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IMPACT AND DISTRIBUTION OF CLIMATIC DAMAGES: A METHODOLOGICAL PROPOSAL WITH A DYNAMIC CGE MODEL APPLIED TO GLOBAL CLIMATE NEGOTIATIONS

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Impact and distribution of climatic damages: a methodological proposal with a dynamic CGE model applied to global climate negotiations

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Abstract

The UNFCCC Parties Paris Agreement entered into force on 4 November 2016 represents a step forward in involving all countries in mitigation actions, even though still based on a voluntary approach and lacking the involvement of some major polluting countries. The underinvestment in mitigation actions depends on market and policy failures and the absence of market signals internalizing the economic losses due to climatic damage contributes to underestimating potential benefits from global action. We highlight how crucial is the vulnerability of a country to climate change in defining the threat and action strategies. A dynamic climate-economy CGE model is developed by including a monetary evaluation of regional damages associated with climate change. By considering alternative damage estimations, results show that internalizing climatic costs changes the bargaining position of countries in climate negotiations. Consequently, damage costs should be given greater importance when defining the implementation of a global climate agreement.

Keywords: Climate change damage costs; Climate negotiations; Burden sharing; Mitigation costs; GTAP; CGE.
J.E.L. Codes: C680; H230; O440; Q540.

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1. Climate negotiations and damage costs

During the twenty-first Conference of the Parties (COP21) held in Paris in December 2015, the Parties under the United Nation Framework Convention on Climate Change (UNFCCC) succeeded in reaching the so-called Paris Agreement. Entered into force on 4 November 2016, it will be effective from 2020. In order to achieve the long-term goal of keeping the global temperature rise this century to well below 2 degrees Celsius above pre-industrial levels, all Parties aim to reach global peaking of greenhouse gas emissions (GHG) as soon as possible. The voluntary approach and the absence of sanctions (Nordhaus, 2015), together with the great country heterogeneity (Brunnée and Streck, 2013; Costantini et al., 2016) make this agreement weak in achieving an inter-generational sustainability goal. Contributions to past GHG patterns reflecting development inequalities create additionally difficulties in designing a burden sharing that exhibits a globally equitable climate mitigation strategy (Matthews, 2016). Such difficulties will increase further if large emitters with historical responsibility do not participate, which is what is happening in the case of the U.S. after the declaration of President Trump in June 2017 to withdraw from the Paris climate accord.

At the same time, the greater vulnerability to negative effects from climate change faced by poor countries is causing an increase in intra-generational inequity of global economic development (Roson and van der Mensbrugghe, 2012). According to the outcome of the most recent meeting in Cancun by the Global Platform for Disaster Risk Reduction, at least 87 countries should systematically account for environmental disaster losses by 2020, around 90% of which will result from climate change. A recent report by the World Bank (Hallegatte et al., 2016) provides a broad monetary quantification of the cost of inaction for the underdeveloped world that would force more than 100 million people into extreme poverty by 2030.

The uneven distribution across countries of losses caused by climatic damage is strictly related to how vulnerable a country is to environmental diseases. Vulnerability increases the likelihood of natural hazards turning into damages (or disasters). The magnitude of the effect depends in turn on how many people are exposed to the hazard and live in areas lacking prevention actions to reduce the impact on anthropogenic activities (Paul, 2011). Accordingly, expenditure to reduce such vulnerability – broadly known as adaptation measures – will be greater the larger is a country's likelihood to experience frequent and strong natural hazards, as long as adequate economic resources are available (Neumayer et al., 2014).

While this reasoning can be fully applied to resilience and adaptation measures, the global public bad characteristic of climate change might lead to diverging positions for the polluter and the agent affected by the damage in the bargaining process of sharing mitigation costs. Thus, if countries responsible for a high share of GHG emissions do not correspond to those most vulnerable to climate change, their propensity to mitigate will decrease. Although this heterogeneous regional distribution of climatic damage and GHG emissions can be considered as a barrier to a global action, the internalization of damage costs into market mechanisms could help to reduce this gap and shape a different geography of climate political economy (Kelly and Adger, 2000; Moore and Diaz, 2015).

Several attempts have been made to analyse the physical impacts of climate change and their monetary evaluation (Anderson, 2006; Arndt et al., 2015; Bosello et al., 2012b, EU, 2011; Fussel and Klein, 2006; Fussel, 2010). Better information on where climatic damages occur, combined with a credible quantification of its monetary costs should increase the likelihood of coalitions succeeding in the bargaining process, thus inducing larger coalitions to be more stable (Dellink et al., 2013; Méjean et al., 2015; Verendel et al., 2016).

The present paper attempts to evaluate to what extent the introduction of monetary costs of climatic damage into climate policy impact assessment might influence the relative attractiveness of potential mitigation actions debated under the Paris Agreement framework. Section 2 provides a brief review of existing contributions on monetary evaluation of climatic damage. Section 3 describes the long-term dynamic climate-economic computable general equilibrium (CGE) model (GDynEP) used to internalize damage cost and evaluate abatement scenarios. Section 4 provides an interpretation of the results under the lens of a cost-benefit analysis approach, while Section 5 provides brief policy conclusions.

2. Economic losses due to climatic damages

Damage assessment is subject to large uncertainties with respect to: the definition of future emission paths, the related change in GHG concentration in the atmosphere, the effect on temperature increase and effects of any adaptation actions on the final outcomes (Markandya, 2014). Furthermore, given that adaptation depends on the interactions between physical climate conditions and socio-economic systems, the climatic economic losses also depend on the future socio-economic scenarios projected.

Applied energy and climate models have been used extensively to measure these economic losses (Markandya et al., 2017) but damage estimations are still quite heterogeneous. For a lower bound temperature increase (around 2-3°C) and a time horizon of 2050, costs range from a low loss of 0.3% of world GDP (Mendelsohn et al., 1998) to a higher impact of 2% (OECD, 2015). Considering a temperature increase between 2.4°C and 5.5°C, the global loss is even greater, on average 3% of global GDP in the range 1.5%-6.1% (Dellink et al., 2014; Nordhaus, 2008, 2011, 2013; Roson and van der Mensbrugghe, 2012; Stern, 2007). Although most of the studies agree on the fact that developing countries will bear the highest costs (DARA, 2012a,b; Moore and Diaz, 2015), there is still no complete consensus about the amount and regional distribution of climatic costs. These differences in estimates arise from the heterogeneity of methods applied to calculate the costs (Tol, 2015) and magnified by the several steps of the climate assessment.

First, monetary evaluation of climate damages varies with the impacts covered (Dellink et al., 2014; Mendelsohn et al., 1998). While some studies only account for market impacts, which are those affecting agriculture, fisheries, tourism or energy sectors (Mendelsohn et al., 2006; OECD, 2015; Roson and Sartori, 2016), others include a wider range of components, considering also non-market impacts related to extreme events, loss of biodiversity or health effects (Bosello et al., 2009; DARA, 2012a,b; Dellink et al., 2014; Nordhaus and Boyer, 2000; Stern, 2007). While estimates for the former are more accurate, non-market impacts are less easily measurable and their inclusion results in higher overall estimates of climate costs especially for developing countries. Indeed, non-market costs can explain most of the discrepancies among existing studies (Stern, 2007). Furthermore, in most cases "loss estimates are lower bound estimates because many impacts, e.g. loss of human lives, cultural heritage, ecosystem services, are difficult to value and monetize, and thus they are poorly reflected in estimates of losses" (IPCC, 2012, p. 7). Accordingly, the inclusion of both market and non-market components is essential for a comprehensive climate cost measurement, notwithstanding the problems with non-market estimation.

To the best of our knowledge, the most comprehensive study providing information on economic losses occurred due to climatic damage for a large sample of countries is the Second Climate Vulnerability Monitor developed by DARA (2012a,b), an independent organization commissioned by the Climate Vulnerable Forum to assess the human and the economic costs of the climate crisis in view of the 18th Conference of Parties.[1] It provides measures of the climate damages effectively sustained by 184 countries for a wide range of impacts summarized in 22 indicators, market and non-market based, covering four different areas: environmental disasters, habitat change, health impact and industry stress.

A second issue is the definition of the damage function, linking damages in monetary terms to climate variables. Damages are mainly represented as a polynomial function (often quadratic) of either global mean temperature change (Bosetti et al., 2006a; Nordhaus and Sztorc, 2013) or the rate and magnitude of temperature increase (Hope, 2010, 2011; Waldhoff et al., 2014). Economic damages can be expressed as a fraction of world output (Bosetti et al., 2006a; Nordhaus and Sztorc, 2013) or, according to the willingness-to-accept (WTA) approach (Bosello and De Cian, 2014; Manne and Richels, 2005; Manne et al., 1995), in terms of the maximum price a consumer accepts to pay to avoid a temperature rise. This is usually the basis for monetizing non-market impacts and represents, at the regional level, the monetary national consumption and income reduction due to climate change. An evolution of the WTA approach is referred to as the Social Cost of Carbon (SCC) approach (van den Bergh and Botzen, 2015). The GHG concentrations give rise to temperature increase, precipitation and frequency of extreme events that in turn might result in damages (or disasters) to various sectors of the economy according to the relative vulnerability of a country to natural hazards. Given that emissions of GHG have the same effect on concentrations irrespective of wherever they are emitted, it is possible to consider the SCC as the global average damage due to an additional ton of GHG emitted at a given point in time, allowing for its natural decay rate.

A third aspect regards the modelling approach adopted to include the damage function into an economic impact assessment model. Among the applied methods used to analyse the economic impact

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[1] The Climate Vulnerable Forum (CVF) is an international cooperation group founded in 2009 by the Maldives, that now includes 20 countries that face significant insecurity due to climate change.

of climate damages on economic system, Integrated Assessment Models (IAM) combine economic and climatic module based on a damage function. In the DICE and RICE models[2] by Nordhaus and Sztorc (2013) climate damages are a quadratic function of the global mean temperature change, while the MERGE Model for Estimating the Regional and Global Effects of GHG reductions (Manne et al., 1995; Manne and Richels, 2005) follows the WTA approach. In the WITCH (World Induced Technical Change Hybrid) model (Bosetti et al., 2006b; De Cian et al., 2012) costs associated to market components[3] are expressed as percentage change of the regional GDP, while for non-market impacts (health, ecosystem and catastrophes losses) it follows the WTA approach.

Due to the high level of aggregation and long time horizon, these models have also been combined with the Computable General Equilibrium (CGE) framework (hybrid approach) to better account for inter-sectoral linkages. Based on a production function approach, climate impacts can be linked to different drivers of economic growth in a CGE framework and expressed as percentage of GDP (OECD, 2015).[4] The evaluation of the effects of climate on GDP depends on the impact under scrutiny. For the agriculture sector for example, the cost is expressed in terms of land (Bosello et al., 2009; OECD, 2015) and crop productivity change (Bosello et al., 2012a; Ciscar et al., 2014). As an example of non-market aspects, health damages are often introduced into the production function as changes in labour productivity (Bosello et. al., 2009). Energy impacts are generally investigated by considering changes in energy demand for cooling and heating (Ciscar et el, 2014; OECD, 2015), while land loss due to sea level rise is the main measure of impacts in coastal zones (Bosello et al., 2009, 2012b; Darwin and Tol, 2001).[5]

A fourth aspect refers to how monetary damages affect GDP in such models. In particular, including the climate cost components only with respect to the direct impacts implies describing the costs of

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[2] DICE (RICE) is the (regional) Dynamic Integrated model of Climate and the Economy model.

[3] These impacts are derived from specific applied models. In particular, the impact on coastal land loss due to the sea level rise is driven by results from the DIVA (Dynamic Integrated Vulnerability Assessment) model (Vafeidis et al., 2008). The ClimateCrop model (Iglesias et al. 2009, 2010) is used for information on changes in the average productivity of crops in agriculture sector, while data on for the energy sector, as the changes in residential energy demand due to increasing temperatures, are derived from the POLES (Prospective Outlook on Long-term Energy Systems) model (Criqui, 2001; Criqui et al., 2009).

[4] An example is the CIRCLE project "Costs of Inaction and Resource Scarcity: Consequences for Long-term Economic Growth Project", where the dynamic general equilibrium ENV-linkages model is used to express climate impacts in monetary term and links them to GDP. In this case, the impacts covered are: loss of land and capital due to sea level rise, capital damages from hurricanes, changes in crop yields, fisheries catches, labour productivity, tourism flows, health care expenditures due to diseases and heat stress and energy demand for cooling and heating.

[5] For an extensive review on sectoral impacts see Markandya et al. (2017).

climate change as a percentage of GDP without taking into account other dynamic effects. When introducing the damage in a recursive way, the multiplicative effects due to economic interactions (indirect impacts) are also captured (Bosello et al., 2012a), with a wider effect on GDP due to sectoral and international adjustments (Eboli et al., 2010).

3. The GDynEP model

In order to make a policy evaluation of economic impacts of mitigation actions and climatic damage jointly, we use a dynamic CGE model based on the GTAP (Global Trade Analysis Project) structure enriched by a climatic exogenous module (GDynEP). GDynEP is a combination of different GTAP model versions and databases with a novel module that allows the cost of climatic damage to be included. The appeal of a CGE approach is the inclusion of detailed market interactions between sectors and countries that represent global economic mechanisms. There are different modelling approaches that could be adopted for such a policy evaluation exercise, as described in the literature review. If the quantitative assessment is built for policy optimization, the modelling choice is likely to be an IAM such as the DICE/RICE. While IAMs have the advantage of directly including environmental science modules, the economic systems are less detailed. In GDynEP we take the GHG concentration and the emission path as exogenously provided by available physical models and we interact it with economic mechanisms via a monetary damage function. This choice is driven by the fact that in this analysis we are not interested in finding an optimizing environmental policy, but we need to explore the influence of climatic damage through the set of detailed inter-sectoral and international economic relationships on economic output and thereby to on bargaining strategies of countries in the climate regime.

In the standard GTAP model versions there is only a stylized environmental mechanism that does not include the full range of factors that influence economic growth in the face of climatic shocks. These models only look emissions produced by anthropogenic production and consumption activities. Consequently, our original contribution is to enrich the standard GTAP dynamic CGE model with a specific module that accounts for long term economic impact of damage.

3.1 Model details

In order to obtain a GTAP-type model that includes both GHG emissions and a complete representation of the energy system the first step is to merge the GDynE (the energy version of the dynamic GDyn) developed by Golub (2013) and improved by Markandya et al. (2015) with the GTAP-Power database (Peters, 2016), which introduces for the first time in GTAP a detailed representation of the renewable electricity sector. The representation of the energy sector with distinguished fossil and non-fossil sources allows a better calibration of the scenarios for the sectors and countries responsible for GHG emissions, in terms of relative costs of reaching the mitigation target given the technical possibilities available for energy production.[6]

The second step is to introduce monetary damage due to climate change in the economic structure. We assume a damage function linked to GHG concentrations at the global level according to the SCC approach. By taking a global damage measure, it is possible to cover all cost types related to climatic damage, including non-market costs that are usually underestimated by those modelling approaches that compute climatic damage costs only directly related to impacts to productivity. We consider that the SCC reduces the global wealth according to a weak sustainability approach, following the methodological assumptions of the Genuine Savings (GS) calculation by the World Bank (Hamilton and Clemens, 1999) where the monetary value of climatic damage is a negative element of the savings function. The adoption of a weak sustainability criterion allows all forms of capital to be considered as perfectly substitutable (Hartwick, 1977, 1978; Solow, 1986). This in turn implies that the cost of damages is a negative component of the capital accumulation function, that could be compensated by

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[6] The included electricity generating technologies are Coal, Gas, Oil, Hydro, Wind, Solar, Nuclear and Other Base Load Power sources, while Gas, Oil, Hydro and Solar generating technologies are further divided between Base and Peak Load. All details on the aggregation choice for this GDynEP model version are reported in Appendix A. In order to merge GDynE and GTAP-Power, it is worth mentioning that in this model version we have adopted two simplifying assumptions. First, the transmission and distribution sector for electricity is included in the service sector and it is not taken as a distinguished one. This implies that there is no technical difference between renewables and the other energy sources in the transmission of electricity. This conservative assumption is adopted because we have no region-based data on distinguished institutional and technical features for the electricity transmission and distribution. Second, given that GDynEP is not a bottom up technical model, it deserves specific exogenous behavioral parameters for each stage of the production function. By introducing the renewable electricity sector, it is necessary to add a specific substitution elasticity parameter between fossil-based and renewable electricity. Given that there is not a specific value provided in the GTAP database, we have derived it from calibrating the BAU scenario in order to have a dynamic trend in renewable electricity production up to 2050 in line with BAU provided by IEA Outlook (IEA, 2015). We acknowledge that this is an extremely conservative hypothesis, especially when carbon mitigation scenarios are considered. Nonetheless, in this paper we test only the emission trading policy option without exploring the role of public support to clean technologies, and this allows taking this substitution parameter as constant. Future research lines would require specific efforts in empirically estimating substitution elasticities at least at the country level as well shaping the evolution of such parameter over time.

additional savings from production activities or additional investments in human or technological capital formation (including investments in adaptation).

Translating these assumptions into model functions can be synthesized as follows.

We first consider the widest computation of global damage due to climate change as the best way to calculate the SCC. To the best of our knowledge the most comprehensive available measure of damage costs provoked by climate change is provided by DARA.

Then, since damage costs are available only till 2012, the evolution over time is shaped according to the SCC approach. From the global costs at 2011 (which is the starting point of the GTAP database) we compute the SCC as an average cost for each ton of GHG concentrations by 2011. The projection of GHG concentrations allows the evolution over time of the SCC to be estimated, according to the specific emission scenario under scrutiny.

Formally, the initial global average SCC (SCC_{t0}) is given by the ratio between the total monetary value of losses due to climatic damage (CCG_{t0}) calculated on DARA data at the world level and the stock of CO_2-eq in the atmosphere ($SCO2_{t0}$) as:

$$SCC_{t0} = \frac{CCG_{t0}}{SCO2_{t0}} \tag{1}$$

The atmospheric concentration enters the model as an exogenous variable with values provided by NOAA historical data.[7] Starting from DARA and NOAA data, the value of SCC_{t0} in 2011 is USD 195 per Gt of CO_2-eq.

Future projections on CO_2-eq concentration are taken from IPCC, as a simple mean between results obtained from different models applied to the IPCC RCP8.5 Reference Scenario (IPCC, 2014) and converted from PPM to CO_2 emissions according to the IPCC conversion factor.[8] The stock of CO_2-eq at time t ($SCO2_t$) is determined as:

$$SCO2_t = SCO2_{t-1} \cdot (1-d) + CO2_t \tag{2}$$

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[7] NOAA estimates the concentration of CO_2 in the atmosphere at 404.06 PPM in 2011.

[8] The stock of GHG concentrated in the atmosphere used for the calculation of the average damage cost is taken from the PPM concentration measure available from IPCC (2014) and expressed in ton of CO_2-eq by applying the conversion criteria used by IPCC: 1 PPM CO_2 = 2.12 Gton Carbon; 1 ton Carbon = 3.66 ton CO_2; 1 PPM of CO_2 rise in the atmosphere is equal to 2.12*3.66 Gton CO_2 emission.

Where $CO2_t$ is the emission flow at time t and d the annual decay rate of CO_2-eq in the atmosphere. The projected concentration in the baseline in 2050 is about 630 PPM and the corresponding temperature increase is about 3°C (in a range from 2.6°C to 4.8°C relative to the period 1986–2005 as in RCP8.5 Reference Scenario in the IPCC Fifth Assessment Report).

The evolution of the SCC over time is calculated according to a simple function that considers average damages from climate change as a function of additional tons of GHG net of natural decay rate:[9]

$$SCC_t = SCC_{t-1} + (SCO2_t - SCO2_{t-1})^{\alpha} \tag{3}$$

Eq. (3) allows different evolution paths to be considered over time given a specific GHG concentrations according to the value assumed by parameter α. Given the purpose of this paper, we are not interested in providing an evaluation of climatic damage *per se*, but at considering how differently shaped profiles of SCC would influence the bargaining position of countries. Accordingly, we need a flexible way to include SCC in the economic system and this is possible by assigning to parameter α different values. According to eq. (1), the evolution over time of the value of the total cost of climatic damage at the global level (that corresponds to the total economic losses) is given by:

$$CCG_t = SCC_t \cdot SCO2_t \tag{4}$$

Given the uncertainties about climate change impact and the exogenous nature of the climatic module into GDynEP, rather than pre-determining alternative damage functions, we test different trends for the costs by using alternative values for the parameter α. The total cost of climate change is calibrated with different levels of global GDP loss provided by models that include different types of cost. This procedure roughly corresponds to accounting for the influence of uncertainty on the level of damages for a given level of warming (Crost and Traeger, 2014). We investigate four different cost patterns by assigning four different values to α, associated with the same level of projected GHG concentration in 2050 (about 630 PPM corresponding to a temperature increase in a range from 2.6°C to 4.8°C relative to the period 1986–2005, in line with projections by the RCP8.5 scenario in IPCC Fifth Assessment Report). The first value (α=0.3) describes a cost path aligned with ENVLINK model by OECD (2015) with a 2% global GDP loss by 2050 for a temperature increase of 3°C where only market-

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[9] For a comparison of alternative damage functions used in other IAM and CGE models, see Markandya et al. (2017).

based costs influencing the production function are included. Then we examine two intermediate levels: a 3% GDP loss (α=0.653) obtained as the average loss taken from recent studies that model recursively the global cost of climate change associated with the aforementioned temperature increase range (AD-RICE, DICE, ENVISAGE, ENVLINK, PAGE); and a second level that corresponds to a loss of global GDP equal to 4% in 2050 (α=0.761). The upper bound is represented by a 5% GDP loss that roughly reproduces the projection up to 2050 of the DARA estimates (available till 2030) representing the widest costs range (α=0.817).

The regionalization of the global cost over time is modelled by assigning the cost in accordance with the vulnerability of each region to climate change. While the initial regional costs is equivalent to those provided by DARA at 2011, the evolution over time is directly linked to the dynamics of a regional net vulnerability measure ($NV_{r,t}$) represented by the ratio between the Vulnerability Index (V_r) and the Readiness Index (R_r) developed by Chen et al. (2015) for the calculation of the Notre Dame Global Adaptation Index (ND-GAIN). This is in line with the definition of environmental disaster as previously mentioned, since the climate disease turns into losses proportionally to the vulnerability of a community and to the population exposed.

The great advantage of the ND-GAIN with respect to other vulnerability assessment is that it synthesized a wide range of information in a single measure that is available for a comprehensive number of countries.[10] As the values available for the vulnerability and adaptation capacity at the country level refer to current situation, the dynamics of the index is proxied by the population trends, that allows consideration of changes in population exposed to climate damages given a certain net vulnerability. In formula we have:

$$NV_{r,t} = \left(\frac{P_{r,t}}{P_{g,t}} \cdot \frac{V_{r,t0}}{R_{r,t0}}\right) \Big/ \sum_{r=1}^{N} \left(\frac{P_{r,t}}{P_{g,t}} \cdot \frac{V_{r,t0}}{R_{r,t0}}\right) \qquad (5)$$

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[10] The Vulnerability Index measures a country's exposure, sensitivity and adaptive capacity (components) to the negative effects of climate change. It considers six life-supporting sectors: food, water, health, ecosystem service, human habitat, and infrastructure. 36 indicators (two per component in each sector) contribute to the measure of vulnerability, obtained as a simple mean of the sector scores, which are the average scores of component indicators. Readiness measures the ability of a country's private and public sectors to absorb investment resources and successfully apply them to reduce climate change vulnerability. Readiness includes indicators for three components (social, economic and governance indicators) not weighted equally (Economic Readiness is 50% of the readiness score while governance and social readiness are 25%).

Where the dynamics of the net vulnerability of a region depend on the relative population share of each region with respect to the world (i.e. $P_{r,t}$ and $P_{g,t}$ the regional and global population, respectively).[11]

The distribution of the global cost among regions ($CCR_{r,t}$) is given by:[12]

$$CCR_{r,t} = CCG_t \cdot NV_{r,t} \tag{6}$$

The regional cost enters the economic system following the Weitzman (1976) approach of an adjusted Net National Product (NNP) that can serve as an indicator of welfare and can measure what can be consumed today without reducing future consumption possibilities. Starting from the standard net savings function in System of National Accounts, as represented by the sum of the difference between the production (Y) and consumption (C) measures of each *i-th* agent in each region r at time t:

$$S_{r,t} = \sum_{i=1}^{N} \left(Y_{i,r,t} - C_{i,r,t}\right) \tag{7}$$

By assuming that all savings are invested $\left(S_{r,t} = I_{r,t}\right)$, we can express the capital stock function as the sum of the capital stock available in the previous period net of the depreciation rate (β) and the total investments (I) net of the regional cost of climate change:[13]

$$K_{r,t} = I_{r,t} + (1-\beta)K_{r,t-1} - CCR_{r,t} \tag{8}$$

The output (Y) produced each period is a function of the endowments available over time (here represented by capital stock, K and labor, L) as follows:

$$Y_{i,r,t} = f\left(K_{i,r,t}, L_{i,r,t}\right) \tag{9}$$

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[11] The ratio between the vulnerability and readiness indices has been normalized (min = 0; max = 2) and then it is kept constant over time, as there is not information about future projections, especially because of uncertainties with regard to readiness issues. Thus, the variation in the regional distribution of damage cost is due to variations in population dynamics data. Population data do not take into account deaths caused by climate change since the vulnerability measure provided by ND-GAIN already includes number of deaths. In particular, the health component captures a country's vulnerability of public health to climate change, including projected change of deaths from climate change induced diseases.

[12] Although Farmer et al. (2015) emphasize the role of uncertainty in shaping the cost of climate change into IAMs, for the sake of simplicity in this work we ignore this factor that will be part of future work. By considering country vulnerability to climate change fixed over time in physical term, our modelling choice underestimates future damages that could be larger if vulnerability raises with increasing temperatures.

[13] Eq. (8) provides a stylized description of how damage cost is considered into the capital stock function of GDynEP. More precisely, GDynEP adopts the same capital accumulation function structure of GDyn (Ianchovichina and McDougall, 2000) in which international capital mobility is allowed. Accordingly, the cost of climate change can be considered as a negative component of the available net investments at the regional level (that derive from national and foreign savings). To this purpose, the adoption of a weak sustainability approach allows including all forms of capital (economic, natural and ecologic) into a unique total capital stock measures assuming full substitutability of different forms of capital (Hamilton, 1996; Neumayer, 2003).

By introducing the cost of climate change into the capital stock function as in eq. (8), and considering the relative use of capital as an input of the production function of each *i-th* agent as in eq. (9), the economic impact of climatic damage is distributed across agents according to their technical production coefficients and their capital intensity. Given that GDP is a monetary measure of the market value of all final goods and services produced in a period, according to eq. (9) the GDP is affected each period by the reduction in production capacity of each agent according to the negative impact on capital stock availability.

3.2 Country and sector coverage and scenarios

This GDynEP version is aggregated into 19 regions and 22 sectors. Regions are formed following the Kyoto Protocol scheme with Annex I and non-Annex I countries. The first group includes the European Union, United States, Russian Federation, Rest of Europe, Rest of OECD East and Rest of OECD West. Within the second group, we distinguish: i) single countries (emerging economies with strong bargaining positions in the negotiations and eligible to emission cut commitments, as Brazil, China, India), ii) three groups (one per geographic area) of energy exporting countries (African Energy Exporters, American Energy Exporters, Asian Energy Exporters) and iii) all the remaining developing countries without an energy-based economy further distinguished according to their geographical location (Western Africa, East and South Africa, American Energy Exporters, South America, Central America and Caribbean, Continental Asia, Rest of South Asia, South East Asia).[14]

We differentiate 22 industries, with the aim of maintaining a deep disaggregation for energy intensive industries and energy producers: agriculture; food, beverages and tobacco; textile; wood; pulp and paper; chemical and petrochemical; non-metallic minerals; iron and steel; other metals ; machinery equipment; transport equipment; other manufacturing industries; transport; water transport; air transport and services, while energy commodities have been disaggregated in coal, oil, gas, oil products, electricity from fossil and nuclear sources, electricity from renewable sources.[15]

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[14] Asian developing and emerging countries have also been distinguished in Rest of South Asia and South East Asian representing, respectively, developing and emerging countries according to their level of development.

[15] See Table A.2- A.5 in Appendix A for a detailed description of regional and sectoral aggregates.

The GTAP-Database (GTAP-Database 9.1, updated to 2011) is used for the starting period, and the temporal structure is a first 4-year period up to 2015 and seven 5-year periods up to 2050.

The Business as Usual (BAU) scenario corresponds to CO_2-eq emission projections provided by IPCC (2014) and distributed across regions according to the International Energy Agency (IEA, 2015) World Economic Outlook. It embodies the effects of only those government policies and measures that had been adopted by mid-2015 and considers the feasible technical change for each region.

BAU is based on projections for macro variables as GDP, population and labor force given by the combination of several sources. In particular, GDP projections are the simple average values of four sources: the OECD Long Run Economic Outlook, the GTAP Macro projections, the IIASA projections used for the OECD EnvLink model, and the CEPII macroeconomic projections used in the GINFORS model. Population projections are taken from the UN Statistics (UNDESA) while projections for the labour force (modelled as skilled and unskilled separately) 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 order to calibrate emissions in BAU according to IEA projections, in GDynEP emissions are exogenously shocked while the endogenous variable adjusting over time is technical change at the regional level.

The burden sharing in the mitigation policy scenario is again consistent with IEA (2015), given by a regional emission path that limits the global increase in temperature to around 2°C, limiting the GHG concentration in atmosphere at 450 PPM, based on the technological capabilities of regions.[16]

The policy instrument to achieve the target is required to meet the following criteria. First, it must be the policy choice that *ceteris paribus* allows overall mitigation costs to be minimized, since we are interested in assessing how such costs could be compensated by potential benefits from damage reduction. Second, it is necessary to assume that all countries have an emission reduction path, in order to have a measure of the cost of participating at a collective action for each country (if one country has no target, by definition it also has no mitigation costs). No additional policy support is

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[16] We acknowledge that the burden sharing adopted for the policy scenario is compatible with technological capabilities of regions but is not chosen on the basis of real policy feasibility (for instance strongly affected by the U.S. defection). The exclusion of the U.S. from mitigation actions would force to recalculate the burden sharing for all the other regions if the final goal is to reach anyway a 450PPM concentration. This modelling choice will reduce comparability across scenarios selected for this specific paper. Further work could be done in the future to evaluate the effect of alternative burden sharing options.

considered (as for instance subsidies for renewable energies) since it would be necessary to make additional assumptions regarding technological feasibility. All these features lead to a policy instrument based on a global emission trading (GET) system that meets the cost effectiveness criterion and involves all regions. In operational terms, each country has a specific mitigation target that is derived by the IEA (2015) on the basis of technical feasibility evaluation, and it imposes a carbon tax to reach the target. Given the possibility to trade permits across regions without any cap or limitation, each agent decides to buy or sell permits on the basis of the relative convenience of the carbon price with respect to its own marginal abatement cost. The market clearing condition allows all marginal costs to equalize the unique carbon price on the global permits market.

To sum up, four scenario settings are shaped:

1. Business As Usual without considering the cost of climatic damage (BAU NO COST)
2. Global Emission Trading without considering the cost of climatic damage (GET NO COST)
3. Business As Usual including the cost of climatic damage (BAU COST)
4. Global Emission Trading including the cost of climatic damage (GET COST)

Settings #3-4 have been run according to the four cost patterns previously described, thus resulting in 8 scenarios.

4. Results

The damage patterns associated to emissions (and relative concentration paths) in BAU and GET scenarios are compared in Figure 1 to visualize the incidence of alternative values of the parameter α on climate cost path. The large distance between GHG concentrations over time in BAU vs. GET scenario allows explaining the huge difference in damage profiles given the same damage function adopted as in eq. (3). Different values assigned to parameter α determine different damage paths given the same GHG concentration, while different emission paths influence GHG concentrations and consequently we see different damage profiles given the same value for the parameter α.

By modelling damage costs in a dynamic framework shows the large discrepancy in GDP growth patterns when both direct and indirect impacts are considered. By comparing the two scenarios with the minimum and the maximum losses, it is worth mentioning that damage cost reduces GDP more than proportionally with respect to the monetary level of climatic damage, with an increasing negative impact associated with the wider range of losses included (Figure 2). The percentage reduction in GDP in the case of the direct impact is obtained by the ratio between the value of $CCR_{r,t}$ and the GDP level in BAU NO COST scenario, where GDP projections do not account for the reduction in capital formation due to damage cost. This result reveals that together with the necessity to converge to an international consensus on the methodology to compute economic losses due to climate change, it is also necessary to reflect on the evaluation method for GDP impact assessment.

Figure 1 – Damage costs in BAU and GET scenarios (constant 2015 Bln USD)

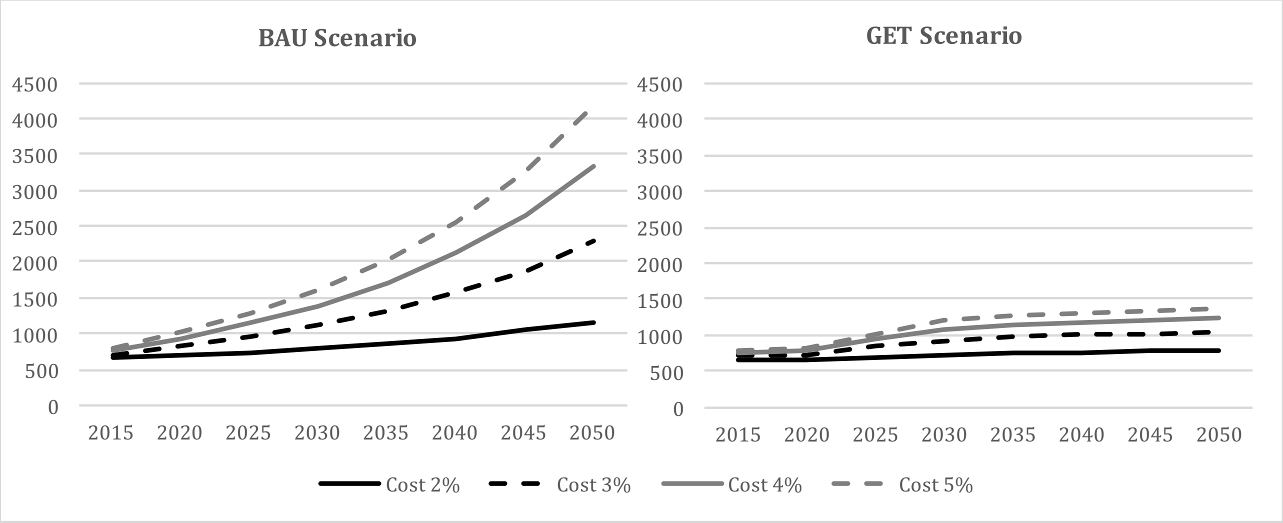
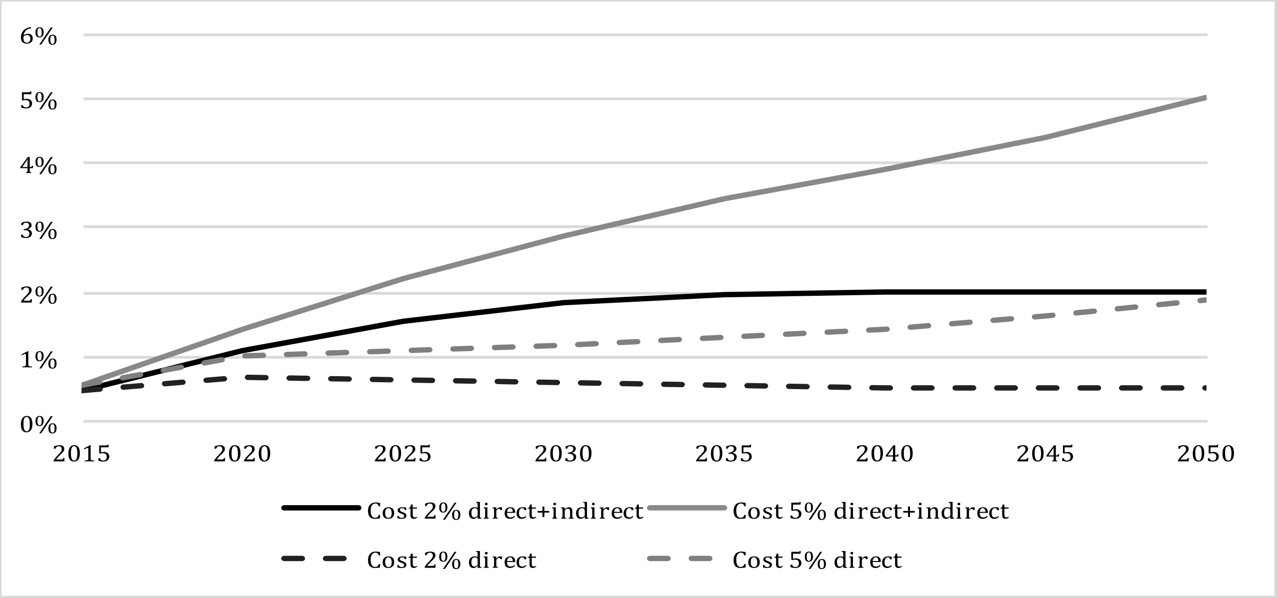


Figure 2 – Direct and indirect impact of damage cost as % of GDP in BAU



This is strongly recommended in light of how the regional distribution of GDP change due to damage is affected by the specific cost pattern under scrutiny. By considering the impact in 2050 (Table 1), China and developed countries are those that suffer the least from climate change whatever damage cost specification is considered.

Table 1 – GDP change in BAU COST w.r.t. BAU NO COST (in 2050)

GDP	Cost 2%	Cost 3%	Cost 4%	Cost 5%
World	-2.0%	-3.0%	-4.0%	-5.0%
Developed	-1.7%	-2.3%	-2.7%	-3.1%
DCs-Eex	-3.3%	-4.8%	-6.2%	-7.3%
DCs	-3.3%	-6.7%	-10.7%	-16.2%
DCs Africa	*-7.1%*	*-14.6%*	*-24.1%*	*-38.7%*
DCs Asia	*-1.9%*	*-4.0%*	*-6.0%*	*-7.7%*
DCs Latin America	*-1.0%*	*-1.4%*	*-1.8%*	*-2.0%*
China	-1.0%	-1.5%	-1.9%	-2.2%
India	-1.7%	-3.6%	-5.5%	-7.3%
RoW	-2.3%	-3.2%	-4.0%	-4.6%

Note: acronyms for regions in GDynEP are DCs-developing countries, Eex-energy exporters, RoW-rest of the world.

On the contrary, India registers low losses in the case when global costs are 2% and α=0.3, but when shifting toward the inclusion of all market and non-market components (α=0.8), it turns out to be among the most affected by climate costs. Developing countries (DCs) are those which suffer the most, with a GDP loss that can reach over 16% if the widest range of impacts and cost estimates is considered. Among the DCs aggregate, Latin American countries register the lowest loss, while the costs associated to African countries are the highest. In fact, if we consider only market impacts (corresponding to the 2% GDP loss case), climate change causes a loss of GDP of about 7% for African countries, while they will face a 38% GDP loss in 2050 when the most inclusive damage function is adopted. Although the quantitative assessment of climatic damage is still uncertain and incomplete, these results confirm that developing countries will suffer the highest costs. Accordingly, an accurate computation of the cost of climate change and its introduction in the definition of a global agreement is essential. In addition, given that the heterogeneous distribution of economic losses across DCs regions is strictly driven by differences in relative net vulnerability, a further issue to be included in the negotiation agenda (and in policy evaluation exercises) should be a greater accuracy in comparing relative vulnerability and adaptation capacity at the country level.

The GDP change due to climate policy with respect to BAU in 2050 reveals that potential gains from mitigation actions would exceed abatement costs for selected regions (Table 2). The implementation of a GET scheme without considering climate damage would cost the world around 5.2% of GDP by 2050. Emerging economies and energy exporters are those that lose the most, the former due to their stringent abatement commitment, the latter as a consequence of the decrease in the international demand for fossil fuels. Conversely, in DCs GDP losses are much lower thanks to their low abatement targets combined with an increase in competitive advantages on the international market with respect to those countries facing higher mitigation burdens.

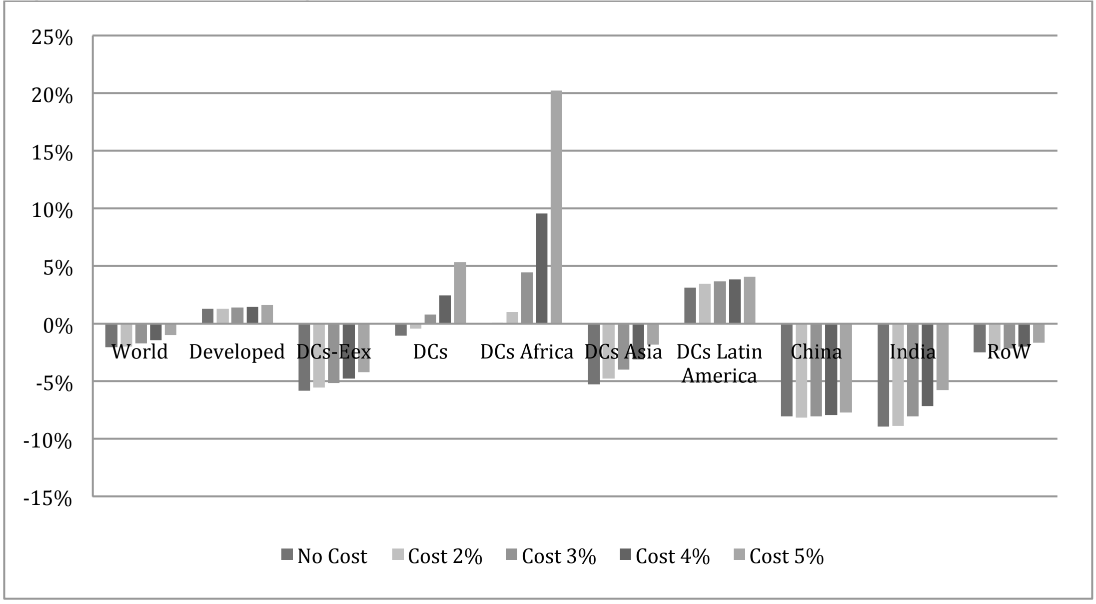
Table 2 – GDP change in GET w.r.t. BAU (in 2050)

	No Cost	**Cost 2%**	**Cost 3%**	**Cost 4%**	**Cost 5%**
World	-5.2%	-5.1%	-4.5%	-3.9%	-2.8%
Developed	3.5%	3.6%	3.9%	4.2%	4.6%
DCs-Eex	-15.6%	-15.0%	-14.3%	-13.4%	-12.3%
DCs	-2.4%	-1.7%	0.6%	4.1%	11.3%
DCs Africa	*0.6%*	*1.7%*	*7.4%*	*18.0%*	*47.3%*
DCs Asia	*-11.5%*	*-11.1%*	*-9.9%*	*-8.4%*	*-6.5%*
DCs Latin America	*6.1%*	*6.7%*	*7.0%*	*7.4%*	*7.7%*
China	-16.2%	-16.3%	-16.2%	-15.9%	-15.6%
India	-17.3%	-17.6%	-16.5%	-15.2%	-13.5%
RoW	-6.5%	-6.3%	-5.9%	-5.7%	-4.9%

The introduction of the costs of climate change into policy assessment changes this picture substantially. The loss in global GDP is reduced up to 2.8% in the 5% cost scenario, since lower emission flows due to mitigation actions will smooth the increase in GHG concentration in atmosphere and, consequently, the cost of climatic damage is lower with respect to BAU over time (as in Figure 1). Not surprisingly, the highest benefits go to DCs, because they are relatively more vulnerable to climate change and do not base their economies on sectors affected by mitigation policies. In particular, African DCs see a shift in the trend of GDP in correspondence to higher costs of climate change reaching also a benefit from the implementation of mitigation policies in terms of GDP change. When considering the widest range of climatic impacts, it may occur that for poor countries the benefits associated with a reduction of climate costs exceed mitigation costs.

In order to better investigate how countries would benefit from the participation in a global climate agreement, we show in Figure 3 the overall GDP change due to mitigation policies calculated as the net present value (NPV) computed at 2015 for the whole period 2015-2050 at a discount rate equal to 3%. The computation of a NPV measure solves the accounting problem related to the temporal gap occurring between the implementation of mitigation actions with respect to the reduction in climatic damage. The fact that the benefits arising from a reduction in temperature increase will occur over a long-time horizon while high mitigation costs might be faced immediately could reduce the likelihood to cooperate, since the position of vulnerable countries would be divergent from that of polluting countries. By considering the discounted cumulative net cost-benefit result, it is possible to better inform countries on their relative position and effective convenience in cooperating.[17]

Figure 3 – GDP %change in GET w.r.t. BAU (NPV in 2015)



At the world level, whatever damage cost function is taken into account, the implementation of a GET scheme always entails a GDP loss at this discount rate. However, the negative GDP impact

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[17] In order to obtain accurate results, the discount rate should be both differentiated by region and declining over time (Philibert, 2003). However, in order to reduce uncertainty and facilitate the interpretability of results, we apply a single discount rate equal to 3%. This value is the most commonly used in SCC calculations and corresponds to the intermediate value applied by the US Government in its latest SCC computation (US Government, 2015).

associated with the highest cost pattern is half the loss observed in the first scenario without damage cost (from a -2.1% GDP change to -1%). The role of damage costs is even more evident if we look at the differences in the regional distribution of GDP changes. Developed countries and Latin American DCs always benefit from mitigation actions in terms of GDP change. As for the other DCs (especially the African ones), they face a reduction in their GDP in the first two scenarios, while they have a GDP increase associated with the participation in mitigation policies when the whole range of damage components are included (α=0.817), since the advantages coming from a reduction in climate change costs are much higher than the mitigation costs associated to their abatement actions.

While for very vulnerable countries the introduction of the cost of climatic damage into the decision making process might persuade them to actively participate in mitigation actions, this is not true for emerging economies. In fact, whatever the damage function considered, they do not benefit from the implementation of mitigation actions, due to their high abatement commitments.

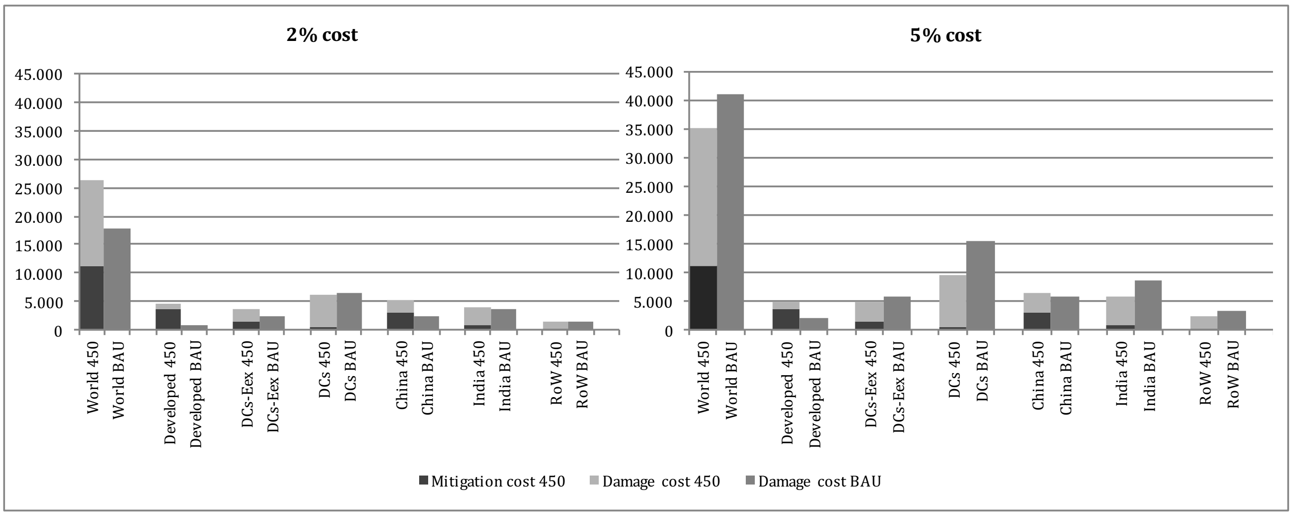
In order to complete the picture of the influence of including damage costs into policy impact assessment, we shift the analysis from the recursive direct and indirect effects on GDP as modeled in eqs. (7)-(9) to the computation of only two cost types. In particular, first we consider the direct cost of climatic damage as provided by eq. (6) for scenarios with 630 PPM (BAU) and 450 PPM (GET), and in this second case the direct cost is represented by the residual damage after mitigation. Second we compute the overall mitigation cost due to reaching the mitigation target via a permit trading system, where the mitigation cost is given by the total value of domestic abatement costs at the regional level net of permits trading value. If the region is a net seller, revenue from permits are subtracted from abatement cost and vice versa. In this way it is possible to quantify only the direct impact on economic wealth related to climate mitigation and damage costs.

We compare the overall costs faced in the GET Scenario (mitigation costs plus residual damage costs after mitigation) with damage costs faced in BAU, in a NPV measure with a 3% discount rate. Figure 4 shows results for the lowest (Cost 2%) and the highest (Cost 5%) pattern, respectively.

When the minimum damage cost function is taken into account, virtually no one would benefit from the implementation of mitigation policies, both at world and regional level. The only exception is represented by DCs, whose costs are higher in a scenario without mitigation, even if only slightly.

Moving to the highest cost pattern, a more comprehensive computation of climate costs may strengthen advantages in participating in mitigation also for countries facing a higher burden, as for India as a consequence of its higher vulnerability to damage with respect to the other emerging economies.

Figure 4 –Costs in GET w.r.t. BAU with the 2% and 5% cost pattern (Bln USD, NPV at 2015)



Such differences in relative advantages from mitigation actions according to the economic measure under scrutiny (GDP change or cost components) and the way damage is included in economy dynamics add evidence on the need to devote further research efforts in finalizing a common analytical framework on the internalization of damage costs into mitigation policy assessment.

5. Conclusions

Internalizing the cost of climatic damage into policy design in a systematic way might influence country behavior and bargaining strategies in global climate negotiations. Mitigation policies entail high GDP losses especially for emerging economies and energy exporters. However, when the cost of climatic damage is considered, GDP losses decrease or they might become even gains. The heterogeneity of countries is reflected in their vulnerability to climate impacts combined with differences in mitigation burdens. These factors explain why the negotiating attitude and the attractiveness of mitigation are both affected by the internalization of damage costs. Accordingly, the vulnerability of a country to climatic damage and the real impact of damages in terms of economic losses should be two additional components of any attempt to define the magnitude of the threat and its burden sharing.

The more exposed to climatic damage a country is, the higher its interest to act and to solicit actions from other parties in climate negotiations. Given that future large emitters are mainly developing countries, the main challenge for the forthcoming years is to persuade them to mitigate. In this respect, a precise evaluation of the cost of inaction might influence their bargaining behavior toward stronger efforts in mitigation activities. More generally, climate negotiations should take into account the whole range of characteristics of each country in order to choose a development path that would include climate change impacts, including mitigation actions and potential vulnerability to damages.

From our results three specific policy implications arise: i) there is an urgent need to develop a widely accepted methodology that provides a proper computation of the costs of climatic damage; ii) if inaction prevails in the coming years, the damage costs after 2050 could enormously affect the GDP growth and would bring the world towards an unsustainable and unequitable development path; iii) together with measures to foster intra-generational equity, efficient compensating measures are required to facilitate the participation of those countries that, in spite of the reduction of climate economic damages, still face mitigation costs that are too high.

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Appendix

Table A.1 - DARA indicators

OVERALL INDEX	SUB-INDEX	INDICATORS
Aggregation of sub-indexes	Habitat Change	• Biodiversity • Desertification • Heating and Cooling • Labour Productivity • Permafrost • Sea-level Rise • Water
	Health Impact	• Diarrheal Infections • Heat & Cold Illnesses • Hunger • Malaria & Vector-borne • Meningitis
	Industry Stress	• Agriculture • Fisheries • Forestry • Hydro Energy • Tourism • Transport
	Environmental Disasters	• Floods and landslides • Storms • Wildfires • Drought

Source: DARA (2012), Methodological Documentation For The Climate Vulnerability Monitor 2nd Edition, p. 7

Table A.2 – ND-GAIN Vulnerability Indicators

Sector	Climate Risk		Adaptive Capacity
	Exposure	**Sensitivity**	
Water	Projected change in precipitation (High)	Internal and external fresh water extracted for all uses (High)	Population with access to improved water supply (Low)
	Projected change in temperature (High)	Mortality among under 5 yr.-olds due to water-borne diseases (High)	Population with access to improved sanitation (Low)
Food	Projected change in agricultural (cereal) yield (High)	Population living in rural areas (High)	Agricultural capacity fertilizer consumption, machinery and % land in irrigation) (Low)
	Coefficient of variation in cereal crop yields (High)	Food import dependency (High)	Children under 5 suffering from malnutrition (High)
Health	Estimated impact of future climate change on deaths from disease (High)	Health workers per capita (Low)	Longevity (Low)
	Mortality due to communicable (infectious) diseases (High)	Health expenditure derived from external resources (High)	Maternal mortality (High)
Human Habitat	Urban concentration in largest city (High)	Urban population living in Slums (High)	Value lost due to electrical outages (High)
	Urban Risk (High)	Excess urban growth (High)	Quality of trade and transport infrastructure (Low)
Ecosystem Service	Projected Biome Threat (High)	Ecological Footprint (Low)	Protected biomes (Low)
	Dependency on natural capital (High)	Threatened species (High)	International Environmental Conventions (Low)
Infrastructure (Coastal)	Land less than 10 m above sea-level (High)	Population living less than 10mabove sea-level (High)	Measured on the Readiness Axis
Infrastructure (Energy)	Population with access to reliable electricity (Low)	Energy at risk (High)	Measured on the Readiness Axis
Infrastructure (Transport)	Frequency of floods per unit area (High)	Roads paved (Low)	Measured on the Readiness Axis

Source: University of Notre Dame (2013). Global Adaptation Index. Detailed Methodology Report

Note: The marker "High" and "Low" refer to the direction of the relationship between each indicator and the overall vulnerability score. The indicator is marked "High" when the indicator contributes positively to vulnerability (i.e. high indicator value leads to high vulnerability score). The indicator is marked "Low" when it contributes negatively to vulnerability (i.e., high indicator value leads to low vulnerability score).

Table A.3 – ND-GAIN Readiness Indicators

Component	**Indicator**
Economic	IEF[18] Business freedom (High)
	IEF Trade freedom (High)
	IEF Fiscal Freedom (High)
	IEF Government Spending (Low)
	IEF Monetary Freedom (High)
	IEF Investment Freedom (High)
	IEF Financial Freedom (High)
Governance	WGI[19] Voice & Accountability (High)
	WGI Political Stability & Non-Violence (High)
	WGI Control of Corruption (High)
Social	Tertiary Education (High)
	IEF Labor Freedom (High)
	Mobiles per 100 persons (High)
	WGI Rule of Law (High)

Source: University of Notre Dame (2013). Global Adaptation Index. Detailed Methodology Report

Note: The marker “High” and “Low” refer to the direction of the relationship between each indicator and the overall vulnerability score. The indicator is marked “High” when the indicator contributes positively to vulnerability (i.e. high indicator value leads to high vulnerability score). The indicator is marked “Low” when it contributes negatively to vulnerability (i.e., high indicator value leads to low vulnerability score).

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[18] Index of Economic Freedom

[19] Worldwide Governance Indicators

Table A.4 – List of GDYnEP Region aggregates

	GDynEP code	Description
1	EU28	European Union
2	USA	United States
3	ROECD1	Rest of OECD East
4	ROECD2	Rest of OECD West
5	BRA	Brazil
6	CHN	China
7	IND	India
8	RUS	Russian Federation
9	REU	Rest of Europe
10	AS1	Asian Energy Exporters
11	AS2	Continental Asia
12	AS3	Rest of South Asia
13	AS4	South East Asia
14	AF1	African Energy Exporters
15	AF2	Western Africa
16	AF3	East and South Africa
17	LAM1	American Energy Exporters
18	LAM2	South America
19	LAM3	Central America and Caribbean Islands

Table A.5 - List of GDYnEP Sector aggregates

	GDynEP code	Description
1	coal	Coal
2	oil	Oil
3	gas	Gas
4	oil_pcts	Petroleum, coal products
5	ely_f	Electricity from fossil and nuclear energy sources
6	ely_rw	Electricity from renewable energy sources
7	agr	Agriculture
8	food	Food
9	textile	Textile
10	nometal	Non-metallic mineral products
11	wood	Wood
12	paper	Pulp and paper
13	chemical	Chemical and petrochemical
14	basicmet1	Basic metal 1
15	basicmet2	Basic metal 2
16	transeqp	Transport equipment
17	machinery	Machinery and equipment
18	oth_Manuf	Other manufacturing industries
19	transport	Transport
20	air_trans	Water Transport
21	water_trans	Air Transport
22	services	Services

Table A.6 - List of GDynEP countries and regions

GDynEP code	GTAP Code	Country	GDynEP code	GTAP Code	Country	GDynEP code	GTAP Code	Country
EU28	aut	Austria	REU	xee	Rest of Eastern Europe	AF2	bfa	Burkina Faso
EU28	bel	Belgium	REU	xer	Rest of Europe	AF2	cmr	Cameroon
EU28	cyp	Cyprus	REU	xsu	Rest of Former Soviet	AF2	civ	Cote d'Ivoire
EU28	cze	Czech Republic	REU	tur	Turkey	AF2	gha	Ghana
EU28	dnk	Denmark	REU	xtw	Rest of the World	AF2	gin	Guinea
EU28	est	Estonia	AS1	kaz	Kazakhstan	AF2	sen	Senegal
EU28	fin	Finland	AS1	bhr	Bahrain	AF2	tgo	Togo
EU28	fra	France	AS1	irn	Iran Islamic Republic	AF2	xwf	Rest of Western Africa
EU28	deu	Germany	AS1	kwt	Kuwait	AF3	eth	Ethiopia
EU28	grc	Greece	AS1	omn	Oman	AF3	ken	Kenya
EU28	hun	Hungary	AS1	qat	Qatar	AF3	mdg	Madagascar
EU28	irl	Ireland	AS1	sau	Saudi Arabia	AF3	mwi	Malawi
EU28	ita	Italy	AS1	are	United Arab Emirates	AF3	mus	Mauritius
EU28	lva	Latvia	AS2	mng	Mongolia	AF3	moz	Mozambique
EU28	ltu	Lithuania	AS2	npl	Nepal	AF3	rwa	Rwanda
EU28	lux	Luxembourg	AS2	pak	Pakistan	AF3	tza	Tanzania
EU28	mlt	Malta	AS2	kgz	Kyrgyztan	AF3	uga	Uganda
EU28	nld	Netherlands	AS2	arm	Armenia	AF3	zmb	Zambia
EU28	pol	Poland	AS2	aze	Azerbaijan	AF3	zwe	Zimbabwe
EU28	prt	Portugal	AS2	geo	Georgia	AF3	bwa	Botswana
EU28	svk	Slovakia	AS2	jor	Jordan	AF3	nam	Namibia
EU28	svn	Slovenia	AS2	xws	Rest of Western Asia	AF3	zaf	South Africa
EU28	esp	Spain	AS3	xoc	Rest of Oceania	AF3	xsc	Rest of South African
EU28	swe	Sweden	AS3	xea	Rest of East Asia	LAM1	mex	Mexico
EU28	gbr	United Kingdom	AS3	brn	Brunei Darussalam	LAM1	arg	Argentina
EU28	bgr	Bulgaria	AS3	khm	Cambodia	LAM1	ecu	Ecuador
EU28	hrv	Croatia	AS3	lao	Lao People's Democratic Republ	LAM1	ven	Venezuela
EU28	rou	Romania	AS3	phl	Philippines	LAM2	bol	Bolivia
USA	usa	United States of America	AS3	vnm	Viet Nam	LAM2	chl	Chile
ROECD1	aus	Australia	AS3	xse	Rest of Southeast Asia	LAM2	col	Colombia
ROECD1	nzl	New Zealand	AS3	bgd	Bangladesh	LAM2	pry	Paraguay
ROECD1	jpn	Japan	AS3	lka	Sri Lanka	LAM2	per	Peru
ROECD1	kor	Korea	AS3	xsa	Rest of South Asia	LAM2	ury	Uruguay
ROECD2	can	Canada	AS4	twn	Taiwan	LAM2	xsm	Rest of South America
ROECD2	xna	Rest of North America	AS4	idn	Indonesia	LAM3	cri	Costa Rica
ROECD2	che	Switzerland	AS4	mys	Malaysia	LAM3	gtm	Guatemala
ROECD2	nor	Norway	AS4	sgp	Singapore	LAM3	hnd	Honduras
ROECD2	xef	Rest of EFTA	AS4	tha	Thailand	LAM3	nic	Nicaragua
ROECD2	isr	Israel	AF1	egy	Egypt	LAM3	pan	Panama
BRA	bra	Brazil	AF1	mar	Morocco	LAM3	slv	El Salvador
CHN	chn	China	AF1	tun	Tunisia	LAM3	xca	Rest of Central America
CHN	hkg	Hong Kong	AF1	xnf	Rest of North Africa	LAM3	dom	Dominican Republic
IND	ind	India	AF1	nga	Nigeria	LAM3	jam	Jamaica
RUS	rus	Russian Federation	AF1	xcf	Central Africa	LAM3	pri	Puerto Rico
REU	alb	Albania	AF1	xac	South Central Africa	LAM3	tto	Trinidad and Tobago
REU	blr	Belarus	AF1	xec	Rest of Eastern Africa	LAM3	xcb	Caribbean
REU	ukr	Ukraine	AF2	ben	Benin			

Table A.7 - List of GDYnEP commodities and aggregates

GDynEP Sector	GTAP Code	Product description	GDynEP Sector	GTAP Code	Products description
agri	pdr	paddy rice	basicmet 1	i_s	ferrous metals
agri	wht	wheat	basicmet 1	nfm	metals nec
agri	gro	cereal grains nec	basicmet 2	fmp	metal products
agri	v_f	vegetables, fruit, nuts	transeqp	mvh	motor vehicles and parts
agri	osd	oil seeds	transeqp	otn	transport equipment nec
agri	c_b	sugar cane, sugar beet	macheqp	ele	electronic equipment
agri	pfb	plant-based fibers	macheqp	ome	machinery and equipment nec
agri	ocr	crops nec	oth_man_ind	omf	manufactures nec
agri	ctl	bovine cattle, sheep and goats, horses	services	TnD	transmission and distribution
agri	oap	animal products nec	ely_f	NuclearBL	Nuclear power
agri	rmk	raw milk	ely_f	CoalBL	Coal-fired power
agri	wol	wool, silk-worm cocoons	ely_f	GasBL	Gas-fired power (base load)
agri	frs	forestry	ely_rw	WindBL	Wind power
agri	fsh	fishing	ely_rw	HydroBL	Hydroelectric power (base load)
Coal	coa	coal	ely_f	OilBL	Oil-fired power (base load)
Oil	oil	oil	ely_rw	OtherBL	Other power
Gas	gas	gas	ely_f	GasP	Gas-fired power (peak load)
nometal	omn	minerals nec	ely_rw	HydroP	Hydroelectric power (peak load)
food	cmt	bovine cattle, sheep and goat meat products	ely_f	OilP	Oil-fired power (peak load)
food	omt	meat products	ely_rw	SolarP	Solar power
food	vol	vegetable oils and fats	gas	gdt	gas manufacture, distribution
food	mil	dairy products	services	wtr	water
food	pcr	processed rice	services	cns	construction
food	sgr	sugar	services	trd	trade
oth_man_ind	ofd	food products nec	transport	otp	transport nec
food	b_t	beverages and tobacco products	wat_transp	wtp	water transport
textile	tex	textiles	air_transp	atp	air transport
textile	wap	wearing apparel	services	cmn	communication
textile	lea	leather products	services	ofi	financial services nec
wood	lum	wood products	services	isr	insurance
paper	ppp	paper products, publishing	services	obs	business services nec
oil_pcts	p_c	petroleum, coal products	services	ros	recreational and other services
chem	crp	chemical, rubber, plastic products	services	osg	public admin. and def., education, health
nometal	nmm	mineral products nec	services	dwe	ownership of dwellings