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Cost effectiveness of climate change policies in the light of updated estimates of climate change damages

By **Valentina Bosetti**
Fondazione ENI Enrico Mattei (FEEM),
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)
valentina.bosetti@cmcc.it

Enrica De Cian
Fondazione ENI Enrico Mattei (FEEM),
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)
enrica.decian@cmcc.it

SUMMARY This report provides an updated reduced-form, regionally specific, climate change damage function to undertake eventually a policy cost-efficiency, cost-effectiveness exercises in a dynamic optimization framework.

Keywords: Integrated impact assessment, climate change, hybrid dynamic optimization models

JEL: Q52, Q54

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1. Introduction

A key challenge today's policy makers are facing, concerns the reduction of greenhouse gases emissions, the major cause of climate change. If emissions continue to grow as they did over the last century, the consequences on the ecologic and human systems could be daunting. This is the economic reasoning that underlines the search for economic efficient climate policies. More precisely, policy makers should base the choice of environmental regulations on analyses allowing reliable and robust comparisons of the costs and the benefits of a given policy.

In the context of climate change, this is very demanding. It means, preliminarly, to give a monetary value to actual and expected consequences of present and future climate change in different locations worldwide, all affected, but in differentiated ways. Coupling climatic, environmental and economic models can help to provide this type of information.

This issue has been addressed in a paper companion to this (Bosello et al. 2012) where a wide set of climate change impacts estimated by different bottom-up modelling exercises has been then economically assessed through a computable general equilibrium methodology.

This paper moves a step forward: starting from this new evidence, it estimates an updated reduced-form, regionally specific, climate change damage function to undertake eventually a policy cost-efficiency, cost-effectiveness exercises in a dynamic optimization framework. The regional scope of the study is global, but particular emphasis is given to Europe.

The logical steps followed in the research, are described below:

- Identification and estimation of a wide set of climate change impacts related to the A1B IPCC SRES scenario through impact-specific bottom-up partial equilibrium studies;
- Joint macro-economic assessment of these climate change impacts occurring in 2050. The assessment is done by means of a top-down recursive-dynamic computable general equilibrium (CGE) model, ICES (Intertemporal General Equilibrium System). The aim is to capture the role of market driven mechanisms able to smooth or amplify the initial climate shocks to the economic system.
- Extrapolation, starting from these outputs, of a reduced-form damage function accounting for autonomous market adaptation.
- The updated damage function is embedded in an Integrated Assessment model WITCH (World Induced Technical Change model)

- The assessment of the social cost of carbon under different policy scenarios is performed using the augmented version of the WITCH model.

In what follows, Section 2 introduces the role of reduced-form damage function and their use in the WITCH model, Section 3 describes the methodology used to update the WITCH damage function, Section 4 presents the regional estimates while global results are given in section 5. Full costs of a stabilization policy costs are then presented in Section 6.

2. A reduced form Damage Function and the link with the WITCH model

This Section puts the focus on the policy implications of the new climate change impact estimates proposed in Bosello et al (2012) and discusses how they can be used to inform policy decision making. This is done applying an integrated assessment model (WITCH, Bosetti et al 2006; Bosetti et al 2009) through which the social cost of carbon (SCC) can be estimated.

The SCC is a useful policy indicator because it reflects the benefits of avoiding the damages caused by one extra ton of carbon released into the atmosphere. In the context of climate change, it is a critical element of cost-benefit analyses (CBA), which can be a useful criterion to assist policymakers when deciding about environmental and climate policy. Just to give few examples of how CBA has been influential in policy, cost-benefit considerations have been a major reason for the leading role the US played in the Montreal Protocol on the protection of the Ozono layer (Barret 2001). Cost benefit analysis is also part of the explanation why the US and other countries such as China are reluctant to sign for ambitious and urgent action in the context of climate change.

By comparing the SCC with mitigation costs, it is possible to have indications of the economic efficient level of mitigation effort. A large SCC would justify massive mitigation investments because the avoided damages – the benefit of those investments – are high. Numerous estimates (more than 300 according to Tol, 2009) can be found in the literature. Most of the studies estimate the global SCC, though some recent papers have investigated regional (Anthoff et al. 2011, Nordhaus 2010), sectoral social costs of carbon (Anthoff et al., 2011), as well as the social cost of different GHGs (Anthoff et al 2011; Marten and Newbold 2011).

Although useful, the social cost of carbon is an indicator that should be used with great caution as it can understate the potential impacts and uncertainty of climate change (see Greenspan and Calla, 2011 for a review on the limitation of SCC).

Because social cost of carbon estimates directly reflect the monetary value assigned to the physical and human damages caused by climate change, it will matter greatly which impacts are included and which ones are left out from the assessment exercise. In particular, estimates of the social cost of carbon rarely reflect the uncertainty surrounding impacts and do a poor job in including large consequences-low probability events. These shortcomings have led many eminent economists to question the applicability of CBA to the problem of climate change (see for example Weitzman, 2009).

Bearing this in mind, the social cost of carbon can still play an important role in shaping climate policy as it can serve as a condensed measure of impact assessments, as in the case of the ClimateCost project, although it is clearly important to complement it with other indicators and information. The remaining of the deliverable contributes to the exiting literature by exploring the implications of new monetary estimates of several impact sources both for the world as well as specifically for some macroeconomic regions, in particular Europe. For this task, we use the WITCH integrated assessment model. As many studies emphasize the relevance of the pure rate of time preference, equity weighting, type of impacts included, and climate sensitivity, in determining the SCC estimates (see for example Kuik et al. 2008), we investigate all these dimensions. Indeed, the deliverable transparently and critically states the key assumptions that play a role in determining SCC. In particular, we focus on the importance of alternative impacts, on how they are extended over temperature ranges to compensate for the lack of existing data, on the role of the pure rate of time preference and discount rates employed. We also look into the sensitivity of results to misspecification of the climate cycle by performing sensitivity analysis on climate sensitivity. Finally we fully employ the integrated assessment model to investigate the full costs of climate action, by looking at both mitigation costs and avoided damages benefits of a stabilization policy.

3. Climate costs inputs and updates of the WITCH damage function

Let us start by comparing, when this is possible, climate change impacts estimated through the ICES model with the latest damage estimates from Nordhaus (2007) (Table 5)[1]. Grey cells represent the most pessimistic impact estimate At the global level and considering all market impacts present in the analysis, GWP losses are higher in latest ICES estimates than in Nordhaus (2007) for a similar increase in temperature (0.5% vs 0.26%).

[1] Nordhaus' impacts, which are reported for a 2.5°C, have been rescaled linearly to match the temperature increase reference for the ClimateCost and ICES exercise. It has to be considered that the regional and impact detail do not match perfectly across the two studies. For instance, the aggregate CAJANZ in ICES is compared just with Japan in Nordhaus (2007). River floods in ICES are contrasted with "settlements" in Nordhaus (2007).

The major differences can be seen in North Africa (NAF), South Asia (SASIA) and South-East Asia (EASIA) and pertain to climate change impacts on agriculture. Estimates coming from the ClimateCost research and monetized using the general equilibrium ICES model are considerably larger than those used in Nordhaus (2007) for these regions.

In agriculture latest estimates are more pessimistic for developing countries, while the inverse holds for developed countries. In tourism, new estimates are, for most countries, more pessimistic, although impacts are still positive for most developed countries. The inverse is true for sea level rise. Energy impacts changes with respect to Nordhaus 2007 estimates present a trend which is opposite to that of agriculture: estimates for developed countries are now more severe, while impact figures for developing countries are smaller, in most cases even positive.

Table 5. Market impacts of 1.92°C global average temperature increase on real GDP by region and impact: % change compared to the case with no temperature increase

	All impacts		**Energy**		**Tourism**		**SLR**		**River Floods**		**Agriculture**		**Forestry**		**Health**	
	ICES	Nordhaus (2007)	ICES	Nordhaus (2007)	ICES	Nordhaus (2007)	ICES	Nordhaus (2007)	ICES	Nordhaus (2007)	ICES	Nordhaus (2007)	ICES	Nordhaus (2007)	ICES	Nordhaus (2007)
USA	0.17	0.12	-0.01	0	0.18	0.22	-0.05	-0.08			0.05	-0.02	0.00			
MEUR	-0.15	-0.25	-0.05	0	0.07	0.33	-0.03	-0.35	-0.01	-0.19	0.07	-0.02	-0.01		-0.19	-0.02
NEUR	0.18	-0.25	-0.07	0	0.15	0.33	-0.11	-0.35	-0.01	-0.19	0.23	-0.02	0.00		0.00	-0.02
EEUR	-0.21	0.15	-0.02	0	0.10	0.28	-0.04	-0.01	-0.05	-0.08	-0.15	-0.02	-0.03		-0.03	-0.02
FSU	0.81	1.78	0.01	0.61	0.32	0.58	-0.03	-0.04			0.49	0.63	0.00			
KOSAU	0.09	0.48	-0.04	0.25	0.15	0.27	-0.04	-0.07			0.01	0.04	0.00			
CAJANZ	-0.09	0.02	-0.02	0	-0.10	0.24	-0.16	-0.21			0.19	-0.02	0.00			
NAF	-2.67	-0.97	-0.03	-0.25	-0.54	-0.19	-0.02	-0.02			-2.10	-0.51	0.01			
MDE	-0.83	-0.64	-0.19	-0.15	-0.42	-0.18	-0.10	-0.03			-0.10	-0.27	-0.03			
SSA	-1.50	-0.97	0.00	-0.25	-0.31	-0.19	-0.02	-0.02			-1.09	-0.51	-0.10			
SASIA	-3.10	-0.77	0.22	-0.22	0.04	-0.23	-0.32	-0.07			-3.02	-0.25	-0.02			
CHINA	0.20	-0.12	0.04	-0.25	-0.24	0.20	-0.03	-0.06			0.43	-0.02	0.00			
EASIA	-2.82	-0.60	0.01	-0.16	-0.36	0.03	-0.10	-0.07			-2.36	-0.40	-0.02			
LACA	-0.71	-0.58	-0.04	-0.22	-0.49	0.03	-0.05	-0.08			-0.11	-0.32	-0.01			

This new set of monetary estimates of selected climate change market impacts leaves us with the task of update the WITCH damage function accordingly, and analyse what this implies[2].

The WITCH model is described in greater detail in Appendix II. We describe here some basic traits of the model that are necessary to follow the rest of the discussion.

WITCH has a neoclassical optimal growth macroeconomic structure which is fully integrated with an energy system module. The optimizing agents are twelve macro-economic regions with perfect foresight. They can anticipate and incorporate the effects of long-term policies, such as climate change targets, into the inter-temporal optimal consumption path over the century, which is the time horizon of the model. A simple climate module describes the physical relationship between GHG emissions, radiative forcing, and global average temperature. Temperature relative to pre-industrial levels increases through augmented radiative forcing of different GHGs. Radiative forcing in turn depends on CO2 and non-CO2 atmospheric concentrations. Stoichiometric coefficients are applied to the use of fossil fuels to derive related CO2 emissions. The climate sensitivity parameter is, in the basic setting of the model, set to three. To close the cycle, economic activity (GDP) is affected by the increase in temperature following a quadratic, region-specific relationship, so far closely based on the regional damage functions presented in Nordhaus (2007).

The project has focused on the consequences of a temperature increase of 1.92°C expected to occur in 2050. Although an important addition to the literature, when it comes to implementing these estimates in IAMs, this information is incomplete in two ways.

First, although extensive, the project did not cover the economic valuation of all impacts. In particular, non-market impacts were left out. The ClimateCost project does not inform on the consequences of catastrophic events. In addition, the impacts on settlements and health have been estimated only for Europe. These are clearly crucial sources of impact and could, according to some studies (as for example Stern, 2006), even double the costs of climate change.

Second, only one point of an unknown relationship has been estimated: the macro-economic cost of market impacts for a temperature increase close to 2 degree Celsius. The damage function, describing the relationship between temperature and GPD is clearly a dynamic relationship and a single point cannot be possibly enough. For example, “hockey-stick” damage functions give results very similar to linear functions before the tipping point is reached, but impacts increase much more sharply in the former than in the latter beyond that point. The inclusion of even small threshold-specific damages can significantly increase the optimal level of abatement, as found for example in Keller et al. (2004).

[2] The WITCH baseline is characterised by a global Gross Domestic Product which is close enough to the baseline used by ICES in the impact assessment. In 2050 WITCH GWP is 10% less than ICES GWP.

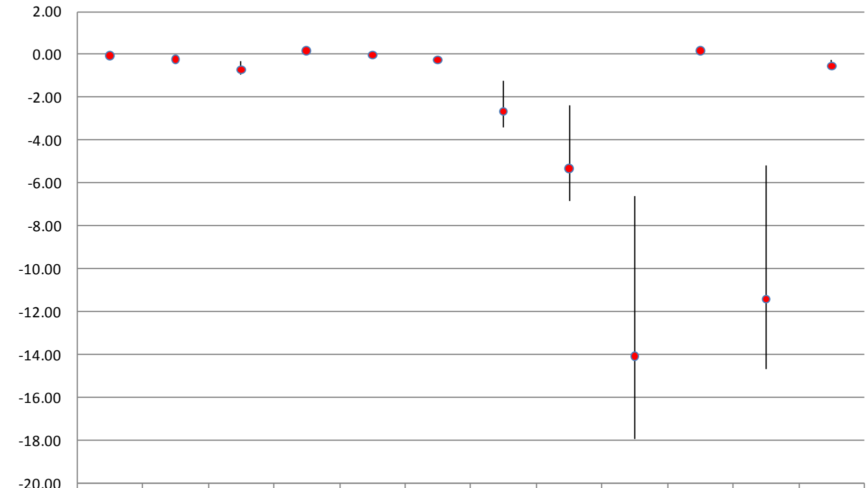
In order to derive damage function(s) that could be included in the WITCH model we complement this missing information with estimates available in the literature and reasonable assumptions.

The impacts that have been quantified for the 1.9°C temperature increase have been extended to other temperature increases using sector specific assumptions and reasonable judgements, based on the available knowledge. For sea level rise and agriculture we use a power relationship (Nordhaus and Boyer, 2000). All other impacts – energy demand, tourism demand and net forest primary productivity for all the world regions, settlements and health for Europe only – have been extended using a linear trend. Especially for energy and tourism demand, since they refer to consumer behaviour, non-linear trend would be hard to justify. For the others (net forest primary productivity, settlements and health for the rest of the world), in absence of strong support for non linearity we chose to be conservative.

Regarding the missing impacts, we combine our impact estimates with the RICE 2010[3] damages (Nordhaus, 2007). Settlements and health are assumed to grow linearly (starting from the estimates of ClimateCost for Europe and from Nordhaus 2007 for the other regions), while catastrophic events are assumed to have a quadratic impact beyond 3°C degree warming. Catastrophic impacts due to a temperature increase of 6°C have been estimated using expert elicitation, as described in Nordhaus and Boyer (2002). Experts were asked about the probability of very high consequences of climate change (in the order of the output loss during the Great Depression). The percentage of income loss was calculated making region-specific assumptions on vulnerability. In particular, Western Europe was assumed to have very high vulnerability. Based on these results, the willingness to pay to avoid catastrophic risk has been computed, assuming a risk aversion of 4. Sectoral impacts are then aggregated and interpolated using a quadratic equation between 0 and 6°C.

According to the new estimates of the ClimateCost project, agriculture seems to be the most vulnerable sector, accounting for 56% of total market impacts already at a 1.92°C warming. Still, at this temperature some regions gain (namely US, Western Europe, Transition Economies, China, Korea-South Africa-Australia, Canada-Japan-New Zealand). We assume that for warming above 3°C all regions begin to lose, following the evidence that crop productivities decline in all regions for such threshold (IPCC 2007). Because agriculture plays such an important role, especially in developing regions, we consider alternative relationships (e.g. linear and quadratic functions) between agriculture damage and temperature increase. The range of variation in agriculture impacts for a 4°C global average temperature increase is substantial in India (SASIA) and East Asia and to a less extent in Sub-Saharan Africa (Figure 11).

[3] Nordhaus damage functions have been calibrated using actual damage impact estimates for a 2.5°C and they have then been extended to other points of temperature increase using sector-specific assumptions described in Nordhaus and Boyer (2002).



	USA	Oldeuro	Neweuro	FSU	KOSAU	CAJANZ	Mena	SSA	SASIA	CHINA	EASIA	LACA
Agr, central	-0.0691	-0.236	-0.7264	0.17774	-0.0205	-0.2681	-2.6595	-5.332	-14.071	0.15309	-11.428	-0.5395
Agr, quadratic	-0.0691	-0.236	-0.9383	0.17774	-0.0205	-0.2681	-3.4137	-6.871	-17.962	0.15309	-14.693	-0.6927
Agr, linear	-0.0691	-0.236	-0.3201	0.17774	-0.0205	-0.2681	-1.213	-2.3806	-6.609	0.15309	-5.1677	-0.2455

Figure 11:Range of variation in agriculture impacts. GDP percentage changes when temperature increases 4°C above pre industrial levels. Negative numbers denote losses, positive gains.

By adding together the impacts in the different sectors and accounting for different relationships between agricultural impacts and temperature increases we get to the global damage functions shown in Figure 12. Damages are expressed as loss in Gross World Product (GWP). Figure 12 shows the three new estimated damage functions in comparison with the WITCH damage function before the update (in the figure the cross marker, Bosetti et al 2009). The top level function considers only the impact categories that have been evaluated with the ICES model (market impacts), for the central case. "Central" refers to the assumption made when extrapolating agriculture impacts, which has been based on a power function with exponent equal to 1.5. Red squares show the combination of these impact estimates with catastrophic impacts, health and settlements, as estimated in Nordhaus (2007), again for the central case. The green and the blue markers denote the resulting global damage function when using quadratic and linear functions, respectively, to extend impacts on agriculture. The two black markers show the estimated impacts for a 1.92°C temperature increase with and without non-market impacts. As previously discussed above, this moderate level of warming already leads to a substantial contribution of non-market impacts. They account for 1.4% GWP loss, as opposed to the 0.5% due to market impacts, and are sufficient to turn negative all regional impacts estimates even though market impacts can be, for some regions, positive.

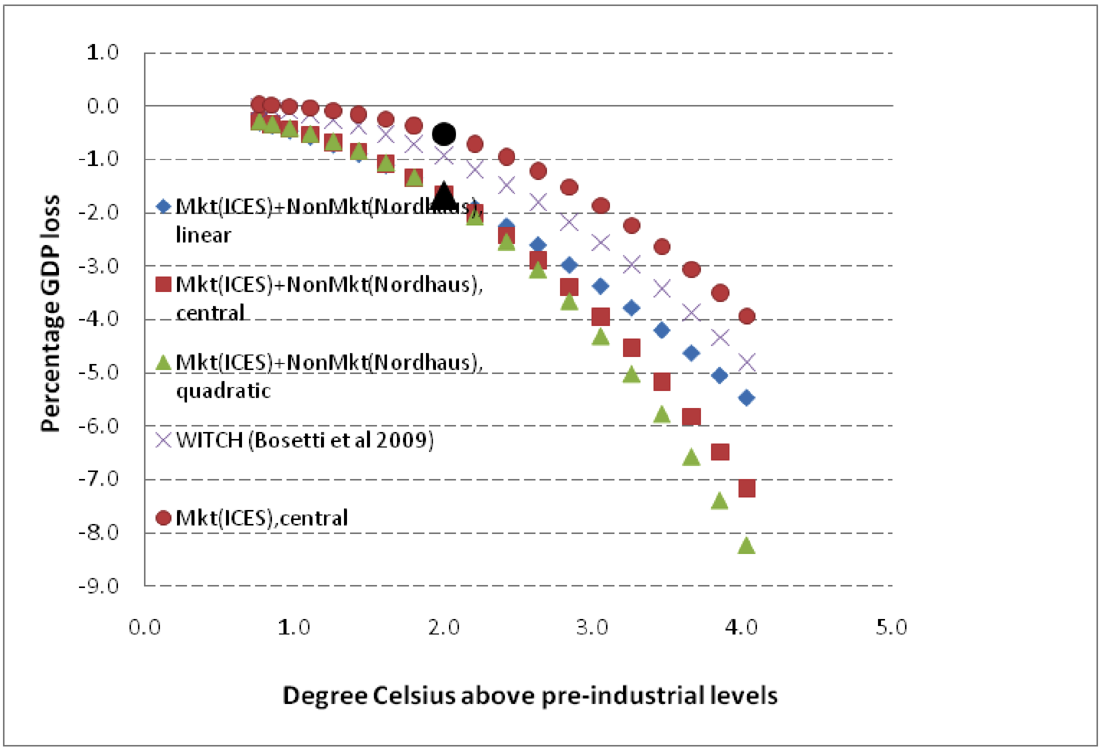


Figure 12: Global damage functions. Negative numbers denote losses, positive gains.

Figure 13 shows regional damages for the central case, including non-market impacts.

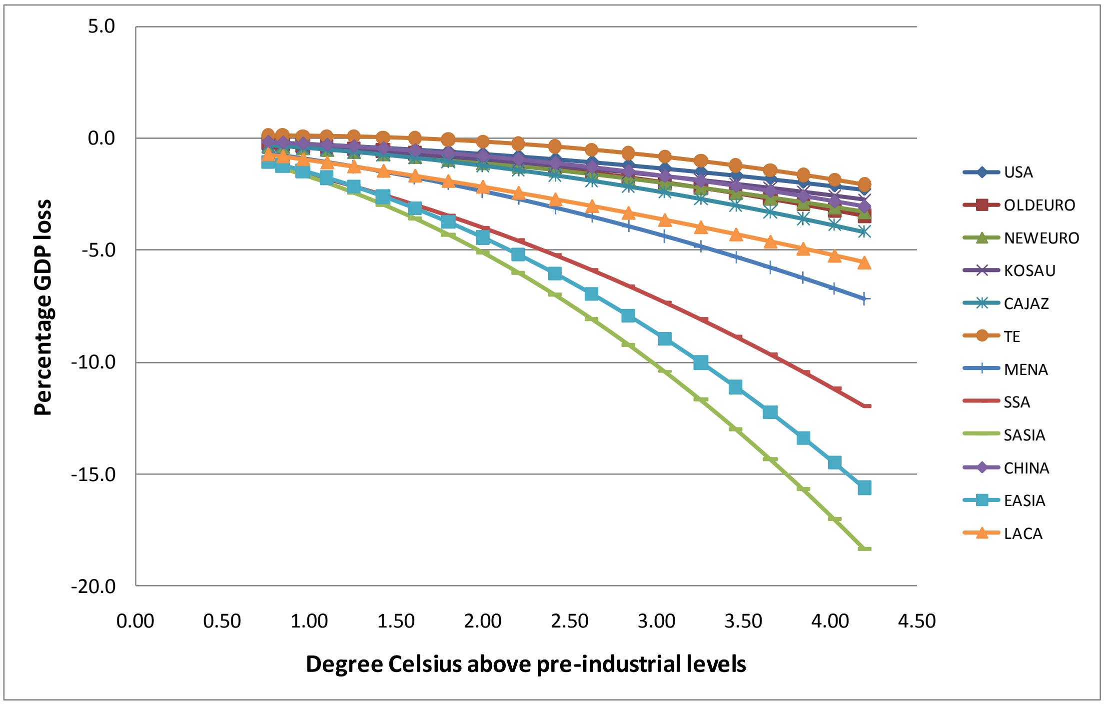


Figure 13: Regional damage functions. Central case, Market +Non Market impacts. Negative numbers denote losses, positive gains.

A final note of caution: The three scenarios proposed are not meant to be forecasts but plausible representations of the future. They are theoretical constructs that can be used to infer useful insights regarding climate change damages for different macro regions as well as for the world. An important extension of the ClimateCost project would call for a more comprehensive (in terms of regions, sources of impacts and levels of temperature increase) assessment of climate change effects on human activities and natural processes.

4. Core regional results and sensitivity

In the WITCH framework the social cost of carbon is the shadow price associated with the emission equation. It indicates the welfare change induced by a marginal increase in emissions in a point in time. More precisely, it is the present value of economic damages caused by an additional ton of carbon emissions.[4]

It corresponds to the Pigouvian tax that the global social planner would set in order to internalise the environmental global externality, when countries are fully cooperating.

The regional social cost of carbon, instead, reflects only the damage internalized by the single region and it is computed by solving the model as a Nash game where all regions compete with each others.

4.1. Contribution of market and non-market impacts for the central case (interpolation of agriculture impacts using a power function with 1.5 exponent.)

Figure 14 shows the social cost of carbon in 2010, 2020, 2030, 2050, and 2100, highlighting the contribution of market (red) and non market (blue) damages. In 2010 estimates are low, but rapidly growing over time, between 2 and 16 times. Today, Western Europe (in the chart OLDEURO) has the largest marginal damage from one additional tonne of carbon, 4.38 $US\$_{2005}$/tC, followed by the USA (3.57 $US\$_{2005}$/tC) and South Asia (2.87 $US\$_{2005}$/tC). In the short run in developed regions the largest share of the social cost of carbon mostly reflects non-market catastrophic damages, events with low probability but implying very large impacts. This reflects the assumptions made to estimate those impacts (Nordhaus and Boyer 2002), namely high risk aversion and higher vulnerability in developed economies, in particular Europe.

[4] As the model has a game-theoretic set-up that accounts for different levels of cooperation among the twelve regions, both regional and global social cost of carbons can be easily estimated. Countries choose their optimal intertemporal path of investments and emission levels maximizing aggregated welfare or their own welfare, depending on whether they are part of a partial or global coalition or acting as singletons.

If we consider only market damages, the main focus of the ClimateCost project, developing countries are the most affected. In the short term, the associated social cost of carbon is about half that of Western Europe and the USA, with the highest estimates being in South (2.26 US$$_{2005}$/tC) and East Asia (US$$_{2005}$/tC 1.65). In particular, the fast increasing social cost of carbon in South-East Asia (EASIA) and India (which is the main region in the regional aggregate South Asia, SASIA) reflects the negative impacts on agriculture. In Latin America (LACA) significant losses are expected in the tourism sector. In the developed world most damages are expected because of sea level rise and increased demand for cooling (Western Europe, USA, Canada, Japan, New Zealand, Middle East and North Africa). Losses in the tourism industry are expected in Canada, Japan and New Zealand (CAJAZ) and in Middle East and North Africa (MENA), where this sector is the second most affected after agriculture.

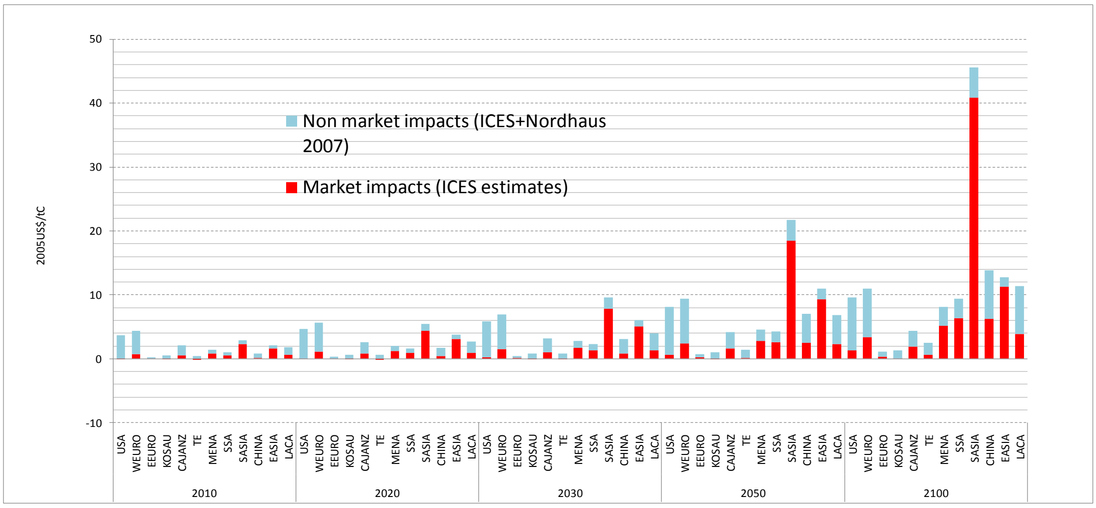


Figure 14: Decomposition of SCC into the contribution of market and non market impacts in 2010, 2020, 2030, 2050, 2100 – (US$/tC), 3% pure rate of time preference

4.2. Contribution of market and non-market impacts: sensitivity to PRTP

The pure rate of time preference is an indicator of the willingness to substitute consumption inter-temporally. The higher, the more impatient the agent is, the larger the compensation she requires in order to forgo present consumption. When climate change damages can reduce future consumption possibilities, a low pure rate of time preference implies a larger willingness to sacrifice consumption today in order to smooth consumption over time and this is reflected in a higher SCC. For a given risk aversion coefficient, a lower pure rate of time preference is reflected in a lower social discount rate. As a consequence, optimizing social planners with perfect foresight give a greater weigh to future damages. Figure 15 shows the impacts of different pure rate of time preferences on the regional estimates of SCC in 2010, distinguishing the contribution of market and non –market impacts. When decreasing the PRTP from 3% to

1% and then 0.1%, the SCC increases in Western Europe from 4.4 US$$_{2005}$/tC to 11.7 US$$_{2005}$/tC and then 20 US$$_{2005}$/tC; in USA from 3.6 US$$_{2005}$/tC to 9.9 US$$_{2005}$/tC and 17.1 US$$_{2005}$/tC; in India (South Asia , SASIA) from 2.9 US$$_{2005}$/tC to 7.8 US$$_{2005}$/tC and 13.4 US$$_{2005}$/tC. In most regions, a low discounting increases the contribution of market impacts to the marginal total damages. In percentage terms this effect is more pronounced in regions with low market impacts but, in absolute level, the increase is larger in developing countries such as India and South-East Asia (SASIA and EASIA).

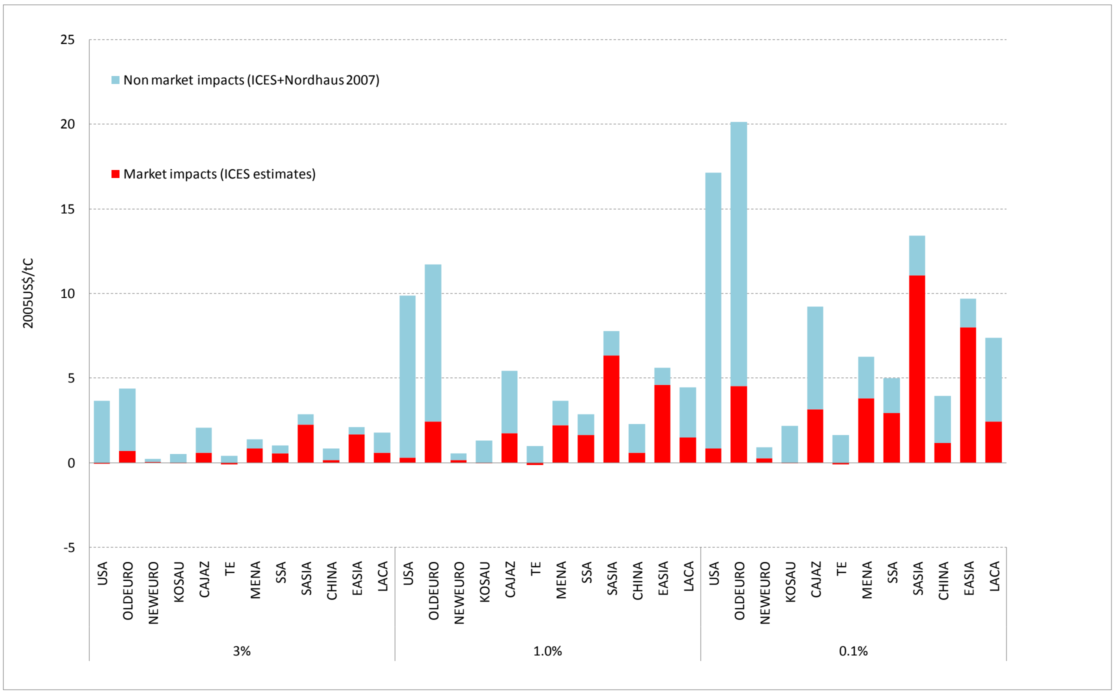


Figure 15: Decomposition of SCC into the contribution of market and non market impacts in 2010, US$$_{2005}$/tC, for different pure rates of time preference

In 2020 and including both market and non market impacts, the highest social cost of carbon is the United States and Western Europe. The ranking is robust to different discounting (see Figure 14a and 14b), although a low PRTP exacerbates the negative long-term impacts on agriculture in South-East and South Asia. A similar ranking has been found by Anthoff et al (2011) using a different set of damage estimates. However, despite the agreement on high impacts on the USA and Western Europe, they find a quite different regional distribution for the rest of the world. According to Anthoff et al (2011), Japan and South Korea have the largest marginal benefit, followed by Middle East. In their paper, Soviet Union and China are among the most harmed regions, especially when low discounting is used. Only when the PRTP is 0.1% all regions bear negative marginal impacts (positive social cost of carbon).

Conversely, our estimates indicate that Transition Economies (TE), including Russia, and Korea, South Africa, and Australia are the only two regions with a negative social cost of carbon (benefit from climate change) when only market impacts are considered (including non-market impacts makes all regional SCC positive even for the 3% pure rate of time preference). For both regions this is true even when the PRTP is 0.1%. Conversely to the Anthoff et al. (2011) paper, the region composed by Middle East and North Africa countries does not face benefits and it ranks third in terms of market marginal damages, which account for 60% of their social cost of carbon. With a PRTP equal to 1% and 0.1% Middle East and North Africa is overtaken by Western Europe. Another noticeable difference with respect to the Anthoff et al (2011) paper regards China. Even with a very low PRTP, according to our estimates China is among the least damaged regions, following TE, KOSAU, and Easter Europe (NewEurope in the charts). It is worth mentioning that in China, lowering the pure rate of time preference increases the contribution of market impacts to the social cost of carbon. From 17% (with 3%) to 29% (with 0.1%), overall a 73% increase of market impacts contribution. Still, in absolute level the social cost of carbon in China is considerably lower compared to that of other, less developed, regions.

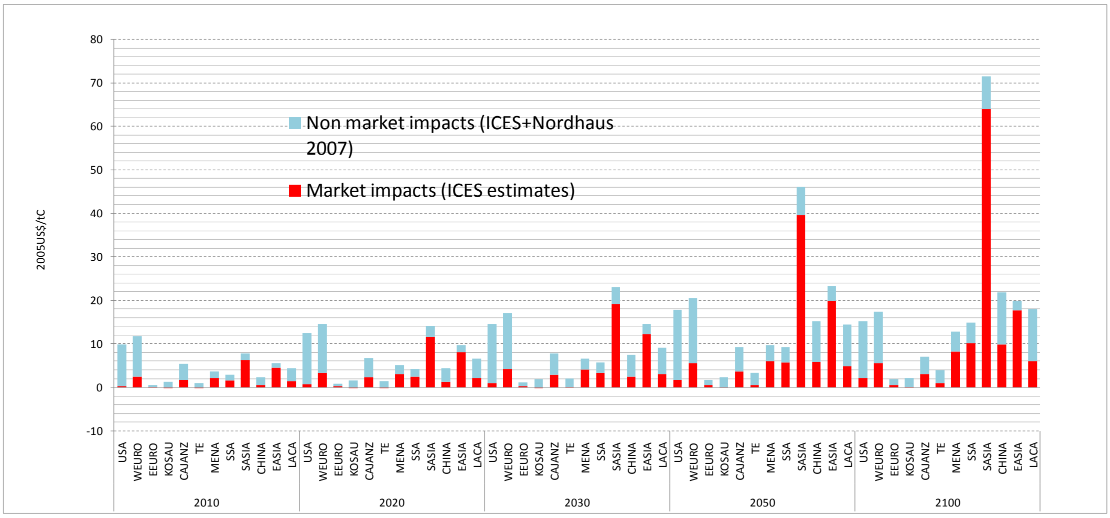


Figure 14a: Decomposition of SCC into the contribution of market and non market impacts in 2010, 2020, 2030, 2050, 2100 – (US$/tC), 1% pure rate of time preference

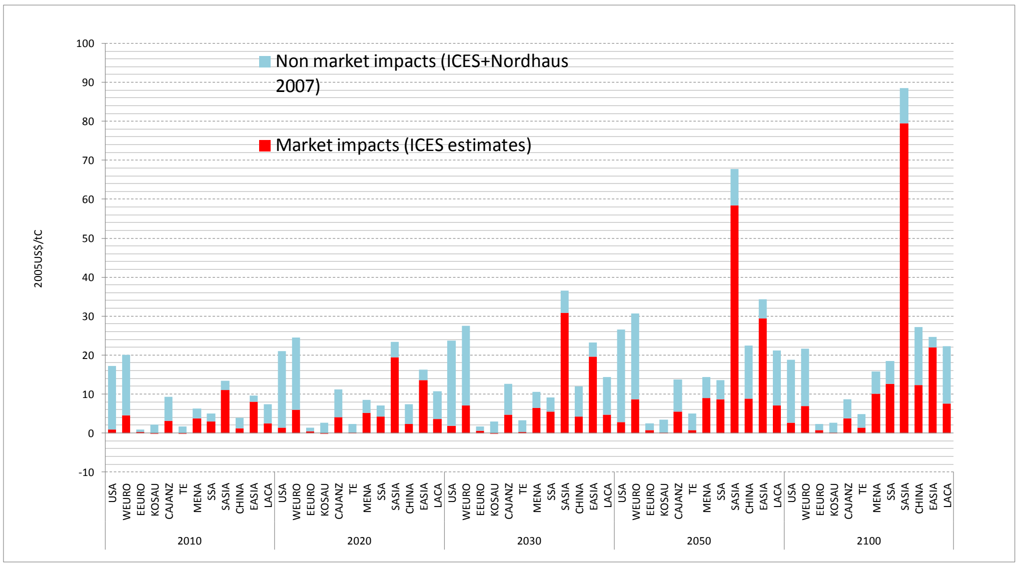
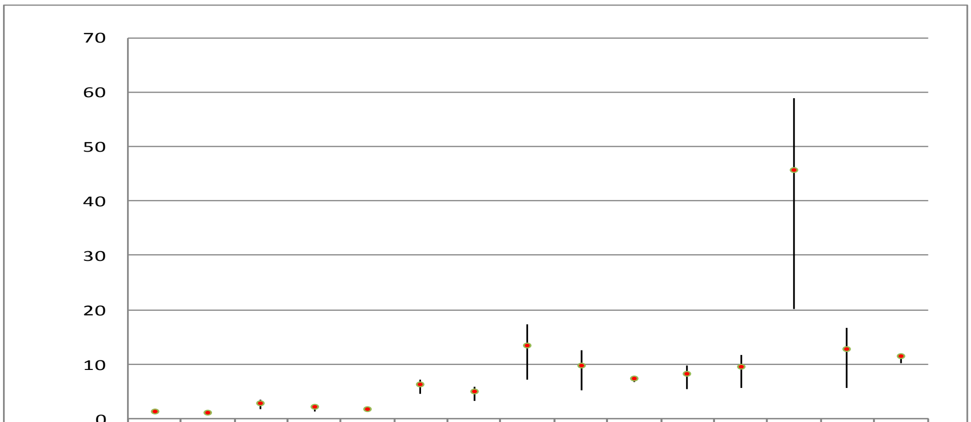


Figure 14b: Decomposition of SCC into the contribution of market and non market impacts in 2010, 2020, 2030, 2050, 2100 – (US$/tC), 0.1% pure rate of time preference

As discussed in Section 3.1, an important assumption we made concerns the trend used to extrapolate future damages. As shown in Figure 15, this assumption has an impact on the SCC if discounting is low (2010_0.1%) or far in the future (2100_3%). In the most vulnerable regions, this assumption can lead to a range of variation in the SCC between 20 and 60 US$$_{2005}$/tC in 2100 and between 7 and 17US$$_{2005}$/tC in 2010 when the pure rate of time preference is low.



	2010_3%					2010_0.1%					2100_3%				
	MENA	SSA	SASIA	EASIA	LACA	MENA	SSA	SASIA	EASIA	LACA	MENA	SSA	SASIA	EASIA	LACA
linear	1.11	0.76	1.80	1.33	1.67	4.66	3.36	7.16	5.20	6.79	5.45	5.62	20.23	5.54	10.10
central	1.37	1.02	2.87	2.08	1.77	6.24	4.98	13.43	9.67	7.37	8.13	9.44	45.61	12.72	11.41
quadratic	1.54	1.17	3.54	2.57	1.78	7.23	5.94	17.24	12.47	7.45	9.77	11.60	58.82	16.65	11.72

Figure 16: Sensitivity to different interpolation of agriculture impacts in 2010 and 2100 with 3% PRTP and in 2010 with 0.1% PRTP , US$$_{2005}$/tC

5. Core global results and sensitivity

This section presents some considerations on the global social cost of carbon, which reflects the effect of one additional ton of carbon on global, rather than regional, welfare. The global SCC is a useful benchmark for seeking the economic efficient global mitigation effort. In fact, although the impacts of climate change will be highly localised in nature, both spatially and temporally, what ultimately matters for the first-best optimal emission path is the aggregate damage. As GHGs become uniformly mixed once the accumulated in the atmosphere, it does not matter who emits, but how much in total goes into the stock. However, this raises the issue of aggregation and equity weighing. Anthoff et al. (2010, 2011) have shown how sensitive SCC is to this assumption. Equity-weighting leads to higher SCC estimates, and it can even reverse its sign. Depending on the region to which equity weights are normalised, the aggregation can change the estimate of SCC by two orders of magnitude. Finally, risk aversion also plays a role.

In the WITCH model the discount rate is pinned down by the pure rate of time preference and an income based component that reflects diminishing marginal utility as the economy becomes richer. The elasticity of marginal utility is also an indicator of risk or equity aversion. When set to zero, the consumption losses that could be induced by climate change count the same in rich and poor countries. When tending to infinity, consumption changes in the poorest regions dominate. Equity aversion equal to one is an intermediate case and this is the assumption implicit in the utility function of the WITCH model. In this case, the aggregation of regional impacts can be based on the following formula (Azar and Sterner 1996; Fankhauser et al. 1997):

$$SCC_{agg} = \sum_{n=1}^{12} \frac{c_{t,ref}}{c_{t,n}} SCC_n$$

Where n denotes the twelve WITCH regions, *SCCn* is the regional social cost of carbon in 2005US$/tC and *SCCagg* is the global social cost of carbon resulting from this aggregation procedure.

Figure 17 illustrates the global social cost of carbon using the world and the USA as reference regions. These are compared with the social cost of carbon that is obtained when one single global social planner maximises world welfare, the cooperative solution of the WITCH model, taking into account damages occurring in all regions and weighting regional consumption using the Neghishi weights.

When equity weighting uses the world average as a benchmark, the SCC increases with respect to the no equity weighting case by a factor of 3, in 2010, and by a factor of 2, in 2050. Interesting is the decomposition in different types of impacts. In 2010, the contribution of market impacts is increased by a factor of 5 while that of non market impacts by a factor of 1.4, reflecting higher market impacts in countries with per capita consumption below world average.

As already noticed in Anthoff et al (2011), using a rich region, such as the USA, as a reference increases the global SCC by a factor of 16 in 2010 and of 9 in 2050. With this normalisation, poor regions, where largest impacts occur, receive a much larger weight.

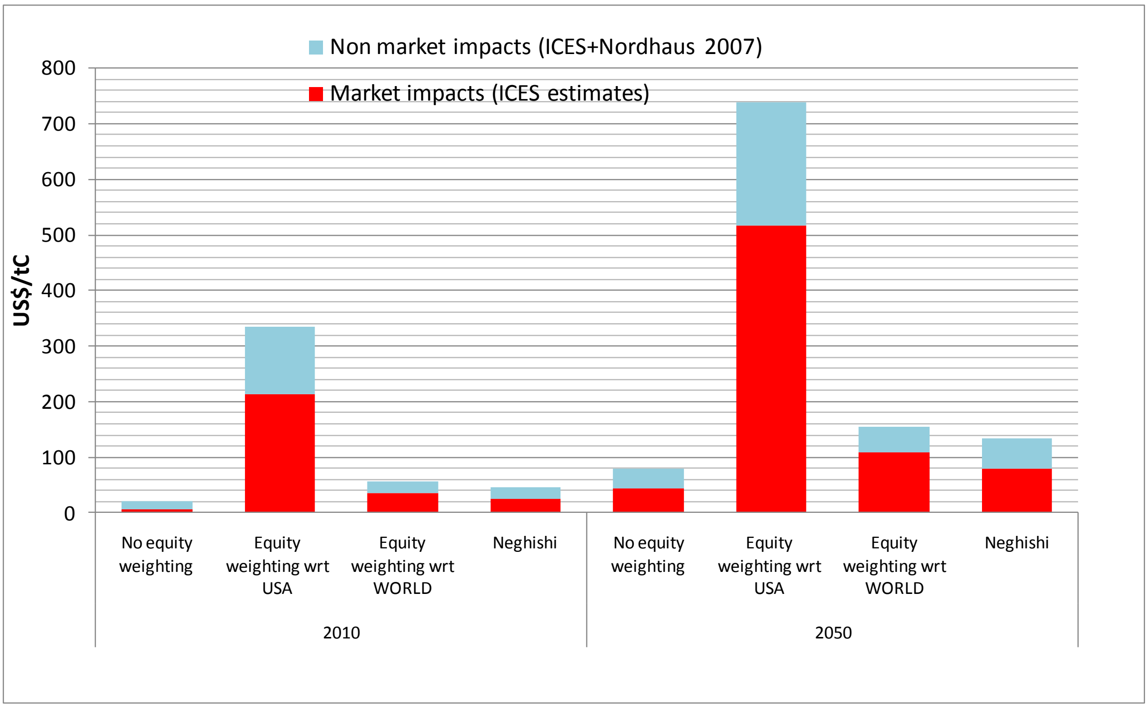


Figure 17:Global Social Cost of Carbon in 2010, 2050, and 2100.

5.1. Sensitivity to different weighting. 3% PRTP

Figure 18 shows the combined effect of discounting and of equity weighting. It illustrates the case in which the WORLD is taken as the reference region. When the pure rate of time preference is 0.1%, the SCC in 2010 goes up to 260 US$$_{2005}$/tC, more than a ten-fold increase with respect to the the world SCC in 2010 when the PRTP is 3% and no equity weighting is used, which is 21 US$$_{2005}$/tC.

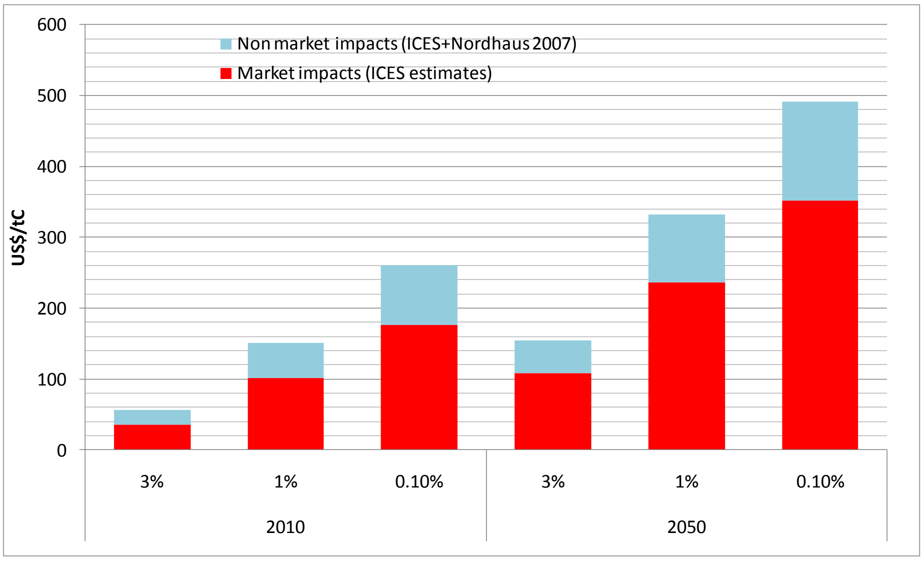


Figure 18: Global Social Cost of Carbon in 2010, 2050, and 2100 using equity weighting relative to WORLD per capita consumption

5.2 Sensitivity to different PRTP

Figure 19 shows the decomposition into regional SCC, under different PRTP, using the world average per capita consumption as benchmark- South Asia alone accounts for about 44% of global SCC. Together with Sub-Saharan Africa and South-East Asia the share on global damage increases to 83%. This is consistent across time and choices of the pure rate of time preference.

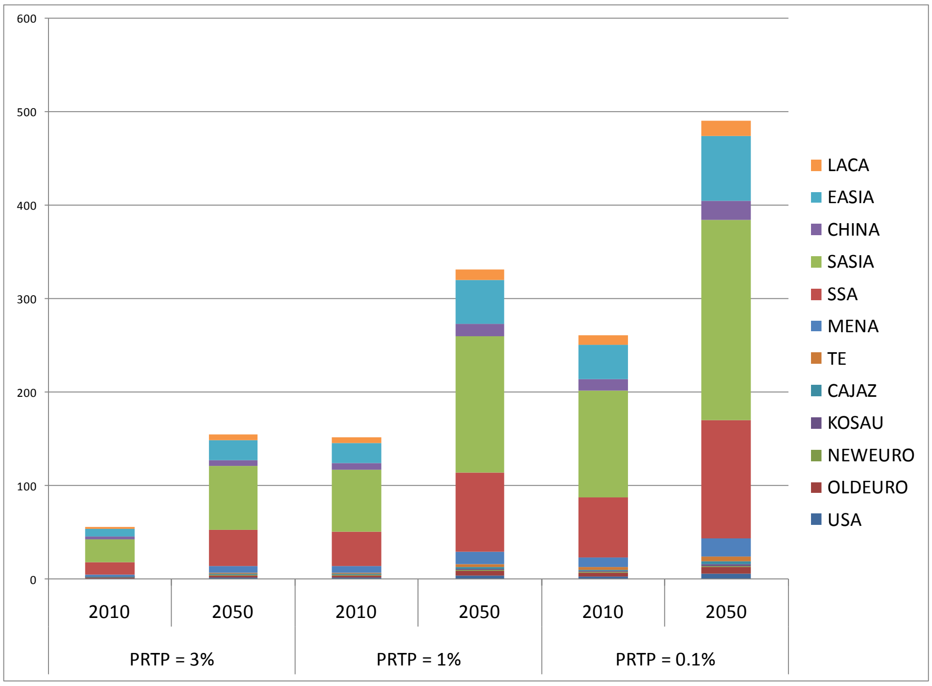


Figure 19: **Regional decomposition of the global Social Cost of Carbon in 2010, and 2050. Equity weighting relative to WORLD per capita consumption. Sensitivity to different PRTP**

Another key parameter in the evaluation of climate change impacts is the climate sensitivity, which is defined as how much the average global surface temperature will increase if there is a doubling of greenhouse gases in the air, once the planet has had a chance to settle into a new equilibrium. The higher the climate sensitivity, the higher the increase in global average temperature, for a given level of concentrations of GHGs. Figure 20 shows the SCC of Western Europe and the global SCC (aggregated using the world average as a benchmark), under three values of climate sensitivity, where 3 is the central value used in the model. As mentioned previously, Western Europe has a significant damage, mostly because of the catastrophic impacts. Still, its social cost of carbon accounts only for 8% of the global marginal value. Higher climate sensitivity slightly increases this share from 8 to 9% in 2010 and from 5 to 6% in 2100. Figure 20 also shows the relevance of this parameter for global estimates. Very high climate sensitivity increases the global SCC up to 60%.

Climate sensitivity plays a moderate role in our analysis (although the global social cost of carbon increases from 28 to 84 US$$_{2005}$/tC in 2010) as the simple climate model used in the present analysis does not mimic disruptive and sudden changes in the climate state that very high climate sensitivity could imply (as for example the shutting down of the thermohaline circulation).

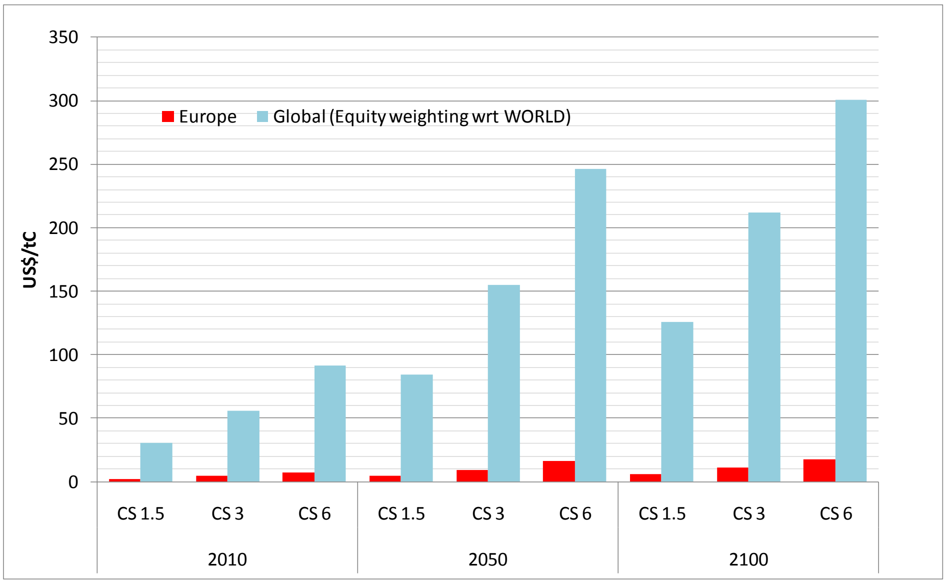


Figure 20: **Global (equity weighting relative to WORLD per capita consumption) and European social cost of carbon in 2010, 2050, and 2100 under three different climate sensitivity (central value: 3). PRTP: 3%**

6. Mitigation scenarios: costs and benefits of policy scenarios

In order to assess the full costs of climate change, we have run mitigation scenarios with and without climate change damages. The most recent debate in the academic environment as well as in the policy arena has been focusing on very low stabilization scenarios that with a sufficiently high likelihood limit global temperature increase below 2° degree. Given the present level of GHG concentration in the atmosphere, the 2° degree target has been frequently considered too ambitious to be achieved by 2100, unless major technology breakthroughs occur. In order to meet this or similar targets, mitigation options able to interfere with the stock of GHG in the atmosphere or the stock of carbon stored in the ground are needed. For example, the EMF22 exercise (Clarke et al 2009) has shown that models featuring a limited bio-energy potential cannot reach GHG concentrations that limit warming below the 2° degree with a probability greater than 50%.

The version of the WITCH model used for the ClimateCost project does not feature negative emission options, and therefore very low stabilization scenarios, as those related to a E1 path of emissions, are not feasible. We explore the full costs of climate change for a stringent GHG concentration target that leads, with high likelihood, to a temperature increase of 2.5°C in 2100. The policy is implemented through the market based instrument of cap and trade. Regions are allocated emission permits on the basis of a contraction and convergence (Meyer 2004) criterion (many different allocations could be considered but that is not the focus of the current analysis). Trade of permits is full and participation to the international carbon market is global.

The global economic policy cost of attaining this objective is a GWP loss of 2.86% (1.97%) computed at a 3% (5%) discount rates. Accounting for the benefits of the policy, that is the damages avoided, reduces the policy costs to 2.24% (1.66%), or by 0.62 (0.31) percentage points. Discounting the policy costs using a very low discount rate equal to 0.1% increases the benefits of avoided damages to 1.22 percentage points. At the very same time a low discount rate magnifies the cost of the policy: GWP losses are now reduced from 3.98% without damage to 2.76% when accounting for the avoided damages. In fact, most of the benefits occur after 2050, as clearly shown in Figure 21. Avoided damages are about 100 US$$_{2005}$ Billions in 2030, but at the end of the century they reach 10 US$$_{2005}$ Trillions.

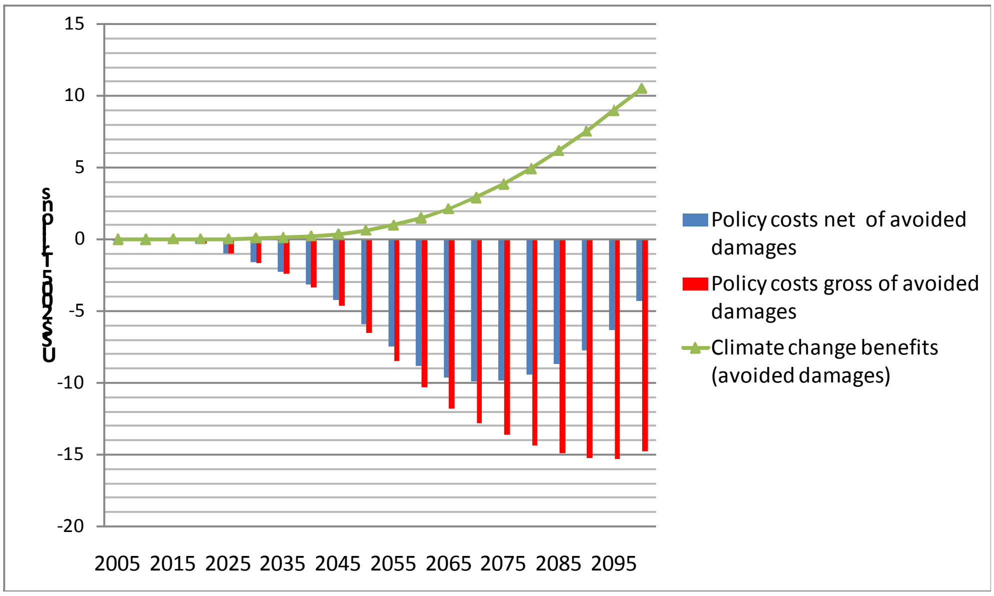


Figure 21: Global GWP change compared to baseline in 2005 US trillions (PRTP 3%, CS 3)

Of particular interest are regional costs, which however depend on the initial allocation of emission permits. For this reason, for each country we directly compare regional GDP policy costs in the two cases, with and without damages. The difference gives the regional benefits from avoided damages implied by this stabilization policy. These are shown in Figure 22, in discounted terms. As expected, benefits are lager where more damages occur. The policy brings some benefits in all regions, with the exception of Transition Economies (TE).

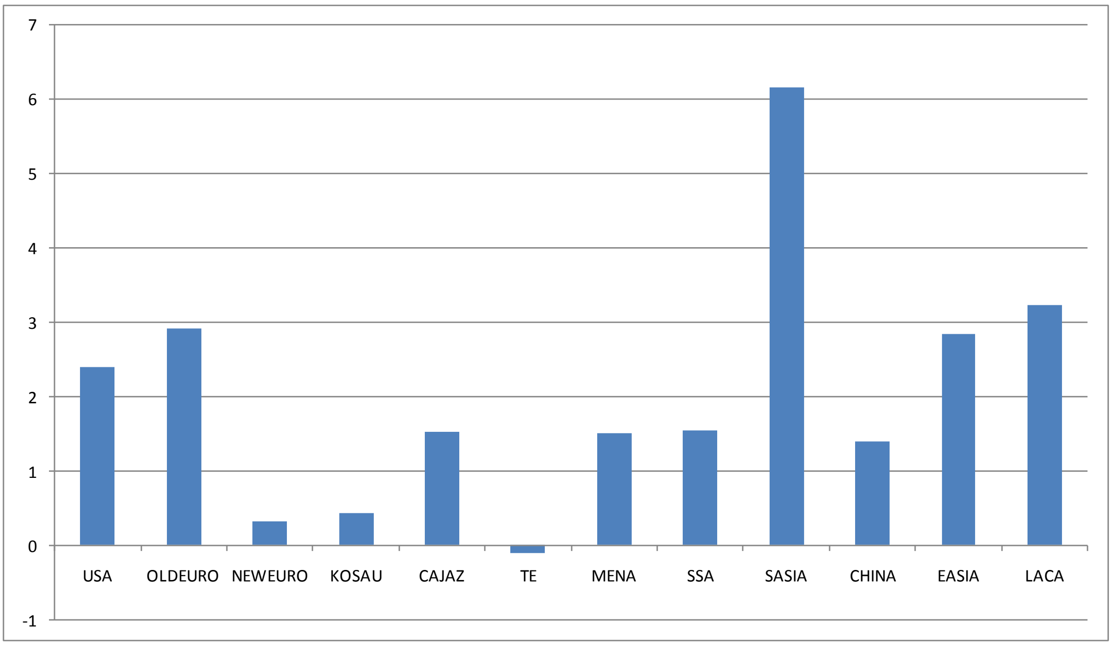


Figure 22: Reduction in discounted policy costs when accounting for avoided damages in 2005 US trillions (PRTP 3%, CS 3)

When damages are accounted for, the carbon price is lower. In 2010, it is reduced from 13 to 10 US$$_{2005}$/tC and in 2020 from 76 to 70 US$$_{2005}$/tC . It is interesting to note that in 2020, the carbon price that clears the carbon market (76 US$$_{2005}$/tC) is quite closes to the global SCC computed using equity weights based on global average per capita consumption, and it falls in the range estimated by other studies. Clarke et al. (2009) report the carbon prices and the present value of global economic policy costs for different stabilisation scenarios (650, 550, and 450 ppme) across 11 models. Carbon prices in Annex I countries in 2020 range between 29 - 158US$$_{2005}$/tC when considering a 550ppme scenario (which is the stabilization scenario considered in the current section).

Conclusions

This document summarizes the process followed within ClimateCost WP 6 and WP 7 in order to provide an updated set of climate change impact estimates and to use them to perform normative analyses of mitigation policies. The deliverable describes in a transparent and detailed way the methodologies used throughout the overall analysis and main results.

The first part of the analysis uses the dynamic-recursive computable general equilibrium model ICES to assess the monetary value of the physical impacts of a 1.92°C global temperature increase with respect to pre-industrial levels in 2050. The second part uses this point estimate to extrapolate a relationship between temperature increases and output losses. The resulting damage functions are then included in the integrated assessment model WITCH, which is used for normative analysis of climate policy to evaluate the social cost of carbon and the full costs of stabilisation policies.

Although the impact assessment is partial because it focuses on market impacts and only on one point temperature increase, still it represents a first step toward the development of a methodology that integrates impact assessments based on CGEs and policy analysis based on IAMs.

The main focus of the project was on Europe, but the global coverage of both ICES and WITCH allows extensions to other regions as well as to global analysis.

ICES estimates indicate that a temperature increase of 1.92°C compared to pre-industrial levels in 2050 could lead to global GDP losses of about 0.5% compared to a hypothetical scenario where no climate change is assumed to occur. Northern Europe is expected to benefit from the evaluated temperature increase (+0.18%), while Southern and Eastern Europe are expected to suffer from the climate change scenario under analysis (-0.15% and -0.21% respectively).

Most vulnerable countries are the less developed regions, such as South Asia, South-East Asia, North Africa and Sub-Saharan Africa. In these regions the most exposed sector is agriculture, and the impact on crop productivity is by far the most important source of damages. Agriculture impacts strongly affect low-latitude regions, even at relatively low temperature increases because of their greater physical vulnerability and of the higher importance of this sector in their economy. Again agriculture and infrastructures are adversely affected by sea-level rise which with its land and capital induced losses is the third major driver of economic impacts at the world level. The tourism sector experiences the second highest losses, given the market impacts analysed. Tourism flows will be gradually re-directed away from warmer regions, becoming increasingly too hot, towards more moderate, high-latitude regions. This trend produces important distributional effects across regions. Other impacts (on energy demand, on forest primary productivity, on river floods, and on the on-the-job performance) are generally of lower importance, but there are several exceptions. For instance, in the Mediterranean Europe, the reduction of the on-the-job performance due to higher temperatures leads to important productivity and then economic losses.

It is worthwhile noting that the general equilibrium estimates tend to be lower, in absolute terms, than the bottom-up, partial equilibrium estimates. The difference is to be attributed to the effect of market-driven adaptation. Markets react to climate change impacts with changes in commodity and primary factor prices that allow for adjustments in consumption and production. This induced adaptation partly reduces the direct impacts of temperature increases, leading to lower estimates. However, this general mechanism is more evident when primary factors of productions are concerned (see land losses to sea-level rise or decrease in land productivity). It is more ambiguous when demand re-composition effects are involved. In this last case substitution mechanism are less clear and it well may happen that a decrease in demand in a sector drives negative impacts in other related sectors with a multiplicative effect that a direct costing approach cannot capture.

In its central specification, the damage function obtained using these new estimates, albeit aggregately more pessimistic than the Nordhaus damage function, do not really change much in terms of suggested policy consequences. In cost-benefit terms stringent (e.g. 2°C target) stabilizations is not justified. However, assuming low PRTP and specific equity weights, stringent stabilization targets *can* find justification. The global social cost of carbon (SCC) in 2020 estimated assuming full and immediate cooperation ranges between 65 (PRTP 3%) and 347 (PRTP 0.1%) US$$_{2005}$/tC. This is an indicator of the marginal benefits climate policy could bring. Cost-effective estimates of the marginal abatement costs of a 450ppme scenario (e.g. carbon price) vary between 55 and 964 US$$_{2005}$/tC in 2020 (Clarke et al 2009).

Climate sensitivity plays a moderate role in our analysis (although the global social cost of carbon increases from 28 to 84 US$$_{2005}$/tC in 2010) as the simple climate model used in the present analysis does not mimic disruptive and sudden changes in the climate state that very high climate sensitivity could imply (as for example the shutting down of the thermohaline circulation).

In particular the current study has taught us that:

- Regional SCC vary widely across studies, reflecting the uncertainty on impact assessments This is a symptom showing us that large research efforts are still required to improve our understanding.
- In the analysis of global SCC, discounting and equity weighting add additional uncertainty. Our analysis shows that different regional weighting can change the 2010 SCC from 21 to 336 US$$_{2005}$/tC. If we focus on market impacts. Leaving aside the uncertainty of non-market impacts, the range is even broader, between 7 and 213 US$$_{2005}$/tC. Discounting has similar impacts, leading to variations in the SCC estimates

in order of ten times. The bottom line is that comparison across studies can be tricky. An effort should be undertaken to collect compare critically existing estimates.

- Most literature, and we are not an exception to this, draws cost-benefit conclusions on the assessment of only a fraction of potential impacts. This is because many processes, feedbacks and unexpected consequences are poorly understood; because data is lacking and, in some cases, impossible to collect; and because
- extending the monetary evaluation to large increases in temperature is extremely complex. Models need to be stretched to cover future scenarios (complex to predict even without any climate change) and to account of potentially disruptive state changes for both the climate and the human systems.

Even though new research efforts, building upon the ClimateCost and other studies, will make new data available and increase the consensus on many open issues, still most of the assumptions that, by means of a cost-benefit analysis, justify immediate and drastic cuts in emissions are extremely controversial. More importantly, a very low pure rate of time preferences and a pro-poor equity weighting are assumptions, even though desirable, very far from reflecting the policy making process.

Conversely, abandoning the concept of cost benefit analysis and that of the social cost of carbon in order to move towards robust decision methods, in order to design adaptive policies that better cope with the many sources of uncertainty, could be the best ways to improve the process of climate change policy making.

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Appendix: The WITCH model

The World Induced Technical change Hybrid (WITCH) model is a global energy-economy-climate model. Full details on the WITCH model can be found in Bosetti et al. (2006) and Bosetti et al. (2009) and in the model website[5].

The WITCH model belongs the family of integrated assessment models, which have become the workhorse for the economic analysis of climate change impacts and policies.

WITCH has a neoclassical optimal growth macroeconomic structure which is fully integrated with an energy system module. The optimizing agents are twelve[6] macro-economic regions with perfect foresight (see Figure A2.1 for a sketch of the model structure).

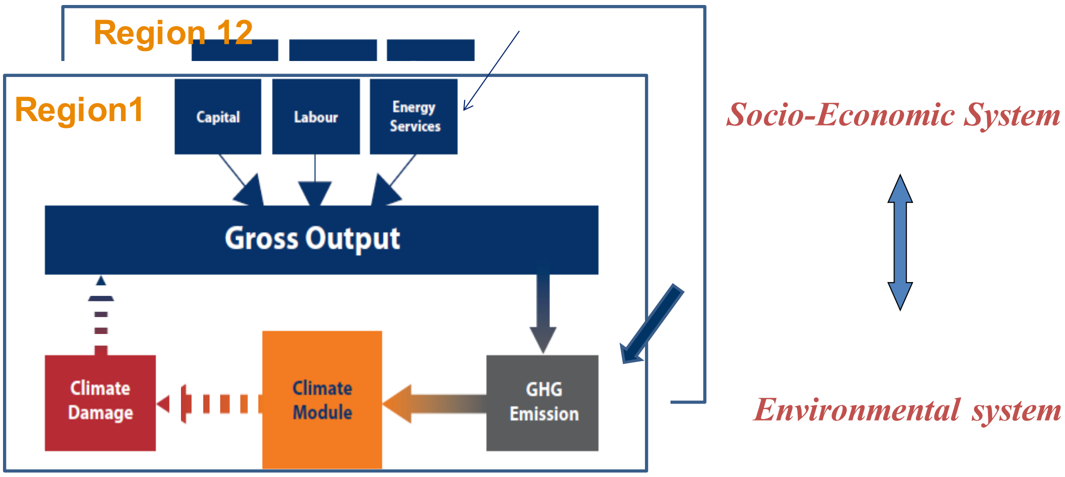

Figure A1: The WITCH model structure

They can anticipate and incorporate the effects of long-term policies, such as climate change targets, into the inter-temporal optimal consumption path over the century, which is the time horizon of the model.

The macro-economic structure of each region, depicted in FigA2.2, is hard-linked to the energy sector, which makes it a hybrid model.

[5] http://www.witchmodel.org

[6] These regions are USA (United States), WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (Korea, South Africa, Australia), CAJANZ (Canada, Japan, New Zealand), TE (Transition Economies), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), CHINA (China and Taiwan), EASIA (South East Asia), LACA (Latin America, Mexico and Caribbean).

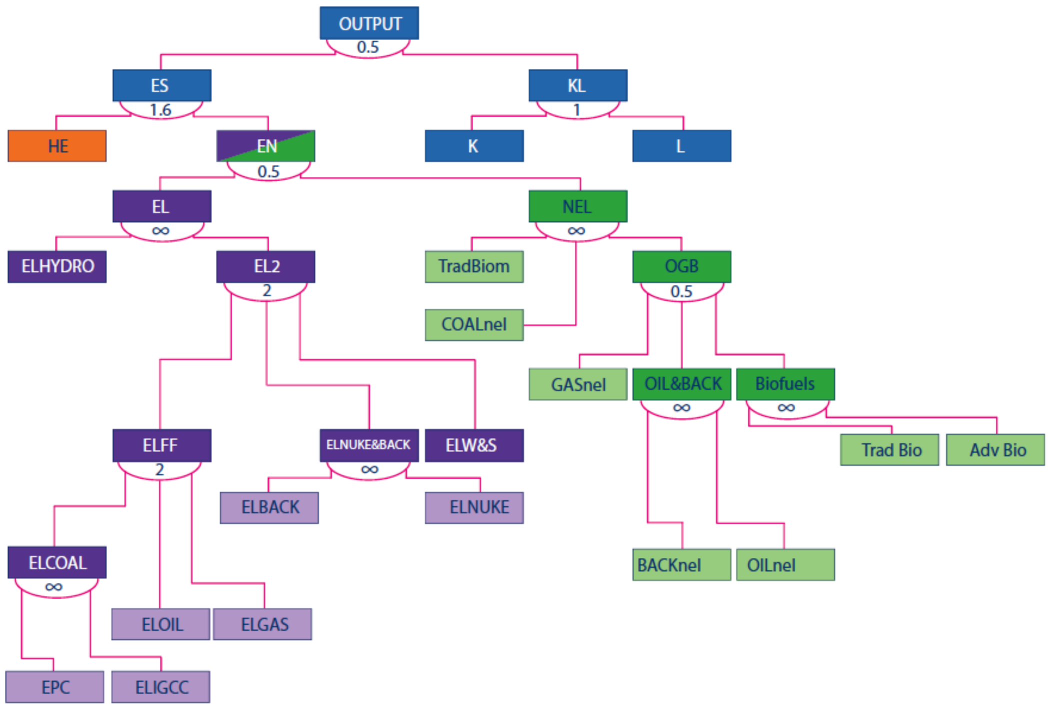

Figure A.2: The WITCH production tree

This ensures consistency between economic output, energy demand, its final use and investments in innovative and conventional power generation facilities. The dynamics of the energy sector and the optimal portfolio of different technologies are fully endogenous and they reflect long-term convenience of alternative investments.

The WITCH model characterizes the endogenous nature of technical progress in the energy sector. Endogenous dynamics make it possible to account for the induced effect of climate policy. Both innovation and diffusion processes are modelled. R&D investments can enhance energy efficiency or facilitate the competitiveness of innovative low carbon technologies in both the electric and non-electric sectors (so called backstop technologies).

Investments in power generating technologies, in innovation, and the demand for fossil fuels are chosen optimally, simultaneously with other macroeconomic variables, such as consumption and investments in final goods. Investments flows, operation and maintenance costs, and the expenditure for fossil fuels are subtracted from the budget constraint and therefore reduce the amount of resources available for final consumption.

Table A1 provides an overview of the key features of the model. The individual modules along with relevant parameters and assumptions are described in more detail in the following sections.

Table A1: Overview of key characteristics of the WITCH model.

key distinguishing feature	**WITCH model**
Solution concept	Intertemporal optimization (Ramsey-type growth model)
Expectations/Foresight	Default: perfect foresight
Substitution possibilities within the macro-economy / sectoral coverage	CES production function of generic final good from primary inputs capital and labor and intermediate inputs energy
Link between energy system and macro-economy	Economic activity determines demand; energy system costs (investments, fuel costs, operation and maintenance) are included in macroeconomic budget constraint. Hard link, i.e. energy system and macroeconomy are optimized jointly.
Production function in the energy system / substitution possibilities	Non-linear substitution between competing technologies for electricity generation modelled with CES production functions. Supply curves for exhaustible resources.
Land use	MAC curves for deforestation
International macro-economic linkages / Trade	Single market for some commodities (permits) International spillovers of knowledge (energy R&D) and of experience (learning-by-Doing for wind and solar)
Implementation of climate policy targets	Emission caps-and-trade, with different allocation rules across or taxes. Banking and borrowing can be switched on/off
Technological Change / Learning	Global learning-by-Doing for wind and breakthrough technologies in power and final sector; learning-by-Researching for breakthrough technologies solar with international spillovers of knowledge; energy efficiency R&D investments with international spillovers
Representation of end-use sectors	Electric, non-electric (plans to disaggregate into transport and rest), final good sector
Cooperation vs. non-cooperation	Nash equilibrium (non-cooperative) or Pareto equilibrium (cooperative)
Externalities	Environmental externality (regional damage function), international energy markets, technology externalities are not internalized in the Nash equilibrium
Discounting	Pure rate of time preference 3% declining
Investment dynamics	Capital motion equations, no vintage

WITCH has a game-theoretic structure which makes it possible to account for the non-cooperative nature of international relationships not only on climate, but also on other externalities that induce free-riding behaviours and strategic interactions. The model can produce two different solutions. The cooperative solution is globally optimal because it maximises global social welfare and it internalises environmental and economic externalities. It thus represents a first-best optimum. The decentralised, or non-cooperative solution is strategically optimal for each given region (Nash equilibrium), but it does not internalise externalities. It thus represents a second-best optimum. The Nash equilibrium is computed as an open-loop Nash equilibrium. It is the outcome of a non-cooperative, simultaneous, open membership game with full information.

The climate change externality is related to the fact that GHG emissions produced anywhere in the world become uniformly mixed in the atmosphere, equally contributing to increase global average temperature, which then has an impact in all regions according to the regional damage function. The climate change damage function used in the basic version of the WITCH model includes a reduced-form relationship between temperature and gross world product which follows closely Nordhaus and Boyer (2000), both in the functional form and in the parameter values. Climate change damage drives a wedge between net and gross output:

$$YN_{n,t} = \frac{1}{1+\theta_{1n}\cdot T_t + \theta_{2n}T_t^2}\cdot YG_{n,t}, \qquad (1)$$

where n and t are country and time indices, and YN, YG and T denote respectively net output, gross output and temperature. The resulting pattern of regional damages also follows Nordhaus and Boyer (2000), with higher estimated losses in developing countries, in particular South Asia (including India) and Sub-Saharan Africa. These two regions are expected to lose the most from climate change, especially because of higher damages in agriculture and the increase of vector-born diseases (Sub-Saharan Africa) and because of catastrophic climate impacts (South Asia including India). Damage estimates for agriculture, coastal settlements and catastrophic climate impacts are significant in Western Europe, resulting in higher damages than in other developed regions. In China, Eastern EU countries, non-EU Eastern European countries (including Russia), Japan-Korea, climate change up to 2.5°C would bring small benefits, essentially because of a reduction in energy demand for heating purposes (non-EU Eastern European countries including Russia) or positive effects on agricultural productivity (China).

A climate module describes the physical relationship between GHG emissions, radiative forcing, and temperature. Temperature relative to pre-industrial levels increases through augmented radiative forcing of different GHGs. Radiative forcing in turn depends on CO2 and non-CO2 atmospheric concentrations. Stoichiometric coefficients are applied to the use of fossil fuels to derive related CO2 emissions. WITCH uses a Simple Climate Model (SCM). CO2 concentrations in the atmosphere have been updated to 2005 at roughly 385ppm and temperature increase above pre-industrial at 0.76°C, in accordance with IPCC 4th Assessment Report (2007).

Other parameters governing the climate equations have been adjusted following Nordhaus (2007)7. We have replaced the exogenous non-CO2 radiative forcing with specific representation of other GHGs and sulphates. Climate sensitivity is set to 3.

Among non-CO2 gases, emissions of methane (CH4), Nitrous dioxide (N2O), short-lived fluorinated gases, (SLF, HFCs with lifetimes under 100 years) and long-lived fluorinated (LLF, HFC with long lifetime, PFCs, and SF6) are explicitly modelled. We also distinguish SO2 aerosols, which have a cooling effect on temperature.

Baseline projections of non-CO2 GHGs are based on EPA regional estimates (EPA, 2006). SO2 emissions are taken from MERGE v.58 and MESSAGE B2: given the very large uncertainty associated with aerosols, they are translated directly into the temperature effect (cooling), so that we only report the radiative forcing deriving from GHGs. In any case, sulphates are expected to be gradually phased out over the next decades, so that eventually the two radiative forcing measures will converge to similar values.

The equations translating non-CO2 emissions into radiative forcing are taken from MERGE v.5. The global warming potential (GWP) methodology is employed, and figures for GWP as well as base year stock of the various GHGs are taken from the IPCC 4th Assessment Report, Working Group I. The simplified equation translating CO2 concentrations into radiative forcing is in line with IPCC9.

We introduce end-of-pipe type of abatement possibilities via marginal abatement curves (MAC) for non-CO2 GHG mitigation. We use MAC provided by EPA for the EMF 21 project10, aggregated for the WITCH regions. MAC are available for 11 cost categories ranging from 10 to 200 US$/tC. We have ruled out zero or negative cost abatement options. MAC are static projections for 2010 and 2020, and for many regions they show very low upper values, such that even at maximum abatement, emissions would keep growing over time. We thus introduce exogenous technological improvements: for the highest cost category only (the 200 US$/tC) we assume a technical progress factor that reaches 2 in 2050 and the upper bound of 3 in 2075. We, however, set an upper bound to the amount of emissions which can be abated, assuming that no more than 90% of each gas emission can be mitigated. Such a framework enables us to keep non-CO2 GHG emissions somewhat stable in a stringent mitigation scenario (530e) in the first half of the century, with a subsequent gradual decline. This path is similar to what is found in the CCSP report11, as well as in MESSAGE stabilisation scenarios. Nonetheless, the scarce evidence on technology improvements potential in non-CO2 GHG sectors indicates that a sensitivity analysis should be performed to verify the impact on policy costs.

[7] http://nordhaus.econ.yale.edu/DICE2007.htm
[8] http://www.stanford.edu/group/MERGE/m5ccsp.html
[9] http://www.grida.no/climate/ipcc_tar/wg1/222.htm, Table 6.2, first Row.
[10] http://www.stanford.edu/group/EMF/projects/projectemf21.htm
[11] http://www.climatescience.gov/Library/sap/sap2-1/finalreport/default.htm

WITCH includes baseline projections for land-use emissions as well as estimates of global potential and costs of reducing emission from deforestation. Two versions of abatement cost curves have been incorporated in the model representing two extreme cases. The first version includes abatement curves for the whole century for the Brazilian tropical forest only and have been developed using Brazil's data from the Woods Hole Research Center (Nepstad et al. 2008)12. A second version includes abatement curves for all world tropical forests, based on the Global Timber Model of Brent Sohngen, Ohio State University, used within the Energy Modeling Forum 21 (2006) and data from the IIASA cluster model (Eliasch 2008).

[12] http://whrc.org/BaliReports/