100.38 | 137.91 | 203.16 | 96.92 | 484.62 |
| GCF-EE | 14.22 | 27.48 | 93.06 | 119.61 | 165.42 | 83.96 | 419.80 |
| GCF-RW | 10.19 | 23.18 | 84.02 | 121.92 | 181.93 | 84.25 | 421.24 |
| GCF-MIX | 10.13 | 22.95 | 82.32 | 116.00 | 168.71 | 80.02 | 400.11 |

*Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario (IEA, 2013b).*

**Figure 1 - Scenarios evaluated in the paper**

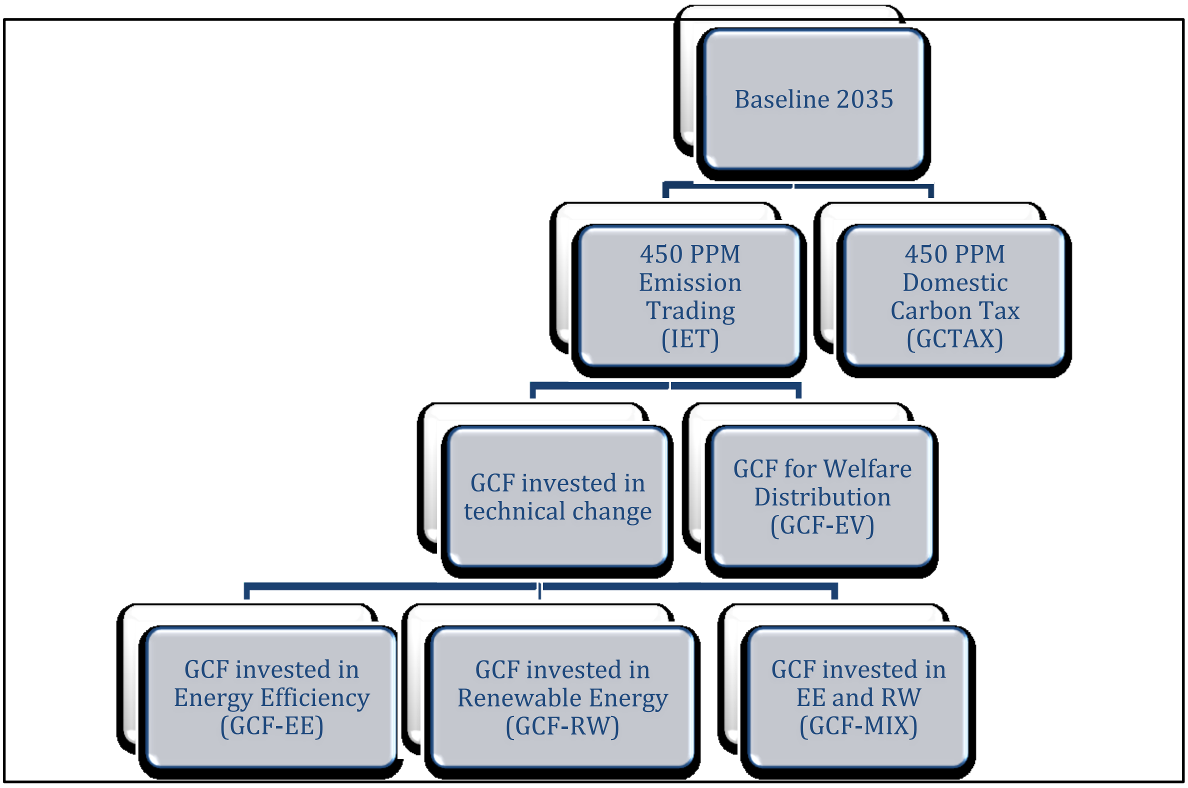
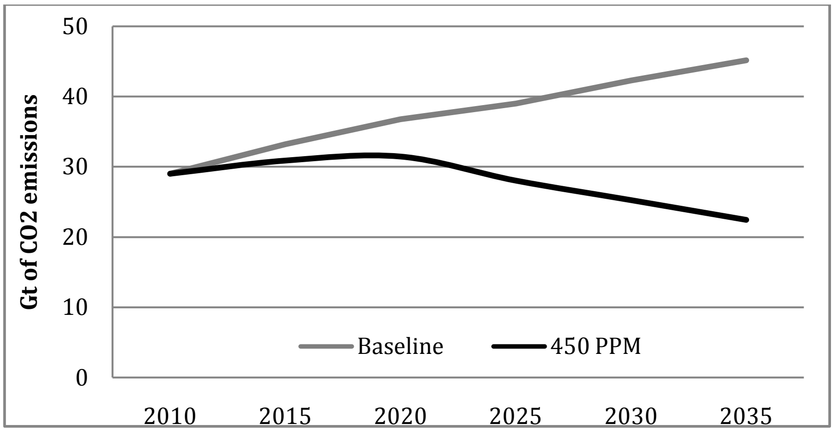
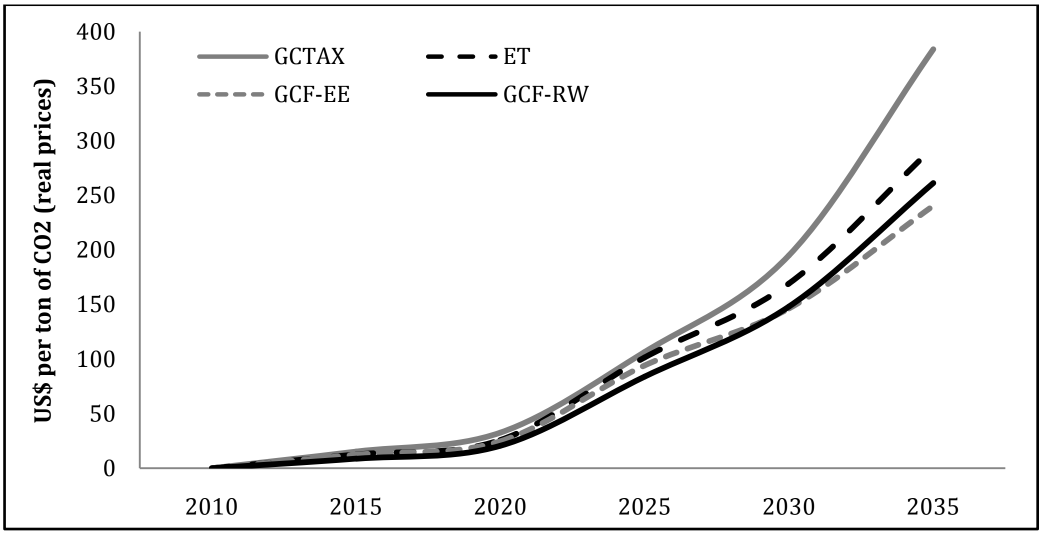



**Figure 2 – $CO_2$ emissions paths along Baseline and 450 PPM (Gt of $CO_2$)**



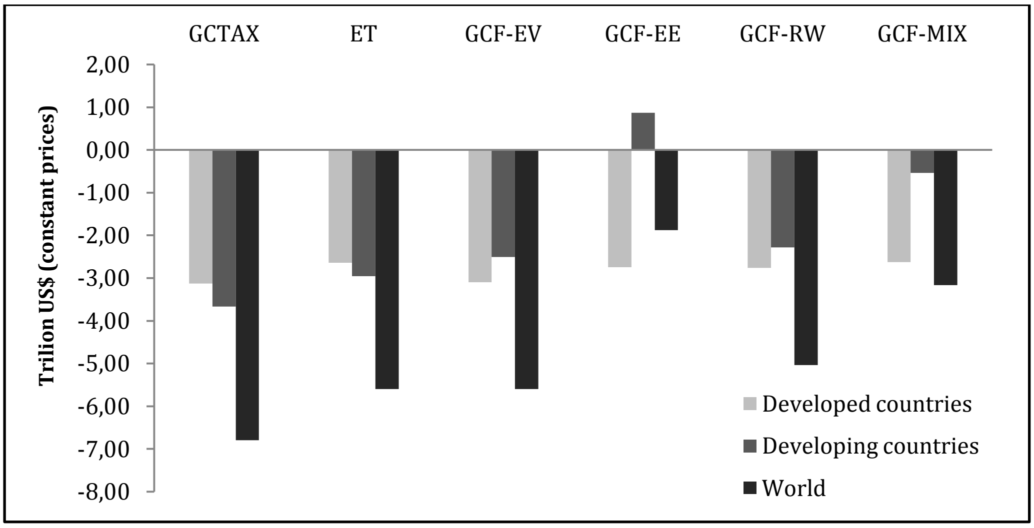

*Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario(IEA, 2013)*

**Figure 3 - Real carbon price in different scenarios on track for 450 PPM (US$ per ton of $CO_2$)**




*Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario (IEA, 2013b).*

**Figure 4 - Difference in EV w.r.t. baseline (total cumulated trillion US$ 2015-2035)**




*Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario (IEA, 2013b).*