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

Antimiani, A.[a], Costantini, V.[b], Markandya, A.[c], Martini, C.[d], Palma, A.[b] and Tommasino, M.C.[d]

Abstract

In this paper we investigate the trade-offs between economic growth and low carbon targets for both developing and developed countries for the period to 2035. The issues examined include the assessment of abatement costs related to two policy options for being on track to meet the 450 PPM target: (a) national targets without international trade in carbon permits and (b) a global market in permits. Policy options are evaluated with an original version of the dynamic CGE model GDynE. The model focuses on bilateral trade flows and links between economies and sectors that capture the realistic economy-wide nature of a globalized world. Abatement costs appear to be strongly detrimental to economic growth for both country groups, but the developing part of the world results particularly affected by active climate policies. We investigate options for reducing these costs that are broadly consistent with a green growth strategy to support low carbon development. We show that a Green Climate Fund financed through a levy on carbon taxation can benefit all parties. Finally, potential larger benefits are associated with the 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

J.E.L. Codes: C68; H23; O44; Q54

a. Istituto Nazionale Economia Agraria (INEA), Italy
b. Department of Economics, Roma Tre Univerity, Italy
c. Basque Centre for Climate Change (BC3), Spain
d. Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA), Italy

1. Introduction

One of the politically most controversial climate change questions is how much will it cost to meet the targets 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 regard several aspects related to climate change actions, going from the quantification of abatement costs to the distribution of such costs across countries. The large uncertainty characterizing the assessment exercises implies a huge difficulty in reaching a global consensus upon the effective actions to be taken by the bargaining parties in the international negotiations.

The main purpose of this paper is to analyse a specific aspect of the difficulty regarding the assessment of alternative policy options aimed at reducing the 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 the different capacities and needs between developed and developing countries, proposing a differentiated approach to compute emission reduction efforts. Namely, although addressing climate change is a global challenge, national responsibilities should be differentiated, with developed countries having a heavier burden in both reducing emissions and providing resources for adaptation measures with respect to developing countries.

The issue of CBDR is currently debated as a crucial point in the Post-Kyoto negotiations. Developing countries consider CBDR as based on historical responsibility to Greenhouse Gas (GHG) emissions whereas developed countries emphasize the role of current and future emissions trend. This different interpretation brings to substantial divergence in bargaining positions of developed vs. developing economies with respect to a potential agreement upon the burden sharing question. Two of the world's top four emitters alone (namely, China and India) have a share in global CO_2 emissions in 2011 that equalizes that of the OECD as a whole (Oliver *et al.*, 2012). Developing countries are now responsible for more than a 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 the global emissions. This figures fully explain why they are asked for actively participating to abatement actions by developed countries.

Starting with the Copenhagen Agreement (UNFCCC, 2009) the interpretation of CBDR has started to be soften, reflecting both the developed countries' position of 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 reliable under the sole condition of adopting a strategy according to which the climate challenge should require global efforts (Brunnée and Streck, 2013).

At the same time, several concerns about potential abatement costs in terms of economic growth expectations reduce the propensity of developing countries to accept binding constraints on GHG emissions since they consider them as a strong reduction in their development perspectives (Golub *et al.*, 2006). Furthermore, the question of equity in climate change should also include how the burden of reducing GHG emissions should be shared across social groups (Markandya, 2011).

While no clear agreement on such negative impacts has been reached at the international level by the scientific community, nonetheless assessment models have emphasized that potential large costs would affect the whole economy. The models used to estimate the costs of different low carbon trajectories over periods to 2100 and beyond differ in many respects. Looking so far into the future requires many 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 decarbonising will be shared across the different nations. Hence, it is not surprising that the results across the models have some variation.

Indeed, given the huge amount of uncertainty it is surprising that there are relatively small differences in the cost of meeting different stabilization targets across the models. Taking one of more recent reviews (Edenhofer *et al*., 2010), the discounted present value of costs of following a path that results in stabilisation of CO_2 concentrations at 450 PPM (a value consistent with a reasonable probability of not having world global mean temperatures rise by more than 2ºC) range from 1.2 to 1.5 per cent of world GDP.[1] The estimates are for the period to 2100 and are based on running five major models on a consistent basis with respect to economic methods used to achieve the low carbon goal (e.g. where taxes on carbon are imposed). In particular they assume that the world pursues a cost effective strategy, which of course may not be the case. As Nordhaus (2013) shows, the costs can be much higher if the reductions are not shared by developing countries: indeed it may be impossible to reach the 450 PPM target in this case.

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) will vary by region. In the majority of models currently available, China has costs consistently higher than the world average and the US has the highest costs within the developed countries.

Costs can also rise if certain technologies that are currently in the development stage fail to materialise, such as carbon capture and storage. This does raise the estimates but for the 450 PPM target the increase is still modest (at most 1-2 per cent, with a couple of exceptions).[2]

Given these results from a formidable set of analysts the question arises, why is the political appetite for adopting carbon policies consistent with these targets so anaemic? 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 take us to a 450 PPM stabilisation target along the paths identified in the mitigation research. The phenomenon is stark enough to deserve the title of a Climate Mitigation Paradox.

There are a number of reasons to explain this paradox.

---

[1] The costs are discounted value of the difference in GDP between the constrained scenario and a baseline with no constraint. The rate applied is 3 per cent.

[2] It is important to note that with some technologies not available in the future the more stringent targets cannot be met at all.

First is the point that even though these costs are small they are significant in the short term and the benefits in terms of avoided damages, while potentially large, are further in the future (2050 and beyond). If we use a high enough discount rate, the net benefits of a 450 PPM action do not come out positive. This debate is familiar (Nordhaus, 2007; Stern, 2007; Tol and Yohe, 2006). When economists are so clearly in disagreement on a question, it is not surprising that politicians choose to listen to those whose opinions are best suited to their political exigencies.[3]

Second is disagreement about the results presented. The cost of mitigation may be underestimated if model runs that yield less optimistic results are not presented. This argument has been looked at by Tavoni and Tol (2010), who find that for the more stringent target the number of scenarios and 'runs' is smaller than for the less stringent targets (for this purpose the 450 PPM is considered as stringent). They report that the loss for the 450 PPM target with full participation of all countries range from just under one per cent of GDP to just over 3 per cent across all models except one. With delayed participation by developing countries the cost goes up by about two per cent. The point being made here is important and if there is a bias in the results that are presented it should be corrected. Of course politicians with a predisposition not to act will always cite the highest possible costs of taking action but even if the costs were to be that high, so could be - in extreme cases - the costs of inaction.

Third is the question of the time profile of costs, which is perhaps the most important factor. These estimates are based on discounted values going to 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. Moreover, it is not a case of simply raising the discount rate, which does not pick up these short term considerations to their fullest extent. To be fair some studies such as Edenhofer *et al*. (2010) do look at the annual cost profile and find that it varies considerably from one to another. Unfortunately they do not present the figures for the 450 PPM case, but the

[3]It is also important to note that the discussion does not really take enough account of uncertainty: the premium to act to reduce emissions based on risk aversion is not really accounted for in the debate.

annual costs for the 400 and 550 PPM vary a lot across the models. This is something that exercises the minds of politicians much more than the discounted present value cost to 2011. 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 the 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 where issue of higher energy prices and budgetary pressures is greatest.

There are models that have carried out such an analysis for individual countries and for the EU. The POLES model, for example, has investigated various policy alternatives over the period to 2050 under different assumptions about carbon tax policies and policies for the use of certain non-carbon energy sources, such as nuclear. POLES, however is a partial equilibrium model and takes growth rates as exogenous, so it cannot address the GDP cost of a strong low carbon option where there are real trade-offs between growth and climate policies and where there is a significant underemployment of resources in the short term, especially labour (Criqui *et al.,* 1999).

Other models that address the more detailed economic questions in the short to medium term include GINFORS and TIAM. GINFORS (Global Inter-industry Forecasting System) is an economic model that depicts in some countries and sectors the relationship between environmental variables such as GHG emissions and the output levels. The model has 50 countries and 48 sectors (Barker *et al*., 2011; Lutz and Meyer, 2009, 2010). The problem with this kind of model is that it has the capacity to model the short term well but, given its econometric structure, it lacks the information on detailed sectoral changes to model over periods of more than ten years or so.

This issue of a lack of long term parametric information is addressed in models such as TIAM-UCL (Anandarajah *et al.*, 2011), which is a 16-region bottom-up model depicting the global energy system in a technology-rich manner from primary energy supply through the conversion sector and the final energy sectors to energy service demands. The aim in on-going work is to link these two models. In the proposed policy simulation with the enlarged GINFORS model it will be possible to identify those mixes of economic instruments that will meet for given world market prices of energy carriers the ambitious climate targets for 2050.

Finally we must not forget those models that, instead of looking to the future, look at the past. They can inform us about the costs imposed by the very modest measures that have been introduced to lower GHG emissions in selected countries (Andersen and Ekins, 2009; Kreiser *et al*., 2011). By and large these studies conclude that the effects of the existing measures have been small in economic terms, even with some positive effects in some cases. While this is worth to be known, it does not answer the question of what will happen 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, assessment in order to facilitate the current international negotiation debate.

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

Much importantly, at 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 where most developing countries are focusing on in order to reach consensus in the Post Kyoto negotiations. The GCF, when operational, would channel significant financial resources into adaptation and mitigation, potentially enhancing also the development of low-emission technologies in developing countries. The introduction of the fund tries to solve a number of instances clearly summarised 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.

Very briefly, the prospect of financing specific countries to reduce GHGs is not new in the political agenda, but it has been affected by fragmentation which strongly limited its effectiveness due to a lack of coherent investments able to develop a critical mass of coordinated measures. During last 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 in different ways by all countries 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 is expected to be fully operational by 2014. It will receive contributions from the Parties, private and alternative sources.

Although the size of contribution is still unclear, it will be significantly larger than the existing climate funds. Such resources will support cost-efficient mitigation and adaptation initiatives in a balanced way, putting an emphasis on potential environmental, 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). The World Bank will serve as an interim trustee for the GCF, subject to review three years after its operationalisation.

Some aspects remain to be further discussed 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 the resources (Schalatek *et al*., 2012). With respect to the last issue, although the current decision-making procedures are under development, we can reasonably assume some definitive points to be decided by the Parties:

- The board will balance the allocation between adaptation and mitigation measures, ensuring also appropriate resources for other activities, with a recommended allocation of no less than 50 per cent of overall funds for the adaptation window.
- The board will give priority to urgent issues and immediate needs of developing countries which are particularly vulnerable to CC, including LDCs, SIDS and African States, using minimum allocation floors for these countries as appropriate.
- All the funds will be subject to a result-based approach as a criterion for allocating further resources.

Regarding the status of the contributions, in 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. 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 to us an important lack in such a global initiative and we see in that a lost chance to address also the growth issue.

By considering this gap in the scientific literature as crucial for depicting a clear assessment of alternative policy options and thus driving the negotiations, we propose an original modelling approach in order to partially fill this gap at least in some evaluation aspects. The following novelties are thus developed:

i) We analyse the effects of starting on path that does not allow the world to exceed 450 PPM equivalent concentrations of GHGs by 2050, with a focus on the impacts of such policies as are necessary to achieve this target over the period to 2035 with a medium term horizon which is more useful for current policy assessment.

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

iii) We explore how the GCF could be reasonably financed and which are the costs for developed countries to create and sustain GCF, since the creation of such a fund responds to the common but differentiated criterion and developed countries are obliged to assist poor economies in combating climate change.

iv) We finally 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 solving the negotiations deadlock and bring a reduction in abatement costs for both developed and developing economies through promoting technological innovation, which will make participating in an agreement more attractive for developing countries.

The rest of the paper is structured as follows: Section 2 lays out a model description and 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 available in static setting (Burniaux and Truong, 2002; McDougall and Golub, 2007) is now also available in 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 a 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 modelling of international trade and transport – it enhances the investment side of the framework to allow for international capital mobility and ownership. A rather sophisticated theory of investments based on adaptive expectations allows for a disequilibrium approach to endogenously model international capital mobility (for a theoretical review see Lancovichina and Walmsley, 2012). Although GDyn uses a recursive solution procedure, time enters the model equations as an explicit variable and not as an index, allowing for an easy implementation of the dynamic aspects into the standard GTAP model with minimum modifications. 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 modelling 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 here adopted uses the last 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 standard GTAP-Database 8.1.

2.2 Model improvements

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

The first and most significant improvement regards the elasticity of substitution values between energy and capital, which are crucial when 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 behaviours for abating countries with substantially different reduction targets related to alternative substitution values is quite large, and it deserves a particular modelling accuracy. Considering that GDynE is a CGE model working in terms changes in monetary values, different elasticity values represent different substitution possibilities in technical terms in the production function which allow for reducing the economic impact on the production function (higher values) or increasing it (lower values).

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 criticised as not empirically based. To this sense, Beckman *et al*. (2011) proposed alternative values (second Column in Table 1) on the basis of a review of past empirical estimations. Such values are too much restrictive reducing model flexibility as well as increasing abatement costs.

The values used in the model here adopted are taken by two wide enough reviews of elasticity values considered for meta-analysis of driving factors explaining estimated values of energy-capital substitution elasticity (ELKEN in GTAP nomenclature) as described in Koetse *et al*. (2008) and for inter-fuel elasticities as given in Stern (2012), as listed in third Column.

It is worth noting that all values except for the substitution between non-electricity energy sources (ELNELY in GTAP nomenclature) are between the GTAP standard values and those proposed by Beckman *et al*. (2011). While the capital-energy elasticity is not far in the three alternatives, what makes the difference in terms of flexibility and abatement costs is the inter-fuel elasticity with respect to the electricity nest (ELFENY) and the non-electricity one (ELFNELY).

Table 1

With respect to the other behavioural parameters adopted in GTAP models as exogenously given, the following further adjustments have been made to the standard model.

i. 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. In addition the elasticity of substitution in household energy sub-consumption has been modified, based on the energy mix in consumption at the country level. In particular, the elasticity has been increased for countries having a relatively highly differentiated consumption mix, and decreased otherwise.

ii. In order to better evaluate the changes in elasticity between capital and energy due to technical change, an additional coefficient has been inserted to allow specific changes in the elasticity in each region based on additional empirical information (Lancovichina and Walmsley, 2012).

iii. An additional variable for augmenting technical change in each sector and in each region has been included to allow for differential changes in productivity by sector.

iv. An autonomous energy efficiency improvement parameter (AEEI) has been modelled in the baseline as an input augmenting technical change exogenously given as a common choice of carrying baselines in bottom-up energy-technology models.

v. Regarding the extra parameters used in the standard GDyn, the parameters which represent the rigidity of allocation of wealth by regional household and the rigidity of source of funding of enterprises have been changed modifying their values in order to improve the capacity of the model to find a convergence solution while maintaining the original differentiation of the GTAP Database.

2.3 The modelling specification of the Green Climate Fund

The main novelty of the modelling approach here adopted is represented by an explicit equations module which allows for shaping the introduction of a GCF. As recently emphasized in the Post-Kyoto negotiation this tool could foster the capacity of developing countries to contribute actively to achieving carbon emission abatement.

The assumption is that a percentage of total carbon tax revenue gathered by governments of developed countries through either a carbon tax or an emissions trading scheme is collected in the GCF. This percentage value can be treated as an exogenous parameter according to a potential international agreement in the sense that all developed countries participating to Post Kyoto agree on drawing a x% from their carbon tax revenue (CTR). This means that when we use a portion of carbon tax revenue to finance GCF, the amount of investment paid by developed countries is subtracted from their equivalent variation (EV), resulting as an additional cost to abatement efforts and a reduction in domestic welfare.

The x% of CTR is applied uniformly to all developed economies, meaning that it is set during international negotiations. Further interesting issues may arise when the x% is endogenously given by some different criteria that should be negotiated (this could be an interesting future research issue to investigate). Given x% as exogenous, the higher the CTR value for one country, the higher its contribution to GCF. The amount of contribution to GCF is thus directly correlated with carbon tax level. By construction, when an international emission trading is allowed, domestic carbon tax levels are all equalized to permits price. By considering abatement commitments as given, the size of the GCF is directly correlated to permits price.

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

We have modelled the contribution that all countries may make to the GCF as a share of the total revenues coming from CO_2 taxation.[4] In formulas, total revenue from CO_2 abatement is computed as:

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

where $CTR(r)$ is the revenue resulting from a tax on a target level for CO_2 emissions and $NCTAXB(r)$ is the domestic level of carbon tax or alternatively the permit equilibrium price if emission trading is allowed. The value of CTR which is devolved towards the GCF is modelled as:

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

where $\alpha(r)$ represents the regional contribution to GCF. $CTRF$ corresponds to a reduction of the total CTR which in turn must be deducted from equivalent variation (EV) computation, since it is to be considered as a net cost (tax payers are less than compensated by the lump sum). The GCF is thus given by the sum of all regional contribution as follows:

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

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

According to the Post Kyoto negotiations the GCF should be funded only by developed economies, hence $\alpha(r)$ will be equal to zero for developing countries and equal to an 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 countries according to a parameter which 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 country (r). This means that in this formulation it is not possible to bank anything and the whole fund is completely used in each period.[5]

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

In this paper we have set the distribution parameters at the regional contribution to the world economy in terms of GDP in 2010. This means that countries with larger GDP shares receive the greater share of GCF. This choice directly depends on the GDynE structure, where CO_2 emissions are directly linked with GDP levels. Further efforts in terms of assessing distributive impacts of GCF would be analysed in the future.

In our scenarios we have also modelled the contribution of GCF going towards solely developing countries. This means that GCF is funded by developed economies and used by developing ones with no overlapping cases. This is a modelling choice adopted only for our demonstrative case, while GDynE can be used for all possible combinations with a full overlapping option.

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

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

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

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

In that way, the total contribution of GCF to receiving regions is modelled as a direct contribution to welfare levels as a positive term of the equivalent variation and the reduction due to funding contribution influence the EV formula as follows:

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

The alternative options here explored refer to using part or total $RGCF(r)$ to improve technological options in receiving countries. In particular here we shape 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 modelled as:

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

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), while for $\gamma(r) < 1$ we are in the case where the GCF is used for changing technology options in receiving countries. Let us explore the first policy option, where $RGCF(r)$ is used for improving energy efficiency. We have modelled the relationship between technical change in energy efficiency and GCF in a very simple way. We have taken an elasticity parameter ($SHAF(i,r)$) in order to transform research and development (R&D) efforts (million of US$) into technical progress in energy efficiency by using an average (and rather low) elasticity value taken by the literature in 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 have adopted an identical value for $SHAF$ for all energy inputs and for all produced commodities. Such an approach represents a rather standard modelling choice when sectoral empirical estimations are not given. The final equation for translating R&D efforts into technical progress is thus given by

$$afallf(i,r) = [SHAF(i,r)] \cdot TechGCF(r) \tag{8}$$

where i stands for inputs, and $afallf(i,r)$ is the technical change 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 are directed towards improvements in energy efficiency ($EGY - COMM$ in GTAP jargon) but it is also possible to model specific gains in input efficiency or a generalized improvement in efficiency across all commodities or across specific ones.

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

$$aoallrw(j,r) = [SHRW(j,r)] \cdot TechGCF(r) \tag{8}$$

where $SHRW(j,r)$ represents the reactivity of the electricity sector to R&D investments. In this specific case the reactivity parameter is calibrated with respect to 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), since no specific empirical estimations are available from literature as detailed in Section 3.

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, since 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 it is possible to disentangle the indirect impacts on developed countries as well. In particular, what we would like to notice is that a sort of active policy adopted into developing countries thanks to financial assistance by GCF funded by developed economies may produce benefits also 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 in 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 10 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 criterion for the classification adopted follows the rationale that we consider as developed economies those 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 respect to developing regions, we have 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 into active abatement efforts in the Post Kyoto negotiations. We have also considered as an aggregate the Energy Exporters since they will face similar impacts due to CO_2 emissions reduction policies even if they are geographically and economically divergent countries. We have then modelled 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. The existence of the aggregate Energy Exporters allows us to disentangle LDC in the African region from those economies rich in natural resources. The regions here presented are also comparable with those used for scenarios presented in WEO, thus this helps us better calibrating CO_2 emission projections.

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. In order to reduce as much as possible computation problems due to excessive number of regions and sectors, we have adopted a final classification with 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 temporal dimension, we have considered a temporal horizon going from 2010 to 2035. The starting date is set at 2010 since data on CO_2 emission level 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 while technology is exogenously given, we have decided to stop our simulation in 2035, according to WEO 2013, where CO_2 projections are given on the road towards 450 PPM concentration, meaning that we trace the path towards the achievement of 2050 abatement goal. As a standard modelling choice, periods here are shaped as a 5-year temporal structure.

The baseline has been built by starting from the new GTAP database which refers to year 2007 and adopts updated Input-Output Leontief coefficients into production function of all commodities.

Standard parameters available in GTAP have been replaced with elasticity of substitution as described in Section 2. Moreover, rigidity parameters regarding capital accumulation function have been calibrated according to our regional aggregation. The higher the aggregation level (we have here 17 regions starting from 129 countries as those available in GTAP Database 8.1) the higher the flexibility necessary to ensure that the model is a faithful representation of reality.[6]

Autonomous energy efficiency improvement (AEEI) is modelled here as an input augmenting technical change with an approximate value corresponding to an increase in energy efficiency per year of 0.5%. This is a value at the lower end of the feasible range since the literature indicates AEEI estimations varying from 0.4% to 1.5% per annum (Grubb et al., 1993; Löschel, 2002; Weyant, 1999).[7]

---

[6] From personal correspondence with modellers of Purdue University, we have reduced parameters of rigidity of allocation of wealth by regional household (CRIGWQH) and the rigidity of source of funding of enterprises (CRIGWQF) by 70% of their initial values obtained by aggregating regions with FlexAgg. This choice allows the capital stock to be accumulated both from domestic and international investment destination with less constraints. The economic effects in terms of abatement costs of making these changes are negligible in all simulations while the lesser the constraints (or the lower the parameters value) the greater the stability and reliability of results. A sensitivity analysis of this modelling choice is available from the authors.

[7] 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 the 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 only partially non-price factors as well as structural changes (for a recent contribution see Webster *et al*. 2008). On the other hand, the AEEI approach is simple and reduces the risk of model nonlinearities, 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),

Projections for exogenous variables are taken as given by major international organizations. GDP projections are taken from the comparison of the Reference case of 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 GINFORS model. Population projections are taken from the UN Statistics (UNDESA). Projections for the labour force (here modeled as skilled and unskilled) are taken by comparing labour force projections provided by ILO (which result as aggregate) with those provided by the GTAP Macro projections (where skilled and unskilled labour force are disentangled).

In terms of CO_2 emissions calibration, this specific issue has been considered carefully, since the starting values as well the whole baseline in terms of CO_2 emission levels are crucial for determining abatement costs. Regarding calibrating emissions to current level, we have projected the global economy from 2007 to 2010 by considering CO_2 emissions as exogenously given, in order to replicate the current distribution of CO_2 emission among regions on the basis of current data. This modelling choice implied considering GDP as endogenously determined over the period. In order to detect the robustness of our results we have considered as a guiding criterion that GDP distribution across countries at 2010 should replicate those values reported in World Bank Statistics (WDI, 2013). By taking into account that GTAP Database 8.1 is calibrated before publication, GDP values are never the same as those published by international databases.

Starting from 2010 CO_2 emission, we have than recursively adjusted the baseline scenario obtained over the period 2010-2035 by retaining macro projections while working on fossil fuels forecasted resource availability. In the GTAP framework all energy commodities are modelled as traded goods and not as resources. This means that in a demand driven context,

---

GREEN (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 World Bank (van der Mensbrugghe, 2008) or EPPA version 3 and 4 (Babiker et al., 2001 and Paltsev et al., 2005, respectively) developed at Massachusetts Institute of Technology. Well conscious of its limitations and aforementioned drawbacks, we decided to incorporate in the GDyn-E model such a parameter, since this still represents a standard modelling approach in E3 literature.

when GDP and population grow, if no constraints are explicitly modelled, 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 have automatically reduced emissions. As a final calibration robustness, we have modelled in the GTAP Tablo an equation able to calculate the final volume (and not value as the standard GTAP approach) of each energy commodity. These volumes have been compared with those available in IEA (energy production in this case), in order to respect also the distribution of different sources in the energy mix. This allows also checking changes over time of the global availability of fossil fuels.

3.2 The 450 PPM scenario

The emissions quota assigned to each region is directly a proportion of the baseline values. Since calibration for the period 2010-2035 mostly reproduce 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 may be compared.[8] 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. It is worth noting that in this simulation exercise we take the burden sharing as given by WEO 2013. To this purpose, further crucial work still needs to be done by applying our modeling framework to an endogenous burden sharing provided by GDynE results, which is exactly our future research task.

The standard market-based policy options available for reaching such emissions path are the implementation of domestic carbon tax (GCTAX simulation as in Figure 1), where each

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

country/region should reduce on 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 450 PPM scenario while IET is the cost-effective one.

In the case of IET, we adopt the same abatement commitments as in the GCTAX scenario, but in this case countries may trade permits in order to reach a higher policy efficiency (same environmental target at lower costs). Since nothing has been still decided at the international level, in this paper we have hypothesized that all countries actively participate to the achievement of the 450 PPM pattern, and all countries may participate to the emission trading market.[9]

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

This scenario has been implemented with the aim of allocating a percentage value of CTR to the GCF in line with ongoing negotiations. For this purpose, we have first identified that percentage value ($\alpha(r)$) able to ensure a financial flow comparable with the $100 billion flow by 2020 emphasized recently by the XVI COP held 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 the permit trading, with the equilibrium permit price). This means that, at a practical level, when abatement targets begin to be more stringent, the permits price rises and consequently the amount of GCF is also increasing. In that sense, a potential bargaining theme could be to set in dynamic terms the percentage values of CTR in order to ensure a constant 100 billion USD

[9] We are aware about all technical and institutional barriers related to the implementation of an IET where all countries participate. Hence our IET case must be considered as a benchmark case where the final goal is to reach the most effective scenario in terms of lowering abatement costs, where no binding constrains are settled in terms of permits quantity assigned to each country. This is clearly contrary to the supplementary principle of the Kyoto Protocol, where countries must first implement domestic actions and require UNFCCC to be authorized to use flexible mechanisms. Although a full IET system is not under negotiations, it is also true that the current Post Kyoto discussion is far from being conclusive, thus giving us the possibility to include a full IET as a possible policy option.

amount. While this is a valid option to be investigated when practical policy implications should 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 equal to 8%,which is the required amount of CTR by developed countries to reach an average annual value of around 100 billion USD all over period 2015-2035.

It is also worth noting that we have fixed this percentage value in this scenario where 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. This is a required simulation artifice in order to have an upper bound with which we can compare results obtained by the other simulations where GCF is used for technical change.

The final issue to be considered for this scenario is the criterion used for distributing GCF between developing countries. In this paper we have considered the cumulated GDP losses over the period 2010-2035 in the 450 PPM scenario with IET, in a way that the higher the GDP loss, the higher the share of GCF obtained (in other words the share of country specific GDP cumulated loss on the total GDP loss faced by developing countries corresponds to the share of GCF going to each country). Also in this case we have adopted a fixed criterion which could be dynamically shaped in the future in order to reply to practical policy design issues. Additionally, further allocation criteria might be tested and proposed, but this is food for thought for future research.

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 by 8% but, considering that the permits price is endogenously determined in IET and that the investment of GCF in energy efficient technologies in developing countries would contribute to reduce equilibrium carbon tax level (we must recall 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 lower) the amount of

CTR, the global available amount of GCF would be reduced by energy efficiency gains. This would mean that from one side the global amount of GCF will be lower (and this could be a negative factor for developing countries, *ceteris paribus*), but effectiveness of the GCF in reducing mitigation costs for developing countries in this scenario with respect to the lump sum option in EV terms could over compensate it.

In order to transform GCF in monetary terms into energy efficiency technical improvement we have 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 have 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). On the basis of historical data (excluding the period of the economic crisis) we have computed 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). We have then taken 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. Finally we have also controlled for how much the economic system gains in terms of reduction in energy intensity. The average gain over the period 2000-2008 in terms of reduction in energy intensity for OECD developed countries is around 2.5% per year, while in our simulation for the first two periods (2010-2020) we obtain an average reduction of 5%.

Assuming that such an improvement in energy efficiency is allocated to developing countries only, we can estimate (under constant returns to scale) how R&D efforts might be transformed into energy efficiency gains. By considering that after 2025, due to a carbon price level which is increasing at an increasing rate, the total amount of GCF is rather higher than in the early periods, efficiency gains go from 5% to 15% per year in the period 2025-2035. Since we do not know whether constant returns to scale is a reasonable assumption, we have also considered diminishing returns to scale by carrying out a sensitivity analysis.

We have also considered the energy-efficient scenario provided by WEO 2013 (Efficiency World Scenario – EWS), and we calibrated the reaction function in order to have a reduction in energy intensity which is similar to that shown WEO 2013. Taking 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 WEO EWS reduces by -18% with respect to 2010 at world level, while in our scenario we obtain a reduction by -16.5%. We are conscious that these two scenarios are far from being comparable since in our case only developing countries will reduce energy intensity, and financial support for such policies comes from GCF which is not investigated in the EWS case. Nonetheless, we are quite confident that these similarities and calibration systems sustain the reliability of our results.

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 capital availability to the electricity sector in order to increase production of renewable energies. In order to model the GDynE structure for this purpose, apart from directing capital flows toward the electricity sector we have also relaxed the substitution elasticity constraint by shocking $ELFKEN$ up to 1.00 only for the electricity sector, thus reducing the technical constraint to produce electric power only by using capital as an input (and wind and solar power which are by definition available for free).

Also in this case we have shaped reaction parameters in order to calibrate the reaction of the energy system assuming four driving criteria: 1) as for energy efficiency we have calculated a reaction function where over the period 2000-2008 a 1% increase in R&D produced an increase by 0.35% in renewable production (in volume terms); 2) we have also calibrated the increase in renewable production by developing countries according to the Renewable Energies Scenario broadly described in WEO 2013, by reaching a total volume of renewable energy for developing countries which almost equal the half of total value in Mtoe for the whole world by 2035; 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 equal to 5-7% per year in a high oil price scenario, while in our case the average growth rate amounts of around 5% per year, which is quite similar to that estimated by EIA-DOE; 4) according to WEO 2013 the total cumulated amount of investments necessary to reach such increase for the whole world is around 6.4 trillion USD in the New Policy Scenario (which is not specifically oriented towards pushing renewable energy production), while in our results the global amount of investment for the period 2015-2035 is around 4.8 trillion USD (in this case invested only in developing countries, while in WEO the investment in non-OECD countries amounts to 3.2 trillion USD, about half the 6.4 trillion).

In our model the average reaction function, when growth rate in renewable production is the leading calibration criterion, produces an increase by 0.7% of renewable energy production. By considering the large amount of money provided by GCF for this purpose, such a higher reaction function with respect to historical data may be acceptable.

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 the energy efficiency (GCF-EE) and the 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 to compare how much the two opposite 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 also in terms of convenience for the financing (in our case the developed countries) and financed countries, and 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 modelling features could be implemented in the future.

4. Results with GDynE

4.1 Baseline

As noted above the calibration process has been carried out using the WEO 2013 emissions projections in the “Current Policy Scenario” as a benchmark and adjusting the level of capital accumulation, technological efficiency of energy input and the output productivity (which also has a price effect on energy products) to align macroeconomic projections with WEO 2013 up to the year 2035. In this way we ensure that the model behaves coherently with respect to the energy structure and allows for a consistent simulation of further policy scenarios. 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%. Rates across the world vary widely, with a low of 1% for Japan to a high of 11.8% for China.

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 to 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.[10] 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

[10] 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.

measures to impose reductions to meet a climate target could 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 stabilising concentrations of CO_2 at 450 PPM by 2050. The WEO 2013 has developed a scenario in which main regions have reductions targets such that the world as a whole is on track to meet the 450 PPM target at 2035.

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 in the baseline, with most regions reducing their emissions relative to the 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 around the CBDRC. In fact, since the sole active role of developed countries will be ineffective in stabilising the global temperature but an active role played by developing countries will bring to them unacceptable abatement costs, affecting substantially their economic development perspectives. It clearly emerges how the implementation of climate finance support mechanisms such as the Green Climate Fund constitutes a key policy strategy.

Table 4

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

Figure 2

As early mentioned in the simulation design description, in order to get to this target we first assume a domestic carbon tax that is collected nationally (GCTAX). The GDynE model is run to endogenously calculate 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.[11] 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 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 that remains considerable.[12]

The next question is how much would such taxes impose in terms of welfare reduction, as measured as loss of GDP in constant prices (Table 6).

Two important remarks follow 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 considerable variation in the losses, with major producers of fossil fuels (the Energy Exporters region) losing more than the 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

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

[12] The taxes we get are somewhat higher than in some other models. For example the POLES model, when run for a similar target with a single tax across all developed countries, comes up with a rate of around $190/ton CO_2 in 2030. This may be partly the result of the fact that the tax is harmonized across a large number of countries but in our view that is not enough of an explanation. The question merits further investigation.

in 2040 of at most 2% whereas we get a loss of around 4-5%. This partly result from GDynE being a top-down model not able to take into account explicitly the entire arena of energy technologies 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.

Table 5

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.

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

Table 6

We have modelled 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 such 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 activities.

The results in terms GDP effects are shown in Table 7, where we find the losses are about 0.7% lower than in the case with separate carbon markets. This result is clearly in line with theoretical framework where emission trading is considered as cost effective with respect to domestic actions. Nevertheless, this higher effectiveness in terms of reduction of abatement costs is always assessed in global terms, while few analyses deserve attention to inter-regional cost effectiveness and economic impacts.

To this purpose, it is important to note that not all parties gain as a result of such a market relative to the 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 targets. 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 monetary revenue for Energy Exporters. This is just an example of how it could be useful to analyse climate change options also from a CGE point of view, since several aspects related to inter-country relationships are not modelled by partial equilibrium or bottom-up models.

Going into further details 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 a IET system. More importantly, the three regional aggregates where most LDC are grouped (i.e., Rest of Africa, Rest of America, Rest of Asia) have further reduction in GDP levels with respect to baseline.

This means that a global carbon market as the sole climate policy option internationally discussed brings necessarily 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 favoured by such policy option. If cost effectiveness should remain as a guiding criterion in order to settle climate reduction policies, further complementary measures are strongly required to achieve a global agreement.

Table 7

4.3 The Green Climate Fund scenario: potential benefits for a 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 in the case of 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 lowers costs for low carbon options, thus reducing the price of CO_2 needed to achieve a given reduction in emissions.

Between the GCF options considered the reduction in permit prices is greatest in the case of the mixed allocation, followed by the renewable energy program and last by the energy efficiency program. The 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. As a remark the GDynE model, differently from an integrated assessment model, does not allows measuring the benefits of lower CO_2 emissions of preventing climate change, since no damage costs function is modelled in the computation of the EV. From one side this constitutes an overall underestimation of expected benefits from reducing CO2 emissions, but from the other side these net benefits are mainly to be considered as long term effects; as emphasized in the previous Sections, most of current negotiations and bargaining positions are manly driven by shorter term costs mainly referred to abatement efforts. This specific feature should be clearly addressed as a future research task to be considered in model improvements.

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).

In Table 10 the size of the fund with the different allocations is compared with a fund that makes no allocations to energy efficiency or renewable energy (GCF-EV), which is modelled according to the ongoing negotiations of a constant year flow of 100 million USD by 2020. In all cases the fund size declines 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.

When comparing EV in the scenario GCF-EV with the one in scenario IET it is worth noting that at a global level losses are equal (-5,600 US$Bn over the period 2010-2035) but their distribution favors developing countries in the GCF-EV. GCF-RW scenario softens the negative impacts on EV with respect to 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 with respect to the baseline and a smaller increase in losses for developed economies compared to 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 aggregate.

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, by increasing the technical efficiency of energy consumption, the CO_2 abatement efforts are feasible at a lower economic impact in terms of resource constraints. In the case of the GCF-RW scenario, the amount of renewable energy available by investing the GCF has not the same (positive) economic impact with respect 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 in the next decades which could represent the first best solution in terms of reducing global abatement costs, but would ensure a higher likelihood to be signed and respected by all Parties.

5. Conclusions

In this paper we have examined the options for a low carbon mitigation strategy for 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 over a 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 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 one per cent of GDP relative to the former. The global carbon market can, however, involve inter-country transfers that need further investigation but according to this analysis indicate some regions or countries can be 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 significant courage on the part of governments to impose them. They also imply losses in GDP that would be hard to sell to a sceptical 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 away from being solved.

We suggest that one way of solving this negotiation lock-in 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 it may have benefits for both the recipients and the funders. In particular, a GCF, financed from the 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. Thus this option is 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 done in the very next future in order to help international negotiations escaping the deadlock. First, negative impacts on Energy Exporters due to low carbon strategies should be carefully considered as long as possible complementary measures in order to reduce such losses. Second, other measures that allocate resources to R&D also 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 in the welfare computation, and also the distribution of costs could be substantially different in a long term horizon.

Acknowledgements

We acknowledge the financial support of: i) the European Union D.G. Research with Grant Agreement number 308680 to the research project “Choosing Efficient Combinations of Policy

Instruments for Low-carbon development and Innovation to Achieve Europe's 2050 climate targets" (CECILIA2050); ii) the Roma Tre University-INEA-ENEA Consortium; iii) the Italian Ministry of Education, University and Research (Scientific Research Program of National Relevance 2010 on "Climate change in the Mediterranean area: scenarios, economic impacts, mitigation policies and technological innovation"). The usual disclaimer applies.

References

Adams, J. D. and Jaffe, A. B. (1996). Bounding the Effects of R&D: An Investigation Using Matched Establishment-Firm Data. *The RAND Journal of Economics*, Vol. 27 (4), pp. 700-721.

Anandarajah, G., Pye, S., Usher, W., Kesicki, F., McGlade, C. (2011): TIAM – UCL Global Model Documentation. REF UKERC/WP/ESY/2011/001. University College London

Antimiani A., Costantini V., Martini C., Palma A. Tommasino, M. C. (2013). The GTAP-E: Model Description and Improvements. In *The Dynamics of Environmental and Economic Systems. Innovation, Environmental Policy and Competitiveness*. (Eds) Costantini V. and Mazzanti, pp. 3-24. Springer. Netherlands.

Babiker, M.H., J.M. Reilly, M. Mayer, R.S. Eckaus, I. Sue Wing and R.C. Hyman (2001). The MIT emissions Prediction and Policy Analysis (EPPA) Model: Revisions, Sensitivities, and Comparisons of Results. *MIT Joint Program on the Science and Policy of Global Change,* Report 71, Cambridge, Massachusetts.

Barker, T., Lutz, C., Meyer, B., Pollitt, H. (2011): Models for Projecting the Impacts of ETR. In: Ekins, P. and Speck, S. (ed.): Environmental Tax Reform (ETR). A Policy for Green Growth. Oxford University Press.

Beckman J., Hertel T., Tyner, W. (2011). Validating energy-oriented CGE models. Energy Economics, Elsevier, vol. 33(5), pages 799-806.

Burniaux J.-M., Nicoletti G., Oliveira-Martins, J. (1992). GREEN—A global model for quantifying the costs of policies to curb CO2 emissions, in *OECD Economics Studies*, 19, pp. 49–92.

Burniaux J.-M.,Truong T. (2002). GTAP-E: An Energy-Environmental Version of the GTAP Model. GTAP Technical Paper No. 16. Purdue University

Brunnée, J. and C. Streck (2013), "The UNFCCC as a negotiation forum: towards common but more differentiated responsibilities", *Climate Policy* 13, pp. 589-607.

Cantore, N., Peskett L., te Velde D. W., (2009)"Climate negotiations and development -How can low-income countries gain from a Climate Negotiation Framework Agreement?", Overseas Development Institute, Working Paper 312.

Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni (2009), 'International climate policy architectures: Overview of the EMF 22 international scenarios', *Energy Economics*, 31, (S2), p. S64-S81.

Criqui, P., Mima, S., Viguier, L., (1999). Marginal abatement costs of CO2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model, *Energy Policy*, 27 10, 585–601.

Dowlatabadi, H. (1998). Sensitivity of Climate Change Mitigation Estimates to Assumptions About Technical Change, *Energy Economics*, 20 (5-6), 473-493.

Dowlatabadi, H., M. Oravetz (1997). Is There Autonomous Energy Efficiency Improvement?. Department of Engineering and Public Policy, Carnegie Mellon University.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magne, B., Scrieciu, S., Turton, H. and van Vuuren, D. (2010). The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. *The Energy Journal* 31 (Special Issue): 11-48.

Edmonds J., Reilly J. M. (1985). Global Energy: Assessing the Future. Oxford University Press. New York.

Golub, A., (2013). Analysis of Climate Policies with GDyn-E, GTAP Technical Papers 4292, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University.

Golub, A., Markandya, A., Marcellino, D., (2006). Does The Kyoto Protocol Cost Too Much And Create Unbreakable Barriers For Economic Growth?," Contemporary Economic Policy, Vol. 24(4), pp. 520-535.

Grießhaber L., Esch A., Harmeling S., Kaloga A. (2012). Green Climate Fund: timely action needs early pledges. Germanwatch e.V. Berlin.

Griffith R., Harrison, R. and Van Reenen, J. 2006. How Special Is the Special Relationship? Using the Impact of U.S. R&D Spillovers on U.K. Firms as a Test of Technology Sourcing. *American Economic Review*, 96(5), pp. 1859-1875.

Griliches Z., Lichtenberg F. (1984). R&D and Productivity Growth at the industry level: is there still a relationship? In *R & D, Patents, and Productivity*, pp. 465 – 502. (Ed.) Zvi Griliches. University of Chicago Press.

Grubb, M., J. Edmonds, P. Ten Brink, M. Morrison (1993). The Costs of Limiting Fossil-Fuel CO2 Emissions: A Survey and Analysis. *Annual Review of Energy and the Environment*, Vol 18, pp. 397-478.

Hall B.H., Mairesse J. (1995). Exploring the relationship between R&D and productivity in French manufacturing firms. *Journal of Econometrics*, 65,pp. 263-293.

Hertel, T.W. (1997). Global Trade Analysis Modeling and Applications. Cambridge University Press.

Hertel, T.W., Hummels, D., Ivanic, M., Keeney, R. (2007). How confident can we be of CGE-based assessments of free trade agreements? Economic Modelling 24 (4), pp. 611–635.

International Energy Agency (IEA), 2013a, *CO2 Emissions from fuel combustion*, International Energy Agency, Paris.

International Energy Agency (IEA), 2013b, *World Energy Outlook (WEO) 2013*, International Energy Agency, Paris.

Koetse, M.J., de Groot, H.L.F., Florax, R.J.G.M. (2008). Capital-energy substitution and shifts in factor demand: A meta-analysis. Energy Economics, 30 (5), pp. 2236-2251.

Kreiser, L., Sirisom, J., Ashiabor, H., Milne, J.E., (2011). Environmental Taxation and Climate Change. Achieving Environmental Sustainability through Fiscal Policy. Edward Elgar Publishing, UK.

Lanchovichina E. Walmsley T.L. (2012). Dynamic Modeling and Applications for Global Economic Analysis. Edited by: Elena Ianchovichina, The World Bank, Washington, DC and Terrie L. Walmsley, Purdue University, Indiana. Cambridge University Press.

Lanchovichina E., McDougall R. (2000). Theoretical Structure of Dynamic GTAP. GTAP Technical Paper 480, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University.

Lichtenberg F. R. , Siegel D. (1991). The impact of R&D investment on productivity – New evidence using linked R&D-LRD data. *Economic Inquiry*, 29 (2), pp. 1465-7295.

Löschel A. (2002). Technological change in economic models of environmental policy: a survey. Ecological Economics, 43 (2-3), pp. 105-126.

Lutz, C. and Meyer, B. (2010): Environmental Tax Reform in the European Union: Impact on CO2 Emissions and the Economy. Zeitschriftfür Energiewirtschaft, 34, pp. 1-10.

Lutz, C. and Meyer, B. (2009): Environmental and Economic Effects of Post- Kyoto Carbon Regimes. Results of Simulations with the Global Model GINFORS. Energy Policy, 37, pp. 1758-1766.

Mabey, N., S. Hall, C. Smith, S. Gupta (1997). Argument in the Greenhouse: The International Economics of Controlling Global Warming. London. Routledge.

Manne A. S., Mendelson R., and Richels R. G. (1994). MERGE: a model for evaluating regional and global effects of GHG reduction policies, in *Integrative Assessment of Mitigation, Impacts and Adaption for*

Climate Change, Nakicenovic, N., Nordhaus, W. D., Richels, R., and Toth, F.L. (eds.), International Institute for Applied Systems Analysis, Laxenberg, Austria.

Markandya, A., (2011). Equity and Distributional Implications of Climate Change, World Development, Vol. 39(6), pp. 1051-1060.

McDougall R., Golub A. (2007). GTAP-E:A Revised Energy-Environmental Version of the GTAP Model. GTAP Research Memorandum No. 15. Purdue University.

Nordhaus, W. D. (2007). A Review of the Stern Review on the Economics of Climate. Journal of Economic Literature 45(3), pp. 686–702.

Nordhaus, W. D. (2013). The Climate Casino: Risk, Uncertainty, and Economics for a Warming World. Yale University Press.

Oliver, J., Janssens-Maenhout, G., & Peters, J. (2012). Trends in global CO2 emissions; 2012 Report. The Hague: PBL Netherlands Environmental Assessment Agency; Ispra: Joint Research Centre.

Paltsev S., Reilly J.M., Jacoby, H. D., Eckaus, R. S., McFarland, J. R., Sarofim. M. C., Asadoorian M. O., Babiker, M.H.M. (2005). The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. *MIT Joint Program on the Science and Policy of Global Change*.

Popp, D., Newell, R. G., Jaffe, A. (2010). Energy, the Environment, and Technological Change. In Handbook *of the Economics of Innovation*, Ch. 21, Vol. 2. pp. 873–937. (Eds). Hall B. H., Rosenberg N. Elsevier B.V.

Schalatek L., Stiftung H. B., Nakhooda S. (2012). The Green Climate Fund. Overseas Development Institute and Heinrich Böll Stiftung North America.

Stern, N. (2007), *The Economics of Climate Change,* Cambridge. Cambridge University Press.

Stern D., (2012). Interfuel substitution: A meta-analysis. Journal of Economic Surveys, Vol. 26 (2), pp. 307–331.

Tavoni M., R.S.J. Tol (2010). Counting only the hits? The risk of underestimating the costs of stringent climate policy: A letter, *Climatic Change*, 100 (3), pp. 769-778.

Tol, R.S.J., Yohe, G., (2006). A Review of the Stern Review. *World Economics.* 7 (4), pp.233–50.

van der Mensbrugghe D. (2008). The ENvironmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model. World Bank Working paper.

Weyant J. P. (1999). Energy and Environmental Policy Modeling. Ed. Stanford University. Kluwer Academic Press.

Table 1 – Comparison of alternative substitution elasticities values in the 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 the 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 the 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 the 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

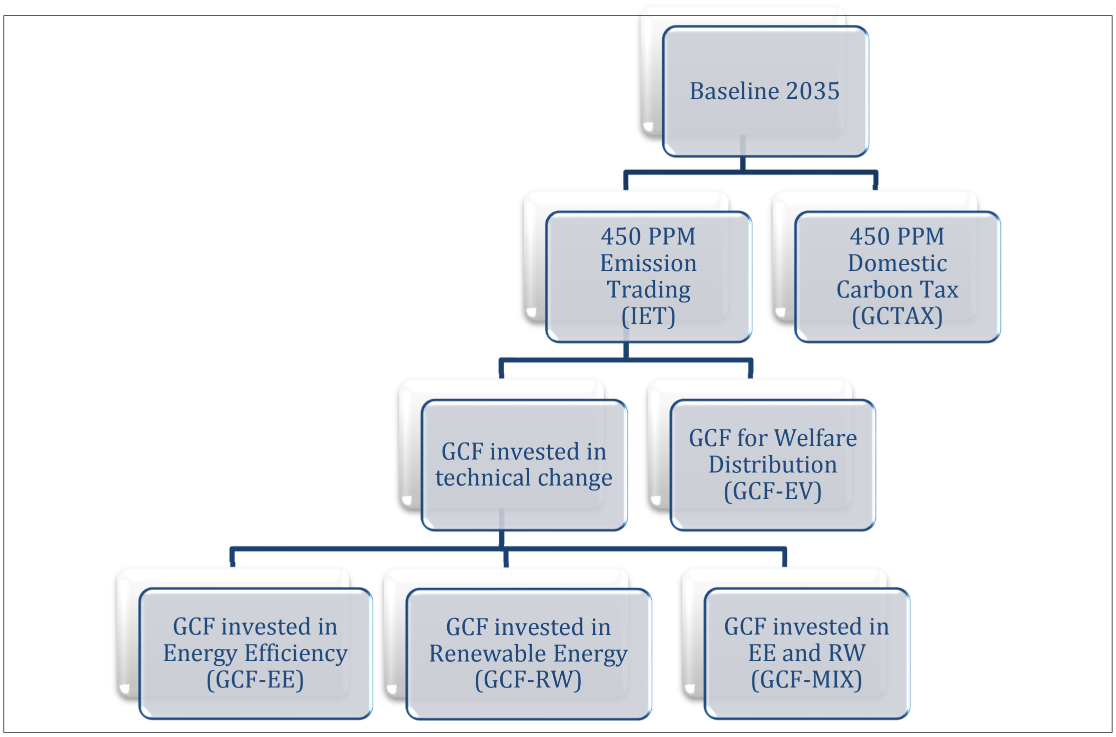
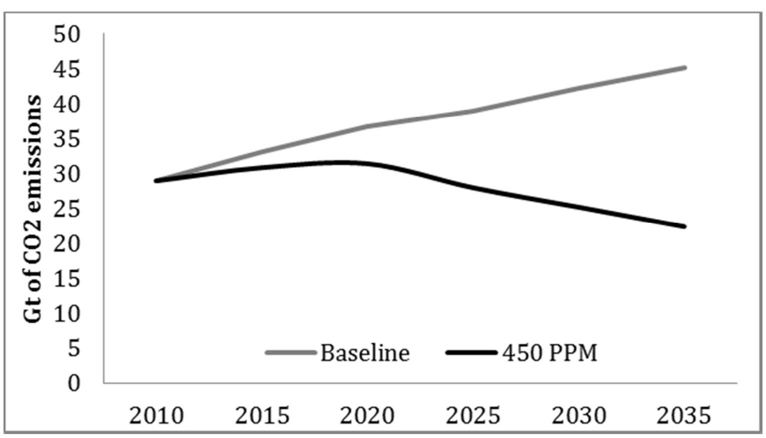
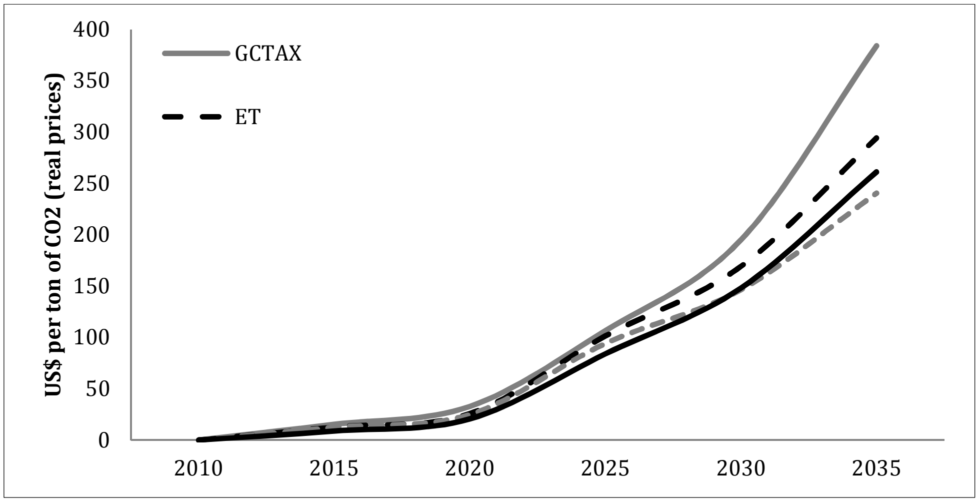


Figure 2 – CO_2 emissions paths along the Baseline and the 450 PPM (Gt of CO_2)



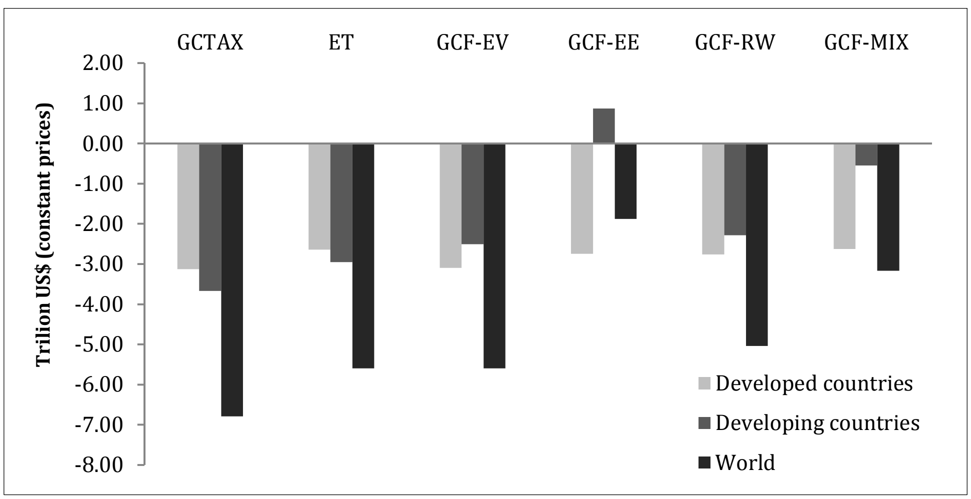
Source: own elaboration on GDynE results calibrated with WEO 450PPM Scenario(IEA, 2013)

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).

Appendix A

Table A.1 - List of GDYnE commodities and aggregates

Sector	Code	Products
Agr	pdr	Paddy rice
Agr	wht	Wheat
Agr	gro	Cereal grains nec
Agr	v_f	Vegetables, fruit, nuts
Agr	osd	Oil seeds
Agr	c_b	Sugarcane, sugarbeet
Agr	pfb	Plant-based fibers
Agr	ocr	Crops nec
Agr	ctl	Bovine cattle, sheep and goats, horses
Agr	oap	Animal products nec
Agr	rmk	Raw milk
Agr	wol	Wool, silk-worm cocoons
Agr	frs	Forestry
Agr	fsh	Fishing
Coal	coa	Coal
Oil	oil	Oil
Gas	gas	Gas
En_Int_ind	omn	Minerals nec
Oth_Ind	cmt	Bovine cattle, sheep and goat meat
Oth_Ind	omt	Meat products
Oth_Ind	vol	Vegetable oils and fats
Oth_Ind	mil	Dairy products
Oth_Ind	pcr	Processed rice
Oth_Ind	sgr	Sugar
Oth_Ind	ofd	Oth_Ind_ser products nec
Oth_Ind	b_t	Beverages and tobacco products
Oth_Ind	tex	Textiles
Oth_Ind	wap	Wearing apparel
Oth_Ind	lea	Leather products
En_Int_ind	lum	Wood products
En_Int_ind	ppp	Paper products, publishing
Oil_pcts	p_c	Petroleum, coal products
En_Int_ind	crp	Chemical, rubber, plastic products
En_Int_ind	nmm	Mineral products nec
En_Int_ind	i_s	Ferrous metals
En_Int_ind	nfm	Metals nec
En_Int_ind	fmp	Metal products
Oth_Ind	mvh	Motor vehicles and parts
Oth_Ind	otn	Transport equipment nec
Oth_Ind	ele	Electronic equipment
Oth_Ind	ome	Machinery and equipment nec
Oth_Ind	omf	Manufactures nec
Electricity	ely	Electricity
Gas	gdt	Gas manufacture, distribution
Services	wtr	Water
Services	cns	Construction
Services	trd	Trade
Transport	otp	Transport nec
Transport	wtp	Water transport
Transport	atp	Air transport
Services	cmn	Communication
Services	ofi	Financial and other services nec
Services	isr	Insurance
Services	obs	Business and other services nec
Services	ros	Recreational and other services
Services	osg	Public admin. and defence, education, health
Services	dwe	Ownership of dwellings

Table A.2 - List of GDYnE aggregates

Sector	Full description
Agr	Agriculture
Coal	Coal
Oil	Oil
Gas	Gas
Oil_pcts	Petroleum, coal products
Electricity	Electricity
En_Int_ind	Minerals nec
Oth_Ind	Bovine cattle, sheep and goat meat
Transport	Air transport
Services	Water

Table A.3 - List of GDYnE countries

GTAP Code	Code	Country	GTAP Code	Code	Country
BRA	bra	Brazil	RAF	sen	Senegal
CAN	can	Canada	RAF	xwf	Rest of Western Africa
CHN	chn	China	RAF	eth	Ethiopia
CHN	hkg	Hong Kong	RAF	ken	Kenya
EEx	ecu	Ecuador	RAF	mdg	Madagascar
EEx	ven	Venezuela	RAF	mwi	Malawi
EEx	kaz	Kazakhstan	RAF	mus	Mauritius
EEx	xsu	Rest of Former Soviet	RAF	moz	Mozambique
EEx	aze	Azerbaijan	RAF	tza	Tanzania
EEx	irn	Iran Islamic Republic of	RAF	uga	Uganda
EEx	kwt	Kuwait	RAF	zmb	Zambia
EEx	omn	Oman	RAF	zwe	Zimbabwe
EEx	qat	Qatar	RAF	xec	Rest of Eastern Africa
EEx	sau	Saudi Arabia	RAF	bwa	Botswana
EEx	are	United Arab Emirates	RAF	nam	Namibia
EEx	xws	Rest of Western Asia	RAF	xsc	Rest of South African
EEx	egy	Egypt	RAM	pry	Paraguay
EEx	xnf	Rest of North Africa	RAM	per	Peru
EEx	nga	Nigeria	RAM	ury	Uruguay
EEx	xcf	Central Africa	RAM	xsm	Rest of South America
EEx	xac	South Central Africa	RAM	cri	Costa Rica
EEx	zaf	South Africa	RAM	gtm	Guatemala
EEx	mys	Malaysia	RAM	hnd	Honduras
EEx	arg	Argentina	RAM	nic	Nicaragua
EEx	bol	Bolivia	RAM	pan	Panama
EEx	col	Colombia	RAM	slv	El Salvador
EU27	aut	Austria	RAM	xca	Rest of Central America
EU27	bel	Belgium	RAM	xcb	Caribbean
EU27	cyp	Cyprus	RAM	xna	Rest of North America
EU27	cze	Czech Republic	RAM	chl	Chile
EU27	dnk	Denmark	RAS	kgz	Kyrgyztan
EU27	est	Estonia	RAS	arm	Armenia
EU27	fin	Finland	RAS	bhr	Bharain
EU27	fra	France	RAS	mng	Mongolia
EU27	deu	Germany	RAS	twn	Taiwan
EU27	grc	Greece	RAS	xea	Rest of East Asia
EU27	hun	Hungary	RAS	khm	Cambodia
EU27	irl	Ireland	RAS	lao	Lao People's Democratic
EU27	ita	Italy	RAS	phl	Philippines
EU27	lva	Latvia	RAS	sgp	Singapore
EU27	ltu	Lithuania	RAS	tha	Thailand
EU27	lux	Luxembourg	RAS	vnm	Viet Nam
EU27	mlt	Malta	RAS	xse	Rest of Southeast Asia
EU27	nld	Netherlands	RAS	bgd	Bangladesh
EU27	pol	Poland	RAS	npl	Nepal
EU27	prt	Portugal	RAS	pak	Pakistan
EU27	svk	Slovakia	RAS	lka	Sri Lanka
EU27	svn	Slovenia	RAS	xsa	Rest of South Asia
EU27	esp	Spain	RAS	xoc	Rest of Oceania
EU27	swe	Sweden	REU	xef	Rest of EFTA
EU27	gbr	United Kingdom	REU	alb	Albania
EU27	bgr	Bulgaria	REU	hrv	Croatia
EU27	rou	Romania	REU	ukr	Ukraine
FSU	blr	Belarus	REU	xee	Rest of Eastern Europe
FSU	rus	Russian Federation	REU	xer	Rest of Europe
IDN	idn	Indonesia	REU	geo	Georgia
IND	ind	India	REU	tur	Turkey
JPN	jpn	Japan	REU	xtw	Rest of the World
MEX	mex	Mexico	ROECD	aus	Australia
NOR	nor	Norway	ROECD	nzl	New Zealand
RAF	mar	Morocco	ROECD	che	Switzerland
RAF	tun	Tunisia	ROECD	isr	Israel
RAF	cmr	Cameroon	ROECD	kor	Korea
RAF	civ	Cote d'Ivoire	USA	usa	United States of America
RAF	gha	Ghana			

Table A.4 - List of GDYnE Regions

GTAP Code	Description
	Developed countries
CAN	Canada
EU27	European Union
FSU	Former Soviet Union
JPN	Japan
NOR	Norway
USA	United States
ROECD	Rest of OECD
	Developing countries
BRA	Brazil
CHN	China
IND	India
IDN	Indonesia
MEX	Mexico
EEX	Energy Exporters
RAF	Rest of Africa
RAM	Rest of America
RAS	Rest of Asia
REU	Rest of Europe