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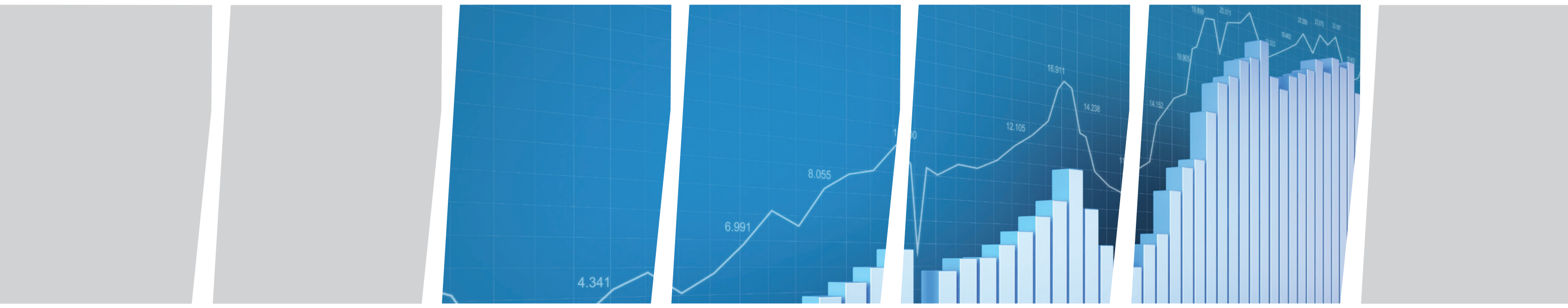

The costs of climate-change adaptation in Europe: a review

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Abstract

Climate change is expected to have significant impacts on Europe that will affect its economic sectors and the distribution of economic activity. While some of those climate-change impacts can be alleviated by mitigation action, some degree of climate change cannot be avoided anymore. This makes adaptation an essential component in addressing the impacts from climate change in the future. The purpose of this review is to compare recent estimates based on their adaptation perspective. This entails a detailed review of the methodologies used, but also of the definition of adaptation adopted. This review investigates those issues with a specific regional focus on Europe.

At present, no study has explicitly and comprehensively estimated the overall costs of adapting Europe to climate change. Available are adaptation-cost estimates for industrialized countries in general, climate-change impact assessments for Europe, as well as several adaptation-cost or climate impact studies on the sector level. For industrialized countries, adaptation-investment needs are estimated to be USD 22-105 billion per year by 2030 (USD 16 billion without the construction sector). For Europe, climate-proofing new infrastructure is estimated to cost EUR 4.6-58 billion; and the economic impact of experiencing 2080s climate change today is valued at EUR 22-67 billion. In comparison, total investments in the EU are about two orders of magnitude larger (EUR 2.6 trillion in 2008).

While those aggregate numbers seem to indicate adaptation costs in the tens of billion EUR for Europe, they have to be seen as highly indicative. First-generational top-down studies, e.g. on the construction sector, lack empirical grounding; and the aggregation routine of second-generational bottom-up studies can hide significant differences in the sector studies included. Those differences concern methodology, coverage of climatic impacts and adaptation options. Although sector estimates provide a clearer picture of the impacts of climate change on Europe, the investment needs to adapt to those impacts are largely unknown. For most sectors, those investment needs can, at present, only be determined robustly on the project level.

JEL classification: H54, Q54, Q56, G58, R11

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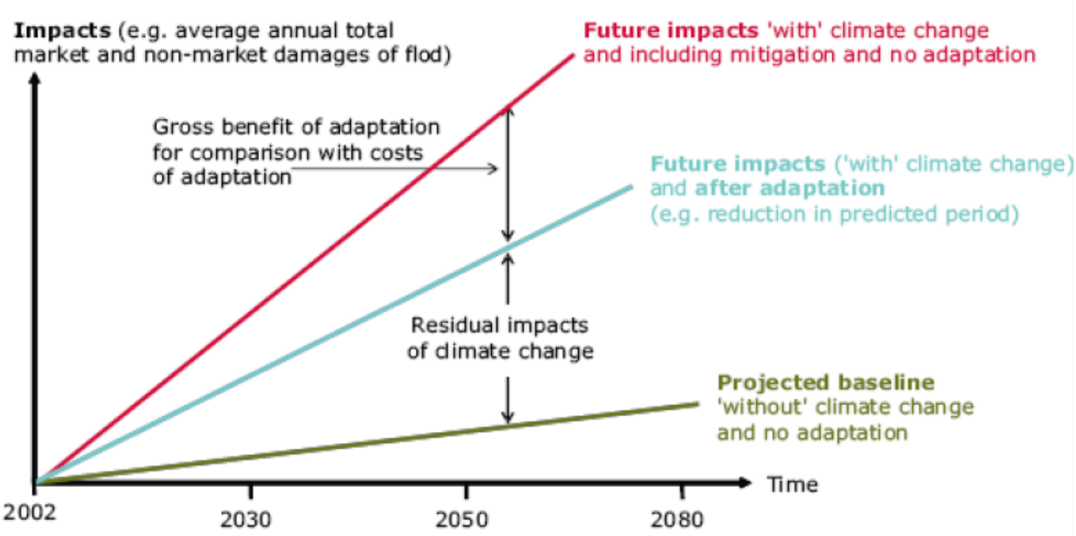
1. Introduction

Climate change is expected to have significant impacts on Europe that will affect its economic sectors and the distribution of economic activity (Alcamo et al., 2007). Agriculture will have to cope with increasing water demand for irrigation, in particular in southern Europe. Winter heating demands are expected to decrease and summer cooling demands to increase. As a result, peak electricity demand is likely to shift from winter to summer in some locations. Tourism is likely to change, e.g. from summer to spring or autumn in the Mediterranean. In addition, climate-related hazards, such as coastal flooding, will mostly increase and will therefore pose a general threat to people and infrastructure.

While some of those climate-change impacts can be alleviated by mitigation action, some degree of climate change cannot be avoided anymore. This makes adaptation an essential component in addressing the impacts from climate change in the future. According to the Intergovernmental Panel on Climate Change (IPCC), adaptation is understood as any adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2001, Chapter 18).

Figure 1. Costs and benefits of adaptation



Source: Boyd and Hunt (2006); see also Stern Review (2007) and EC (2009b).

Assessing the costs of adaptation can contribute to identifying and prioritizing investment needs among projects, sectors, but also among countries and regions. For this purpose it is instructive to consider adaptation in a cost-benefit framework. Therein, adaptation reduces the negative impacts of climate change as long as the costs of adaptation are less than the costs of climate damages that would occur. Some residual damage occurs, either when the costs of adaptation exceed the costs of climate damages avoided (so that it would be more economical to endure those impacts of climate change), or when full adaption is practically infeasible. The total cost of climate change includes therefore both the cost of adaptation and the cost of residual damages (Figure 1).

An important issue from a policy perspective is the incidence of adaptation costs. The IPCC (2001) differentiates between autonomous and planned adaptation (see also Smith et al., 1996). Autonomous adaptation describes actions taken by private actors, such as individuals, households and firms in response to actual or expected climate change. Planned adaptation describes actions that are associated with public agencies, either through public investment or through the drafting of public policies – the Stern Review (2007) uses the term policy-driven adaptation instead of planned adaptation. There are, of course, interlinkages between autonomous and policy-driven adaptation. For example, one goal of public policies and therefore policy-driven adaptation is to create the right framework for autonomous adaptation to take place. Further differentiations along the time dimension, e.g. between reactive and anticipatory planned adaptation, and along regional dimensions are possible (see IPCC, 2001, Chapter 18).

Given the many differentiations of adaptation, it is not surprising that adaptation-cost estimates are crucially influenced by the specific adaptation focus adopted. The purpose of this review is to compare recent estimates based on their adaptation perspective. This entails a detailed review of the methodologies used, but also of the definition of adaptation adopted. The questions that are guiding the review are the following:

- What are the assumptions underlying recent adaptation-cost estimates?
- What are the methodologies applied?
- How much of adaptation investment is supposed to be public and how much private?
- Are residual damages estimated?
- What are the sectors with the highest adaptation-investment needs, i.e. the most vulnerable to climate change?
- How do adaptation costs relate to overall investments in a given sector?

This review investigates those questions with a specific regional focus on Europe. While there has been strong political interest in estimating adaptation costs for developing countries (see e.g. World Bank, 2006, 2010; UNFCCC, 2007), especially in the context of international negotiations on climate change, the political context in European and industrialized countries is such that specific adaptation policies are already in the making for several sectors (see e.g. the EC White Paper, 2009a, and the review by Gagnon-Lebrun and Agrawala, 2006). Therefore comparably more information is available about adapting those regions or specific sectors within those regions to climate change. Focussing on the European context also leaves aside the issue of development deficits and their feedbacks on adaptation in developing countries (see e.g. Burton, 2004). Thus, adopting a European focus allows for a concentrated analysis of investment needs solely into adaptation.

This review is structured as follows. Section 2 gives an overview of current adaptation-cost estimates and provides a categorization of methodologies based on the depth of analysis. It then highlights specific adaptation-cost estimates provided for Europe, or industrialized countries in general, and discusses the estimates' strengths and weaknesses. This discussion is focussed on the aggregated regional level. Section 3 adopts a more detailed focus and concentrates on specific sectoral studies that make up the aggregate estimates discussed in Section 2 or that are provided as stand-alone studies. Section 3 thereby aims at highlighting the differing complexity of analysis across sectors, but also at providing an in-depth investigation of the methodologies used in each study and sector. Section 4 offers a brief summary and concludes.

2. Overview of adaptation-cost estimates and methodologies

2.1. General overview

The recent years have seen a proliferation of global and multi-regional adaptation-cost estimates and studies intended to inform spending on adaptation. Those include the "Investment Framework for Clean Energy and Development" of the World Bank (2006), the Stern Review (2007); reports by Oxfam (2007), the UNDP (2007), and Project Catalyst (2009); more detailed assessments by the UNFCCC (2007), Parry et al. (2009), and the World Bank (2010); as well as the PESETA (Ciscar et al., 2009) study.

Those studies can be differentiated along various dimensions which are highlighted in Table 1. With respect to coverage, many of the studies cited above focus on estimating adaptation costs for developing countries (World Bank, 2006, 2010; Oxfam, 2007; UNDP, 2007; Project Catalyst, 2009); the PESETA (2009) study focuses on climate change impacts in Europe; and the Stern Review (2007) and the UNFCCC (2007) report (and its commentary by Parry et al., 2009) attempt a global assessment differentiating between developing and developed countries.

There are also big differences with respect to the methodological approach followed. Fankhauser (2009, 2010) divides adaptation-cost studies into first-generation and second-generation estimates. First-generation estimates follow a top-down methodology, primarily based on the method used by the World Bank (2006). Therein, current financial flows, such as official development aid, foreign direct investment, and gross domestic investment, are estimated and a mark-up is applied which is based on their assumed climate sensitivity and costs of climate-proofing those investments. The Stern Review (2007) and the reports by Oxfam (2007), UNDP (2007), Project Catalyst (2009), and UNFCCC's (2007) estimate for the infrastructure sector all follow this approach and add several modification and extensions, such as different mark-ups or baseline estimates.

Due to their lack of empirical grounding, first-generation estimates are best described (also by the respective authors) as ballpark estimates or guesstimates. Agrawala et al. (2008) and Fankhauser (2009, 2010) provide a detailed review of first-generation estimates in which they highlight their inter-dependency and the sensitivity of results to the assumptions made regarding the percentage shares of climate-sensitive investment flows and costs to climate-proof those shares. They note that the estimates obtained can quickly escalate given the large baseline to which the mark-up percentage assumptions are applied. Agrawala et al. (2008) and Fankhauser (2009, 2010) further point to the lack of empirical grounding of those assumptions, and the lack of representation of specific adaptation activities in those top-down estimates. As first-generation estimates are based on current financial flows, mostly to developing countries, they can only inform the short-term adaptation needs for that part of the world.

Table 1. Methodological differences between multi-regional adaptation-cost and climate-impact studies.

Study	Regional coverage	Methodology	Target year	Adaptation considered
First-generation estimates				
World Bank (2006)	developing countries	top-down	current	climate-proofing of investments
Stern Review (2007)	global	top-down	current	climate-proofing of investments
Oxfam (2007)	developing countries	top-down plus project-based	current	climate-proofing of investments plus adaptation plans
UNDP (2007)	developing countries	top-down	current	climate-proofing of investments plus poverty reduction
Project Catalyst (2009)	developing countries	top-down	current	climate-proofing of investments plus soft-adaptation strategies
Second-generation estimates				
UNFCCC (2007)	global	bottom-up (5 sectors)	2030	private and planned adaptation
PESETA (2009)	Europe	bottom-up (5 sectors)	2020s, 2080s	private/autonomous adaptation
World Bank (2010)	developing countries	bottom-up (8 sectors)	2050	private and planned adaptation

Second-generation estimates follow a bottom-up methodology that takes into account responses to climate-change impacts in several sectors. Studies such as those undertaken by the UNFCCC (2007) and the World Bank (2010) derive the additional investment due to climate change by comparing the investment under a scenario based on the current climate with investment under a scenario based on one or more projected future climate scenarios. Second-generation estimates can therefore be differentiated further with respect to the climate scenarios used, the time horizon, the socio-economic development pathway considered, as well as the explicit representation of adaptation options and even with respect to the definition of adaptation used – see EEA (2007, Chapter 3) for a detailed discussion on general methodologies. Due to their bottom-up methodology, second-generation studies generally combine sector assessments which have varying degrees of complexity and empirical grounding. Aggregating different sector estimates can therefore conceal uncertainties on the sector level and suggest false robustness.

2.2. Adaptation-cost estimates for Europe

At present, no study has explicitly and comprehensively estimated the overall costs of adapting Europe to climate change. What is available however are adaptation-cost estimates for developed countries in general (Stern Review, 2007; UNFCCC, 2007), sometimes with specific sector estimates for Europe. Also several sector-focussed adaptation-cost estimates exist (e.g. Richards and Nicholls, 2009). However, aggregating different sector estimates or multiple studies is complicated by various methodological differences as noted above. No full adaptation-cost estimate can therefore be provided for Europe at the moment (as of 2011).

Despite this, some detailed impact assessments exist. A recent bottom-up assessment commissioned by the EU, the PESETA (2009) study, contains detailed economic estimates of the impacts of climate change on Europe. Those estimates do not constitute a consistent estimate of adaptation costs, as the representation of adaptation options differs by sector, is in general limited to private/autonomous adaptation, and not always costed. The PESETA (2009) results have therefore limited relevance for informing concrete adaptation-investment needs. However, they may give indications for informing the overall economic impacts of climate change on Europe, i.e. of the costs of adaptation plus residual damages (see Section 1). This can provide both an upper bound to adaptation costs, as well as an identification of sectors most vulnerable to climate change.

The following contains an overview of the adaptation-cost and economic-impact assessments produced for industrialized countries, and in particular for Europe. The studies reviewed include the Stern Review (2007) and related first-generation estimates; the UNFCCC (2007) study on “Investment and Financial Flows to Address Climate Change”, as well as the PESETA (2009) study which represents a "Projection of the Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis".

First-generation estimates for Europe

First-generation adaptation cost estimates for developed countries are available from Simms et al. (2004), the Stern Review (2007), and the European Commission (2009b). Those studies are primarily concerned with estimating adaptation costs for the construction sector, i.e. for climate-proofing new buildings and infrastructure. Adaptation-relevant portions of the construction sector include water and coastal infrastructure, such as flood protection and coastal defences to adapt to sea-level rise and more intense coastal storms, but also infrastructure for water supply management, water quality treatment, hydropower production, as well as infrastructure used for heating and cooling purposes.[1]

Andrew Simms and colleagues from the New Economics Foundation (NEF) produced, with the support of Greenpeace, one of the first reports investigating

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[1] In second-generation estimates those contributions are spread over several sectors.

the costs of adapting to climate change for industrialised countries. In particular, Simms et al. (2004) assessed current and prospective spending in climate-sensitive areas. For the built environment (buildings and construction), Simms et al. (2004) adopt an estimate for the UK that the costs for climate proofing new buildings could amount to 1-5% of current buildings costs (ERM, 2000). The authors further assume that this percentage-cost share is broadly representative of other OECD countries and then calculate, based on annual investment flows into construction for the years 2001-2003, that USD 15-74 billion per year could be needed to adapt new buildings in industrialised countries to climate change; of that, USD 6-28 billion per year could be needed in the EU.

The Stern Review (2007) adopts the approach followed by Simms et al. (2004) but increases the percentage-cost share needed to adapt new buildings and infrastructure to climate change from 1-5% to 1-10% of current spending on construction. The review states that a percentage cost of 10% is possible, particularly with the prospect of higher temperatures in the future. The Stern Review (2007) also contrasts this percentage-cost for industrialised countries with the World Bank (2006) methodology of assuming a 10-20% mark-up for climate-proofing development investments. As a consequence of assuming a higher percentage cost, the adaptation-cost estimate for industrialised countries in the Stern Review (2007) increases from USD 15-74 billion per year to USD 15-150 billion per year and the EU share from USD 6-28 billion per year to USD 6-60 billion per year.

The European Commission’s (2009b) “Impact Assessment (IA) accompanying the White Paper on Adapting to Climate Change” applies the same methodology followed by Simms et al. (2004) and the Stern Review (2007). The IA presents two estimates. For the first estimate it is assumed that the costs of adapting new buildings and infrastructure to climate change represent 0.05-0.5% of GDP, a value calculated in the Stern Review (2007) which is based on GDP expenditure on construction for the years 2001-2003 as reported by Simms et al. (2004) and in turn based on ERM (2000). This yields an estimate of EUR 5.8-58 billion per year using the EU27-GDP of 2006. The IA states that alternatively it was assumed that Europe invests 20% in fixed capital of which one quarter is used for construction and that 1-10% of this amount is needed to make new buildings and infrastructure more resilient to climate. Multiplying out the percentages results in the same GDP percentages as reported above (0.05-0.5%); however, the IA reports an estimate of EUR 4.6-46.4 billion per year, which is significantly different than the estimate of EUR 5.8-58 billion reported earlier.[2] Either way, the addition to Simms et al. (2004) and the Stern Review (2007) is the use of GDP values for 2006 (to obtain the first estimate) instead of values from the years 2001-2003 (although the applied percentage-shares were estimated with the GDP values from those years).

The IA notes that the lower values could be representative of an earlier time period, e.g. the 2030s, while the higher ones could represent adaptation costs in 2100 in a scenario without successful mitigation. However, it should be noted

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[2] The difference could be explained by computational errors or by using different (older) GDP values; for example, using the GDP values of 2003 as in Simms et al. (2004) and converting them from USD to EUR (with a exchange rate of 1.26 EUR/USD) yields the range of EUR 4.6-46.6 billion per year as reported above.

that the methodology followed does not include any reference to a future time dimension, since costs are calculated as percentages of current expenditures without reference to any concrete climate scenarios or time horizon.

In summary, the first-generation adaptation-cost estimates for the EU indicate that about EUR 4.6-58 billion could be needed to adapt new buildings and infrastructure in the EU to climate change (see Table 2). This result has a large range, which complicates any definite quantitative conclusion on potential investment needs. The result is also subject to several methodological limitations which apply to the broader group of first-generation cost estimates as mentioned above, i.e. sensitivity to percentage-cost assumptions, lack of empirical grounding, no representation of explicit adaptation options and sectors other than construction, no information on residual damages or cost of adapting existing buildings and infrastructure to climate change, no integration of climate or development projections, no consideration of the time dimension, and no account of policy or other feedbacks, such as potential mitigation action. In that light, the results presented by Simms et al. (2004) and slightly modified by the Stern Review (2007) and the European Commission's IA (2009b) can only be seen as educated guesses. More in-depth assessments have to be conducted before such aggregate numbers can be used for public-policy or investment purposes.

Table 2. First-generation adaptation cost estimates for Europe. Sectoral coverage is limited to the construction sector; no explicit time horizon is considered.

Study	Adaptation-cost estimate	Comment
Simms et al. (2004)	USD 6-28 billion per year	Assumes 1-5% of current buildings costs is needed to climate proof new infrastructure.
Stern Review (2007)	USD 6-60 billion per year	Assumes 1-10% of current buildings costs is needed to climate proof new infrastructure.
EC (2009b)	EUR 6-58 billion per year	Same assumption as used in the Stern Review (2006), but applied to GDP of 2006 instead of 2001-2003.

Second-generation estimates for industrialized countries

UNFCCC (2007)

A more detailed assessment of potential adaptation costs is provided by a study undertaken for the United Nations Framework Convention on Climate Change (UNFCCC, 2007). The UNFCCC (2007) study "Investment and Financial Flows to Address Climate Change" estimates the global cost of adaptation defined as additional investment and financial flows for the year 2030. The study covers five sectors: agriculture, forestry and fisheries; water supply; human health; coastal zones; and infrastructure. The sector assessments are based on different methodologies, but all incorporate climate and development projections for 2030 to ensure that the adaptation cost-estimate is additional to baseline projections and in line with climatic data. When possible, the split between private/autonomous and public/policy-driven adaptation is highlighted in the sector studies, but it is not provided in aggregate.

Table 3. UNFCCC (2007) estimate of additional annual investment and financial flows needed in 2030 to cover the costs of adapting to climate change (billion USD per year in present day values (2005-USD), no discounting).

Sector	Costs (billion USD per year in 2030)		
	global	developed countries	developing countries
Agriculture, forestry and fisheries	14	7	7
Water supply	11	2	9
Human health	5	Not estimated	5
Coastal zones	11	7	4
Infrastructure	8-130	6-88	2-41
Total	49-171	22-105	27-66

The UNFCCC (2007) analysis indicates that additional annual investments and financial flows of USD 49-171 billion per year by 2030 could be needed to adapt to climate change globally – the estimate is in 2005-USD and no discounting is applied.[3] Table 3 disaggregates this number by sector and region. USD 22-105 billion per year in 2030 could be needed in developed countries, whereas USD 27-66 billion per year in 2030 could be needed in developing ones. No separate estimate is provided for Europe or the EU, although some sector analyses disaggregate their results for OECD Europe – these are reviewed in Section 3.

Those sums can be compared with global investment flows, as well as with spending needs for mitigation. With respect to the former, the additional annual investment and financial flows for adaptation correspond to 0.2-0.8% of global investment flows or 0.06-0.21% of projected GDP in 2030 (Smith, 2007). With respect to mitigation investment needs, the UNFCCC (2007) estimates that USD 380 billion would be required globally in 2030 to return greenhouse-gas emission to current levels by 2030. Industrialized countries would need to shoulder USD 203 billion and developing countries USD 176 billion. Compared to those amounts, the investment needs for adaptation correspond to 11-52%.

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[3] The estimate relates to additional annual investment and financial flows in the year 2030. It is obtained by projecting forward current investment and financial flows to 2030 in a climate-change scenario and in a baseline scenario without climate change. The difference yields the additional annual investment and financial flows. No temporarily aggregated numbers are involved in this methodology, since only annual flow variables (investment and financial flows) are projected forward and subtracted from each other in different scenarios. Thus, no information on the timing of investments besides for the target year of 2030 can be inferred from the estimate.

The UNFCCC (2007) acknowledges several limitations. In particular, it states that the analysis does not aim to provide a precise estimate of the total cost of adaptation, but assesses the order of magnitude of additional investment and financial flows in 2030. It thereby ignores differences in adaptive capacity between countries, as well as pre-existing adaptation deficits, especially in developing countries. A detailed review by Parry et al. (2009) criticise in particular the latter point. The review estimates that the UNFCCC (2007) study might underestimate investment needs by a factor of between 2 and 3 for the sectors included (and several times more for the infrastructure estimate). The authors also note that the UNFCCC's sectoral coverage is only partial. For example, sectors, such as mining and manufacturing, energy, retailing, and tourism, were not included in the analysis.

Another point of criticism concerns the heterogeneity of sector analyses. The depth of analysis between the sector studies differs substantially. For example, the infrastructure study and the analysis of investment needs in agriculture, forestry and fisheries adopt a simple mark-up methodology. In contrast, the coastal-systems study employs detailed physical-impact modelling together with cost-benefit analysis. Aggregating the sector estimates hides those differences.[4]

Agrawala et al. (2008) note that a particular distortion might be introduced by the infrastructure estimate which represents up to three quarters of the total estimate and therefore has a large influence on the aggregate result. They also highlight the risk of double-counting investments, since infrastructure is also the main component of the coastal and water sectors, among others, including coastal defences and flood protection, but also infrastructure used for heating and cooling purposes and for hydropower production (UNFCCC, 2007). The infrastructure estimate is obtained by applying a simple mark-up methodology similar to the studies by Simms et al. (2004), the World Bank (2006), and the Stern Review (2007) which were discussed above. Two differences are that total infrastructure investment is projected forward to the year 2030 and that the portion of climate-sensitive infrastructure investments is estimated based on insurance data. However, the UNFCCC (2007) study applies the same uniform mark-up (5-20%) to estimate the additional costs of climate proofing sensitive infrastructure as the Stern Review (2007) applies for developing countries. Thus, this methodology is subject to the general criticism of first-generation adaptation-cost estimates raised above and stressed in a detailed review of the UNFCCC infrastructure estimate by Satterthwaite and Dodman (2009).

A sensitivity analysis can be undertaken to remove the risk of double-counting the infrastructure component by removing the infrastructure estimate from the aggregate result. The UNFCCC (2007) infrastructure results indicate global additional investment needs to adapt infrastructure to climate change in 2030 of USD 8-130 billion per year; for OECD Europe the share is USD 1-17 billion per year in 2030. Removing the sector estimate leaves additional investment and financial flows needed in 2030 for climate-change adaptation of USD 16 billion per year in industrialised countries and of USD 25 billion per year in developing countries. This estimate might well constitute an underestimate, e.g. due to the

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[4] Section 3 contains detailed reviews of the methodology employed in each sector analysis.

omission of sectors (and impacts within sectors) as already highlighted for the full estimate (UNFCCC, 2007). The percentage split of adaptation costs between developed and developing countries reverses from 60:40 to 40:60, which indicates to a greater extent the widely perceived adaptation deficit in developing countries (see e.g. Burton, 2004)

Finally, Parry et al. (2009) highlight the lack of estimating residual damages in the UNFCCC study. In cost-benefit analyses, residual damages exist, because it might not be economic or not feasible to pursue total adaptation, in particular when adaptation costs exceed damage costs. Parry et al. (2009) estimate residual impacts of about a fifth of all impacts in agriculture in 2030 and of up to two-thirds of all potential impacts across all sectors in the long run. However, those percentages can only be seen as indicative numbers. A reason for the absence of residual-damage estimates in the UNFCCC (2007) study is that it did not apply cost-benefit analyses in most of its sector analyses.

In summary, the UNFCCC (2007) study “Investment and Financial Flows to Address Climate Change” presents sectorally differentiated adaptation-cost estimates for the year 2030 for developing and developed countries. Its sector-based assessment is a considerable scale-up compared to earlier first-generation assessments. However, the infrastructure estimate, which has the greatest influence on the aggregate result, still relies on the first-generation mark-up methodology which was heavily criticised above. The lack of using a consistent methodology across sectors stresses the indicative nature of the aggregated result obtained in the UNFCCC (2007) study.

PESETA (2009) study

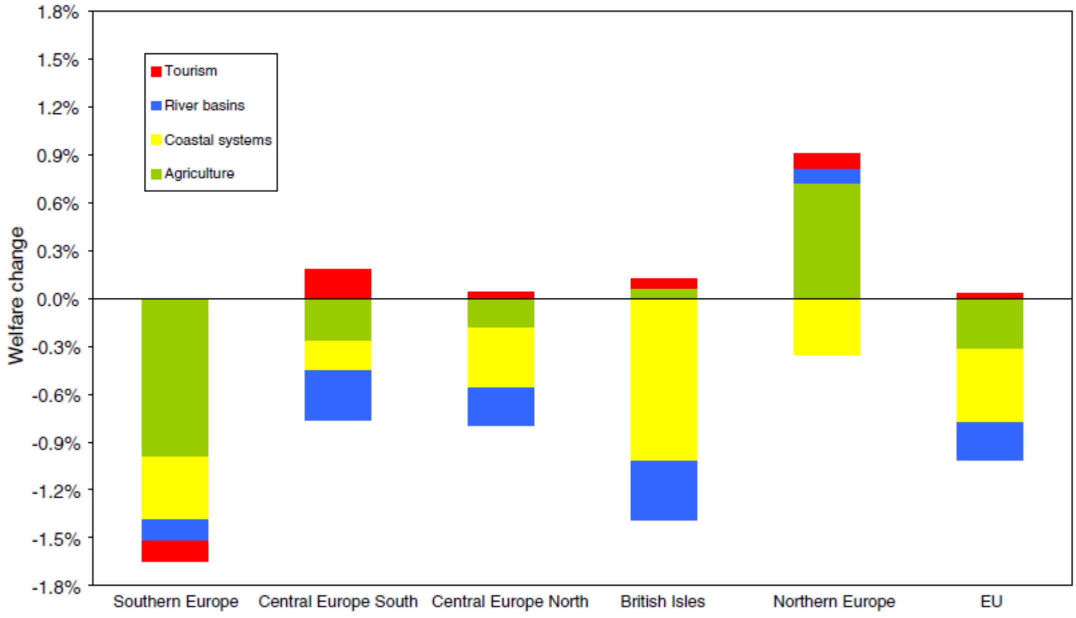
With the aim to design and prioritize adaptation strategies the European Commission (2009) White Paper on Adaptation indicated the need for a detailed assessment of the impacts of climate change in Europe. Such an impact assessment was carried out within the PESETA (Projection of the Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) project. The results have been published as a report in 2009 (Ciscar et al., 2009) and recently as a special peer-reviewed issue of the journal Climatic Change (Ciscar, 2011; see also the PNAS publication by Ciscar et al., 2011a). The PESETA study estimates the physical and economic impacts of climate change by sector and region while taking into account some degree of private and autonomous adaptation strategies, such as farm-level adaptation and acclimatization. However, the study does not in general assess the investments needed in the EU to adapt to climate change and does not include a thorough economic analysis of adaptation (e.g. the autonomous adaptation measures included in the study are not costed in most sector analyses).

However, the results of the PESETA study are reviewed here to give an indication of the potential economic impacts without broadly planned adaptation. This can be seen as an upper bound for adaptation costs as adaptation measures would need to be cheaper than the expected climate damages to pass a cost-benefit test (see Section 1). In the absence of detailed adaptation-cost estimates on a European scale, the PESETA study also provides an indication of the sectors and regions most vulnerable to climate change and can therefore inform the prioritization of adaptation investments along those dimensions.

The PESETA study assesses climate impacts in five impact categories: agriculture, river floods, coastal systems, tourism, and human health. For each sector, physical impact models were used to estimate the physical and economic impacts that climate change in the 2080s would have on the current economy. Each analysis was undertaken for four regional climate scenarios whose temperature projections range from a warming of 2.5°C to 5.4°C by the 2080s compared to the 1970s. However, no projections about the economic development up to the 2080s were considered, so that the climatic impacts are studied with respect to current economic conditions. The estimated sector impacts (with the exception of the human-health study) were integrated into a general-equilibrium (CGE) model to assess the economy-wide impacts in EU countries (i.e. also the indirect market-feedback effects) and to calculate the associated changes in consumer welfare and GDP.

The PESETA study indicates that if the climatic changes expected in the 2080s occurred today, the European economies would experience GDP losses of EUR 22-67 billion and consumer-welfare losses of 0.2-1%. For comparison, the historical annual GDP growth in the EU is around 2% (Ciscar et al., 2009). Another point of comparison can be made to annual investments in the EU. Those were EUR 2.6 trillion in 2008 and EUR 2 trillion in the Euro (EU-27) area (EUROSTAT, gross fixed capital formation). Compared to those EU investments, the economic impacts of future climate change correspond to 1-3.4%.

Figure 2. Welfare changes in the 5.4°C warming scenario with high sea-level rise.



Source: Ciscar et al. (2011b).

Figure 2 displays the welfare impacts by region for the different sectors in the highest global-warming scenario. While the relative sectoral magnitudes differ across warming scenarios, the distribution of impacts by region is similar. Northern Europe experiences some welfare gains, while Southern Europe is the hardest hit region. For both regions, improvements and losses in agricultural yields are identified as the main impacts. On the other hand, the economic losses in the British Isles and Central Europe North are affected mostly by changes in coastal systems and river floods.

The impacts on GDP have a similar regional distribution (Table 4). Southern Europe experiences the highest losses, especially in the high 5.4°C warming scenario where it shoulders 66% of all GDP impacts (EUR 42 billion). In the lower warming scenarios, Central Europe North is heavily affected with up to EUR 18 billion.[5] Northern Europe is the only region which experiences GDP gains in all climate scenarios (up to EUR 8 billion).

Table 4. Change in GDP (in billions of 2008-EUR)

Scenarios	Impact of climate change in 2080s on current European economies (GDP change in terms of billion 2008-EUR)					
	Southern Europe	Central Europe South	Central Europe North	British Isles	Northern Europe	*Total EU*
2.5°C	-6.0	1.6	-15.3	-6.4	5.7	-21.6
2.9°C	-18.3	0.1	-18.3	-7.3	6.0	-37.8
4.1°C	-9.3	-2.4	-13.1	-2.2	5.4	-21.6
5.4°C	-42.0	-8.6	-22.5	-2.1	8.0	-63.6
5.4°C high SLR	-41.9	-8.9	-25.3	-2.2	7.7	-67.1

Source: Ciscar et al. (2011b).

It should be noted that the PESETA report (Ciscar et al., 2009) and the PNAS publication (Ciscar et al., 2011a) interpret the results as annual values, but such interpretation is misleading as no time horizon is considered within the CGE analysis. Instead, the economy-wide estimates are the result of a comparative static analysis (in terms of 2008-EUR; see Ciscar et al., 2011b) that purely indicates the economy-wide impacts of experiencing the climatic conditions of the 2080s today (on current economic conditions).

While the PESETA study represents a concentrated effort to integrate bottom-up analysis into an overall EU-wide impact assessment, it has several shortcomings. First, the coverage of sectors and impact categories is not complete. For example, the energy sector is not included in the analysis, as well as the impacts of

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[5] The reason for this shift in incidence is the climate sensitivity of sectors. Central Europe North is primarily affected by impacts on the coastal system which are sensitive even to mild warming/sea-level rise; in contrast, Southern Europe is mostly affected by impact on agriculture which are less sensitive to moderate warming.

extreme weather events and catastrophes. Ciscar et al. (2011) note that the results are therefore an underestimate of the climate damages that can be expected in the EU.

Another important limitation of PESETA's CGE analysis is the absence of a clear development trajectory and time dimension. Estimating the effect that climate change in the 2080s would have on today's economy might be a useful exercise, but could deviate substantially from a full climate-impact projection that would take into account socio-economic developments until 2080. For example, the World Bank's "Economics of Adaptation to Climate Change" (2010) study which focuses on developing countries finds that the impact of GDP is larger than the impact of climate change over time; as a result, developing countries become less vulnerable over time to climate change. Although the study also notes that GDP impacts may remain stable in Europe, not studying the effect in the PESETA study represents a major omission, also because the tools for conducting dynamic CGE analysis (including socio-economic projections related to the climate scenarios used in the PESETA study) are readily available.

Table 5. Comparison of economy-wide GDP effects obtained in PESETA's CGE analysis with direct-cost estimates obtained in the different sector analyses.

Sector	Change in GDP (%)		Change in GDP (billion EUR)		Direct cost (billion EUR)	
	2.5°C	5.4°C	2.5°C	5.4°C	2.5°C	5.4°C
Agriculture	-0.02	0.29	-2.39	34.65	N/A	N/A
River floods	0.01	0.01	1.19	1.19	7.73	15.03
Coastal system	0.19	0.24	22.70	28.68	10.32	44.61
Tourism	0	-0.01	0.00	-1.19	-1.86	-15.27
Tourism (zero-sum)*					0.00	0.00
Total	0.18	0.53	21.51	63.33	13.80	79.02
*Total**					15.66	94.29

Source: Based on results presented in Ciscar et al. (2009).

Notes on table: Assumes a 2010-GDP value of EUR 12 trillion (EUROSTAT, excl. Cyprus, Luxemburg, and Malta in accordance to PESETA study); aggregate sector estimates for agriculture are not provided in the PESETA report, so that economy-wide GDP impacts are used to obtain different aggregations in the third column; sector estimates of health impacts range between benefits of EUR 0.05-0.1 billion which were not included in the economic (CGE) impact assessment and due to its magnitude omitted in the sector estimate. The 5.4°C warming scenario with high sea-level rise is not included in the table.

Other caveats of PESETA's CGE analysis relate to its implementation of physical impacts as derived in the sector analyses (see Ciscar et al., 2011b). The implementation is usually undertaken as economic shocks – for example, the yield changes derived in the agriculture impact assessment are represented as changes in total factor productivity. While such a representation might be considered standard, it ignores more detailed cross-sectoral interactions that cannot be represented, such as competition for water resources between agriculture and tourism.

The economy-wide impacts can also hide larger direct impacts within a sector. Table 5 compares the economy-wide GDP impacts obtained by the CGE analysis with direct-cost estimates obtained from the sector studies. The table indicates that especially the impact of river floods is diminished in the CGE analysis compared to the sector result. Ciscar et al. (2011b) note that the focus on GDP obscures the direct and welfare impacts from river floods, because the majority of impacts relate to damages to residential buildings whose repair spurs production and thus GDP. Also the analysis of the tourism sector comes to different results than the CGE analysis. The sector study indicates larger positive impacts, especially for the British Isles. However, the sector analysis also considers a scenario in which tourism is modelled as a zero-sum game with absolute tourist flows into Europe remaining constant. That scenario results in a mere re-distribution of tourist flows within Europe. Aggregating the different direct-cost estimates can lead to aggregate cost estimates which differ by up to 50% (EUR 95 billion compared to EUR 63 billion; the EUR 95 billion estimate takes into account also the GDP effect of the agriculture sector as no direct-cost estimates were available in that case). This underlines the sensitivity of the aggregate-cost estimate to the CGE analysis, but also to the sector scenarios selected.

In summary, the PESETA study provides a detailed assessment of the effects of future climate change on today’s economies. However, it estimates those impacts on an unrealistic basis (today’s economy instead of the projected one). Moreover, its omission of a coherent treatment of adaptation measures makes its input into policy frameworks regarding adaptation illusive. In particular, there is no clear connection between the impacts of future climatic change and the investments needed to adapt to such impacts. The most the PESETA study can do is therefore to identify the sectors most vulnerable to climate change. The results of the PESETA study indicate that agriculture, coastal systems and rivers all represent vulnerable sectors, albeit highly differentiated by region.

Aggregating across sectors hides sectoral differences and masks sector-specific uncertainties. The sector analyses of the UNFCCC (2007) and PESETA (2009) studies are characterized by different levels of depth. The next section therefore contains a detailed assessment of available sector studies. It discusses, among others, the sector estimates of the UNFCCC and PESETA studies and supplements those with stand-alone studies if such studies were available.

3. Adaptation-cost estimates by sector

Sectoral estimates of adaptation costs can, in principle, provide a more in-depth picture of vulnerabilities to climate change and adaptation-investment needs. While there has been a considerable literature on climate-change adaptation on the sector level (see e.g. the review by Agrawala et al., 2008), the information usable for cost-benefit assessments of adaptation options is unevenly distributed both by sector and by region (Table 6). Most detailed cost-benefit assessments exist for the coastal system. Detailed studies on the benefits of agricultural adaptation are also available, but little is known about the costs associated of such measures. Some costs and benefits in the energy sector have been assessed, in particular those associated with less demand for heating and increased demand for cooling due to global warming. Beyond that, the literature on costs and benefits is limited, although recent bottom-up studies, such as the UNFCCC (2007) and the PESETA (2009) studies provide some information on other sectors, such as health and tourism.

The following subsections review the climate-change impact and adaptation-cost literature focussed on Europe for seven sectors: river floods, water supply, agriculture, human health, energy, tourism, and the coastal system. The level of depth corresponds largely to the general overview given in Table 6. Some benefit estimates in the health sector have become available through the PESETA (2009) study and the regional coverage of the water sector has been scaled up in the UNFCCC (2007) study. However, with the exception of the coastal system, very few comprehensive cost-benefit analyses of adaptation options exist.

Table 6. Coverage of sectoral estimates of adaptation costs and benefits.

Sector	Analytical coverage	Cost estimates	Benefit estimates
Coastal zones	Comprehensive	xxx	xxx
Agriculture	Comprehensive	-	xxx
Water	Isolated case studies	x	x
Energy	North America, Europe	xx	xx
Infrastructure	Cross-cutting, partly covered in other sectors	xx	-
Health	Selected impacts	x	-
Tourism	Winter tourism	x	-

Source: Agrawala et al. (2008); see also Fankhauser (2009, 2010).
Note: More crosses denote greater coverage; dashes indicate very limited coverage.

3.1. *River floods*

The European Environment Agency (2004) states that river floods are the most common natural disasters in Europe. Global warming is generally expected to increase the magnitude and frequency of extreme precipitation events (Christensen and Christensen, 2003; Frei et al., 2006) and could therefore lead to more intense and frequent river floods (Ciscar et al., 2009).

While there have been physical impact assessments at the European scale (Lehner et al., 2006; Dankers and Feyen, 2008, 2009), Feyen et al. (2011) note that monetary estimates of the impacts of climate change on floods (and adaptation to those impacts) have been poorly covered to date. Hall et al. (2005) estimate current and future coastal and river flood risk in England and Wales.[6] They find that economic risk (in real terms) increases 20-fold by the 2080s for the scenario with the highest economic growth. The European Environment Agency (2007) examined the impact of climate change on river-flood management for the River Rhine and concluding that about EUR 1.5 billion of optimal flood defence investments are needed. However, it is not clear how those estimates relate to the wider European context.

While there exists no comprehensive adaptation-cost assessment for Europe, some indications on the potential EU-wide climate-induced damages due to river floods have been estimated within the PESETA (2009) study. In particular, the PESETA project assesses the impact of climate change in the 2080s on river floods. The methodology is based on Feyen et al. (2006, 2011). Estimates of changes in the frequency and severity of river floods are based on simulations with the LISFLOOD model, which is a spatially distributed, conceptually mixed, and physically based hydrological model developed for flood forecasting and impact assessment studies at the European scale (van der Knijff et al., 2010). The LISFLOOD model transfers climate-forcing data into river-runoff estimates. An extreme value analysis (Dankers and Feyen, 2008) has been performed with those estimates and direct monetary damages have been calculated by using country-specific flood depth-damage functions (Huizinga, 2007) and land-use information (EEA, 2000).

The results indicate that the impact of climate change in the 2080s on today's economy would result in total additional damages from river floods of EUR 7.7-15 billion per year. Table 6 lists those damages by region. While Northern Europe would experience fewer damages from river floods, Central Europe and the British Isles would experience significantly more. To put this number into context, Feyen et al. (2011) note that the simulated present-day damage costs (historical average) are about EUR 6.4 billion (Table 6, last column) which broadly agrees with estimates from the Association of British Insurers (ABI, 2005). The effects of climate change in the 2080s on today's economy therefore increase the expected damages due to river floods by factors of 2.2 to 3.4.

The results listed in Table 6 show a great inter-model variability between climate scenarios with similar global warming, such as the 3.9°C and the 4.1°C warming scenarios. Feyen et al. (2011) explain the great inter-model variability by two factors. First, flood risk does not scale linearly with rising temperatures. Second, decadal-scale internal variability in the simulated climate runs likely plays an important role in determining the changes in extreme discharge levels (Dankers and Feyen, 2009). The uncertainty of results is therefore largely driven by uncertainties in the climate scenarios.

The PESETA study for river floods by Feyen et al. (2011) acknowledges several other methodological uncertainties. First, the two global climate scenarios

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[6] Hall et al. (2005) perform national-scale risk assessments based on information on the location, standard of protection and condition of flood defences in England and Wales, together with datasets of floodplain extent, topography, occupancy and asset values.

considered in the analysis (A2 and B2) may ignore further inter-model variability. Second, no downscaling or bias correction was applied to the climate data due to lack of high-resolution data. This might locally lead to underestimation of flood frequencies. Third, hydrological uncertainty is not accounted for. Fourth, the extreme value analysis used only a time horizon of 30 years, so that an extrapolation bias might exist. Fourth, changes in land use and land cover are not incorporated in the estimates, which might lead to an underestimation of future flood risk. Lastly, the construction of damage probability functions, which are used to estimated expected annual damages, is broad-brush in estimating current flood protection by GDP per capita ratios without attempting further validation.

Table 6. PESETA's estimate of additional expected economic damages due to river floods (billion EUR per year).

Region	Climate Scenario				Historical average (1961-1990)
	2.5°C	3.9°C	4.1°C	5.4°C	
Northern Europe	-0.3	0.0	-0.1	-0.1	0.6
British Isles	0.8	2.9	2.8	5.0	0.8
Central Europe North	1.5	2.2	3.0	5.3	1.6
Central Europe South	3.5	4.3	2.9	5.0	2.2
Southern Europe	2.3	2.1	0.3	-0.1	1.2
Total EU	7.7	11.5	8.9	15.0	6.4

Source: Ciscar et al. (2009), Feyen et al. (2011).

Further, it should be noted that the projections assume no growth in exposed values and population or adjustments of current flood protection. No forward projection of socio-economic variables was attempted, which therefore ignores the impacts from development and socio-economic change until the 2080s. This might call into question the robustness of the results – for example, Barredo (2007) finds that the observed increase in the costs from floods during the last decades can be largely attributed to socioeconomics factors.

In addition, it should be noted that the study looks only at direct damage costs. On the one hand, this ignores the impact of adaptation measures and cannot provide information on the optimal scale of, or investment in, adaptation measures (as it is done e.g. in the coastal-system analysis). On the other hand, it ignores indirect economic losses caused by changes in prices and market feedbacks. Also other factors that might contribute to the increase of losses, such as flood velocity, building characteristics, content of sediment water, are not accounted for.

The final chapter of the PESETA study sheds light on the indirect costs of flood damages by integrating the physical impacts into a computable-general-equilibrium model of the European economy (see also Ciscar et al., 2011b). The CGE analysis states that 80% of the total economic impact of river floods relate to damages in residential buildings. This makes the damages from river floods a distinctively private problem. For the CGE analysis, it has been assumed that households would repair buildings and replace lost equipment. This is interpreted as additional expenditure needed. The other 20% of total damages relate to the productive sector and are modelled as production and capital losses in the economy.

Results indicate that welfare would decrease by 0.08-0.24% in the EU in the 2.5°C and 5.4°C climate scenarios due to damages from river floods.[7] GDP would decrease marginally in all climate scenarios, by about 0.01%. The GDP effects are significantly lower than the welfare impacts due to less damage from river floods related to productive capital. Multiplying the change in GDP by 2010-GDP values obtained from EUROSTAT yields absolute values of about EUR 1.19 billion. This number is considerably lower than the direct damage costs due to river floods of EUR 8-15 billion per year. The difference in the CGE analysis is explained by the production-spurring effect of repairing residential buildings which hides the cost incidence on private households in the aggregate GDP estimate.

In summary, detailed expected-damage-cost estimates for river floods are available for the EU and its member countries through the PESETA study. They indicate additional expected damages of EUR 8-15 billion per year if the climate change of the 2080s would occur today. Since most of the costs incurred due to river floods are expected to fall on private households (through flooding of houses), the expected damage estimates can provide a basis for informing the incidence of climate change in that sector. However, it is not clear how adaptation measures would influence this amount, nor how the superposition of the climate impacts expected in the 2080s on today’s economy could inform current household’s adaptation strategies.

3.2. Water supply

The changes in temperature and shift in precipitation patterns associated with climate change are expected to affect many sectors that depend on water supplies (Alcamo et al., 2007). Agrawala et al. (2008) note that the literature on adapting the water supply and demand to the impacts of climate change at the regional level is too sparse and context specific to make a broad assessment with regard to the costs. However, the UNFCCC (2007) study on “Investment and Financial Flows to Address Climate Change” provides a global estimate with separate numbers available for developed and developing countries.

The methodology applied in the UNFCCC (2007) study on the water sector is based on Kirshen (2007). The baseline water supply and demand in 2030 is estimated for two climate scenarios (IPCC SRES A1B and B1) by assuming planning for the next 20 years and perfect knowledge about climate change impacts in 2050 (Kirshen, 2007). Generalized cost functions were derived by applying uniform rules of thumb to estimate costs for specific sectors

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[7] PESETA's CGE estimates are the result of a comparative static analysis (in terms of 2008-EUR; see Ciscar et al., 2011b) that indicates the economy-wide impacts of experiencing the climatic conditions of the 2080s today (on current economic conditions) (see Section 2).

(groundwater extraction, building of water storage and desalinization plants, etc.), but differentiated for developing and developed countries.

The UNFCCC (2007) report indicates total investments needed in 2030 in the water sector of USD 720-898 billion. The fraction of investment needs attributable to climate change alone is assumed to be 25%, i.e. USD 180-225 billion. Further assuming that funding is provided through grants for a 20-year period, annual investment needs in climate-change adaptation in the water sector would be USD 9-11 billion annually. Those investment needs are likely to fall largely on the public sector, since the majority of present financing for all aspects of water-resource use comes from public sources (Briscoe, 1999; Winpenny, 2003). About 85% of the investment is estimated to be needed in non-Annex-I parties. Thus, about USD 1.35-1.65 billion per year, would be needed in industrialized countries.

The UNFCCC/Kirshen study has a number of limitations. No hydrological model has been used and the costs of unmet irrigation demands have not been considered in the analysis. The latter means that there exists a potential adaptation deficit. Fischer et al. (2007) conduct an assessment of the prospective costs of unmet irrigation demands using an agro-ecological zone model. They find that by 2080 climate change would increase the cost of providing additional irrigation by USD 24-27 billion per year in an unmitigated climate scenario (similar to the SRES A2 scenario but with lower population projections) and by USD 8-10 billion per year in a mitigation scenario. For the year 2030, they estimate global additional costs of USD 7-8 billion per year, which approaches the Kirshen/UNFCCC estimate to adapt the whole water supply to climate change. This shows that the costs omitted in the UNFCCC/Kirshen study can be substantial.

Arnell (2009) reviews the Kirshen/UNFCCC study in more detail. He notes that the Kirshen/UNFCCC study represents a coherent attempt to estimate costs of increasing water supply capacity. However, the total is likely to be a considerable underestimate due, in addition to the reasons highlighted above, to the omission of operation and maintenance costs and of the cost of adapting to water shortages, which leaves out the costs of flood management, storm drainage, water quality enhancement, among others. The aggregation at the national and temporal levels and not at river-basin and seasonal levels, and the use of an average climate-change scenario instead of the mean from several scenarios might further contribute to a downward bias in the Kirshen/UNFCCC study. However, Agrawala et al. (2008) note that the inclusion of demand-side measures, such as promotion of indigenous practices for sustainable water use, increased use of rain-fed agriculture or expanded use of water markets and other economic incentives could significantly lower the adaptation costs.

Finally, Arnell (2009) criticize that the assumption that 25% of costs represent the fraction attributable to climate change as unclear and arbitrary (similar to the first-generation mark-up methodology followed by the World Bank, 2006). Since the final estimate critically depends on the assumption on climate-sensitive investment, the Kirshen/UNFCCC should be considered as an indicative first guess. Agrawala et al. (2008) further note that the empirical numbers on costs of specific measures are typically taken from specific examples from the United States before being scaled up to various regions based upon the regional differences of costs. This underlines the indicative nature of the results obtained.

In comparison, The World Bank's "Economics of Adaptation to Climate Change" (EACC, 2010) study uses a more detailed methodology. It assesses the effects of climate change on the water cycle out to the year 2050. For that, the Climate and Runoff model (CLIRUN-II) is applied to a set of climate scenarios. The analysis of the costs of adaptation for water management includes industrial and municipal water supply and excludes water for agriculture and ecosystem services (those were included in different sector studies undertaken within the EACC).

Results indicate that the annual costs for adapting the water supply and riverine flood protection to climate change amount to USD 13.3-26.2 billion annually for 2010-2050 (USD billions at 2005 prices, no discounting). Unfortunately no separate numbers were given for developed countries. Compared to the UNFCCC (2007) estimate of USD 9-11 billion per year until 2030, a clear cost-increase seems visible.

However, it is not clear how large the influence of the methodology is over the target year and climate scenarios. Instead of UNFCCC (2007) study's 2030 time horizon, the EACC study considers a longer time horizon up to 2050. The EACC study includes an analysis of the baseline without climate change and of the baseline changes under climate change, whereas the UNFCCC study examined the combined costs of adaptation to socioeconomic development and climate change and then assumed the costs related to climate change to be 25% of the total. The EACC study uses hydrologic models to estimate the change in generic reservoir capacity. The EACC study also estimates the global costs of adaptation related to riverine flood protection (similar to the PESETA study), which UNFCCC (2007) did not consider.

In summary, the results of the UNFCCC (2007) study on "Investment and Financial Flows to Address Climate Change" indicate investment needs to adapt the water sector of industrialized countries to climate change in 2030 of about USD 1.35-1.65 billion per year. Given the limitations of the UNFCCC (2007) water-sector estimate, its result should be regarded as indicative. Fischer et al. (2007) indicate that the costs by 2030 of additional irrigation water withdrawals alone caused by climate change could be USD 7-8 billion per year globally, with a likely developed country share of above USD 2 billion per year (based on the cost division of their 2080 estimate). They estimate that those costs increase by 2080 to USD 8-10 billion per year in developed countries. The costs to adapt the whole water sector to climate change can be expected to be larger than the Kirshen/UNFCCC (2007) and the Fischer et al. (2007) estimates. No separate cost estimates are available that indicate the specific adaption-investment needs in the European water sector. Although the investment needs in the water sector can be considered largely public, especially in developing countries, some percentage might fall onto the private sector in developed countries.

3.3. Agriculture

Climate change is expected to lead to increasing crop yields in Northern Europe and decreasing ones in Southern Europe (Alcamo et al., 2007). Several studies indicate that climatic impacts can be substantially reduced by farm-level adaptation (Reilly et al., 1994; Darwin et al., 1995; Rosenzweig and Parry, 1994; Tan and Shibaski, 2003). Agrawala et al. (2008) note that while the benefits of adaptation in the agricultural sector are relatively well researched, the literature on the costs of adaptation is almost entirely lacking. They explain this by pointing to the focus on (private) farm-level adjustments which are shown to significantly offset climate change impacts on yields at little costs. However, the public dimension in the agricultural sector may still be considered, e.g., in the role of providing public goods, such as research on drought resistant crop varieties and on climate forecasts. Wreford et al. (OECD, 2010) stress that public policies need to provide the right environment for farm-level adaptation to take place.

Two broad-scale studies can give an indication of adaptation costs in the agricultural sector. The UNFCCC (2007) study on adaptation-investment needs in the agricultural sector considers both public and private adaptation. The PESETA (2009) study assessed the impacts of climate change on agriculture despite private farm-level adaptation, which give an indication of residual damages in the absence of public contribution to adaptation. Both studies are reviewed in the following.

UNFCCC (2007)

For the UNFCCC (2007) report, McCarl (2007) estimates the additional investment and financial flows to adapt the agriculture, forestry, and fishery (AFF) sectors to climate change. For that purpose, McCarl projects forward to 2030 the investment and financial flows needed to cope with expected economic and population growth (based on assumed rates of growth and IEA WEO estimates on investments in physical assets). On top of the growth estimate, it is assumed that a 10% increase in research expenditure (subjective estimate) and a 2% increase in new capital expenditure are needed to meet climate change adaptation needs. It is noted that those percentages are informed by the needs for new facilities for the development of new and larger land areas to cope with regionally diminished production plus expanded irrigation and other inputs, relocation of food, wood industry, and pulp and paper manufacturing facilities.

McCarl (2007) estimates that an additional USD 14 billion in investment and capital flows is needed in 2030 globally to adapt the AFF sectors to climate change. USD 11 billion of the total is estimated as capital expenditure and USD 3 billion as research and extension expenditure. The study notes that roughly half of the total amount, i.e. USD 7 billion, will be needed in high-income countries. No separate estimate is provided for Europe. Based on current investment, capital expenditure can be expected to be made privately by AFF producers and processing firms, multinational seed companies, and chemical and manufacturing industries. However, public resources could be needed to cover the research expenditure.

To put those numbers into perspective, current expenditure on AFF capital formation, research and extension is estimated to be about USD 591 billion (USD 383 billion in high-income countries), with another USD 574 billion additional investment needed due to economic and population growth. The additional investment needed for climate-change adaptation constitutes 2% of current (and future) investment (by assumption). However, Agrawala et al. (2008) note that McCarl (2007) does not calculate the costs of adaptation in the AFF sector independently, but that the estimates follow directly from the assumed percentages of incremental investments. This raises questions about the reliability of the results. Similarly, The World Bank's EACC (2010) study criticizes that the UNFCCC estimate includes no explicit link to climate impacts or any accounting for autonomous farm-level adaptation.

Further criticism concerns the aggregate AFF estimate obtained by McCarl (2007). Three single-sector studies estimate adaptation costs and climate change impacts that approach the three-sector aggregate of McCarl. First, the World Bank's (2010) EACC study contains an estimate of the fishery sector which indicates that climate change could lead to losses in landed catch values or gross fisheries revenues of \$10–\$31 billion globally by 2050 and \$7–\$19 billion for developing countries. Although this estimate is made for a different time horizon (up to 2050 instead of up to 2030), it indicates significant economic impacts on the fishery sector due to climate change that could be comparable to the aggregate AFF investment estimate obtained by McCarl (2007) for 2030.

Fischer et al. (2007) offer another partial comparison to the McCarl (2007) assessment. They estimate the climate-change impacts on irrigation water requirements for agriculture from 1990-2080 under a mitigation and business-as-usual emissions scenario (both are modification of the SRES A2 scenario) using an agro-ecological zone model. The results indicate global annual costs by 2080 of additional irrigation water withdrawals caused by climate change of USD 24-27 billion; of that amount, USD 8-10 billion per year by 2080 fall onto developed countries. Under the mitigation scenario, global annual costs are reduced by USD 8-10 billion per year by 2080 (USD 3-4 billion per year by 2080 for developed countries). Although physical impacts were calculated on a finer scale (including for Western Europe), no separate cost estimates are provided for Europe. Estimates for 2030 indicate global annual costs of USD 7-8 billion per year, with a developed-country share that is likely above USD 2 billion per year in 2030. Although this cost share is smaller than McCarl's (2007) estimate of USD 7 billion per year for all AFF sectors in 2030, it constitutes only a single component of the AFF aggregate.

Finally, Wheeler and Tiffin (2009) contrast McCarl's (2007) estimate with a comprehensive study on climate-change impacts on the agricultural sector by Cline (2007). Cline (2007) estimates that the overall impact of climate change on agriculture will be a reduction in the value of output of the order of USD 38 billion by 2080. Wheeler and Tiffin (2009) scale back this estimate assuming a linear increase of cost over time. This yields a cost estimate of USD 14.3 billion for the year 2030, which is close to the cost estimate provided by McCarl (2007). However, the scaled-back Cline (2007) estimate focuses on the climatic impacts on crop production, while the McCarl (2007) estimate includes the entire agriculture, forestry and fisheries.

Taken together, the three single-sector study results (Cline, 2007; Fischer et al., 2007; World Bank, 2010) suggest that the McCarl (2007) estimate represent an underestimate of the full costs of adapting the AFF sectors to climate change. This, together with the methodological limitations highlighted above, underline the highly indicative nature of the McCarl/UNFCCC estimate.

PESETA study

Although the PESETA study on agriculture does not cost adaptation options, it provides a detailed picture of the likely impacts of climate change on the agricultural sector in Europe. The monetized impacts give an indication of the burden that can be expected to fall on agricultural producers despite private farm-level adaptation, but in the absence of public intervention or more planned structural adjustments. A prospective cost-benefit analysis of adaptation options in the agricultural sector could regard the monetized impacts of the PESETA study as maximum costs adaptation measures would need to meet to be preferred over accepting those impacts.

For the PESETA study, Iglesias et al. (2009) assessed the expected change in crop productivity in Europe due to climate change. For that purpose, they identified future changes in agroclimatic regions and developed statistical models of crop-yield response based on the DSSAT process-based crop models for wheat, maize, and soybeans. Farm-level adaptation, including changes in planting date, use of fertilizer, and water for irrigation, was accounted for in the modeling approach.

Results indicate overall yield improvements in the EU of 17% in the 2020s climate scenarios, although southern regions will suffer losses. In the 2080s climate scenarios, the spatial distribution of effects widens. Northern Europe experience high yield improvements, while crop productivity decreases in the south. In the 5.4°C warming scenario, overall crop yields fall by 10% in the 2080s compared to the baseline (present) year.

Although the bottom-up modeling approach followed by Iglesias et al. (2009) is a considerable improvement over the top-down assessment of McCarl (2007), it has several limitations. No restrictions of water availability for irrigation were considered, nor restrictions of the application of nitrogen fertilizer. The results might therefore overestimate production and ignore environmental degradation caused by increased fertilizer use. The implementation of production function in future agroclimatic regions represents a situation in which farmers in each location in the future have knowledge of how and what to produce. This might again introduce an optimistic bias into the estimates. Finally, socio-economic changes associated with changes of land-use and changes in agricultural policies were not incorporated. The lack of considering political changes and the international context are a major omission for a globally integrated sector like agriculture.

The physical impact estimates of Iglesias et al. (2009) are used for two economic impact assessments that were conduced within the PESETA project. The sector report uses a global CGE model (GTAP; Hertel, 1999) to evaluate the economic impacts of climate change in agriculture. The physical impacts have been introduced in GTAP as land-productivity-augmenting technical change over the crop sector in each region. The model is calibrated to the base year of 2001 and the increase in population projected for each climate scenario has been considered. It should be noted, however, that this does not represent a complete forward projection, as it ignores other changes of production and consumption patterns which have influence on GDP and welfare metrics.

Although the PESETA report states that the simulation results are consistent with the physical impacts, the GDP effects shown in Figure 10 of the PESETA report (p. 42) show a different picture: highest GDP increases in the Continental South and much lower increases in the Continental North. A reason for the discrepancy might be the approach of implementing land-productivity-augmenting technological change in the crop sectors as this induces GDP effects for the crops affected by climate change. The sector report states that “[t]he monetary estimates show that in all cases uncertainty derived from socio-economic scenarios (i.e. A2 versus B2) has a larger effect than uncertainty derived from climate scenarios.” However, there seems to be little basis for this conclusion, since no full development path was considered within the CGE modeling exercise. In sum, the sector CGE analysis provides too little information for a consistent interpretation of results.

A further CGE analysis has been conducted within the PESETA project to integrate the various sector impacts (PESETA, 2009, Chapter 8). The sectoral effects of climate change have been integrated into the General Equilibrium Model for Energy-Economy-Environment interactions (GEM-E3) Europe model (van Regenmorter, 2005). Within this framework, the effects of climate change in the 2080s on today’s economy (base year 2010) are assessed. The yield changes computed with the agricultural model have been interpreted as productivity shocks to the production side of the agricultural sector.

Results indicate that in the 5.4°C climate scenario the agricultural sector is the most important impact category in the EU average compared to tourism, river floods, and coastal systems. Damages in the South are not compensated by gains in the North. Over all climate scenarios, welfare impacts range from +0.01% in the 2.5°C warming scenario to -0.32% in the 5.4°C warming scenario. The associated GDP effects range from +0.02% to -0.29% for the 2.5°C and 5.4°C warming scenarios respectively. Unfortunately no baseline GDP values were reported in the PESETA study, but multiplying the percentage values with EUROSTAT’s 2010-GDP values (excluding Luxemburg, Malta, and Cyprus to match the coverage of the PESETA study) yields absolute values of EUR -2.39 billion to EUR 34.65 billion for the 2.5°C and 5.4°C warming scenarios.

Table 7 shows a breakdown of this aggregate number for the five European regions covered in the PESETA study. Southern Europe is affected most, while Northern Europe and partially the British Isles gain from climate change. However, the range of possible impact is huge. Taking into account the uncertainty associated with future climate scenarios, it seems hard to make any forecast even on the sign of impacts. What is clear is only that the detrimental impacts are likely to dominate for temperature increases beyond 2.5°C.

It should be noted that the PESETA study assesses only the damage costs on the agricultural sector due to climate change. While it takes into account some farm-level adaptation measures, it does not cost those and can therefore not give an indication of investment needs. The same argument applies to the farm-level studies reviewed by Agrawala et al. (2008). For example, Rosenzweig and Parry (1994) using a crop-impact modeling approach find that (modest) adaptation could offset yield declines anywhere from 37.5% to 200%. Darwin et al. (1995) computed global adaptation benefits to range from 78-90% of the initial impact. A more detailed study by Tan and Shibasaki (2003) who account for inter and intra-regional bioclimatic differences in their crop model find global adaptation benefits of low-cost adjustments in the range of 23-48%. Howden et al. (2007) estimate the potential benefits of adaptation in temperate and tropical wheat-growing systems to be18% on average. Those studies show that the benefits from adaptation can be substantial, but they give no indication on private investment needs or public policy frameworks that would facilitate those adaptation measures taking place.

Table 7. Annual economic impacts in agriculture for 2080s climate change scenarios in the current European economy.

Region	Climate Scenario	Change in GDP (%)	Change in GDP (billion EUR)
Northern Europe	2.5°C	-0.81	-4.75
	5.4°C	-1.09	-6.40
British Isles	2.5°C	0.10	1.86
	5.4°C	-0.16	-2.97
Central Europe North	2.5°C	0.02	0.75
	5.4°C	0.17	6.42
Central Europe South	2.5°C	-0.11	-2.96
	5.4°C	0.28	7.53
Southern Europe	2.5°C	0.13	3.96
	5.4°C	1.26	38.35
Total EU	2.5°C	-0.02	-2.39
	5.4°C	0.29	34.65

Source: Percentage values adopted from Ciscar et al. (2009), multiplied by EUROSTAT 2010-GDP values to obtain absolute numbers.

In summary, there exist some adaptation-cost studies focused on the agricultural sector, in particular studies by McCarl (2007), Fischer et al. (2007), and the World Bank (EACC, 2010). However, the divergence in methods, sectoral and regional coverage, and the difference in time horizon hinder the extraction of a credible estimate for industrialized countries. The PESETA (2007) study includes more detailed impact estimates for the agricultural sector on the

European scale. However, the results show a large variance and have only limited use for informing adaptation-investment needs due to the lack of considering the costs of specific adaptation measures. Although adaptation in the agricultural sector can be considered largely a private farm-level matter, public policies could be needed to foster research focused on agricultural adaptation and the spread of information, but also to bolster economic losses that are likely to fall on private farms due to climatic changes.

3.4. Human Health

Climate change has direct, as well as indirect effects on human health (Menne and Ebi, 2006; Confalonieri et al., 2007). Direct effects include changes in temperature-related illness, mortality from heat and cold, and fatalities from extreme weather events. Indirect effects are related to changes in water- and food-borne diseases or in the transmission of vector-borne disease.

Watkiss and Hunt (2011) state that although there is a considerable literature on the physical impacts of climate change on health, there is a more limited set of studies that assess the economic costs of climate-changed induced health impacts. However, the economic impacts of climatic changes can in principle be captured by measures of willingness to pay for avoiding adverse health outcomes. The following reviews three such studies: two global economic impact studies by Tol (2002a, b) and Bosello et al. (2006) and one impact assessment on the European scale by Watkiss and Hunt (2011).

Tol (2002a, b) estimates the damage costs of climate change. For his health sector assessment, he derives damage functions for vector-borne diseases and for cold- and heat-related deaths from a meta-analysis by Martens et al. (1997), Martin and Lefebre (1995), and Morita et al. (1994). His results indicate a positive effect of a 1°C rise in global mean temperature on mortality in OECD-Europe. In particular, the number of deaths decrease by 90.9 thousand, primarily due to less cold-related deaths. Vector-borne diseases have no impact on OECD-Europe. Tol (2002b) uses this data in a dynamic cost assessment of climate change. However, he only provides globally aggregated results for the health sector.

Bosello et al. (2006) use the same data as Tol (2002b) to estimate the economy-wide effects of climate change on human health. They calibrate the GTAP-E computable general equilibrium model to the year 2050 and implement changes in morbidity and mortality as changes in labour productivity and demand for health care. The results indicate that GDP, welfare and investment change the same way as the health impacts. Due to the positive impact of climate change (through global warming) on human health in the EU, they find a positive effect on labour productivity, less private and public expenditure for health care and, consequently, more private demand and consumption of other commodities. Associated with that, they find an increase in GDP of 0.070% and an induced increase in investment/capital flows of 0.082%. The direct monetary benefits in the EU are assessed at 9.664% of 2050-GDP. Unfortunately no baseline GDP values are provided by Bosello et al. (2006) to calculate the absolute impact. However, using the GDP projection in IPCC’s A2 scenario for the EU in 2050 of

USD 20.2 trillion to calculate absolute benefits yields an estimate of about USD 1.95 trillion by 2050 (or USD 39 billion annually from 2000 to 2050).

The study by Bosello et al. (2006) has several caveats. First, they use a static analysis which does not include changing investment until 2050 or other dynamic responses. They suggest that including those effects would shift investments away from countries and sectors which are negatively affected and therefore increase regional impacts, but also reduce vulnerability overall. Second, Bosello et al. (2006) omit the direct effects of health impacts on education and dynamic effects of changes in public health care. Finally, they consider only a subset of possible climate-sensitive diseases for which data was available. They state that the direction of the bias generated by this selection is unknown and can be positive or negative. Ackerman and Stanton (2008) criticise the analysis of Bosello et al. (2006) on several more grounds. However, a rejoinder by Bosello et al. (2008) rebuts their arguments persuasively.

For the PESETA study, Watkiss et al. (2009) (subsequently published as Watkiss and Hunt, 2011) assess the potential impacts of climate-change induced temperature changes on mortality. They link climate parameters of two downscaled climate scenarios (SRES A2 and B2) to health outcomes to derive climate-impact response functions for the 2020s and the 2080s. Two sets of climate-impact response functions were derived: country-specific functions which come from different national studies (Menne and Ebi, 2006), and climate-dependent functions which are based on statistical analysis of temperature changes and region-specific thresholds after which temperature has an effect on health outcomes. Since the latter method is internally consistent, it is better suited for comparison across EU countries. For the economic valuation, two metrics were used: the value of statistical life (VSL) and the value of life year lost (VOLY). The latter metric recognises the loss of life expectancy involved, which is important in the health context as many deaths from cold and heat related mortality occur among the elderly. Finally, Watkiss et al. (2009) assume that acclimatisation to 1°C warming would occur every three decades (Dessai, 2003). The change in mortality rates due to socio-economic development is subtracted from the total estimate, so that the results indicate additional deaths due to climate change only.

Watkiss et al. (2009) and Watkiss and Hunt (2011) find that, in general, the decrease in cold-related deaths outweigh the increase in heat-related deaths due to climate change. However, large variations of one order of magnitude exist even for the same climate scenario and time horizon. Table 8 details the results for the climate-dependent impact functions. As noted above, those functions are better suited for cross-country comparison than the country-specific ones. The table presents netted impacts, i.e. the value of heat-related deaths minus the benefits from avoided cold-related deaths. It should be noted that Watkiss et al. (2009) caution against the netting impacts.

In the 2020s net benefits range from EUR 7-11 billion per year using the VOLY metric and from EUR 17-25 billion per year using the VSL metric. Acclimatisation reduces mortality from heat by a factor of 5 and that from cold by a factor of about 2. In the 2080s, benefits from less cold-related deaths range from EUR 0-2 billion per year with acclimatisation depending on the climate scenario. Without acclimatisation, net costs of EUR 10-22 billion per year are possible in the high-warming climate scenario.

Table 8. Economic impacts of climate change on mortality using the VOLY and VSL approaches (million EUR per year)

	Value of life years (VOLY)			Value of statistical life (VSL)		
	2020s	2080s		2020s	2080s	
		2.5°C	3.9°C		2.5°C	3.9°C
with acclimatisation	-7.3	0	-0.8	-17.1	0	-1.9
without acclimatisation	-10.8	-3.4	9.5	-25.5	-7.9	22.3

Source: Ciscar et al. (2009); the same information is contained in Watkiss et al. (2009) and Watkiss and Hunt (2011).

The PESETA study on health (Watkiss et al., 2009; Watkiss and Hunt, 2011) has several limitations. First, it omits the urban and extended heatwave effects. The heat-related results might therefore be underestimated. Second, it does not account for other health impacts, such as heat and cold related morbidity (illness). Third, the study has a very partial representation of uncertainty and does not identify a best-assumption scenario. The high variability across scenarios could therefore make central estimates, as well as ranges of extremes, misleading. Fourth, the account of acclimatisation is very approximate, as it assumes the same acclimatisation without accounting for regional and socioeconomic differences (McMichael et al., 2004).

The authors note that planned, proactive adaptation may play a strong role in reducing the potential health impacts from climate change, in addition to acclimatisation. Such adaptation strategies could include the strengthening of surveillance and prevention programmes, sharing lessons learnt across countries and sectors, introducing new prevention measures or increasing existing measures, and development of new policies to address new threats (Menne and Ebi, 2006). However, an explicit assessment of the costs and benefits of adaptation for heat-related effects has not been undertaken by Watkiss et al. (2009) due to lack of quantitative information.

Compared to the studies by Tol (2002a, b) and Bosello et al. (2006), the PESETA study agrees with their general conclusion that the benefits from reduced cold-related deaths are likely to outweigh the costs of heat-related deaths in the EU. While the former set of studies focus on a generic 1°C increase in global average temperature, the PESETA study uses a downscaling method to derive regionally differentiated impacts for the EU. Its 2080s scenario is associated with increases in average temperature of 2.5-3.9°C. For that range of warming, heat-related deaths become more prevalent, which might explain the lower benefit estimates in PESETA’s 2080s high-warming scenario.

In addition to heat and cold-related impacts from climate change, Watkiss and Hunt (2011) also estimate the impact of climate change on food-borne diseases (salmonellosis) and the health-effects of coastal flooding. With regards to the former, they estimate costs of EUR 69-139 million per year in the 2020s and of EUR 89-284 million per year in the 2080s. Acclimatisation was not accounted for in those estimates. With regards to the latter, they estimate the potential costs associated with psychological stress resulting from coastal flooding using the PESETA results from Nicholls et al. (2009) that do take into account adaptation measures. The results indicate potential costs of EUR 0.8-1.4 billion per year in the high-sea-level-rise scenarios in the 2080s. The estimates for low-SLR scenarios are 3-4 orders of magnitude lower. In sum, those impacts may decrease the net health benefits from temperature changes and, depending on the scenario, result in a small net cost.

In summary, the studies reviewed (Tol, 2002a, b; Bosello et al., 2006; Watkiss and Hunt, 2011) indicate positive effects of climate change on health, in particular due to less cold-related deaths. Those positive effects could be diminished if other climate-induced health effects, such as food-borne diseases and psychological stresses, are taken into account. While Watkiss and Hunt (2011) find that acclimatization could have a significant mortality-reducing effect, some shifts from less cold-related deaths to more heat-related deaths could necessitate adaptive shifts in the provision of health care. However, no quantitative information is available on the investment needs or savings from such shifts, nor from other planned adaptation responses.

3.5. Energy

Climate change is expected to have a variety of impacts on the energy sector (Alcamo et al., 2007). For example, higher temperatures reduce the operating efficiency of thermal power plants and shift heating and cooling patterns. Damages to energy infrastructure might increase due to a higher frequency of extreme weather conditions. Changing precipitation patterns might affect flow conditions for hydropower plants.

Mideksa and Kallbekken (2010) provide a comprehensive literature review of the physical impact of climate change on the electricity market. They note that relatively many studies are available assessing the effect of climate change, in particular the change in temperature, on the demand for heating and cooling. For example, Benestad (2008) estimates that in most countries the number of heating days will decrease, while the number of cooling days are likely to increase. However, the magnitude of effect varies across regions (see e.g. Mansur et al., 2008; Eskeland and Mideska, 2009). With regards to electricity supply, studies exist that indicate reductions in power output from thermal power plants due to temperature increase (e.g. Durmayaz and Sogut, 2006); increases in wind power potentials due to higher wind speeds in northern Europe (Pryor et al., 2005) and the Eastern Mediterranean (Bloom et al., 2008); and increase in energy supply from hydropower plants due to greater river inflows in Northern Europe (Bye, 2008); a EU-wide assessment of this effect was conducted within the EuroWasser study (Lehner et al., 2001; 2005). Finally, Mideksa and Kallbekken (2010) highlight the potentially high cost to the transmission system due to extreme weather events (see e.g. Peters et al., 2006).

However, common in all studies on impacts is that they are rarely monetized and they do not include analyses of possible adaptation scenarios. Possible adaptation measures in the energy sector include, among others, enhancing the interconnection capacity of electricity grids and the use of decentralized micro grids to reduce vulnerability to climate change, mitigation measures that would reduce the impacts of climate change through the use of more renewable energy resources and greater energy efficiency, but also behavioural changes targeting the demand side (Alcamo et al., 2007). Studies estimating the economic impacts of climate change on the energy system rarely contain a detailed assessment of such adaptation measures, but instead focus mostly on changes in the energy supply and demand. The following reviews studies that are currently available.

Temperature-related changes in energy consumption

Tol (2002a) estimates the effects of climate change on energy consumption mediated through changes in heating and cooling days. For OECD-Europe, he finds that a 1°C increase in global mean temperature would induce benefits of USD 22.1 billion due to reduced heating demand and costs of USD 10.9 billion due to increased cooling demand. Tol (2002b) uses a dynamic integrated assessment model (FUND) to assess the impact of climate change on the whole economy disaggregated by sector from the year 2000 until 2200. For the impact on energy consumption, he finds that, under best guess assumptions, the money saved from reduced demand for heating remains below 1.0% of GDP, whereas the additional amount spent on cooling rises to 0.6% of GDP by 2200. However, no disaggregation by region is provided and the estimate depends crucially on parameter values, such as the income elasticity of heating energy demand and the autonomous energy efficiency improvements assumed in the model.

Effects on European electricity markets

Golombek et al. (2011) assess the impacts of climate change on electricity markets in Western Europe. They estimate the effect of changes in temperature on electricity demand, the effect of changes in precipitation and temperature on electricity supply from hydropower, and the effect of changes in temperature on (thermal) plant efficiency. Using the energy market equilibrium model LIBEMOD, Golombek et al. (2011) find only small to modest impacts on electricity price and supply. The net effect on the electricity price is 1%, with partial effects of less than 2%. Net electricity supply decreases by 4%. However, Nordic countries with a large share of hydro power can increase their annual electricity production by 8% due to more inflow of water.

The Golombek et al. (2011) study has several limitations. First, it should be noted that the methodology employed by Golombek et al. (2011) is somewhat inconsistent with regards to climate and electricity projections. In particular, they assume that the average climate of 2070-2099 materializes in the year 2030. Their results are therefore not to be seen as predictions of actual behaviour, but as an exploration of the effects that climate change has on a power system that has had time to adapt (by anticipating future climate change). With this assumption, the authors circumvent the lack of robust projections of the composition of future energy markets beyond 2050. Second, the study focuses on the impacts of climate change and does not assess adaptation measures. As such, it cannot give an indication of potential investment flows needed to adapt the energy system to future climate change.

Cost-of-climate-change estimates for the European energy system

The ADAM project (Adaptation and Mitigation Strategies: Supporting European Climate Policy) simulates adaptation and mitigation options and their related costs for Europe until 2050 and 2100, respectively (Work Package Mitigation 1 (M1); Jochem and Schade, 2009). The M1 group assesses the impacts of climate change on the European energy system. They identify the impact of climate change by subtracting a baseline scenario without climate change from a reference climate scenario that results in a 4°C average increase in surface temperature until 2100. The reference scenario assumes constant present policy trends in energy and a moderate climate policy. While the M1 group interprets the difference between the two scenarios as adaptation costs, they do not include specific adaptation responses beyond changes in energy generation and consumption. The costs estimated by the M1 group are therefore better described as costs of climate change instead of adaptation costs.

The results of the M1 group of the ADAM project indicate that the impact of a 4°C temperature increase during the 21st century on the European energy system is small, in particular until 2030. Due to the warmer climate in the reference scenario, the final net energy demand of Europe is reduced by about 3.3% in 2050 relative to the base scenario without climate change. Total energy costs (composed of costs for fuel and electricity) are projected to drop by EUR 16 billion in 2035 and by more than EUR 27 billion in 2050 – Table 9 provided an overview. (The M1 report nets those costs with yearly investment estimates, which suggests that those costs can be interpreted as annual costs.)

The benefits from reduced energy demand, in particular the reduced demand for heating fuels due to higher temperatures, contrast with increased electricity demand and investment needs in air conditioning and cooling and in thermal power plants whose efficiency is negatively affected by decreased precipitation and higher temperatures. Using bottom-up energy sector models, the M1 group estimates the additional investment needs for conventional thermal generation to be about EUR 1 billion per year. The additional yearly investments in air conditioning and cooling in Europe are projected to exceed EUR 8 billion in 2050 (see Table 9). Adding those costs means that Southern countries bear net costs, while Western ones still enjoy the benefits from reduced energy demand (Table 9). Although run-off water from increased precipitation could increase the potential for hydropower, the M1 group finds no big changes in hydro-power investments. Finally, the group notes that there will be an increased risk of electricity supply disruptions associated with extreme weather events, but no quantitative calculations have been made on this issue.

Table 9. Additional costs in the energy sector due to climate change in 2035 and 2050 in billion EUR; AC stands for additional investments in air conditioning and cooling.

Region	2035				2050			
	Fuels	Electricity	AC	*Net effect*	Fuels	Electricity	AC	*Net effect*
North	-1.08	-0.16	0.20	-1.04	-1.65	-0.25	0.40	-1.50
West	-13.29	1.20	2.90	-9.19	-21.75	1.21	4.40	-16.14
Central-East	-1.81	0.22	0.30	-1.29	-3.16	0.27	0.50	-17.64
South	-5.31	4.62	2.70	2.01	-8.42	6.08	3.20	0.86
Total Europe	-21.48	5.88	6.10	-9.50	-34.98	7.32	8.50	-19.16

Source: Jochem and Schade (2009).

The report also estimates the energy-related effects of climate change on GDP. However, the results are dominated by an assumption about extreme weather events which had been adopted as a sensitivity analysis. Since no disaggregated results are provided and the authors express no trust in their GDP results (Jochem and Schade, 2009, Chapter 8, p.226), the effects are not discussed here.

The ADAM-M1 study on adaptation of the energy sector to climate change has several limitations. First, the study adopts a very narrow definition of adaptation as the costs of climate change in a scenario without mitigation. A full cost-benefit analysis of specific adaptation options in the energy sector could therefore result in different estimates. Second, the study aggregated various results from different energy sector models which differ significantly in their estimates. For example, it was found in the study that the projections for electricity demand differ by up to 30% between the POLES model and other bottom-up models. A clearer indication on the drivers of the specific estimates would therefore be desirable. Third, the adaptation part of the M1 report was not published in a peer-reviewed journal. Parts of it are still in manuscript form and lack clarity in writing and in discussing results. This makes reviewing the report difficult and potentially sensitive to errors.

Adaptation-cost estimates for electricity-generating technologies

A study carried out by Ecorys in consortium with ECN and NRG for the Directorate-General for Energy in the European Commission (EC, 2011) estimates the investment needs to adapt the EU's electricity sector (electricity generation and distribution) to climate change. The study derives adaptation-cost functions on the basis of interviews with stakeholders in the electricity industry, literature reviews, and internal resources. Those cost functions include technology-specific investment cost and threshold values for which climate-change effects generate an investment need. The technology-specific adaptation-cost functions are applied to the EU electricity demand and the associated climate conditions in the year 2080. For this purpose, the study uses three regional climate scenarios (for the year 2080) based on the A1B climate scenario of the IPCC. It divides the EU-27 countries into four regions and constructs eight climate-change indicators which it pairs with the electricity-generation technologies affected by the associated changes. Finally, the study uses the

Eurelectric baseline scenario to project the electricity demand forward to the year 2050 (the inconsistency in time horizon introduces possible bias which is remarked on below).

The study estimates that EUR 15-19 billion per year are necessary (from now until the year 2080) to adapt EU's electricity sector to climate change in the year 2080. The largest investments will be needed for electricity generation from off-shore wind to adapt to sea-level rise (over EUR 4 billion), followed by investments in electricity grids to adapt to more intense storms and higher temperatures (EUR 2-4 billion). The increased incidence of flood impacts on thermal power plants (nuclear, biomass, and fossil-fuel based) amount to EUR 3-6 billion. Although several European regions have been considered in the report, no regionally disaggregated cost estimates are provided in the final report.

The study has several limitations. First, the documentation is lacking clarity and rigor, which obscures important modelling assumptions. Apparently, no attempt was made to publish the study in a peer-reviewed journal, which would have given the study greater credibility and robustness; for example, it is absolutely silent about its own limitations. Second, the electricity scenario was projected forward only to 2050, while the climate scenario was projected forward to 2080. This could introduce considerable bias as more renewable resources are expected to be installed until 2080 which, in the present analysis, have higher adaptation-investment needs. The investment estimates might therefore be underestimated. Third, it is not clear whether the investment flows were estimated in a dynamic analysis. Both electricity demand and climate indicators are available for multiple time steps which could be used in a dynamic analysis. The disadvantage with a static one is that it is not clear when investments need to be made. For example, the (delayed) effects of climate change will likely not affect current electricity-generating stocks, but the ones going into operation from 2030 onwards. A dynamic analysis could resolve those timing issues. Fourth, the study does not take into account potential technological innovation. Instead it assesses adaptation costs at current state of technology. However, the engineering and CGE literatures indicate that technological innovation can have a significant effect on future costs and composition of technology shares. Fifth, the study's narrative suggests a pro-nuclear bias, which might be due to the involvement of the Nuclear Research and consultancy Group (NRG). However, it is not clear whether this bias in the presentation of the results also affected the generation of the results. Lastly, the study only reports average values in its final report, which makes it impossible to produce different aggregations and conduct further sensitivity analyses. It also leads to the strange situation that an announcement of the study by ECN contains more detail about the range of values (on half a page) than the whole final report (224 pages). Taking into account those limitations, the study's result should be taken with a grain of salt. However, they present a first indication of potential investment needs to adapt the electricity sector differentiated by generation technologies to future climate change.

In comparison to the ADAM-M1 study (Jochem and Schade, 2009) reviewed above, the study commissioned by DG Energy (EC, 2011) does not include possible changes in the demand for heating fuels. The ADAM-M1 study indicates that reduction in the demand for fuels due to higher temperatures could offset the increased expenditure for electricity needed for cooling. While the DG-Energy study contains a more explicit treatment of climate-change effects that also include sea-level rise and changes in wind speeds, it focuses on impacts on the electricity system and not the energy system as a whole. Trading-off costs and benefits across the energy system might require regulation to realise those trade-offs across energy-service providers.

In summary, the studies reviewed indicate that climate change will have a variety of impacts on the energy system. Higher average temperatures are likely to result in monetary benefits due to a reduction of the demand for heating fuels. On the other hand, electricity demand is expected to increase due to higher demand for air conditioning and cooling. While the ADAM-M1 (2009) study indicates that climate change could have net benefits when taking into account those effects and a small projected decrease in the efficiency of thermal power plants, studies focussing on the electricity sector alone paint a different picture. The DG-Energy (2011) study indicates that investments in the European electricity system of EUR 15-19 billion per year could be needed by 2050 (anticipating the climatic conditions of 2080). The majority of investment needs are expected to fall onto private utility companies and energy-service providers. However, as those utility companies make, in general, frequent use of loans, guarantees and other financial instruments, it can be expected to involve, at least indirectly, the public realm. Governments are also directly involved in the sector due to regulatory policies. Indeed, there is the need for public policies and regulation to build resilience to climate change of the energy system as a whole. The development of a pan-European electricity grid and the drafting of energy strategies that take into account adaptation and mitigation measures are but two examples.

3.6. Tourism

Europe is the world's leading continent in tourism activity and tourism is one of Europe's largest sectors (Todd, 2003). The largest single flow of tourists within Europe is the mass transfer during summer from the colder northern regions of Europe to the warmer southern regions of the Mediterranean (Todd, 2003).

Climate is not the only determinant of tourism (Lohmann and Kaim, 1999). However, tourism is closely linked to climatic contrasts of the source and destination countries that drive demand for summer vacations in Europe (Viner, 2006). Hanson et al. (2006) therefore expect conditions for tourism to improve in northern and western Europe. On the other hand, summer tourism may decrease in the Mediterranean due to higher temperatures (Amelung and Viner, 2006). Shifts of tourism flows from south to north during the summer are also indicated by Hamilton et al (2005). With respect to winter tourism, climate change is expected to lead to disruptions of (traditional) winter tourism due to reduction in snow cover in the ski areas of central Europe and the Alpes (Hantel et al., 2000; Elsasser and Burki, 2002; Beniston et al., 2003).

There are several measures to adapt tourism to climate change. For summer tourism, promoting changes in the temporal pattern of seaside tourism, e.g. by encouraging visits during cooler months, may compensate the expected reductions in summer-tourism flows to the Mediterranean (Amelung and Viner,

2006). Other adaptation measures include promoting new forms of tourism, such as eco-tourism or cultural tourism (Hanson et al., 2006), as well protecting coastlines with barriers and dikes or moving tourism infrastructure further back from the coast (Pinnegar et al., 2006).
For winter tourism, the retreat of snow cover may be adapted to by landscaping and slope development, a move to higher altitudes and north-facing slopes, glacier skiing, and artificial snow making (Agrawala, 2007). Behavioural adaptation strategies could include the diversification of activities (Fukushima et al., 2002).

While the physical impacts of climate change on tourism are studies primarily for summer tourism in Europe (see Alcamo et al., 2007), adaptation-cost studies have mainly focussed on winter tourism and the ski industry (Agrawala et al., 2008). For example, Mathis et al. (2003) found that high-mountain extensions of ski areas in Switzerland would cost between EUR 25-30 million. The investment costs for snow-making material in France in the 2003-2004 winter season reached EUR 60 million (Agrawala et al., 2008). However, Alcamo et al. (2007) and Agrawala et al. (2008) note that such adaptation strategies might not be sustainable in the long term (in light of retreating snow cover and glaciers) and generate negative externalities that have detrimental environmental impacts. For example, artificial snow making impacts water supplies and increases energy consumption with the further impacts on greenhouse-gas emissions (Abegg et al., 2007).

For the PESETA (2009) study, Amelung and Moreno (2011) assess the impact of future 2080s climate change on today's tourism industry (concentrating on summer and off-season tourism, but without explicit consideration of winter tourism). Their analysis follows two steps. In the first step, changes in bed nights due to climate change are calculated by a regression analysis based on suitability estimates of present and future climates to tourism (as expressed by the Tourism Climatic Index, TCI). In the second step, the economic impacts of changes in tourism flows are obtained by multiplying the change in the number of bed nights by the country-specific average expenditure per bed night. Several scenarios are considered. Those include a fully flexible tourism scenario which allows for flexible demand for bed nights across seasons, a scenario with fixed tourism volume which assesses the distributional effects of climate change on tourism within Europe, and a scenario with fixed seasonal distribution of bed nights and fixed volume that mimics existing institutional constraints, such as holiday seasons for schools.

The results indicate positive effects (in terms of increased bed nights) in most areas of Europe except Southern Europe across several climate and tourism scenarios. In the fully-flexible tourism scenario, the benefits range from EUR 2-15 billion depending on the climate scenario (Table 10) – this constitutes a change of up to 8% relative to the bed nights registered in 2005. Central Europe South enjoys the greatest increases in bed nights (valued at EUR 9-10 billion), while Southern Europe shoulders the greatest losses (valued EUR 0.8-5 billion). Those receipts and losses are the monetization of the change in tourism flows that is expected to occur between 2005 and the 2080s holding economic conditions constant.

Table 10. Changes in expenditure receipts in the 2080s, central tourism scenario (billion EUR).

Region	Climate scenario (temperature change)			
	2.5°C	3.9°C	4.1°C	5.4°C
Northern Europe	0.4	0.6	1.9	2.4
British Isles	0.7	0.9	3.6	4.5
Central Europe North	0.6	0.9	3.2	4.2
Central Europe South	0.9	1.8	7.7	9.6
Southern Europe	-0.8	-1.0	-3.1	-5.4
Total EU	1.9	3.3	13.4	15.3

Source: Ciscar et al. (2009) and Amelung and Moreno (2011).

The other tourism scenarios yield very different aggregated results. The tourism scenario with fixed tourist volumes discards the extra tourist demand in Europe that was projected in the main scenario. The overall EU impact is therefore a redistribution among its regions with no net effect (similar to a 'zero-sum' game). This scenario lowers the benefits for Central and Northern Europe and accentuates the losses of Southern Europe. The tourism scenario with fixed seasonal demand patterns (and fixed overall volumes) yields similar results than the previous scenario, but mildly increases the redistribution of bed nights among EU member states.

The study by Amelung and Moreno (2011) has several limitations. First, it's assessment is based on an index of thermal comfort, which ignores other climate-change-related factors affecting tourism, such as water availability, landscape, biodiversity, beach erosion, and deterioration of monuments. Amelung and Moreno (2011) also concede that the understanding of tourists' preferences with respect to climate and weather conditions remains very limited. Second, the results obtained differ considerably between climate scenarios, which underlines the general uncertainty associated with the estimates. Third, winter sports were not covered in the assessment. The omission of potential trade-offs between summer and winter holidays could mean that the estimate for regions with high proportion of winter sports, such as Austria, could be an overestimate. Fourth, the authors state that the predictive value of the econometric model used is not very large. This suggests that important determinants may be missing and indicates that the uncertainties associated with the results are large. Fifth, the authors suggest that another source of uncertainty stems from the quality of data used. In particular, there have been very large differences between the average receipts per tourist night which could not be explained by differences in price levels and wealth between countries. Sixth, the study ignores the potential economic development until the 2080s and does not model changes in tourism unrelated to climate change that might occur during that time horizon. Finally, the study only considers spatial and temporal adaptation by tourists, which ignores other adaptation options by tourists (e.g. staying inside) and the tourist industry (e.g. diversification of offers). Because of those omissions, the authors state that the impacts of climate change on tourism in Europe may well have been overestimated.

A few studies attempt to estimate the economy-wide effects of climate-change induced changes in the tourism sector. Ciscar et al. (2011) assess the economy-wide impacts of the changes in tourism flows estimated by Amelung and Moreno (2011). They interpret the changes in expenditure per country as changes in exports of the "Market services sector" in their CGE model (GEM-E3). Ciscar et al. (2011) find that the impact on EU GDP due to the effects of climate change on tourism is very small (see Table 5). The "Other market services" sector sees an increase in production of around 0.1%, but that is not enough to greatly affect GDP and welfare.

Berrittella et al. (2006) arrive at quite different results than Ciscar et al. (2011). They use a basic CGE model (GTAP; Hertel, 1999) and implement changes in international tourism flows as changes in expenditure for market services (which is similar to the methodology followed by Ciscar et al. (2011)). Their target year is 2050 for which they project forward population growth and economic development (following the SRES A1 scenario). The changes in tourism flows are adapted from Hamilton et al. (2005) who use an econometric model for their projection. The results of Berittella et al. (2006) indicate that the EU could experience positive effects in the short and medium term (2010-2030), but negative effects in the long term (2050) due to climate-change induced changes in tourism. In particular, private households are projected to gain USD 0.3 billion in 2030 (expressed at constant 1997-USD), but to loose more than USD 9 billion by 2050. GDP is projected to decrease by 0.1% in the EU by 2050 with respect to the baseline year 1997 and the welfare measure of equivalent variation of income indicates a change from USD 20 million to USD -10 billion between 2010 and 2050.

The substantial losses indicated for the EU by 2050 by Berrittella et al. (2006) are in stark contrast to the positive effects found by Amelung and Moreno (2011). One of the reasons for this difference can be explained by the econometric models underlying both analyses. While Amelung and Moreno (2011) focus on thermal comfort, the model devised by Hamilton et al. (2005) and used by Berrittella et al. (2006) takes into account also the effects of temperature change on winter tourism. In particular, their model resolves the effect that if a cool country gets warmer, it first attracts less tourists until it gets warm enough and generates more tourists. This might explain part of the more negative estimate obtained by Berrittella et al. (2006). Anther reason could be the different climate scenario used. While Amelung and Moreno (2011) consider the effect on tourism in four different global-warming scenarios, Berrittella et al. (2006) only consider the SRES A1 scenario which exhibits a comparatively minor global warming of 1°C in 2050 compared to 1997. In comparison, the low-end of global warming considered by Amelung and Moreno (2011) is 2.5°C. Other differences include that Berrittella et al. (2006) explicitly resolve international tourist flows, whereas Amelung and Moreno (2011) concentrate mainly on intra-EU tourists (something also projected to decline in the EU by Hamilton et al. (2005)). However, both econometric models are admittedly simple and it would be a fruitful exercise to devise a detailed model comparison.

Finally, the model by Hamilton et al. (2005) and the study by Berrittella et al. (2006) take into account economic development and population growth, something totally ignored by Amelung and Moreno (2011) and Ciscar et al. (2011). Taking into account those factors, Hamilton et al. (2005) find that the change in tourism flows induced by climate change is smaller than that induced by population and income changes.

In summary, the assessments of the effects climate change has on tourism are still very coarse. The PESETA study (Amelung and Moreno, 2011) indicates significant benefits for the EU of up to EUR 15 billion if the climate change of the 2080s would be experienced today. However, this number was obtained in a scenario in which tourists can adjust their holiday times flexibily. In more institutionally rigid scenarios, the same study assumes no net effect for the EU as a whole, but estimates increasing losses for Southern Europe. The latter fact is replicated by other studies (e.g. Berrittella et al., 2006), albeit with different results in aggregate. Given that aggregate estimates range from positive to negative, it is not possible to provide a conclusion even on the direction of change for the EU as whole. What is clear is only that tourism in Southern Europe, in particular in the Mediterranean, will suffer with increasing temperatures, while Central and Northern Europe might benefit. No clear adaptation-investment needs can be identified as adaptation options range from autonomous adaptation of tourists (Sievanen et al., 2005) to diversification of the tourism sector as a whole. The direct incidence of the costs of climate change and of potential adaptation measures is on the private sector. However, economy-wide losses (or benefits) are possible.

3.7. Coastal system

The economic impacts that climate change is expected to have on coastal systems is relatively well studied. Part of the reason might be economic vulnerability. The value of economic assets within 500 m of the EU coastline is estimated at EUR 500-1000 billion. One third of the EU population lives within 50 km of the coast and 35% of the total GDP of the 22 European coastal member states is generated in that area – this amounts to EUR 3.5 trillion (EC, 2009c).

Climate-change impacts relevant for coastal systems include rise in sea level, changes in temperature, the direction and power of waves, wind, precipitation and ice-cover, as well as an increase in extreme weather events (IPCC, 2007). Despite those multitude of impacts, most studies on climate-change impacts on coastal zones have concentrated on sea-level rise (SLR). But also SLR can have a variety of consequences, including flooding, coastal erosion, the loss of flat and low-lying areas, enhanced saltwater intrusion and an endangerment of coastal eco-systems (EEA, 2008).

The most detailed estimates of the costs for adapting coastal systems to climate change have been made with the Dynamic Interactive Vulnerability Assessment (DIVA) model (Hinkel and Klein, 2006; http://diva-model.net). The DIVA model is an integrated model of coastal systems that assesses biophysical and socioeconomic impacts of sea-level rise (SLR) and socioeconomic development. It assesses the physical impacts of SLR on four categories: dry land loss caused by coastal erosion, flooding caused by surges and the backwater effect on rivers, salinity intrusion in deltas and estuaries, and coastal wetland change and loss.

The DIVA model evaluates the impacts of SLR in socioeconomic terms, such as forced migration and people affected by sea floods. It also assesses the economic impacts. Costs are categorized as total damage costs, optimal adaptation costs, and residual damage costs, i.e., damage costs that remain despite adaptation. For the economic-impact assessment, the DIVA model explicitly incorporates a range of adaptation options, the two main ones being dike building/raising and beach/shore nourishment. Adaptation costs are estimated by a cost-benefit framework and, hence, represent the costs needed to achieve an optimal level of protection and adaptation. This differs from full adaptation, since an optimal adaptation strategy might consider adapting to all climate impacts infeasible and economically inefficient as bearing some degree of residual damage might be tolerable and cheaper in monetary terms.

Although much coastal infrastructure may be private (e.g., buildings and homes), efforts to protect coastal areas from coastal storms and sea level rise are typically undertaken by government, thus publicly-funded. Similarly, the adaptation measures considered in the DIVA model (dike building and beach nourishment) can be considered to be largely publicly funded. The DIVA results therefore directly indicate public investment needs. Caveats of this approach are the omission of other adaptation responses or “soft” adaptation measures associated with changes in resource management – those are noted in more detail below.

The following reviews three DIVA-based studies. Those include the coastal-systems studies undertaken within the PESETA (2009) and UNFCCC (2007) projects, as well as an exploration of the effects of high-end SLR by Nicholls et al. (2011). Those direct adaptation-cost estimates are then compared to economy-wide impact analyses by Bosello et al. (2007, 2011), Darwin and Tol (2001), and Deke et al. (2001).

PESETA estimate

As part of the PESETA project Richard and Nicholls (2009) use the DIVA model to assess the adaptation costs of sea-level rise (SLR) for the European Union for a range of climate scenarios in the 2020s and the 2080s. The climate scenarios cover a range of socioeconomic variables and are associated with SLR in 2100 relative to 1990 ranging from 19.4 cm (HADCM3-B2) to 58.5 cm (ECHAM4-A2) in the PESETA-specific climate scenarios. Those scenarios are supplemented by generic IPCC scenarios from the Third Assessment Report (TAR; Church et al, 2001) which are associated with SLRs in 2100 ranging from 9 cm (B2) to 88 cm (A2).

Table 11. Additional adaptation costs due to sea-level rise in the EU (million 1995-EUR per year).

Sea-level-rise scenario	Additional costs of SLR with adaptation (million EUR per year)				without adaptation (million EUR per year)	
	A2		B2		A2	
	2020s	2080s	2020s	2080s	2020s	2080s
IPCC Low	41	-9	42	-12	1,335	1,841
IPCC High	804	2,320	807	2,350	3,077	36,040
ECHAM4 Low	175	635	237	361	1,809	3,352
ECHAM4 Medium	356	1,012	392	707	2,407	5,230
ECHAM4 High	564	1,429	608	1,051	2,880	10,066
HADCM3 Low	145	518	207	246	1,762	3,070
HADCM3 Medium	322	906	387	629	2,340	4,591
HADCM3 High	527	1,382	598	1,005	2,727	9,814

Source: Richard and Nicholls (2009); see also Bosello et al. (2011).
Note: Costs are calculated by subtracting the costs of (optimal) adaptation under the scenario without climate change from the costs of (optimal) adaptation under each sea-level rise scenario.[8]

Table 11 provides an overview of adaptation costs in the different scenarios considered. For the IPCC scenarios, the results indicate adaptation costs ranging from almost zero to EUR 0.8 billion per year in the 2020s and to EUR 2.3 billion per year in 2080s respectively. The adaptation costs of the PESETA-specific climate scenarios lie in between those associated with the IPCC low and high SLR scenarios and range from EUR 0.14 billion per year to EUR 1.4 billion per year. In general, adaptation costs increase over time and with SLR. These estimates represent the additional adaptation cost to SLR due to climate change. In particular, the study isolates the effect of SLR by subtracting a no-SLR reference scenario from the SLR scenarios considered. This way of calculating adaptation costs accounts for effects of economic development and existing development deficits during the model's timeframe.

To put those numbers into perspective, Richard and Nicholls (2009) also report the total damage costs that would occur if no adaptation measures were implemented (Table 11). Those costs amount to EUR 1.3-3.1 billion per year until the 2020s in the IPCC low and high SLR scenarios and to EUR 1.8-36.0 billion per year until the 2080s. Implementing adaptation measures reduces those damage costs by 74-97% in the 2020s and by 94-100% in the 2080s; it also reduces almost completely the need for people to migrate due to SLR. Some residual damage costs remain, ranging from EUR 0.8-2.2 billion per year, but for most scenarios (with the exception of the IPCC high SLR scenario in the 2080s) they remain below the residual damage costs in the model's base year of 1995 and could therefore be seen as reflecting (pre-)existing adaptation deficits.

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[8] To explain negative numbers, Bosello et al. (2011) note that there are some damages without climate-induced sea-level rise due to uplift and subsidence. Therefore some areas experience relative sea-level rise without climate change and flooding and salinisation also occur under the present climate. There are also some adaptation costs without global sea-level rise due to a combination of responding to relative sea-level rise due to uplift and subsidence, and dike upgrade due to increasing risk aversion with rising living standards. The costs of habitat change and loss or possible adaptation costs for coastal habitats are not considered.

Richard and Nicholls (2009) conclude that Europe is potentially highly threatened by sea-level rise and that adaptation can greatly reduce the associated impacts. As caveats of their analysis, they note that the adaptation options considered in DIVA are not comprehensive and lack, e.g., soft adaptation measures aimed at changes in flood management, as well as sustainable management techniques, such as the creation of flood storage areas. General uncertainties are associated with the projected level of SLR, the availability and quality of coastal data at the European scale, the resolution of coastal segments, the lack of considering land-use change during the model horizon, and the exclusion of uncertainties due to ice-sheet instability and melting in Antarctica (see e.g. Church et al., 2001). Another uncertainty might be connected to the costs of adaptation measures which, in the case for dikes, are assumed to be constant, i.e., to only rise with inflation based on the view that dike-building is a mature technology. However, increased demand for dikes or beach nourishment and potential supply constraints could lead to increases in prices which are not considered in the DIVA model.

Comparison with other DIVA studies

The EU-focused results obtained by Richard and Nicholls (2009) for the PESETA project can be compared with other applications of the DIVA model. In the following, two further studies are considered: one study that was conducted as part of UNFCCC's report on 'Investment and Financial Flows to Address Climate Change' (Nicholls, 2007) and a recent assessment of the possible effects of sea-level rise associated with a 'beyond 4°C world' (Nicholls et al., 2011).

UNFCCC adaptation-cost estimate for OECD Europe

For the UNFCCC, Nicholls (2007) uses the DIVA model to assess the financial needs for coastal adaptation in 2030 due to climate change. Investment needs in 2030 were analysed for two planning scenarios, one assuming that decision makers plan for sea-level rise out to 2080 and one with no anticipation of SLR. The UNFCCC report considers two climate scenarios: a business-as-usual scenario (SRES A1B) and a mitigation scenario (SRES B1). For each scenario, the mean and maximum SLR was implemented into the DIVA model, i.e., up to 53 cm above 1990-levels in the A1B scenario and up to 44 cm in the B1 scenario.

The development path was calibrated to the socioeconomic conditions of the A1B scenario. As for the PESETA study, the cost estimates represent the additional investment needs to adapt to climate-change-induced SLR. For that purpose, the reference development path without SLR was subtracted from the SLR-scenario results. (The no-sea-level-rise estimate includes the costs of adapting to subsidence and flooding not induced by sea-level rise.)

The results indicate that additional adaptation costs for OECD Europe in 2030 amount to USD 0.6-0.7 billion for the SRES scenarios B1 and A1B respectively not taking into account anticipation of future SLR, and to USD 1.6-1.8 billion taking into account future SLR in 2080. Nicholls (2007) notes that planning for

SLR in100 years rather than in 50 years would increase costs by about two thirds, since dikes would have to be build higher in anticipation of greater SLR.[9]

The results obtained for the UNFCCC report cannot be compared directly with the PESETA results due to difference in climate and planning scenarios, target years, and regional aggregation. In addition, for the PESETA study Richard and Nicholls (2009) have increased the costs of beach nourishment from the standard costs to a higher European average to adapt the global DIVA model to the European context.

Despite those differences, the order of magnitudes of adaptation costs obtained in the PESETA study and in the UNFCCC report are broadly in line with each other. The USD 0.6-0.7 billion of adaptation costs estimated for OECD Europe in 2030 assuming no adaptation are the same order magnitude as the EUR 0-0.8 billion of adaptation costs estimated for the EU in 2020, whereas the costs estimated for OECD Europe in 2030 assuming anticipation of SLR in 2080 (USD 1.6-1.8 billion) approach the costs estimated for the EU in the 2080s (EUR 0-2.3 billion). This similarity suggests at least internal consistency between studies using the same model (DIVA) as assessment framework.

Possible effects of sea-level rise associated with a ‘beyond 4°C world’

As part of a review of the UNFCCC adaptation-cost estimates, Nicholls (2009) comments on his own study made for the UNFCCC (2007) report. He notes that the UNFCCC results are underestimates if responses to high-end SLR and extreme events are considered. Accounting for the former could roughly double global adaptation costs and considering both, high-end SLR and more intense storms, could triple the estimate.

Nichols et al. (2011) offer a more comprehensive assessment of high-end SLR and its effect on adaptation costs. They explore the potential consequences of SLR associated with a beyond 4°C scenario. In reviewing recent global SLR estimates, they suggest a pragmatic range of 0.5–2m for twenty-first century global sea-level rise, assuming a 4°C or more rise in temperature. (They also note that “since it is not certain that recent observed increases in ice discharge from the ice sheets will continue to accelerate, we must also be clear that the upper part of this range is considered unlikely to be realized.”)

They assess the potential impacts of this magnitude of SLR (0.5-2m SLR by 2100) as bounding cases using the DIVA model. As SLR impacts they focus on the effects of flooding/submergence and erosion; further modifications of the modelling framework include the accounting for maintenance costs for dikes (about 1% per year) which can become significant cost component by 2100, as well as a parameterisation for the abandonment of coastal zones obtained from the FUND model.[10]
Nicholls et al. (2011) estimate the additional adaptation costs for the globe to be about USD 25-270 billion (1995 values) per year for a 0.5-2.0m SLR in 2100.

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[9] Sea-level rise is expected to rise exponentially with temperature change which itself is projected to increase with time.

[10] FUND estimated that 25 per cent of the developed coastal zone is abandoned if the costs of protection increased fourfold (Nicholls et al., 2008), and this correction is applied for the 2m rise scenario.

Although they do not present a detailed regional disaggregation, they list the percentage shares of global adaptation costs per coastal region. Aggregating the European ones, i.e. the Baltic Sea (3%), northern Mediterranean (2-2.3%), north and west Europe (10-12%), yields a total share of adaptation costs for Europe of about 15-17.3% which, in absolute terms, amounts to USD 3.75-46.71 billion per year to adapt to a 0.5-2m SLR in 2100.

Again, direct comparisons of this beyond 4°C estimate with earlier assessments made within the UNFCCC and PESETA projects are complicated by the use of different climate scenarios, target years, and methodological extensions. However, all three estimates cover a similar region[11] and they have all been conducted with the same assessment tool (DIVA). A partial comparison should therefore be possible.

Table 12. Comparison of adaptation-cost estimates.

Year	SLR (cm)	Adaptation costs (billion (1995-)USD per year)	Reference
2020s	2 - 12	0 - 0.8	PESETA (2009); Richards and Nicholls (2009)
2030	15 - 53	0.6 - 1.8	UNFCCC (2009); Nicholls (2009)
2080s	6 - 67	0 - 2.3	PESETA (2009); Richards and Nicholls (2009)
2100	50 - 200	3.8 - 46.7	Nicholls et al. (2011)

Table 12 lists the ranges of adaptation costs associated with different levels of SLR contained in the climate scenarios considered. Notable from the table is the increase of adaptation costs over time, from about USD 0.3-1.2 billion in the 2020s to about USD 0.4-3.6 billion in the 2080s and possibly to about USD 3.8-46.7 billion by 2100 in case of high-end SLR.

The cost ranges obtained above can be compared with other impact-based cost estimates that utilize different models. For example, Tol (2002a) presents estimates of optimal coastal protection costs in a static impact analysis that considers SLR of 1m. He follows a cost-benefit approach taking into account the capital costs of protective construction, the costs of foregone land services (of dryland and wetland), and people migrating due to SLR. Results indicate an optimal level of coastal protection of 86% for OECD-Europe and a total cost of protection of USD 1.7 billion per year (with a standard error of USD 0.5 billion per year). Those costs represent average costs per year over the twenty-first century. Tol (2002a) uses some crude assumptions to calculate the level of protection (see Fankhauser, 1994) and a lower-quality database compared to the latest estimates reviewed above. This might explain why his estimate is considerably lower than the one obtained by Nicholls et al. (2011) who also analyzed, among other things, a 1m SLR. Despite the difference in methodology

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[11] There is a difference in coverage between OECD Europe and PESETA's EU coverage regarding 8 countries; the overall number of countries included in both sets is the same.

and database, the cost estimate of Tol (2002a) still lies within the same order of magnitude.

Earlier assessments are summarized in Tol et al. (1998) but omitted here in the interest of space and to focus on the studies reviewed above that use the most up-date methodology and data.

Indirect cost effects on the whole economy

The studies on adaptation-cost estimates reviewed above assess the direct costs of adaptation of coastal areas to SLR resulting from climate change. However, they generally do not take into account indirect effects resulting from changes in prices and influences that one market has on others. In particular, increased or decreased demand for a good could change its price; the resulting market adjustment could have further repercussions on other connected markets. Such economy-wide cost estimations have been undertaken with computable general-equilibrium (CGE) models – examples include Bosello et al. (2007, 2011), Darwin and Tol (2001), and Deke et al. (2001).

Instead of providing cost estimates in absolute numbers, those studies usually report the effects on a country’s welfare or GDP level in percentage terms. In principle, those percentages can be converted into absolute numbers, but unlike the direct costs those numbers cannot be interpreted as optimal adaptation costs, but should be rather seen as possible costs or benefits (in terms of costs forgone) for the whole economy.

There is no clear relationship of the economy-wide impacts and the investments necessary to optimally adapt to climate change. However, they provide a more complete indication of the residual costs that occur despite adaptation. In particular, CGE analyses can estimate the residual costs that fall on the whole economy instead of the residual costs of a single sector as estimated by studies using the direct-cost method reviewed above. The following contains a brief review of the CGE studies focussing on adaptation to SLR.

Darwin and Tol (2001) illustrate the limitations of the direct-cost method. They combine estimates from two models (FUND and FARM) to compare direct costs with economy-wide impacts resulting from a 0.5m SLR in 2050 that is projected on the economic conditions of 1990. A cost-benefit framework considering the capital cost of protective construction and the costs of forgone land services (for dryland and wetland) is used to calculate the optimal level of coastal protection. Their results indicate that global costs to the whole economy (measured by equivalent variation) are 13% higher than direct costs estimated with the same models. For the European Community (EC) they estimate direct costs of USD 0.55 billion per year (assuming a 1% discount rate and a time horizon from 1990 to 2050) and economy-wide costs of USD 0.84 billion per year. Both estimates are within the ranges of the latest direct-cost studies that have been reviewed above. However, direct comparisons are hindered, e.g., by the absence of baseline development in Darwin and Tol (2001). Therefore the percentage difference between direct and economy-wide costs carries more weight than the absolute numbers.

The economy-wide estimate is higher, because it takes into account two effects: higher prices that are generated by the loss of endowments due to SLR; and spillover effects generated by international trade which redistributes losses from regions with relatively high damages (e.g. Asia) to regions with relatively low ones (e.g. Europe). The existence of spillover effects imply that also regions without coastlines are likely to be economically affected by SLR. Finally, Darwin and Tol (2001) highlight the sensitivity of direct-cost estimates to the uncertainty about the value of land and capital endowments threatened by SLR. However, it should be noted that this sensitivity also affects economy-wide estimates.

Deke et al. (2001) use a recursive-dynamic CGE model (DART) to estimate the economy-wide implication of a SLR. (They also assess the effect of climate change on agriculture.) Their analysis considers the costs of full coastal protection and trades off unproductive coastal protection with productive net investment. As input into their CGE analysis, they estimate that Western Europe will spend USD 176 billion for total protection of coasts against a 1m SLR between 1990 and 2100. This compares with the total (undiscounted) protection costs of USD 136 billion estimated by Tol (2002a). Deke et al. (2001) then calculate the protection investment per GDP (in percent) and use this as input to their CGE model to analyze the impact of a SLR of 13 cm in two CO2-emission scenarios. Results indicate small welfare reductions for Western Europe of 0.006-0.011% (in terms of equivalent variation). However, it should be noted that their SLR scenario is on the low-end of earlier projections which have been revised considerably upwards since 2001 (see, e.g., Nicholls et al., 2011). A further caveat is Deke et al.’s rather simplistic method of representing the effects of SLR which ignores land loss, migration, and salt-water intrusion, among others. Their estimate should therefore be seen as a first exploration of the issue.

Bosello et al. (2007) follow a similar method as Darwin and Tol (2001). They use the physical impacts of land losses and direct-cost estimates of coastal protection obtained with the FUND model to simulate the general-equilibrium effects with the GTAP-EF CGE model. Compared to Darwin and Tol (2001), they use newer data on national production and international trade. Another difference is that Deke et al. (2001) and Darwin and Tol (2001) model investments in coastal protection as general loss of productive capital; Bosello et al. (2007) state that this way of accounting for protection investment overstate the negative impact of SLR, since both papers ignore the induced investment demand for coastal protection. Bosello et al. (2007) model coastal protection explicitly as additional investment, which takes into account those induced demand effects. In contrast to Darwin and Tol (2001) and Deke et al. (2001), Bosello et al. (2007) assume that investing in coastal protection crowds out consumption rather than other investment. A caveat of Bosello et al. (2007) is that the CGE model used has a much cruder representation of land than the FARM model used in Darwin and Tol (2001).

Bosello et al. (2007) estimate the economy-wide effects of a SLR of 25cm in the year 2050 in a no-protection and total-protection scenario (development paths are taken into account by forward projection). Their results indicate coastal-protection expenditure of USD 11 billion in the EU and a GDP loss of 0.022%.

Spreading the protection expenditure over the modelling horizon (without discounting) yields USD 0.22 billion per year from 1997 to 2050. This amount is on the low end of estimates reviewed above. However, compared to the direct-cost studies less effects of SLR were taken into account and the simulations were based on an older database and with less regional detail. Bosello et al. (2007) compare those economy-wide costs with their own direct cost calculation and find that, in general, the economy-wide costs are larger than the direct ones. For the EU, they calculate direct costs of USD 0.19 billion; thus, the economy-wide costs of USD 0.22 billion are about 13% higher than the direct ones. This is much less than the 53% EU-specific increase found in Darwin and Tol (2001). However, Darwin and Tol (2001) used higher regional disaggregation, higher SLR, and a different methodology of investment modelling, so that results are not directly comparable.

Bosello et al. (2011) use the same model as Bosello et al. (2007) to assess the economy-wide impacts of SLR on the EU for the SLR scenarios considered in the PESETA study (Richard and Nicholls, 2009). They focus in particular on the high-SLR scenario for the year 2085 (IPCC A2). They find mixed impacts on GDP, with 11 countries gaining from increased investment in coastal protection (e.g. the UK and Denmark) and slight losses in the other countries (e.g. Poland and Finland). No aggregated results for the EU as a whole are provided.[12] A limitation of the analysis is that Bosello et al. (2011) only include the physical impacts of lost land. In the CGE model used, land is an input into production only for the agricultural sector, which ignores potential effects of SLR on infrastructure and population, among others.

In summary, the studies modelling the impacts of climate change on the coastal system provide comprehensive regional data, not only on the physical and economic impacts, but also on the investment needs in proactively planned adaptation measures, such as dike raising and beach nourishment. However, it should be noted that the DIVA studies’ focus on protective adaptation is a stylised approach which ignores lower-cost adaptation responses, such as accommodate or retreat, that might be preferable in some circumstances (Klein et al., 2001). A gap analysis by the EC Coastal Report (EC, 2009) shows that actual spending on coastal protection in the EU is not far off the projected spending needs for adaptation. Indeed, it is found that adaptation measures are undertaken together with the ordinary coastal protection activities in which exposed regions have already gained long experience. Thus, adapting the European coastal system to climate change appears to be an issue on which considerable progress has been made both scientifically and politically.

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[12] Ciscar et al. (2009) indicate potential GDP losses for the EU of 0.19-0.24% which correspond to EUR 23-29 billion (see Table 5). They use the same physical-input data and a similar methodology, but a different CGE model than Bosello et al. (2011). A direct comparison of both studies in complicated by the presentation of different regional aggregations in the respective studies. (See Section 2.2. for a detailed discussion of the CGE analysis by Ciscar et al., 2009).

4. Conclusion

At present, no study has explicitly and comprehensively estimated the overall costs of adapting Europe to climate change. What is available are adaptation-cost estimates for industrialized countries in general (UNFCCC, 2007), climate-change impact assessments for Europe (PESETA, 2009), as well as several adaptation-cost or climate impact studies on the sector level. For industrialized countries, adaptation-investment needs are estimated to be USD 22-105 billion per year by 2030 (USD 16 billion without the construction sector) (UNFCCC, 2007). For Europe, climate-proofing new infrastructure is estimated to cost EUR 4.6-58 billion (Simms et al., 2004; Stern, 2007; EC, 2009b); and the economic impact of experiencing 2080s climate change today is valued at EUR 22-67 billion (Ciscar et al., 2009). In comparison, total investments in the EU are about two orders of magnitude larger (EUR 2.6 trillion in 2008; EUROSTAT).

While those aggregate numbers seem to indicate adaptation costs in the tens of billion EUR for Europe, they have to be seen as highly indicative. In the case of first-generation studies on the construction sector (Simms et al., 2004; Stern, 2007; EC, 2009b), the estimates lack empirical grounding and follow directly from the assumption that a 1-10% mark-up on current construction costs would be needed for climate-proofing. In the case of second-generational bottom-up studies (UNFCCC, 2007; Ciscar et al., 2009), the aggregate numbers hide significant differences in the sector studies included. Those differences concern methodology, coverage of climatic impacts and adaptation options.

Sector estimates provide a clearer picture of the impacts of climate change on Europe. The valuation of future climatic impacts within the PESETA (2009) study indicates that the sectors of agriculture, river floods and coastal system are particularly vulnerable to future climate change. Yield improvements and losses in agriculture are projected to greatly affect Northern and Southern Europe, respectively. The British Isles and Central Europe North are projected to experience economic losses mostly in coastal systems and due to river floods.

While the impacts of climate change in Europe are assessed in detail, the investment needs to adapt to those impacts are largely unknown. An exception exists for coastal systems. While climate damages in coastal systems are valued in the tens of billions EUR, Richard and Nicholls (2009) suggest that adaptation measures that cost just a fraction of this amount could greatly reduce the impacts. This cautions against the use of climate-impact studies to inform adaptation-investment needs and highlights the need for more explicit consideration of adaptation measures and of the associated costs and benefits in sectoral bottom-up studies. For most sectors, adaptation-investment needs can therefore only be determined on the project level, as robust sector-wide estimates are not available at present.

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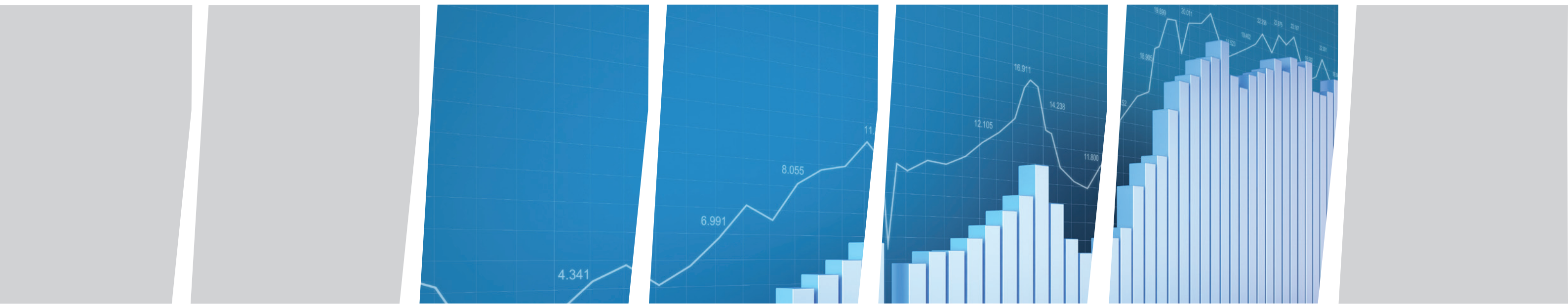

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