BOTTOM-UP CLIMATE ADAPTATION STRATEGIES FOR EUROPE

Title: **Report documenting the selected integrated assessment models for top-down analysis used in BASE**

Summary: this deliverable reports the advancements of the work accomplished by WP3 under Sub-Tasks 3.2. Its objective is to improve selected tools and methodologies for integrated assessment of climate change adaptation costs and benefits. The selected integrated assessment models will provide information for the policy decision process on the design of cost effective and cost efficient climate policies, allowing a prioritization of adaptation measures, both across different sectors, and over time, considering their potential interactions with other policies.

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SEVENTH FRAMEWORK PROGRAMME

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Contents

1 Introduction and aims of this document

The main aim of the BASE project is to address the need for research on sustainable climate adaptation strategies, which promote interactions between bottom-up and top-down activities and assessments. BASE seeks to evaluate the environmental, social and economic impacts, costs and benefits, policy coherence and stakeholder and citizen perceptions of different climate adaptation pathways from an interdisciplinary perspective.
This requires primarily more complete quantitative information on costs and benefits of adaptation strategies/measures, and a higher integration, access and use of this information. Last, but not least, key prerequisite is the development of appropriate quantitative investigation methodologies.
This deliverable contributes specifically to this last goal describing the improvement/development of the integrated assessment top-down economic models used within the BASE project to better analyze cost and effectiveness of adaptation strategies at the EU level.

The suit of models used in the BASE project are described in D3.1 (Bosello et al. 2013). The bottom-up, partial-equilibrium or sectoral models developed by the consortium are revised by D3.2 (Iglesias et al. 2014). This deliverable focuses on the two top-down models which complement the sectoral assessments.

The two top-down models are different in nature: the first is the WITCH model, a dynamic optimization hard-link integrated assessment model for the world economic system, the second is the ARIO Input output model meant to address adaptation at the urban level first and then to upscale the information at the wider national scope.

Both models, with their different characteristics, aim to analyze cost and benefit of adaptation with a cross sectoral perspective. The WITCH model will develop an analysis of adaptation strategies at the EU and world level, differentiating adaptation into large "types": anticipatory, reactive, adaptive capacity building and comparing these with mitigation. Specific research developed within BASE consists in updating the WITCH adaptation module incorporating the information provided by the sectoral models/studies developed within the project. Indeed its calibration, especially that pertaining to costs and benefit of adaptation in the health sector, agricultural sector and against floods in the EU, will derive respectively from the analysis developed by BC3 and Exeter University, from the UPM ClimateCrop model and from the DELTARES flood risk model. Policy indications from WITCH will be thus grounded on quantitative evidence produced by bottom-up models.

The ARIO model – as anticipated - will instead focus on adaptation at the urban level. It adopts an intersectoral perspective. The aims of this input-output approach are: to quantify cost-benefits of adaptation measures for case study cities from a macroeconomic perspective; to link the city scale ARIO models with national input-output tables (for each case study city) to estimate the cost and benefit of implementing local adaptation measures to the national economy; further integrate the national scale ARIO model with the World Input-Output Database (WIOD) to estimate the cost and benefit of implementing local adaptation measures to the EU and other countries' economies.

This deliverable, enriches the description of D3.1 reporting the advancements in the basic structure of the two models to better serve the purposes of the BASE project research needs. Nonetheless it focuses mostly on the WITCH model, as the use of ARIO has been described in D3.1 and the mathematical implementation of shocks into the model in a dedicated section of D3.2 and in D6.2 (Guan et al., 2014).

Finally, it is worth mentioning that the work reported in this deliverable will be further refined under WP6 which aims, among other, to perform the analysis of adaptation proper synthesizing the output of WP3, WP4 and WP5 especially in Task 6.3 to derive a EU-level picture of challenges and opportunity for adaptation. There, the different insights from case studies, sectoral models and also from WITCH and ARIO will be compared and when possible cross-validated to offer a comprehensive and consistent analysis.

In what follows, section 2 introduces the development of the WITCH model, section 3 summarizes that of ARIO and section 4 concludes.

2 Developing the WITCH model for the BASE project

The WITCH model developed by Bosetti et al. (2006, 2007) and then enriched with adaptation (Bosello et al. 2010, 2013) is an intertemporal, optimal growth model in which forward-looking agents choose the path of investments to maximise a social welfare function subject to a budget constraint. A reduced-form global circulation model links emissions from industrial activities to temperature increase. In turn the temperature increase translates into GDP losses via a reduced-form climate change damage function (Figure 1 left). The model depicts 12 world macro-regions[1] and simulates changes until 2100. It uses a disaggregated representation of the energy system detailed into many energy production technologies.

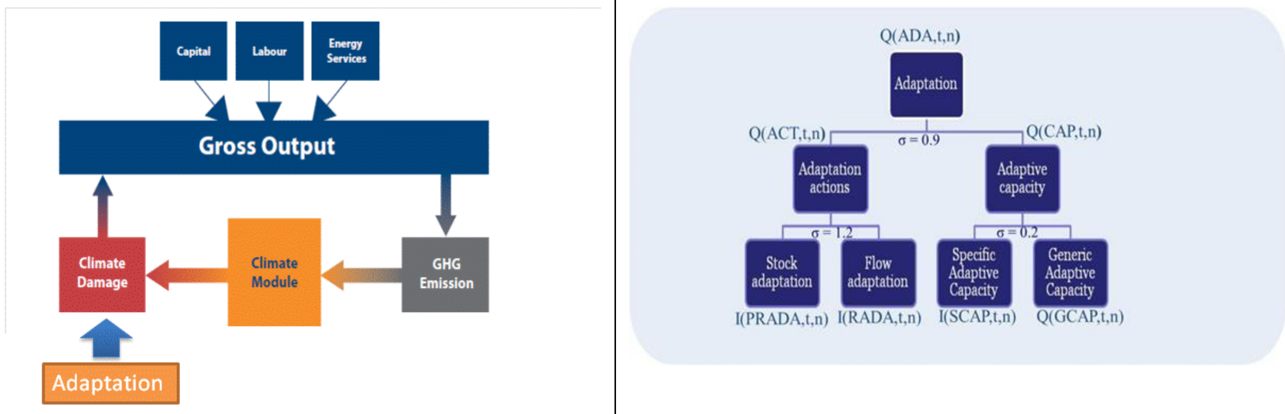
The model can be solved in two alternative game theoretical settings. The non-cooperative one yields a Nash equilibrium, which does not internalise the environmental externality. The cooperative setting describes a first-best world, in which all externalities are internalised.

More relevant for BASE is the treatment of adaptation. In the WITCH model with adaptation (AD-WITCH thereafter), adaptation is modelled as a set of control variables chosen optimally together with all the other controls, namely investments in physical capital, R&D, and energy technologies. The large number of possible adaptive responses has been aggregated into four macro categories: generic and specific adaptive capacity building, anticipatory and reactive adaptation, organized by a nested sequence of CES functions (Figure 1 right).

[1] These 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). Focus of BASE is the EU. In AD-WITCH WEURO includes: Andorra, Austria, Belgium, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, United Kingdom. EEURO includes: Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia

Figure 1. The WITCH model with adaptation

Structure of the AD WITCH model	Adaptation "tree" in the AD-WITCH model



Generic adaptive capacity building captures the link between the status of the development of a region and the final impact of climate change on its economic system. Specific adaptive capacity building accounts for all investments dedicated to facilitate adaptation activities (e.g. improvement of meteorological services, of early warning systems, the development of climate modelling and impact assessment etc.). Anticipatory adaptation gathers all the measures where a stock of defensive capital must already be operational when the damage materialises (e.g. dike building). By contrast, reactive adaptation gathers all actions that are put in place when/after the climatic impact effectively materialises (e.g. use of air conditioning) to accommodate the damages not avoided by anticipatory adaptation or mitigation.

2.1 Model improvements

Model improvements under D3.3 moved along three lines: the calibration of the model references to replicate the Shared Social Economic Pathways 2 and 5; the enrichment of the WITCH damage component introducing ecosystem-related non-market damages and its re-calibration according to more recent evidence; the re-specification and re-calibration of the model adaptation functions. Following these developments, the model now incorporates more up to date information on the economic cost of climate change while presenting a calibration of adaptation costs and effectiveness which is closer to the available observed and projected data.

2.1.1 Calibrating the WITCH model to the SSP2 and SSP5

As described in D3.1 (Bosello et al. (2013)) the BASE project is currently adopting two social economic scenarios as representative references for its analysis of adaptation. These are the Shared Social Economic Pathways 2 and 5, SSP2 and SSP5 thereafter (O'Neill et al., 2011). They span the ranges of possible futures from the “continuation of current trends” (SSP2) to “conventional development” oriented to economic growth (SSP5). Both scenarios, will present challenges for adaptation (for further comments please refer to Bosello et al. (2013)).

To each of these scenarios is also associated a potential profile of carbon concentration, radiative forcing, temperature increase and thus of climate change damages. These are the Representative Concentration Pathways 4.5 (RCP4.5), implying a carbon concentration of roughly 650 ppm by the end of the century, deemed consistent with the “middle of the road” SSP2, and the RCP8.5, which foresees the much higher concentration of roughly 1350 ppm by the end of the century and is associated to the high growth SSP5 (for a detailed description of RCPs see Van Vuuren et al. 2012).

The WITCH model has been recalibrated accordingly, replicating the two SSPs. The results of the procedure are reported in Figure 2

Figure 2. The WITCH model and the SSPs

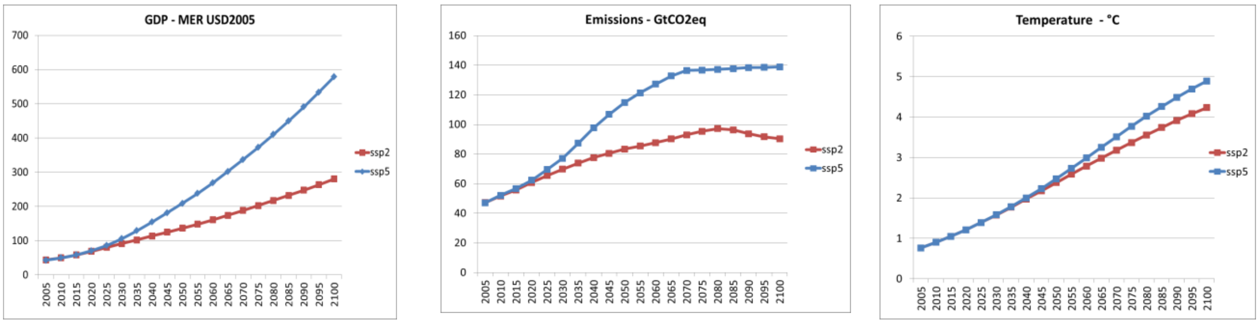


Figure 2 also reports the emission (and temperature) profiles that the WITCH model endogenously produces for the two scenarios. Those of the SPP5 are consistent with the high concentration and forcing implied by RCP8.5. Those of the SSP2 are lower than that of SSP5, but anyway higher than those that would produce the concentration levels characterizing RCP4.5. In fact, they are consistent with a radiative forcing of roughly 7 W/m^2 instead of 4.5. This is deliberate. In fact, RCP4.5 is a mitigation policy scenario[2]. What presented here is the SSP2-RCP 4.5 baseline without policy. The desired carbon concentration and forcing shall be obtained once an appropriate mitigation policy is implemented.

2.1.2 The new climate-change damage specification of the WITCH model

As standard in fully linked, fully intertemporal dynamic optimization Integrated Assessment Models (IAMs) (Bosello, 2014), the climate change damage function (CCDF) in WITCH is a reduced form linking temperature increase to regional GDP losses according to:

[2] In fact this is one of the major novelties introduced by the new IPCC scenario exercise: that to include some policy action, whereas the “old“ IPCC SRES scenarios were strictly “no policy“ scenarios.

$$Y(t,n) = \frac{YP(t,n)}{1+\omega_{1,n}T(t)+\omega_{2,n}T(t)^{\omega_{3,n}}} \quad (1)$$

As shown in equation (1), in each period t temperature increase T(t) drives a wedge between potential region n output YP(t,n) and net regional output Y(t,n). The ωs are region-specific damage coefficients. ω_3 in particular shapes the convexity-in-temperature of the damage function and is typically greater than 1. WITCH original calibration derives from the work of Nordhaus and Boyer (2007). Original work within the BASE project is the revision of this calibration. It now incorporates more recent knowledge on climate change damages. Most of these new data derive from the FP7 project CLIMATECOST[3] (see Bosello et al. 2012) offering updated estimates of the market component of climate change damages. That project quantified the physical and economic impacts of climate change on sea-level rise, energy demand, agricultural productivity, tourism flows, net primary productivity of forests, floods, reduced work capacity because of thermal discomfort. All impacts, except those on floods and health, which focus on the EU, have been assessed for a number of macro regions covering the world as a whole. The joint macro-economic effect of all climate change impacts (GDP change) has then been assessed using the top-down, recursive-dynamic computable general equilibrium (CGE) model ICES (Eboli et al. 2010). The advantage of this procedure is to embed into GDP losses -that market or autonomous adaptation processes driven by price changes that a CGE analysis typically captures. Therefore the new calibration of the ω coefficient in (1) accounts, although partially, for autonomous adaptation.

More specifically, we used the economic impacts related to sea-level rise, changes in crops' productivity and in energy demand from CLIMATECOST to replace the respective damage categories in WITCH derived from Nordhaus and Boyer (2007).

A further refinement concerned the non-market damage component of the WITCH CCDF capturing effects on ecosystems.

The health costs and effects from catastrophic events in the WITCH CCDF remained those of Nordhaus and Boyer (2007), but (see section 2.1.5) will be also revisited according to information produced within the BASE project.

The new "market damage" component

Estimates of coastal land loss due to sea-level rise, are based on the DIVA model outputs (Vafeidis et al. 2008). DIVA (Dynamic Integrated Vulnerability Assessment) is an engineering model designed to study the vulnerability of coastal areas to sea-level rise. The model is based on a world database of natural system

[3] CLIMATECOST; research program: FP7 Environment; project reference number: 212774. http://cordis.europa.eu/search/index.cfm?fuseaction=result.document&RS_LANG=EN&RS_RCN=11479505&q=; www.climatecost.cc

and socio-economic factors for world coastal areas reported with a spatial resolution of 5°. The temporal resolution is 5-year time steps until 2100 and 100-year time steps from 2100 to 2500. Changes in natural as well as socio-economic conditions of possible future scenarios are implemented through a set of impact-adaptation algorithms. Impacts are then assessed both in physical (i.e. sq. km of land lost) and economic (i.e. value of land lost and adaptation costs) terms.

Changes in the average productivity of crops are derived from the ClimateCrop model (Iglesias et al. 2009; Iglesias et al. 2010). Crop response depends on temperature, CO2 fertilisation and extremes. Water management practices are also taken into account. Spatially integrating all these elements, the model estimates climate change impacts and the effect of the implementation of different adaptation strategies.

Responses of residential energy demand to increasing temperatures derive from the POLES model (Criqui 2001, Criqui et al. 2009). It is a bottom-up partial-equilibrium model of the world energy system extended to include information on water resource availability and adaptation measures. It determines future energy demand and supply according to energy prices trend, technological innovation, climate impacts and alternative mitigation policy schemes. The present version of the model considers both heating and cooling degree-days in order to determine the evolution of demand for different energy sources (coal, oil, natural gas, electricity) over the time-horizon considered.

In CLIMATECOST the outputs from these partial equilibrium models have been used as an input to the ICES CGE model which then quantified the related GDP effects on each of the model regions. The outcome of the procedure, that also provides the new values to recalibrate the WITCH CCDF, are reported in Table 1[4]. Comparison with the original values reported by Nordhaus and Boyer (2007) is also reported.

[4] Note that in CLIMATECOST the ICES model reported a geographical characterization of the EU slightly more resolved than that of WITCH. Three rather than two EU maro-regions are in fact considered. The other regions coincide across the two models.

Table 1. Market impacts of 1.92°C global average temperature increase (reference year 2050) on real GDP by region and impact: % change compared to the case with no temperature increase

	Energy		Sea-Level Rise		Agriculture	
	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)
USA	-0.01	0	-0.05	-0.08	0.05	-0.02
MEUR	-0.05	0	-0.03	-0.35	0.07	-0.02
NEUR	-0.07	0	-0.11	-0.35	0.23	-0.02
EEUR	-0.02	0	-0.04	-0.01	-0.15	-0.02
FSU	0.01	0.61	-0.03	-0.04	0.49	0.63
KOSAU	-0.04	0.25	-0.04	-0.07	0.01	0.04
CAJANZ	-0.02	0	-0.16	-0.21	0.19	-0.02
NAF	-0.03	-0.25	-0.02	-0.02	-2.10	-0.51
MDE	-0.19	-0.15	-0.10	-0.03	-0.10	-0.27
SSA	0.00	-0.25	-0.02	-0.02	-1.09	-0.51
SASIA	0.22	-0.22	-0.32	-0.07	-3.02	-0.25
CHINA	0.04	-0.25	-0.03	-0.06	0.43	-0.02
EASIA	0.01	-0.16	-0.10	-0.07	-2.36	-0.40
LACA	-0.04	-0.22	-0.05	-0.08	-0.11	-0.32

The non-market damage component

The extension to non-market damages, pertains to the specific dimension of ecosystem. Estimating economically ecosystem losses is a challenging task as the services they provide are largely non marketed, and not easily transformed into monetary values. Accordingly, their value can be only extracted through elicitation of preferences. In particular, the WTP to avoid a given loss in ecosystems is used to approximate the lost value in case they are not protected.

In the original RICE99 model Nordhaus and Boyer (2000) estimated impacts on “settlements and ecosystems”, which include natural settlements (ecosystems) together with human settlements (cities, states). The authors derived the values from unpublished estimates of the capital value of climate-sensitive human settlements and natural ecosystems in each region of the RICE99 model. Then they estimated that each of them has an associated annual WTP of 1% of the capital value of the vulnerable system, for a 2.5°C temperature increase (which in the US amounts to roughly 0.1% of GDP). We replace these estimates applying the partly different methodology used in the MERGE model (Manne et al., 1995). There, the monetized ecosystem losses related to a 2.5°C temperature increase above pre-industrial levels is set equal to the 2% of GDP when per capita income is above $ 40,000. The 2% figure is the US EPA expenditure on environmental protection in 1995. The implicit assumptions are that what actually paid is reasonably close to the WTP, and also roughly equivalent to the ecosystem damages experienced in a world warming moderately.

This approach has been applied here, but rescaling all to the more recent data of the EU 2007 expenditure on environmental protection by the public sector (0.62% of GDP according to EUROSTAT, (2013)), and assuming more conservatively than Manne et al., (1995) that the observed expenditure allows to recover damages related to 2°C warming. Then, to derive WTP in non EU countries the logistic function (1) proposed by Warren et al., (2006) is used:

$$WTP_{n,t|t=2.°C} = \gamma \Delta T^{\varepsilon}{}_{n,t|t=2°C} \frac{1}{1+100e^{(-0.23 * GDPn,t|t=2°C \,/\, POPn,t|t=2°C)}} \quad (2)$$

The parameter calibration in equation (2) derives from EU data, thus γ is set to give exactly 0.62% of GDP when per capita income is the 2007 EU average ($34,262), and ΔT=2°C. The last step is that to use the WTP to measure the direct cost of losses in ecosystem and their services.

Table 2 reports the results of the procedure and a comparison with Hanemann (2008) - another study applying the same approach, but starting from a WTP estimates for the US equal to 0.1% of GDP - Nordhaus and Boyer (2000), and with the MERGE model as described in Warren (2006).

Table 2. WTP for ecosystems protection (ecosystem damages) related to a temperature increase of 2.5°C (% of regional GDP)

	This study	Hanemann (2008)	Nordhaus and Boyer (2000)	Merge model as in Warren, (2006)
USA	0.69	0.10	0.10	2.00
Western EU	0.69	0.10	0.25	2.00
Eastern EU	0.69	0.10	0.10	2.00
KOSAU	0.69	0.10	0.10	1.99
CAJAZ	0.69	0.10	0.25	2.00
TE	0.50	0.08	0.05	1.47
MENA	0.31	0.05	0.05	0.89
SSA	0.01	0.002	0.10	0.04
SASIA	0.06	0.009	0.10	0.18
CHINA	0.61	0.09	0.05	1.76
EASIA	0.10	0.02	0.10	0.30
LACA	0.66	0.099	0.10	1.92
WORLD	0.49	0.07	0.10	2.00
USD billion (2005)	1120	169		4569

As shown in Table 2, the reference WTP value used for rich countries crucially determines the final results. Using the EU values as the benchmark for calculations gives lower damages than in the MERGE model, but anyway higher than in Hanemann (2008) and Nordhaus and Boyer (2000). This also emphasises the large uncertainty when assigning an economic value to non-market impacts.

Table 2 also shows that a WTP approach tends to produce higher evaluations for non-market ecosystem losses in high-income countries, although ecosystem/biodiversity richness is highly concentrated in developing countries.

Figure 3 summarizes all the impact categories considered, showing the damage magnitude at the calibration point (2.5°C above preindustrial levels)[5] while

[5] The damage function is a quadratic function and therefore has two parameters to calibrate. We also consider a higher temperature level, 4°C, as second point for calibration.

Figure 4 compares the new impacts with that of the original specification in WITCH.

Figure 3. Climate change impacts at calibration point (2.5°C above pre-industrial levels).

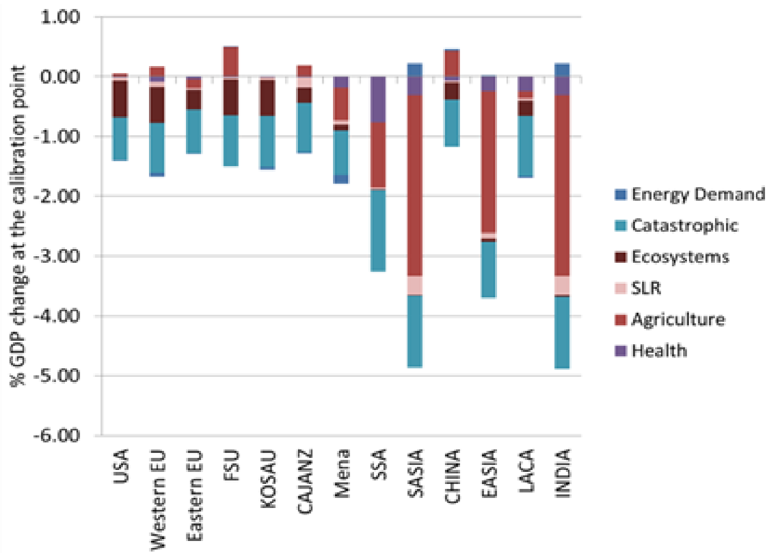
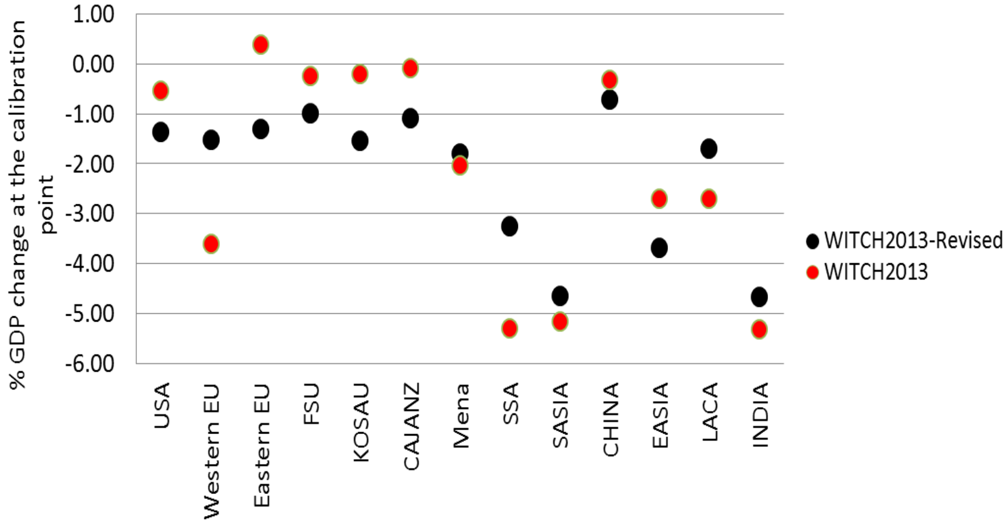


Figure 4. Comparison of revised and previous damage estimated in the WITCH model at calibration point (2.5°C above pre-industrial levels).



The new estimates point out a generalized increase in damages at the calibration point. The most notable differences are however the decrease in damages in the Western EU and Sub Saharan Africa. The first is mainly driven by the positive impacts of climate change on agriculture that the CLIMATECROP model, in moderate warming scenarios, devises for the area. This, in contrast with the decrease in crop productivity assumed by Nordhaus and Boyer (2007). The second is due to the climate-change induced effects on ecosystem losses and partially energy demand. Ecosystem losses, albeit positive, are much smaller than in Nordhaus and Boyer (2007), while dynamics in the energy markets leave SSA GDP unaffected against a loss of 0.25% in Nordhaus and Boyer (2007).

2.1.3 Specifying the adaptation module in the WITCH model

As a first step, the original functional form describing adaptation cost and effectiveness in the WITCH model has been re-specified.

As represented in Figure 1 (left) adaptation enters the model damage function as an expenditure which is able to decrease climate change damage. Then (Figure 1, right) the different adaptation types are specified by a sequence of nested CES functions.

Equation (3) below represents the new specification of the first adaptation node in Figure 1 (right), and, more precisely, how adaptation affects the WITCH CCDF:

$$\Omega(t,n) = 1 + \frac{[\omega_{1,neg(n)}T(t)+\omega_{2,neg(n)}T(t)^{\omega_{3,neg(n)}}]}{1+Q(ADA,t,n)^{\varepsilon(n)}} + \omega_{1,pos(n)}T(t) + \omega_{2,pos(n)}T(t)^{\omega_{3,pos(n)}} \quad (3)$$

$\Omega(t,n)$ is the modified denominator of equation (1) accounting for adaptation. Differently from the original AD-WITCH model, it is now split into a negative-in-temperature (damage) part, the second term in (3), and into a positive-in-temperature part, the last two terms in (3), each with a specific parameterization. This accounts for the fact that climate change may exert, at a time, positive and negative effects, that negative effects could be present even though the net effect is positive, and *vice versa*. This modification is crucial as it allows to calibrate in, and replicate with the model, positive adaptation costs even in those years and regions showing net gains from climate change. This typically happens for instance for low levels of temperature increase in mid-high latitude countries when positive economic effects on crop yields from moderate warming tend to overcompensate other losses. This however does not mean that the regions concerned do not show positive adaptation expenditure. More specifically, in equation (3) total adaptation expenditure, Q(ADA,t,n), decreases just the damaging effects of climate change and not the welfare enhancing ones.

Another feature of adaptation is worth stressing. The SSP storylines (O'Neill et al. 2011) include a qualitative discussion of the potential challenges for mitigation and adaptation in the various socio-economic scenarios. In the SSP5 scenario the challenges to adaptation are lower. As explained in O'Neill et al. (2011), there are two contrasting effects at work. On the one hand climate change impacts are stronger, implying more adaptation effort, on the other hand high social-economic development implies more investment in protection and more resilient infrastructures, which decrease the challenge for adaptation. We capture this aspect imposing that the marginal productivity of reactive and proactive adaptation is 25% higher in the SSP5 case (see also the mathematical Appendix, parameter $\omega_{eff(n)}^{ACT(n)}$ in Eq. (A3)) than in SSP2.

The functional specification of the remaining adaptation nodes is described in detail in the mathematical appendix to this deliverable and follows the structure of Bosello et al., (2010).

2.1.4 Calibrating adaptation in the WITCH model

This section briefly reports the calibration procedure and data used for the WITCH adaptation module. In practice this amounts to establish at a given calibration point (+2.5°C wrt preindustrial level) the costs and benefits of different adaptation strategies, belonging to the different adaptation nodes, in the different regions of the model. The current calibration, when related to the EU and to the specific fields of health, agriculture and floods/extreme events, will be revisited using the information provided by the models developed under D3.2.

Anticipatory adaptation

Agriculture

The most significant cost component of climate change adaptation in agriculture is presumably related to irrigation practices. These are forms of adaptation that can be classified mostly as proactive. The UNFCCC , based on Kirshen (2007), reports some estimates of the future total cost on water infrastructure in the B1 SRES scenario, also assuming that 25% of that investment will be climate change-driven. WITCH assumes that the agricultural sector absorbs 70% of the water infrastructure costs reported by the UNFCCC study, and that between the 15% and 25% of these will be necessary in the future to adapt to climate change. The effectiveness of adaptation in agriculture is instead based on Tan and Shibasaky (2003) reporting changes in yields with and without adaptation under climate change for different crops and world regions.

Sea-level rise

Costs and effectiveness of coastal protection are directly derived from the already quoted DIVA model. That model can be run under different scenarios of coastal protection. In this case results derived from the "optimal protection" mode of DIVA and are related to an average level of sea-level rise of 0.44 meters and to a temperature increase of 2.5°C above pre-industrial levels. Coastal protection costs include all adaptation costs (dike building, beach nourishment and wetland nourishment) and average protection level is measured in terms of years of protection, where maximum protection (100%) corresponds to 10000 years.

Ecosystems

This is probably the most problematic component of adaptation costs to estimate due to the shortage of useful data. Our estimates derive mostly from UNFCCC (2007). This study uses the observed global expenditure on conservation of protected areas (PAs) to identify the investment needed for protecting natural ecosystems. Their reported values is $ 7 billion globally. UNFCCC (2007) also reports an annual increase in expenditure of $ 12-22 billion to increase protected areas by 10%. That range refers to the estimated cost of improving protection, expanding the network of protected areas and compensating local communities that currently depend on resources from fragile ecosystems[6]. We use the range 12-22 USD billion to compute a lower and higher bound for adaptation.

Infrastructure

The estimate of investments needed to adapt infrastructure to climate change is based upon UNFCCC (2007) and then applied to the WITCH investments in physical capital in 2060. According to that study, the average annual share of infrastructure vulnerable to the impacts of climate change is 2.7% of average annual investments in infrastructure globally. The World Bank (2006) estimate the additional costs of adapting vulnerable infrastructure to climate change between 5% and 20% of investments. For this study we consider the conservative rate of 5%. These estimates however do not consider the "infrastructure deficit" i.e. the fact that current infrastructure investments are already inadequate which is likely to imply higher needs of climate proofing investments.

We use aggregate figures for low and middle income countries provided by Parry et al. (2009), (Table 6.1) to compute the average annual regional investments needed to address the infrastructure adaptation deficit as a component of the specific capacity.

[6] Upper figures provided by Parry et al. (2009) are in the range of USD 291-341.5 billion.

No precise estimates are available to determine the effectiveness of this kind of adaptation even though it can be reasonably inferred that these protections activities are relatively effective. Accordingly, we set it to 40%.

Reactive adaptation

Energy

Adaptation costs in the energy sector is determined in WITCH by changes in heating and cooling expenditure. These are derived from De Cian et al. (2013), a panel-data econometric study estimating world-wide demand elasticity of different energy vectors, electricity, natural gas, coal and oil products, in response to temperature changes. The effectiveness of this adaptation, is difficult to be assessed. It is assumed, quite arbitrarily that in developed countries it is quite high, 80% while it is 40% in developing countries. This would mean that in 2060 80% and 40% of population in developed and developing countries respectively would be able to protect themselves from thermal discomfort .

Health

Costs of adaptation in the health sector derive from Tol et al. (2001), who assess the additional climate change driven treatment cost associated with malaria, dengue, schistosomiasis, diarrhoeal, cardiovascular and respiratory diseases, for different scenarios of temperature increases, for all countries of the world. The effectiveness of adaptation is based on survey literature which shows that protection levels range from 20% in Africa to 40% in other non OECD countries. In developed regions it is assumed that protection levels, also considering financial resources, is much higher, ranging from the 60% to the 90%.

Specific capacity

Determining the cost of adaptive capacity building (specific capacity) is another challenging task. In the present exercise four specific components for that expenditure are identified:

1. Expenditure needed to eliminate the infrastructure gap. These derive from Parry et al. (2009) and are assumed to be zero in developed countries.
2. Expenditure needed to empower women through education based upon Blankenspoor et al. (2010).
3. Costs and effectiveness of early warning systems, from Adam et al. (2000).
4. R&D expenditure in the agriculture sector from UNFCCC (2007).

As will be noted (Table **5**) the first item accounts for 95% of the investments in specific adaptive capacity building.

Table 3 to Table 6 summarize all the data used for the calibration of the protection costs and protection levels. Figure 5 represents the cost/effectiveness adaptation curves obtained for each model region.

Table 3. Anticipatory protection costs at the calibration point (+2.5°C increase above pre-industrial levels, 2055)

	Agriculture (irrigation) (Billion $)	Coastal Protection (Billion $)	Infrastructure (Billion $)	Ecosystems (Billion $)	TOTAL (Billion $)	Agriculture (irrigation) (% of GDP)	Coastal Protection (% of GDP)	Infrastructure (% of GDP)	Ecosystems (% GDP)	TOTAL (% of GDP)
USA	3.0	3.6	10.4	6.0	23.0	0.009	0.010	0.030	0.017	0.07
Western EU	4.7	5.0	9.6	5.8	25.1	0.015	0.016	0.031	0.019	0.08
Eastern EU	7.4	0.3	0.6	0.4	8.6	0.301	0.010	0.024	0.015	0.35
KOSAU	11.0	1.8	2.0	2.1	16.8	0.141	0.023	0.026	0.027	0.22
CAJAZ	1.6	2.9	3.2	5.8	13.5	0.013	0.024	0.026	0.048	0.11
TE	10.1	1.7	1.7	0.2	13.6	0.103	0.017	0.017	0.002	0.14
MENA	28.8	1.2	2.1	0.2	32.3	0.258	0.011	0.019	0.001	0.29
SSA	30.2	2.7	2.8	0.1	35.8	0.254	0.022	0.024	0.001	0.30
SASIA	11.7	1.3	0.9	0.1	13.9	0.288	0.032	0.021	0.002	0.34
CHINA	6.5	1.3	7.1	0.1	14.9	0.020	0.004	0.022	0.000	0.05
EASIA	2.3	4.3	2.9	0.1	9.6	0.016	0.030	0.021	0.001	0.07
LACA	4.3	7.7	5.1	0.2	17.3	0.022	0.039	0.025	0.001	0.09
INDIA	34.4	1.3	5.1	0.1	40.9	0.161	0.006	0.024	0.000	0.19

Table 4. Reactive protection costs at the calibration point (+2.5°C increase above pre-industrial levels, 2055)

	Cooling Expenditure (Billion $)	Disease Treatment Costs (Billion $)	TOTAL (Billion $)	Cooling Expenditure (% of GDP)	Disease Treatment Costs (% of GDP)	TOTAL (% of GDP)
USA	3.3	1.1	4.4	0.009	0.003	0.013
Western EU	-7.8	-0.7	-8.5	-0.025	-0.002	-0.028
Eastern EU	-0.5	-0.1	-0.6	-0.022	-0.003	-0.025
KOSAU	11.3	1.9	13.2	0.145	0.024	0.169
CAJAZ	-7.3	3.0	-4.3	-0.060	0.025	-0.035
TE	0.8	0.1	0.9	0.008	0.001	0.009
MENA	22.3	2.1	24.4	0.200	0.019	0.219
SSA	23.8	0.5	24.3	0.200	0.004	0.204
SASIA	10.3	0.2	10.5	0.255	0.004	0.259
CHINA	42.8	0.3	43.1	0.131	0.001	0.132
EASIA	35.7	4.7	40.4	0.255	0.034	0.289
LACA	1.9	5.7	7.6	0.009	0.029	0.038
INDIA	54.2	19.7	73.9	0.255	0.092	0.347

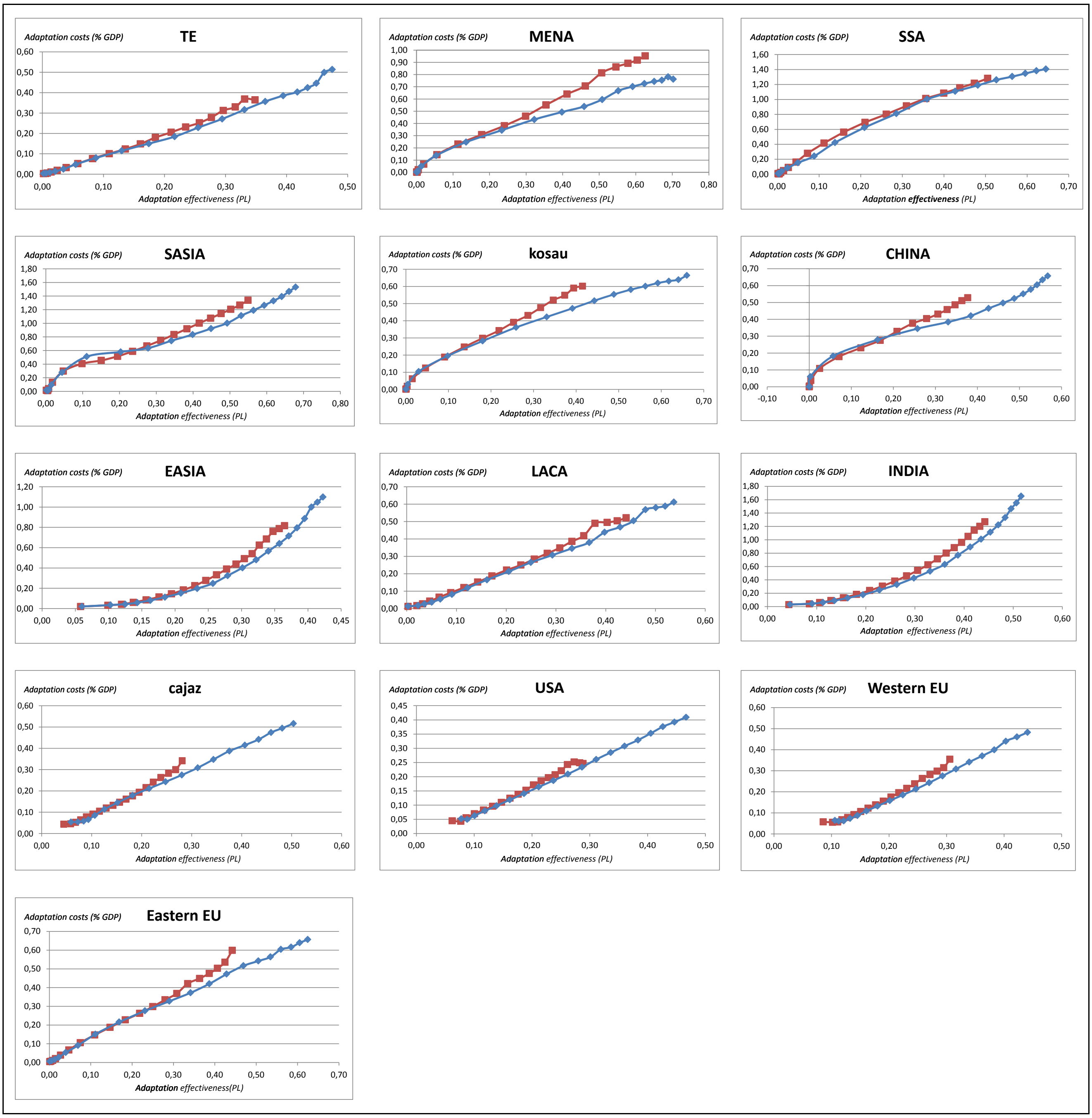
Table 5. Expenditure in specific adaptive capacity building at the calibration point (+2.5°C increase above pre-industrial levels, 2055)

	Expenditure in adaptation R&D (Billion $)	Early Warning Systems (Million $)	Empower women (bn $)	Address infrastructure deficit (bn $)	Total (bn $)	Expenditure in adaptation R&D (% of GDP)	Early Warning Systems (% of GDP)	Empower women (% of GDP)	Address infrastructure deficit (% of GDP)	Total (% GDP)
USA	3.2192	5.0000	0.0000	0.0000	3.2242	0.0093	0.000014	0.000000	0.000000	0.0093
Western EU	2.4189	5.0000	0.0000	0.0000	2.4239	0.0079	0.000016	0.000000	0.000000	0.0079
Eastern EU	0.0671	5.0000	0.0000	0.0000	0.0721	0.0027	0.000203	0.000000	0.000000	0.0029
KOSAU	0.3317	5.0000	0.0000	0.0000	0.3367	0.0043	0.000064	0.000000	0.000000	0.0043
CAJAZ	1.1092	5.0000	0.0000	0.0000	1.1142	0.0091	0.000041	0.000000	0.000000	0.0092
TE	0.0932	5.0000	0.0000	0.0000	0.0982	0.0009	0.000051	0.000000	0.000000	0.0010
MENA	0.1888	5.0000	0.0000	21.0980	21.2919	0.0017	0.000045	0.000000	0.189172	0.1909
SSA	0.0109	5.0000	2.2493	22.5427	24.8078	0.0001	0.000042	0.018876	0.189172	0.2082
SASIA	0.0099	5.0000	0.8216	7.6467	8.4833	0.0002	0.000124	0.020327	0.189172	0.2099
CHINA	0.2688	5.0000	0.0000	61.6905	61.9643	0.0008	0.000015	0.000000	0.189172	0.1900
EASIA	0.0383	5.0000	1.7163	26.4720	28.2315	0.0003	0.000036	0.012265	0.189172	0.2017
LACA	0.0734	5.0000	1.1794	37.7641	39.0219	0.0004	0.000025	0.005908	0.189172	0.1955
INDIA	0.0402	5.0000	4.3288	40.2860	44.6599	0.0002	0.000023	0.020327	0.189172	0.2097

Table 6. Protection level at the calibration point (+2.5°C increase above pre-industrial levels, 2055)

	Agriculture (irrigation) (%)	Coastal Protection (%)	Infrastructure (%)	Ecosystems (%)	Cooling Expenditure (%)	Disease Treatment Costs (%)	Expenditure in adaptation R&D (%)	Early Warning Systems (%)	Address infrastructure deficit (%)	Simple average	Weighted average (with damage share)	Weighted average (with protection costs)
USA	0.48	0.75	0.40	0.40	0.80	0.90	0.48	0.10	0.40	0.62	0.27	0.46
Western EU	0.43	0.54	0.40	0.40	0.80	0.90	0.43	0.10	0.40	0.57	0.30	0.49
Eastern EU	0.43	0.63	0.40	0.40	0.80	0.60	0.43	0.10	0.40	0.54	0.26	0.32
KOSAU	0.27	0.62	0.40	0.40	0.80	0.81	0.27	0.10	0.40	0.54	0.24	0.48
CAJAZ	0.38	0.37	0.40	0.40	0.80	0.69	0.38	0.10	0.40	0.52	0.25	0.54
TE	0.38	0.37	0.40	0.40	0.80	0.70	0.38	0.10	0.40	0.51	0.22	0.33
MENA	0.33	0.55	0.40	0.40	0.40	0.60	0.33	0.10	0.40	0.43	0.28	0.36
SSA	0.23	0.30	0.40	0.40	0.40	0.20	0.23	0.00	0.40	0.26	0.13	0.31
SASIA	0.33	0.47	0.40	0.40	0.40	0.35	0.33	0.00	0.40	0.35	0.26	0.33
CHINA	0.33	0.76	0.40	0.40	0.40	0.40	0.33	0.10	0.40	0.44	0.21	0.39
EASIA	0.33	0.25	0.40	0.40	0.40	0.36	0.33	0.01	0.40	0.31	0.25	0.36
LACA	0.38	0.46	0.40	0.40	0.40	0.80	0.38	0.00	0.40	0.45	0.22	0.41
INDIA	0.33	0.47	0.40	0.40	0.40	0.80	0.33	0.00	0.40	0.44	0.29	0.42

Figure 5. Regional adaptation cost and effectiveness curves in the WITCH model



Note: in red adaptation cost and effectiveness in SSP2, in blue that in SSP5. PL in figures stands for "protection level". Adaptation in SSP5 is more effective than in SS2 (the blue line is to the right of the red line), to capture the higher adaptive capacity characterizing the social economic system of SSP5.

2.1.5 Information on adaptation cost and effectiveness from BASE and further improvement

The calibration of the adaptation module currently implemented in WITCH is already an improvement compared to the original specification. It will be further developed including updated estimates of costs and effectiveness of adaptation in the EU related to the agricultural sector, flood risk and health. This last in particular, that in the current version of WITCH is based upon Tol (2001), would benefit from an update in the light of the more recent evidence. The necessary information to these improvements will be produced, in the form of cost and effectiveness for different temperature increase scenarios, respectively by the flood risk model of DELTARES, the crop model of UPM and the survey work on health conducted by BC3 and Exeter University.

Some preliminary data are already available for health, highlighting however the difficulty to derive an aggregated measure for cost and effectiveness of adaptation practices in that sector (for more on this refer to BASE D3.2).

Table 7 reports for instance an example of the kind of information currently being gathered by BASE partners that will be used as an input to adjust the calibration of the adaptation module in the WITCH model. They are (preliminary) estimates of cost and effectiveness of health-sector adaptation against gastro-enteric diseases in the EU. The idea is to collect similar information for a wider set of climate-related pathologies (particularly relevant will be cardio-vascular and respiratory diseases) and to gather a sufficient number of “couplets” cost and effectiveness to replace for EU regions the figures actually reported in the second column of Table 4 and the sixth column in Table 6. A similar procedure will be applied to the domains of extreme events and agriculture.

This would allow a different characterization of curves for Eastern and Western EU in Figure 5.

Table 7. Estimates of cost and effectiveness of adaptation against gastro-enteric disease in the EU

Region	Scenario	Temp. increase	Measures	Coverage of adapt.	COST mid (million US$ 2000)	COST high (million US$ 2000)	year
Western EU	stabilization at 550ppm CO2 equiv by 2170	+1 °C	children<5: immunization + improvement of water and sanitation services	100%	0,000	19,774	2030
	stabilization at 750ppm CO2 equiv by 2210	+1.2 °C	children<5: immunization + improvement of water and sanitation services	100%	0,000	22,368	2030
	unmitigated emission (IS92a)	+1.8°C	children<5: immunization + improvement of water and sanitation services	100%	0,000	39,439	2030
Eastern EU	stabilization at 550ppm CO2 equiv by 2170	+1 °C	children<5: immunization + improvement of water and sanitation services	100%	1,572	18,406	2030
	stabilization at 750ppm CO2 equiv by 2210	+1.2 °C	children<5: immunization + improvement of water and sanitation services	100%	1,827	22,666	2030
	unmitigated emission (IS92a)	+1.8 °C	children<5: immunization + improvement of water and sanitation services	100%	2,516	33,904	2030

Source: Elaboration from OECD (2009)

By the same token, the current calibration of adaptation can be also revised in the light of new information contained in the 2014 IPCC AR5, even though the majority of the data used in the WITCH adaptation module are already referring to post IPCC AR4 (2007) research. In a dedicated appendix to this deliverable a summary of the evidence on adaptation cost-effectiveness from IPCC AR5 is reported.

3 The IO model to upscale Urban adaptation

The ARIO input output model and its application within BASE have been extensively described in BASE D3.1 (Bosello et al. 2013), D3.2 (Iglesias et al. 2014) and D6.2 (Guan et al. 2014) therefore here its main features are just briefly summarized. The reader interested in further details is addressed to the cited documents.

Analysis of the urban economy is central to understanding the broad costs and benefits of climate change adaptation and is thus one of the focus of the BASE project. Assessments of the adaptation measures on cities have traditionally been based on on-site and local level cost-benefit analysis. Nonetheless, since economies are connected, either the costs or the benefits of implementing adaptation measures can be amplified, but also smoothed, throughout the wider economic systems (regional/ national/global).

The aims of applying an input-output modelling approach to study urban adaptation are thus to quantify cost-benefits of adaptation measures for case study cities from a macroeconomic perspective (this will be implemented in WP6) which means:

- estimate the cost and benefit of implementing local adaptation measures to the national economy,
- further estimate the cost and benefit of implementing local adaptation measures to the EU and other countries' economies.

Input-Output model presents the complex transactions in an economy in a transparent and simple way. It is grounded in the technological relations of production and provides a full accounting for all inputs into production, intermediate consumption and demand. Furthermore, it's fully capable of analyzing households and other institutions. Its characteristics make it well-suitable for risk analysis through the use of IO multipliers and to provide distributional analysis.[7]

Within the BASE project, the adaptive regional input-output model (ARIO) (preliminary version described in BASE D3.2, development and potential application in D6.2, final application in D6.3) is designed to explore the vulnerability of city economy to climatic change induced extreme events (i.e. flood / drought) and quantify the cost-benefit of adaptation measures implementation. The ARIO model will be adjusted for each case study cities according to the features of the city and nature of extreme events that can potentially affect it.

The following model building steps are currently being undertaken:

- Review of cost-benefit analysis definition in climate change adaptation context.

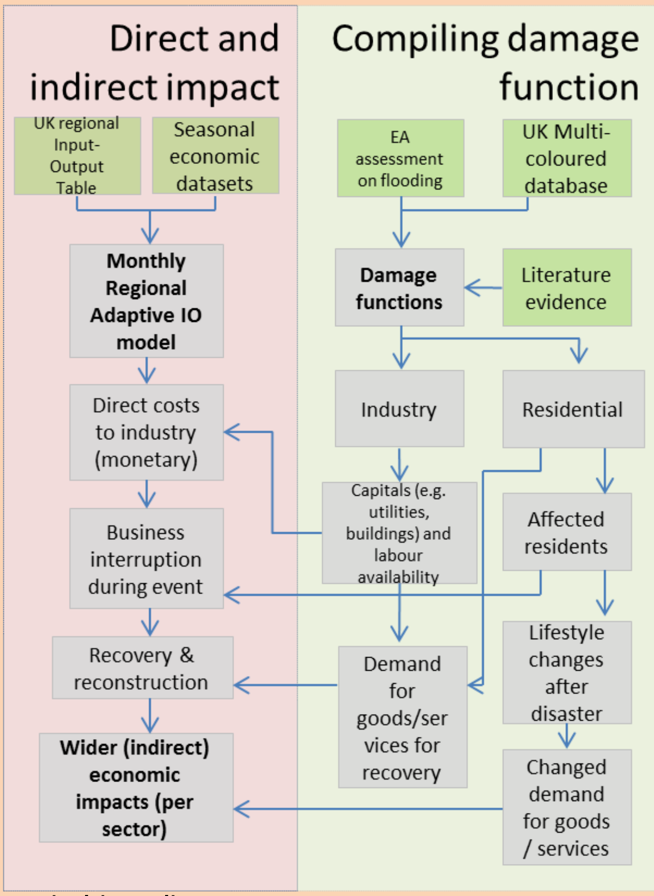
[7] For all these characteristics, IO models and extensions have been widely used in impact analysis (see e.g. Li et al., 2013; Okuyama, 2007; Rose, 2004) and specifically to the assessment of the economic impact of a natural disasters. For criticisms to and limits of I/O approach please refer to BASE D3.1 and D3.2.

- Quantification of direct cost and benefit of adaptation measures. Here:
    - Marginal abatement cost analysis evaluates the cost of any adaptation measures
    - Event Accounting Matrix (EAM) will be developed to specify initial damage of potential extreme events to case study cities without adaptation measures. The EAM consists of a set of damage functions at the scale of case study regions including direct damages and business interruption. Information on recovery costs after damaging events will be compiled. The physical damage can be seen as 'direct benefits' of adaptation measures.
- Measurement of indirect cost and benefit:
    - Estimate economic cost/benefit triggered by investments in constructing adaptation infrastructures and other spending
- Quantification of indirect cost/benefit by integrating EAM (damage functions) into the ARIO models. Such cascading impacts can be seen as 'indirect benefit' of adaptation measures. The cascading impacts can be measured at city/national/global (e.g. EU) levels.

A concrete example of how different shocks for the urban economic systems can be implemented into the modelling structure of ARIO is reported in D3.2 (Iglesias et al. 2014) and mathematical extensions are reported in D6.2 (Guan et al. 2014). Figure 6 exemplifies graphically the procedure that will be followed to upscale urban damages at the wider national and EU level.

Figure 6. Exemplifying the link between climate damage functions to study direct and indirect economic impact of extreme events (2007 UK national floods).

The key dataset for compiling the damage functions are from the Environmental Agency (EA) reports on 2007 flooding (e.g. report entitled by "cost of 2007 floods"); the EA funded handbook of "The benefits of flood and coastal risk management – A handbook of assessment techniques" (so-called Multi-coloured manual); and evidence from the literature.



The damage function would have three outputs:

- Industry capital loss – including infrastructure damage, building and production capital loss.
- Labour productivity and availability during and after the event.
- Residential capital loss – including houses and household appliances.
- Affected population – death and hospital visits and admission.

In order to estimate the direct and indirect impact to wider economic systems, a monthly regional adaptive input-output model is constructed. The data required are the UK regional input-output model and seasonal national / regional accounts data.

The outputs from the damage function will feed into the regional input-output model to estimate the direct economic costs in 40+ production sector details, business interruptions due to capital and labour loss, and finally the cascading effects via economic supply chains to the disaster region and beyond (e.g. national or EU scale).

As clearly emerges, two levels of data are required to upscale the benefit of adaptation: data for the evaluation of direct disaster effects, and data for evaluation of indirect effects (for the complete input requirement description refer to D3.1 (Bosello et al. 2013)).

The evaluation of direct physical damages will form the event damage function, which will act as input to estimate the cascaded effects throughout the national and international supply chain. For each climate extreme (floods or drought) various physical, economic and social direct effects will be quantified.

The evaluation of indirect effects is necessary for the construction of the modelling tools themselves including IO tables. These can be updated building upon previous efforts like that of the FP7 EXIOBASE project providing data for 200 commodities and 164 sectors, and data on inter-regional transport and trade flows from the ETIS-Plus project, integrated with regional level data from SBS of EuroStat.

4 Conclusions

This report describes the improvement and application of the two top-down models that are used within the BASE project for the macro-economic assessment of adaptation in the EU.

The first is the WITCH hard-linked, dynamic optimization integrated assessment model. It will be used to analyze adaptation in both a cost effectiveness and cost efficiency framework and to highlight potential complementarity and trade off with mitigation. The original version of the model has been improved along different lines: its baseline has been recalibrated in order to replicate SSP2 and SSP5 scenarios chosen as reference by the BASE consortium; part of its climate change damage function has been revised incorporating more recent scientific evidence; its adaptation module presents a new functional form and include an improved calibration of costs and effectiveness of different adaptation types. The calibration of adaptation in the EU will be further improved incorporating information produced by BASE partners related to the domains of health, agriculture and floods.

The second is the ARIO I/O model. It is a designed adaptive regional input-output model that will be applied to explore the vulnerability of city economy to climatic change induced extreme events (i.e. flood / drought) and quantify the cost-benefit of adaptation measures implementation. Developing this I/O analysis with ARIO requires: adjustment of the model to each case study cities according to the features of the city and nature of extreme events that can potentially affect it, upscale the results at the national level linking the city scale ARIO models with national input-output tables to track how local effects spread to the national economy. A further up-scaling process will be potentially explored: that of linking the national scale ARIO model with the World Input-Output Database (WIOD) to estimate the cost and benefit of implementing local adaptation measures to the EU and other countries' economies.

These two top-down models are meant to complement the sectoral assessments performed within the BASE project. In WITCH the link with the sectoral studies is provided by the model adaptation. Indeed its calibration, especially that pertaining to costs and benefit of adaptation in the health sector, agricultural sector and against floods in the EU, will be derived respectively from the analysis developed by BC3 and Exeter University, from the UPM ClimateCrop model and from the DELTARES flood risk model. Policy indications from WITCH will be thus grounded on quantitative evidence produced by bottom-up models. The ARIO model will interface directly with urban case studies developed by the BASE consortium. Finally, it is worth mentioning that this work will be further refined under WP6 which aims, among other, to perform the analysis of adaptation properly synthesizing the output of WP3, WP4 and WP5 especially in Task 6.3 to derive a EU-level picture of challenges and opportunity for adaptation. There, the different insights from case studies, sectoral models and also from WITCH and ARIO will be compared and when possible cross-validated to offer a comprehensive and consistent analysis.

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Appendix 1: The adaptation module in the WITCH model

This section reports extensively the equations of the damage and adaptation modules in the WITCH model.

Production function

Equation A1 reports the net production function of WITCH, analogous to Equation (1) in the text, but explicating at the numerator potential output which is a CES composition of capital, labour and energy. Total-factor and factor-specific productivity parameters account for technical progress.

$$Y(t,n)=\frac{tfp0\left[\alpha(n)\left(\left(tfp_y(t,n)K_C(t,n)^{\beta}L(t,n)^{1-\beta}\right)^{\rho}+(1-\alpha(n))ES(t,n)^{\rho}\right)^{\frac{1}{\rho}}\right]}{\Omega(t,n)} \quad (A1)$$

Damage function

The main characteristic of the damage/adaptation module is to split damages into a positive and negative component, see Eq.(A2). Adaptation has the role of reducing negative impacts while it is implicitly assumed that it does not contribute to enhance positive impacts.

$$\Omega(t,n)=1+\frac{\left[\omega_{1,neg(n)}T(t)+\omega_{2,neg(n)}T(t)^{\omega_{3,neg(n)}}\right]}{1+Q(ADA,t,n)^{\varepsilon(n)}}+\omega_{1,pos(n)}T(t)+\omega_{2,pos(n)}T(t)^{\omega_{3,pos(n)}} \quad (A2)$$

Adaptation is on its turn specified by a sequence of nested CES aggregates.

The adaptation nest between adaptation measures ("activities" – Q(ACT,t,n)) and adaptive capacity building Q(CAP,t,n) is described by Eq. (A3).

$$Q(ADA,t,n)=\omega_{eff(n)}^{ADA(n)}\left(\omega_{act(n)}Q(ACT,t,n)^{\rho_{ADA}}+(1-\omega_{act(n)})Q(CAP,t,n)^{\rho_{ADA}}\right)^{\frac{1}{\rho_{ADA}}} \quad (A3)$$

The adaptation nest between reactive adaptation expenditure I(RADA,t,n) and proactive adaptation measures K(PRADA,t,n) is described by Eq. (A4).

$$Q(ACT,t,n)=\omega_{eff(n)}^{ACT(n)}\left(\omega_{rada(n)}I(RADA,t,n)^{\rho_{ACT}}+(1-\omega_{rada(n)})K(PRADA,t,n)^{\rho_{ACT}}\right)^{\frac{1}{\rho_{ACT}}} \quad (A4)$$

The adaptation nest between generic adaptive capacity Q(GCAP,t,n) and specific adaptive capacity K(SCAP,t,n) is described by Eq. (A5).

$$Q(CAP,t,n) = \left(\omega_{gcap(n)} Q(GCAP,t,n)^{\rho_{GCAP}} + (1-\omega_{gcap(n)}) K(SCAP,t,n)^{\rho_{GCAP}}\right)^{\frac{1}{\rho_{GCAP}}} \quad \text{(A5)}$$

Generic capacity is defined in Eq. (A6). It is specified as an exogenous trend growing at the same pace of total factor productivity, tfpy(t,n). Its initial level is given by the 2005 average stock of knowledge K(R&D,t,n) and human capital K(EDU,t,n).

$$Q(GCAP,t,n) = \frac{K(R\&D,t,n)+K(EDU,t,n)}{2} tfp_y(t,n) \quad \text{(A6)}$$

Specific adaptive capacity and proactive adaptation are modelled as “stocks” of “knowledge/defensive” capitals that accumulate over time following dedicated investments in each period according to the standard perpetual accumulation rules of capital reported respectively by Eq. (A7) and (A8).

$$K(SCAP,t,n) = K(SCAP,t-1,n)(1-\delta_{SCAP}) + I(SCAP,t,n) \quad \text{(A7)}$$

$$K(PRADA,t,n) = K(PRADA,t-1,n)(1-\delta_{PRADA}) + I(PRADA,t,n) \quad \text{(A8)}$$

Adaptation investments and expenditure finally enter the regional budget constraint (A9).

$$Y(t,n) = C(t,n) + I_C(t,n) + I(PRADA,t,n) + I(SCAP,t,n) + I(RADA,t,n) + I_{GRID}(t,n) + \sum_j (I_{R\&D_j}(t,n) + +I_j(t,n) + OM_j(t,n)) + \sum_j (I_{OUT,f}(t,n) + OM_{OUT,f}(t,n)) + + \sum_f C_f(t,n) + \sum_j C_j(t,n) + \sum_e C_e(t,n) + \sum_{ghg} C_{ghg}(t,n) \quad \text{(A9)}$$

Table A1.1 Variables' definitions

	Definition	Unit
$C(t,n)$	Consumption	Trillon $
$I_C(t,n)$	Investment in final good	Trillon $
$I_j(t,n)$	Investment in energy tech.	Trillon $
$I_{GRID}(t,n)$	Investment in electric grid	Trillon $
$I_{OUT,f}(t,n)$	Investment in extraction	Trillon $
$I_{R\&D_j}(t,n)$	Investment in R\	Trillon $
$OM_j(t,n)$	O&M costs in energy tech.	
$OM_{OUT,f}(t,n)$	O&M costs in extraction	
$Y(t,n) - I_C$	Net Output	Trillon $
$tfp0$	Initial level of TFP	unitless
$C_e(t,n)$	GHG emissions costs	Trillon $
$C_f(t,n)$	Net cost of Primary Energy Supplies	Trillon $
$C_j(t,n)$	Energy technology penalty costs	Trillon $
$C_{oghg}(t,n)$	Carbon tax	Trillon $
$ES(t,n)$	Energy services	Trillon $
$K_C(t,n)$	Capital in final good	Trillon $
$Q_E(ghg,t,n)$	Emissions	Gt-eqC
$tfp_y(t,n)$	Total factor productivity	unitless
$L(t,n)$	Population	Million people
$I(PRADA,t,n)$	Investment proactive adaptation	Trillon $
$I(RADA,t,n)$	Investment reactive adaptation	Trillon $
$I(SCAP,t,n)$	Investment specific capacity	Trillon $
$K(PRADA,t,n)$	Capital in proactive adaptation	Trillon $
$K(SCAP,t,n)$	Capital in specific capacity	Trillon $
δ_{SCAP}	Proactive adaptation capital depreciation rate	
δ_{PRADA}	Proactive adaptation capital depreciation rate	

Appendix 2: Cost and effectiveness of adaptation in the IPCC AR5

This Appendix reviews the 2015 IPCC AR5 (Working Group II) to offer an overview of the most recent estimates of costs and benefits of adaptation. Such analyses are quite heterogeneous in terms of methodology used and -sectors analyzed, nonetheless we can group them into two broad categories: global/regional and sectoral estimates. The former can provide a full assessment of the costs of adaptation for one country/region, while the latter mainly focuses on specific more vulnerable sectors/domains. Especially the second aims to inform policy makers on how allocate resources more efficiently.

The fifth IPCC report WGII devotes chapter 17 of Volume I to the “Economics of Adaptation”, focusing on the “Costing of adaptation” in paragraph 17.4 with a global perspective. Volume II, where regional aspects are explored, contains useful information on regional and local-scale estimates. Europe has a specific section dedicated to “Cross-Sectoral Adaptation Decision-making and Risk Management” where paragraph 23.7.6, “Economic Assessments of Adaptation”, explicitly provides a comparison of recent adaptation assessments for Europe.

Looking at global scale estimates, still a limited number of adaptation cost assessments has been produced namely: World Bank (2006); Stern (2006); Oxfam (2007); (UNDP) 2007; UNFCCC (2007); World Bank (2010). The variability of these cost estimates is considerable (see Table A2.1) —and the focus is mainly on developing countries.

From a methodological point of view, following Fankhauser (2009, 2010), we can characterize first-generation studies (i.e. World Bank, 2006; Stern, 2006; Oxfam, 2007; UNDP 2007) and second-generation studies (NFCCC, 2007; World Bank, 2010). First-generation studies start from estimates of financial flows as foreign direct investments (FDI), gross domestic investments (GDI) and Official Development Assistance (ODA) and add a mark-up derived from the costs of “climate-proofing” those investments. Second-generation studies use a bottom-up approach and consider impacts of climate change in different sectors. UNFCCC (2007) and World Bank (2010) derive the additional investment in adaptation comparing investments in a scenario with current climate (baseline scenario) to one or more scenarios where future climate is projected. The IPCC report points out that, compared to UNFCC (2007), the World Bank (2010) study has more detailed information, provides marginal cost curves and climate stressor-response functions for adaptation actions and included maintenance and coastal port upgrading costs.

Indications from these studies have been already used for the calibration of the adaptation module in WITCH.

A shortcoming of the studies mentioned is the aggregated level of information and their specific focus on developing countries. According to IPCC AR5, a full assessment of adaptation costs for Europe is still not available. There are several analyses from bottom-up and sector-specific studies but the evidence base is still fragmented and incomplete. As the IPCC has noted “the coverage of adaptation costs and benefit estimates is dominated by structural (physical) protection measures, where effectiveness and cost components can be more easily identified. For energy, agriculture, infrastructure there is medium coverage of cost and benefit categories. There is a lack of information regarding adaptation costs in the health and social care sector” (IPCC AR5 2014, WGIII CH. 22, pp.32-33).

Against this background the work currently developed within BASE with the WITCH model is particularly valuable.

Table A2.2 summarises some of the more comprehensive cost estimates for Europe for sectors at regional and national level.

Table A2.1 – Recent analyses on the costs of adaptation

	Results billion USD/year	Time frame	Sectors	Methodology and comment
World Bank, 2006	9-41	Present	Unspecified	Cost of climate proofing foreign direct investments (FDI), gross domestic investments (GDI) and Official Development Assistance (ODA)
Stern, 2007	4-37	Present	Unspecified	Update of World Bank (2006)
Oxfam, 2007	> 50	Present	Unspecified	WB (2006) plus extrapolation of cost estimates from national adaptation plans (NAPAs) and NGO projects.
UNDP, 2007	86-109	2015	Unspecified	WB (2006) plus costing of targets for adapting poverty reduction programs and strengthening disaster response systems
UNFCCC, 2007	28-67	2030	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure	Planned investment and Financial Flows required for the international community
World Bank, 2010	70-100	2050	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure; extreme events	Improvement upon UNFCCC (2007): more precise unit cost, inclusion of cost of maintenance and port upgrading, risks from sea-level rise and storm surges.

Source: IPCC (AR5), WGII Ch. 17

Table A2.2 – Recent analyses on the costs of adaptation

Region	Results billion USD/year	Time frame	Sectors	Reference
Europe	€2.6-3.5 billion/a	In 2100	Coastal adaptation costs	Hinkel et al. 2010
Europe	€1.7 billion/a €3.4 billion/a €7.9 billion/a	By 2020s By 2050s By 2080s	Protection from river flood risk for EU27	Rojas et al., 2013
Netherlands	€1.2–1.6 billion/a €0.9–1.5 billion/a	Up to 2050 2050-2100	Protection from coastal and river flooding	Delta Committee, 2008
Sweden	total of up to €10 billion	2015	Multisector	Swedish Commission on Climate and Vulnerability, 2007
Italy	€0.4-2 billion Up to € 44 billion	By 2080s	Coastal protection Hydrogeological protection	Bosello et al. 2012 Medri et al. 2013
Greece	€0.4-3.3 billion	Up to 2100	Coastal protection	Bank of Greece, 2011
UK	€1.8 billion €2.2 billion €7.8 billion	Until 2035 2035-2050 At 2100	Maintain and improve Thames flood protection Renew and improve Thames flood protection New Thames barrier for London	EA, 2011

Source: IPCC (AR5), WGII, Ch. 23