

## JRC TECHNICAL REPORTS

# Resilience of large investments and critical infrastructures in Europe to climate change

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*"Resilience of large investments in Europe to climate change (CCMFF)"*

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# Resilience of large investments and critical infrastructures in Europe to climate change

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## **Executive Summary**

Critical infrastructures refer to the array of physical assets, functions and systems that are vital for ensuring the EU's health, wealth, and security. Ensuring climate resilience of critical infrastructures and EU regional investments and measures is an important component of EU policies and funding mechanisms. Information on the resilience of critical infrastructures and large investments to climate change, however, is staggeringly lacking in literature. The CCMFF project aim was to fill this gap by providing insight on current and future impacts of climate extremes on the present stock of critical infrastructures in Europe and on regional investments under the EU Cohesion Policy for the 2007-2013 programming period.

The project performed the first comprehensive multi-hazard multi-sector risk assessment for Europe under climate change to identify the most vulnerable and impacted regions in Europe throughout the 21<sup>st</sup> century. The methodology applied integrates a set of coherent, high-resolution climate hazard projections, a detailed harmonized representation of sectorial physical assets, productive systems and investments, and estimates of their sensitivity based on surveyed expert opinion and literature review. The three components are linked with recorded climate disaster damages in order to derive quantitative estimates of risk under current and future climate conditions. Costs required to make infrastructures and investments climate resilient are evaluated based on possible avoided damage scenarios and cost-benefit information derived from literature.

The key findings of the study can be summarized as follows

- **Europe will see a progressive and very strong increase in overall climate hazard with a prominent spatial gradient towards south-western regions. Key hotspots emerge particularly along coastlines and in floodplains.**
- **Climate hazard impacts to critical infrastructures and EU regional investments may strongly rise in Europe: damages could triple by the 2020s, multiply six-fold by mid-century, and amount to more than 10 times**

present damages by the end of the century.

- **Economic losses are highest for the industry, transport and energy sectors. The strongest increase (>1,500% by the end of the century) in damage is projected for the energy and transport sectors, and for EU investments in environment and tourism.**
- **Floods currently account for approximately half of climate hazard damages, but in the future droughts and heatwaves may become the most damaging hazards.**
- **Substantial resources may be required to increase the resilience of critical infrastructures and EU regional investments against future climate**
- **Impact and adaptation costs do not fall equally across Europe. Southern and south-eastern European countries will be most impacted.**

Notwithstanding that the numbers presented may be subject to uncertainty, they do highlight some important issues. The distribution of economic costs in space and amongst sectors provides an indication of the regions and sectors that may face substantial efforts for making present and planned critical infrastructures resilient to future climate. The disproportionate distribution of impacts across the EU leads to the question of how these costs could be shared. A better understanding of the regional and sector distribution of impacts could aid in orienting further EU investments such that Cohesion policy also gains meaning as a burden sharing instrument for adaptation to climate change.

We further stress that the myriad of climate change impacts go far beyond those of the 7 climate hazards considered in this study; hence, it should be kept in mind that the damages presented here only reflect a fraction of the potential climate change impacts to society.

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# 1 Introduction

## 1.1 General aim and settings

Critical infrastructures represent a large economic value, both as capital asset and essential element in the functioning of the economy. Different types of infrastructures and investments have different levels of vulnerability to climate change. Moreover, as climate change impacts are manifested locally, individual assets have different hazard exposures depending on the geographic location.

The potential negative consequences of climate change and the need to increase the resilience of our society to unwelcome impacts has received increased attention in the scientific and policy debate in recent years. The EU has made strong efforts for augmenting the profile of climate change in their budget and policies. This is expressed by the following actions.

- The European Council has set as political objective to earmark at least 20% of the entire EU budget for climate-relevant actions in the period 2014-2020<sup>1</sup>.
- The current programming period is the first in which climate considerations have been included. Major projects funded by ESIF will need to be screened against climate-related vulnerabilities and necessary adaptation measures need to be reported<sup>2</sup>.
- For European and Structural Investment Funds (ESIF) there is now the specific requirement that adaptation to climate change is part of the horizontal principle of sustainable development<sup>3</sup>.
- One of the 11 thematic objectives under the new ESIF interventions includes specific measures for adaptation (Thematic Objective 5 – Promoting climate change adaptation, risk prevention and management)<sup>4</sup>.

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<sup>1</sup> Conclusions of the European Council (7/8 February 2013) as regards the Multiannual Financial Framework.

<sup>2</sup> Article 101 of Regulation (EU) No 1303/2013 of the European Parliament and of the Council of 17 December 2013; Commission Implementing Regulation (EU) 2015/207 – Annex II, Section F.8.

<sup>3</sup> Article 8 of Regulation (EU) No 1303/2013 of the European Parliament and of the Council of 17 December 2013.

<sup>4</sup> Article 9 of Regulation (EU) No 1303/2013 of the European Parliament and of the Council of 17 December 2013.

- Guidelines and tools that have become available on how to take into consideration climate change adaptation actions in EU funded investments and measures<sup>5,6</sup>.

Despite this increased attention and recent scientific advances, quantitative information on the vulnerability and risks of critical infrastructures and large investments to climate change and variability is barely available in literature. The CCMFF project aims to fill this gap by evaluating current and future impacts of climate extremes on the current stock of critical infrastructures in Europe and on regional investments under the Cohesion Policy for the period 2007-2013.

Critical infrastructure are defined by the EC<sup>7</sup> as “an asset, system or part thereof (...) which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions”. According to this definition, critical infrastructures considered in this study include existing transport systems (roads, railways, airports, ports, and inland waterways), energy production (renewable and non-renewable energy power plants) and transmission (electricity distribution and transmission infrastructures, gas pipelines) systems, heavy industries (metal, chemical, mineral + refineries), water and waste treatment facilities, and social infrastructures (education and health).

The EU regional investments refer to projects financed by the Cohesion policy (CP), also referred to as ‘Regional policy’. They are a key financial instrument in the EU, redistributing about a third of the entire EU budget (347 billion € for the period 2007–2013) among European regions based on economic and population indicators such as regional and national prosperity, unemployment rates and population

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<sup>5</sup> CLIMA.C.3/SER/2011/0011: Methodologies for climate proofing investments and measures under cohesion and regional policy and the common agricultural policy.

<sup>6</sup> ENV/CLIMA.C.3/SER/2011/0037r - Guidelines for project managers: "Making vulnerable investments climate resilient".

<sup>7</sup> COUNCIL DIRECTIVE 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection.

density<sup>8</sup>, with the aim of achieving social, economic and territorial cohesion across the EU.

## **1.2 Scientific challenges**

Five fundamental scientific challenges have been identified which have driven the strategic research activities within the project. The problem to be addressed is highly complex and the development of a comprehensive assessment framework for appraising the risks to critical infrastructures of climate hazards in present and future climates requires the integration of different scientific disciplines across physical, social and economic fields.

### **Challenge 1: Understanding how multiple climate extremes will evolve in Europe along the twenty-first century.**

Europe is expected to face major impacts from a changing climate over the coming decades. The hazard to society and environment will be largely connected to changes in extreme climate events, due to their disproportionate rise compared to changes in climatological averages. Threats will be more pronounced in areas prone to multiple climate hazards. In this context, a multi-hazard assessment accounting for possible regional variations in intensity and frequency of climate extremes is essential to identify areas potentially more exposed to climate change. The detailed multi-hazard assessment at pan-European scale as the one presented herein has not been documented in literature.

### **Challenge 2: Developing a spatially coherent dataset of existing critical infrastructures.**

Geographic information on infrastructures is crucial to assess with spatial detail the potential impacts of climate change. Datasets of existing infrastructures collected

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<sup>8</sup> European Council (2006) Regulation (EC) No 1083/2006 laying down general provisions on the European Regional Development Fund, the European Social Fund and the Cohesion Fund and repealing Regulation (EC) No 1260/1999.

and maintained by different organizations in Europe lack homogeneity in spatial and thematic coverage and measurement units. Filling incompleteness in the source databases and designing a harmonization framework to allow for comparability between infrastructures are key tasks to properly accounting for regional differences in infrastructures distribution and quantifying the potential exposure.

**Challenge 3: Determining the sensitivity to climate hazards of critical infrastructures and EU-funded projects.**

Climate sensitivity of a given infrastructure/investment depends on multiple factors including the nature of the climate-induced shock (e.g., temperature-based stress, dry spells, flood inundation, fire or windstorm damage), the on-site structure and processes (e.g., physical properties of the material) and the input sources exploited (e.g., water, energy). Establishing the climate sensitivity for a large set of infrastructures/investments is essential to comprehensively account for the diverse degrees of susceptibility of the current multifaceted socio-economic systems.

**Challenge 4: Assessing impacts at pan-European scale consistently and comparably across multiple sectors and climate-related hazards.**

Projected increases in frequency of multiple climate hazards in many regions of Europe emphasize the relevance of a multi-hazard multi-sector risk assessment. This requires the integration of the climate hazard, exposure and sensitivity components within a complex framework that allows to translating modelled impacts into cost figures. Deriving a comprehensive and comparable measure of expected monetary damages is fundamental to provide useful guidance for developing adaptation strategies and mitigate impacts of multiple hazards in Europe in relation to critical infrastructures.

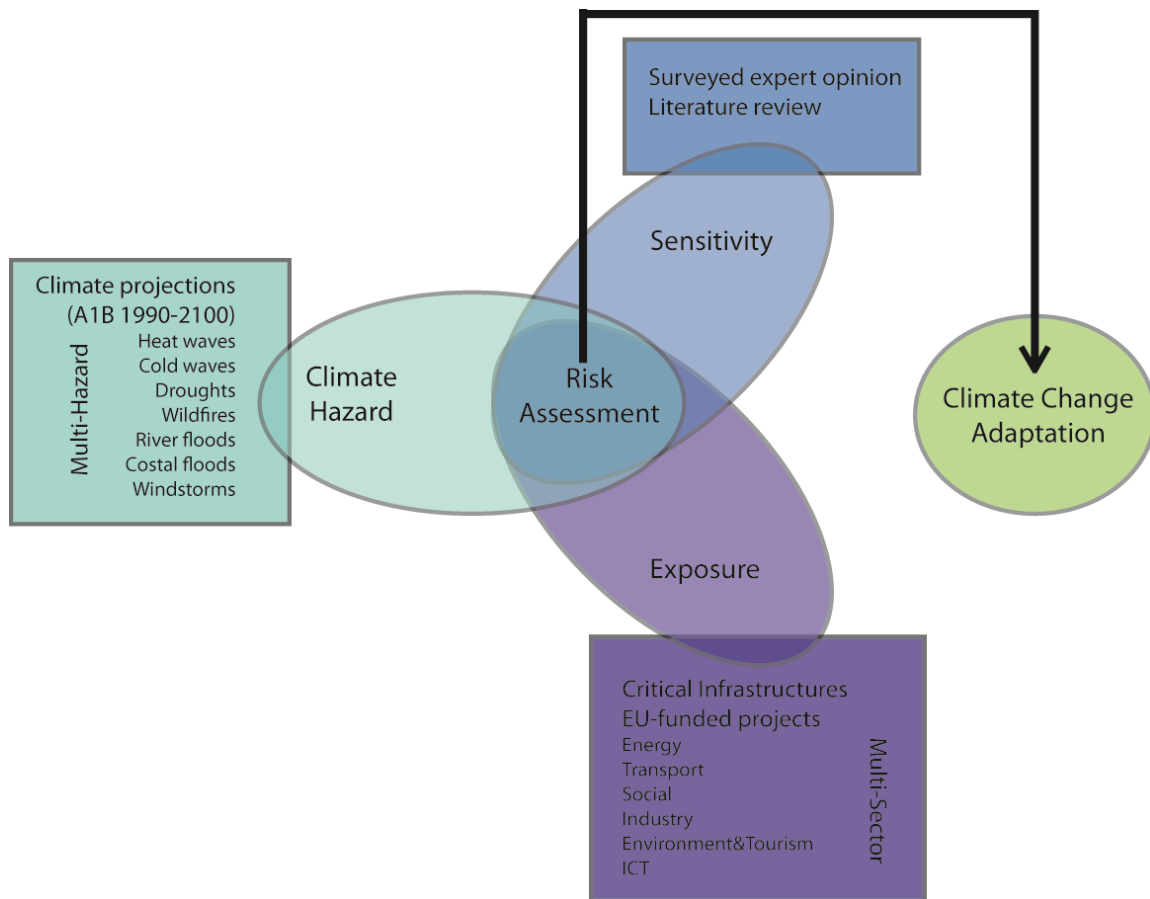
**Challenge 5: Appraising the cost of adaptation of infrastructures.**

To make optimal use of limited resources for investments in climate impact mitigation, information about the cost and the appropriateness and effectiveness of



adaptation is needed. This involves an evaluation of different adaptation options and their costs and benefits. This task is complex as comprehensive frameworks for addressing costs and benefits of adaptation options are largely absent and quantitative information on these aspects are very limited and fragmented.

These five challenges raised a series of methodological issues and scientific questions that have been addressed in a coherent workflow of which the different steps are detailed separately in Chapters 2-6. We focus on seven climate hazards including heat and cold waves, wildfires, droughts, river and coastal floods and windstorms. Future climate hazards in Europe have been generated for an ensemble of regional climate simulations under a “business-as-usual” (SRES A1B) greenhouse gas (GHG) emissions trajectory over the 1990-2100 period. Climate-induced expected annual damages to infrastructures and EU-funded investments related to the industry, energy, transport, social, environment and tourism and ICT sectors are quantified. Although these sectors do not cover the full range of possible societally relevant climate-change impacts, they include crucial aspects of livelihoods for Europe. Cost estimates reported in this study refer to damages to property due to direct physical contact with the hazard and damages related to the reduction in primary sources and productivity. The methodology, graphically represented in Figure 1.1, integrates a set of coherent, high-resolution climate hazard projections (Chapter 2), a detailed harmonized representation of sectorial physical assets and productive systems and investments (Chapter 4), and semi-quantitative estimates of their sensitivity based on surveyed expert opinion and literature review (Chapter 3). The three above-mentioned components have been combined in a coherent vulnerability framework based on recorded climate disasters in order to derive quantitative estimates of risk (Chapter 5). Additional costs required to climate proof infrastructures and investments are then evaluated based on possible avoided damage scenarios and cost-benefit analysis (Chapter 6).



**Figure 1.1** Flow diagram of the proposed multi-hazard multi-sector risk assessment.

Results are shown throughout the document in spatial maps as well as aggregated for five European regions to simplify interpretation: Southern (SEU), Western (WEU), Central (CEU), Eastern (EEU) and Northern (NEU) Europe (Figure 1.2).



**Figure 1.2** European regions. Grouping of countries in macro-areas shown in different colors. Southern Europe (Albania, Bulgaria, Bosnia and Herzegovina, Croatia, Cyprus, Greece, Italy, Kosovo, Malta, Montenegro, Portugal, Republic of Macedonia, Serbia, Slovenia, Spain, Turkey), Central Europe (Austria, Czech Republic, Germany, Liechtenstein, Poland, Slovakia, Switzerland), Western Europe (Belgium, France, Ireland, Netherlands, Luxembourg, United Kingdom), Eastern Europe (Belarus, Estonia, Hungary, Latvia, Lithuania, Republic of Moldova, Romania, Russian Federation, Ukraine), and Northern Europe (Denmark, Iceland, Finland, Norway, Sweden). Hatched areas are only covered (sometimes partly) in the hazard assessment and not in the risk assessment.

This work provides the first comprehensive multi-hazard multi-sector risk assessment for Europe under climate change and identifies the most vulnerable and impacted regions in Europe throughout the 21<sup>st</sup> century. We believe that it significantly contributes to a better understanding and awareness that is crucial for the management of future climate risks.

## 2 Multi-hazard assessment in Europe under climate change

### 2.0 Key messages

- Projected changes in the occurrence of the seven climate extremes depict important variations in hazard scenarios with large spatial patterns modulated by local climate conditions.
  - Heat waves show a progressive and highly significant increase in frequency all over Europe. By the end of this century, a current 100-year heatwave may occur almost every year in Southern Europe, whereas in other regions of Europe such events may happen every 3 to 5 years.
  - Cold waves show an opposite significant trend with current cold extremes tending to mostly disappear in Europe in more distant futures.
  - Streamflow droughts are projected to become more severe and persistent in Southern and Western Europe, with current 100-yr events that could occur approximately every 2 to 5 years by 2080, respectively. In other regions of Europe an opposite trend can be expected, with a strong reduction in drought frequency in most areas.
  - In most regions of Europe wildfires may happen more frequently in the future, especially in Southern, Eastern and Central Europe, albeit that the signal is not always very strong and only significant in limited areas.
  - Western Europe shows a consistent rise in future flood occurrence (current 100-yr events could manifest every ~30 years in 2080s). In other regions projections of river floods show higher spatial and temporal variability, with lower and less significant changes. In Southern and Eastern Europe more areas (30%) show a significant decrease (vs 10% with increase) in flood hazard, in Northern Europe areas with a significant increase in flood hazard (24%) balance those with a significant decrease (23%), and in Central Europe more areas show a significant increase (26%) than decrease (15%).

- Coastal floods show a progressive and pronounced increase in recurrence frequency along Europe's coastlines mainly due to sea level rise, with a current 100-yr event that may occur every 2 to 8 years, or even sub-annually in Eastern Europe.
- Evidence for changes in windstorms remains largely elusive. Areas with increases in windstorm hazard are mainly located in Western, Eastern and Northern Europe, while Southern regions present slight reductions in windstorm frequency.
- Europe will see a progressive and strong increase in overall climate hazard with a prominent spatial gradient towards south-western regions.
  - By the end of this century, 76% of the area in Southern Europe is expected to be exposed annually to at least one climate hazard with a current 100-year intensity, or more than 15-fold the baseline value. For the other regions in Europe changes are somewhat less pronounced, but still considerable: for Western, Central, Eastern and Northern Europe, about 50% (+1,021%), 36% (+732), 31% (+614) and 29% (+597%) of the territory, respectively, will by the end of this century be exposed annually to at least one hazard with a current 100-year intensity.
  - Due to the increase in frequency of multiple hazards in many regions of Europe, the joint annual exposure expectancy to multiple hazards shows rises much sharper than for single hazards. In Southern Europe, 25% of the area could be annually exposed to at least two hazards with a 100-year intensity by the end of this century, or nearly 250-fold the baseline value. When considering three hazards, the increase is 700-fold. For the other regions, rises in joint annual exposure expectancy for two and three hazards, respectively, amount to 24,500% and 9,500% for Western Europe, 6,250% and 2,100% for Central Europe, 4,335% and 1,400% for Eastern Europe, and 1,324% and 1,000% for Northern Europe.
- Key hotspots emerge particularly along coastlines and in floodplains in Southern and Western Europe, which are often highly populated and economically pivotal.

## 2.1 Introduction

Europe is expected to face major impacts from a changing climate over the coming decades (Collins et al., 2013). The hazard to society and environment will be largely connected to changes in extreme climate events due to their disproportionate rise compared to the corresponding change in climatological averages (Rummukainen, 2012). Threats will be more pronounced in areas prone to multiple climate hazards. In this context, a multi-hazard assessment accounting for possible regional variations in intensity and frequency of climate extremes is essential to identify areas potentially more exposed to climate change.

A number of climate change impact studies at the European level have been achieved, usually for a single specific climate or weather hazard, such as river floods (Lehner et al., 2006; Rojas et al., 2012), coastal floods (Hinkel et al., 2010; Nicholls and Klein, 2005), heat waves (Christidis et al., 2015; Fischer and Schär, 2010), streamflow droughts (Forzieri et al., 2014; Lehner et al., 2006), windstorms (Nikulin et al., 2011; Outten and Esau, 2013) and wildfires (Bedia et al., 2013; Mirco Migliavacca et al., 2013). The study of multiple hazards poses two major challenges: (a) hazards are not directly comparable as their processes and describing metrics differ; and (b) hazards can interact triggering cascade effects and coupled dynamics. In the existing literature, the first issue has been mainly addressed through standardization approaches, such as classification of hazard intensity and development of continuous indices (Dilley, 2005; Kappes et al., 2012; Lung et al., 2013). While these approaches represent a starting point, they describe only a limited set of climate hazards and the techniques used to make different hazards comparable are largely subjective and inconsistent. The second issue has been addressed mainly qualitatively through descriptive matrices where coupled mechanisms are conceptualized based on multi-hazard dynamics observed at local scale and largely influenced by landscape features (Gill and Malamud, 2014; Kappes et al., 2012). Deeper data-driven investigations are needed before interactions between hazards can be reliably incorporated into large-scale predictive systems. Thus, in this study we mainly focus on the first above-mentioned challenge.

Through a unique collaborative effort of different European modelling groups, a consistent set of climate hazard modelling data has been produced for this study including heat and cold waves, river and coastal floods, droughts, wildfires and windstorms. Future climate hazards in Europe have been generated for an ensemble of regional climate simulations under a “business-as-usual” (SRES A1B) greenhouse gas (GHG) emissions trajectory (Solomon, 2007) and synthesized in a coherent multi-hazard framework. The method is based on the analysis of the changes in frequency of climate-induced extreme events and the corresponding variations in expected annual exposure to these events. The latter is hereafter defined as Expected Annual Fraction Exposed (EAFE), where the fraction can relate to any variable of interest (e.g., population, infrastructure, cropland). For a range of hazard severities, single-hazard EAFEs and changes therein are combined into multi-hazard indices to synthesize the potential exposure to multiple climate hazards (2.2 Methods).

This work provides the first comprehensive multi-hazard assessment for Europe under climate change and focuses in particular on the comparability amongst single hazards and on the degree of overlap between areas exposed to multiple hazards throughout this century. The overall goal is to identify geographic areas with the highest potential exposure to multiple climate hazards in order to better steer adaptation efforts and land planning across Europe. It is worth to stress that this chapter should not be confused with a risk assessment study. A risk assessment implies the combination of hazard, vulnerability and spatial distribution of exposed assets, which is presented in Chapter 5.

## 2.2 Methods

### 2.2.1 Climate hazard indicators

The analysis focuses on seven critical climate hazards for Europe: heat and cold waves, river and coastal floods, droughts, wildfires and windstorms. Climate hazard indicators were derived for the baseline (1981-2010), 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100) for an ensemble of bias-corrected climate projections obtained from different regional climate model simulations under the A1B emissions scenario (Solomon, 2007) (Table 2.1).

**Table 2.1** Climate simulations used to derive climate hazard indicators in the period 1981–2100.

Driving GCM	RCM	Acronyms	Heat waves	Cold waves	Droughts	Wildfires	River floods	Windstorms
HadCM3Q16	RCA3.0	C4I-RCA-HadCM3	X	X	X	X	X	
ARPEGE	ALADIN-RM5.1	CNRM-ALADIN-ARPEGE			X		X	
ARPEGE	HIRHAM5	DMI-HIRHAM5-ARPEGE	X	X	X	X	X	
BCM	HIRHAM5	DMI-HIRHAM5-BCM			X		X	X
ECHAM5-r3	HIRHAM5	DMI-HIRHAM5-ECHAM5	X	X	X	X	X	X
HadCM3Q0	CLM	ETHZ-CLM-HadCM3			X		X	
ECHAM5-r3	RACMO2	KNMI-RACMO2-ECHAM5	X	X	X	X	X	
HadCM3Q0	HadRM3Q0	METO-HadRM3-HadCM3	X	X	X	X	X	
ECHAM5-r3	REMO	MPI-REMO-ECHAM5			X		X	
BCM	RCA3.0	SMHI-RCA-BCM			X		X	X
ECHAM5-r3	RCA3.0	SMHI-RCA-ECHAM5			X		X	X
HadCM3Q3	RCA3.0	SMHI-RCA-HadCM3			X		X	

Heatwaves were defined by the Heat Wave Magnitude Index (HWMI) that is based on the 3-day maximum temperature anomalies (Russo et al., 2014). Cold waves were similarly calculated by referring to minimum temperatures. Return levels of heat and cold waves were retrieved by empirical cumulative distribution functions. Wildfires were derived from projections of the monthly percentage of burned area (Mirco Migliavacca et al., 2013). Beta functions were selected to fit the annual fractions of burned area and to derive extreme events. Extreme windstorms were calculated using the Generalized Pareto distributions that have been derived through a peak-over-threshold analysis for daily maximum wind speeds (Outten and



Esau, 2013). Relative Sea Level Rise projections were combined with current extreme value distributions of total water levels obtained using a peak-over-threshold approach (Cid et al., 2014; Pardaens et al., 2011). Following, a static inundation approach was applied to generate inundation maps along the coastline. For inland flooding the annual maximum discharges and flood inundation maps were derived from earlier works (Rojas et al., 2013, 2012). For drought the minimum discharges and return levels were obtained from a previous study (Forzieri et al., 2014).

### 2.2.2 Frequency of extreme events in current and future climate

Baseline return levels ( $R_{L,b}$ ) of the climate hazard indicators with return periods ( $T_{R,b}$ ) from 2 to 100 years were obtained at each grid cell. Future return periods ( $T_{R,f}$ ) of  $R_{L,b}$  were calculated by inversion of the fitted probability functions ( $G$ ).

$$T_{R,f}(R_{L,b}) = \frac{1}{1 - G(R_{L,b})} \quad [2.1]$$

Climate model variability was quantified by the coefficient of variance of the future return periods retrieved for the different climate realizations. The significance of the changes in climate hazard was evaluated by the Kolmogorov-Smirnov test applied on the annual values of future time windows versus baseline, separately for each climate model.

### 2.2.3 Expected Annual Fraction Exposed

By analogy with risks of extreme events that are often communicated in terms of expected annual impact, the fraction expected to be annually exposed to a hazard – the Expected Annual Fraction Exposed (EAFE) – was calculated by integrating the exposure to hazard events over the probability of occurrence distribution of the hazard. The EAFE to hazard events with return period  $\geq T_R$  was obtained as in the following:

$$EAFE(T_R) = \frac{1}{T_R(R_L)} \int_0^1 f dp \quad [2.2]$$

where  $f$  is the exposure-probability function. In the case of river and coastal floods  $f$  is a dummy function with value 1 when the pixel is flooded, 0 otherwise. For the remaining climate hazard indicators  $f$  is a constant function equal to 1, under the assumption that exposure to the hazard is spread homogeneously within the pixel. Future return periods retrieved from equation [2.1] are used to truncate the integration for future EAFE. For pixels with non-significant changes we keep baseline values for future EAFE. EAFE ranges between 0 (no fraction exposed to the hazard) and 1 (whole fraction expected to be annually exposed to climate hazard). The use of EAFE allows comparing quantitatively multiple hazards characterized by different processes and time scales based on a common intensity scale derived from the probability of occurrence of extreme events in the current climatology.

#### 2.2.4 Combining multiple hazards

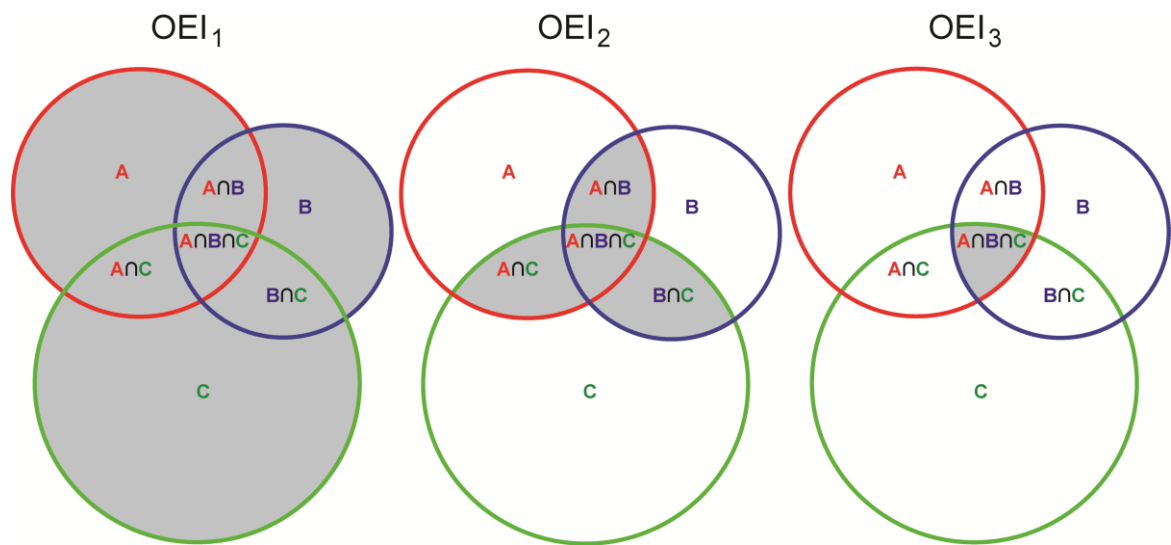
To quantify the total expected annual exposure to multiple hazards we define the Overall Exposure Index (OEI). Under the assumption that the considered hazards are mutually non-exclusive, from the inclusion-exclusion principle of combinatorics the OEI can be expressed as follows for a given  $T_R$ :

$$OEI(T_R) = \bigcup_{i=1}^n EAFE_i(T_R) = \sum_{k=1}^n \left( (-1)^{k-1} \sum_{\substack{I \subset \{1, \dots, n\} \\ |I|=k}} EAFE_I(T_R) \right) \quad [2.3]$$

where  $i$  refers to the hazard-specific EAFE,  $n$  is the number of hazards considered, the last sum runs over all subsets  $I$  of the indices  $\{1, \dots, n\}$  containing exactly  $k$  elements, and

$$EAFE_I(T_R) := \bigcap_{i \in I} EAFE_i(T_R) \quad [2.4]$$

expresses the intersection of all those  $EAFE_i$  with index in  $I$ . Equation [2.3] quantifies the expected annual exposure to at least one climate hazard. To account for the overall exposure to  $m$  overlapping hazards, equation [2.3] can be generalized using the intersections of  $m$  EAFEs in place of single-hazard components. Here, we use  $m$  values up to three to quantify different degrees of overlap amongst hazards. The scheme of calculation in a simplified case with three hazards is shown in Figure 2.1.

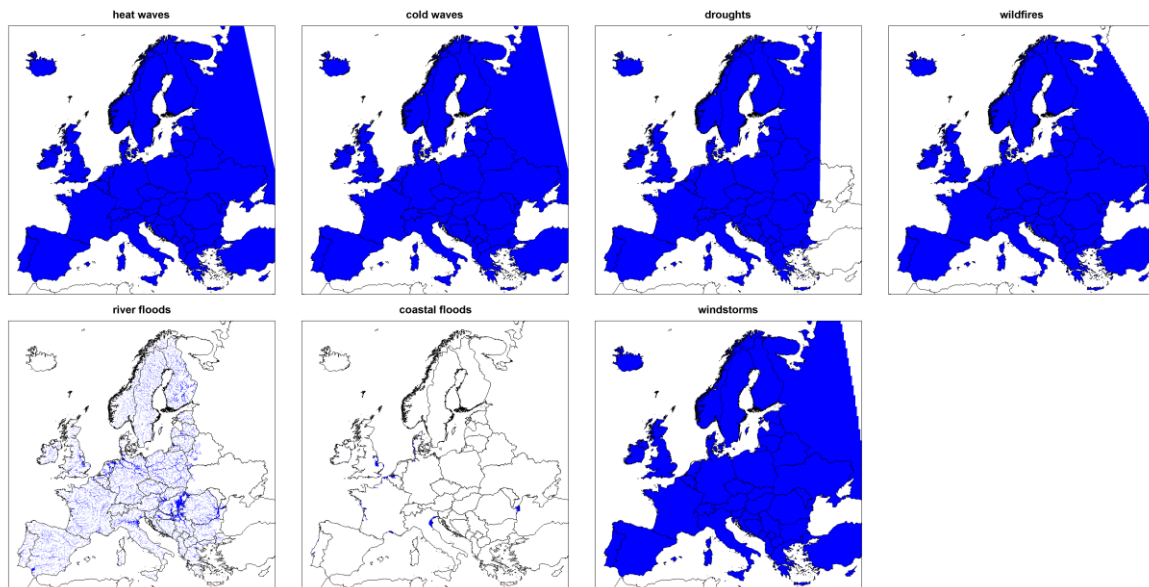


**Figure 2.1** Schema of calculation of Overall Exposure Index. Example of calculation of Overall Exposure Index in a simplified case with three hazards, here visualized by coloured circles, named A, B and C, respectively. Grey areas represent the Overall Exposure Index with different degree of overlapping.

To identify areas subject to large increases in exposure to multiple hazards, we define the Change Exposure Index (CEI). CEI expresses the number of hazards - of a given baseline return level - with a future relative increase in EAFE over a certain threshold (20%, 100% and 1000%). The use of three different thresholds allows capturing moderate, strong and extreme changes in hazard exposure. Note that an increase in EAFE of a current 100-year event by 20%, 100% or 1000% means that the future event will happen every 80, 50, or 9 years. The number of hazards for which there is an increase in exposure to the hazard over the given threshold is calculated in each grid cell and then aggregated at NUTS3 level as the 0.99<sup>th</sup> percentile of this distribution over all cells. The 99<sup>th</sup> percentile of the exposure

change distribution within the NUTS3 region excludes local fitting extrapolation errors and is considered representative of the maximum degree of change in exposure. CEI allows identifying key hotspots subject to predefined levels of change in exposure.

Both OEI and CEI are calculated for each return period and time slice using the ensemble median of all climate model combinations for each hazard as inputs. Note that multi-hazard indices in regions close to the geographical limits of our domain, such as Island, Russian Federation and Turkey, may be underestimated due to the incomplete spatial coverage of some hazards (see Figure 2.2).



**Figure 2.2** Spatial domains of climate hazard models. Note that the model domain for floods and droughts does not include Cyprus and Malta, the coastal model domain excludes only Cyprus.

## 2.3 Results and discussion

### 2.3.1 Single hazard projections

Figure 2.3 shows the projected changes in frequency of climatic extreme events with respect to current climate, where increasing (decreasing) hazard occurrences are denoted by lines under (over) the bisector, the coefficient of variance (CV) describes the inter-model spread (climate uncertainty) and S values the percentage of area subject to significant changes (5% level). The frequency analysis is complemented with the corresponding variations in Expected Annual Fraction Exposed (EAFE) shown in Figure 2.4 both in terms of its magnitude and relative change with respect to the baseline. Spatial patterns of EAFE are shown in Figure 2.5. Note that climate-related uncertainty in the frequency of extreme events translates into analogous estimates of uncertainties in EAFE, which are not shown here to avoid redundancy.

Heat waves show a progressive and highly significant increase in frequency all over Europe ( $S > 74\%$  in near future climate, approaching 100% in all regions by the end of this century), with larger climate variability in long-term scenarios ( $40 \leq CV \leq 60$ ) and a more pronounced intensification in Southern Europe (where current 100-yr events could occur almost every year in the 2080s) (Figure 2.3). Consistently, EAFE values show a progressive increase as time proceeds, especially in Southern Europe where, by the end of the century, up to 60% of the territory could be annually exposed to a current 100-year heat wave (Figure 2.4).

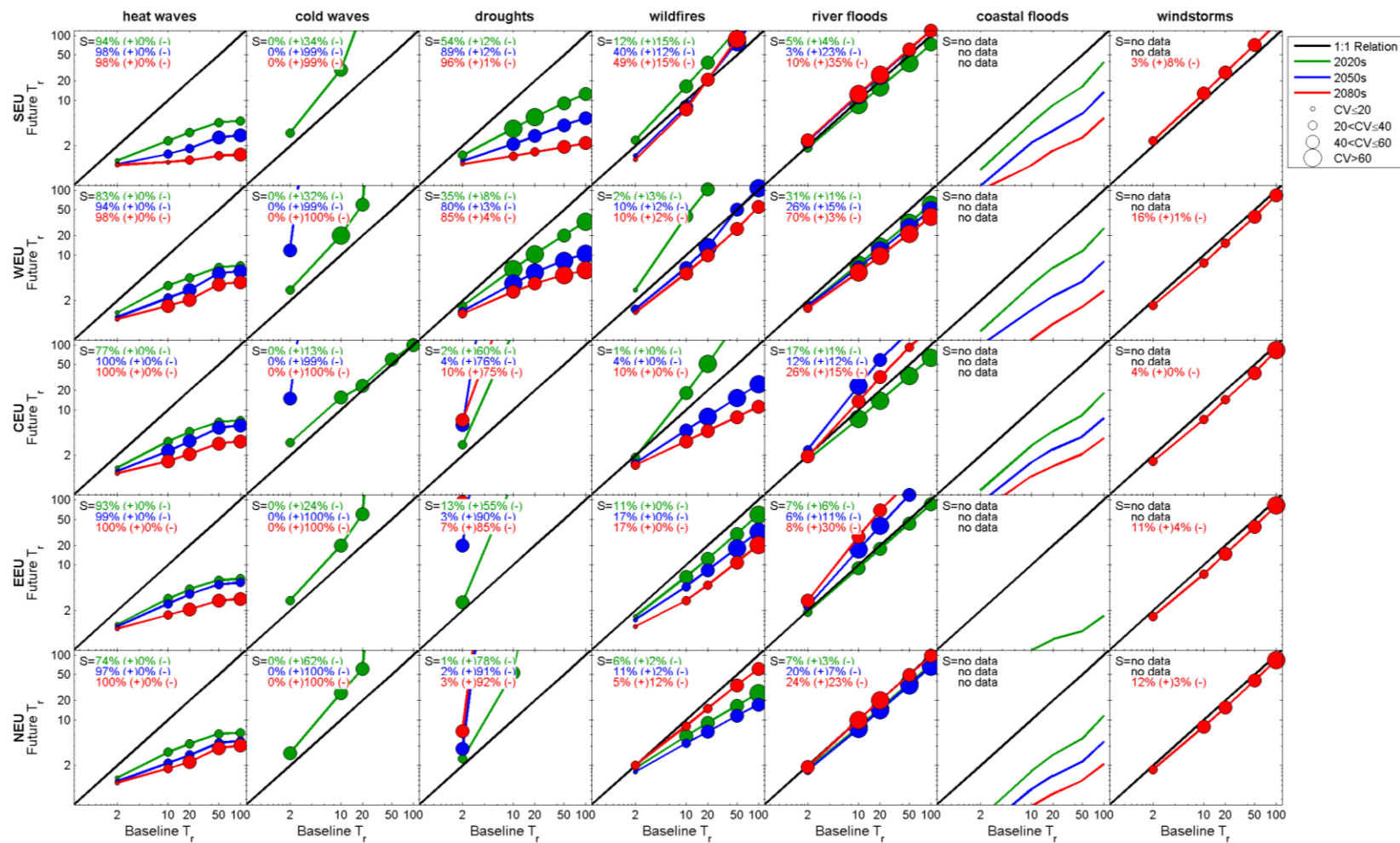
Cold waves show an opposite trend with current cold extremes tending to mostly disappear in Europe in more distant futures (current 2-yr event may occur less than every 100 years by the end of the century, significant almost everywhere, Figure 2.3). Accordingly, cold waves could experience a rapid decrease in EAFE and a change up to -100% by the end of the century (Figure 2.4).

Streamflow droughts may become more severe and persistent in Southern and Western Europe (current 100-yr events could occur approximately every 2 to 5 years by 2080, respectively,  $S \geq 85$ ) resulting from the reduced precipitation and increased evaporative demands with higher temperatures (Figure 2.3). This leads to

a consistent increase in EAFE and by the end of the century over 25% of the territories could be affected every year by baseline 100-yr droughts (Figure 2.4). Northern, Eastern and Central Europe show an opposite tendency with a strong reduction in drought frequency caused by higher precipitation that outweighs the effects of increased evapotranspiration (Forzieri et al., 2014). Such effects translate into consistent decreases in EAFE by up to 100%. Significance increases with time while climate variability shows variable tendencies depending on the return levels ( $S > 75\%$  and CV over 60% by the end of the century).

Most of Europe, especially Western, Eastern and Central regions, could experience an increase in the frequency of extreme wildfires (current 100-yr events will occur every 5 to 50 years) with a progressive rise in significance and model agreement ( $S > 10\%$  and  $CV \leq 60\%$  by the end of the century) (Figure 2.3). Interestingly, Southern Europe shows a decrease in the frequency of very extreme events, which is likely due to the expected reduction in net primary productivity of terrestrial ecosystem that may limit the fuel availability and, ultimately, the propagation of large wildfires (Mirco Migliavacca et al., 2013). Progressive increases in EAFE are visible for wildfires over the whole domain (one to three-folds the baseline value, Figure 2.5).

River floods show in general more spatial variability and fluctuations with time in the frequency of extreme events as well as a larger climate-induced spread compared to the other hazards (higher CV values, Figure 2.3). This relates to the high variability in projected geographical patterns of heavy precipitation intensity due to structural and parametric model uncertainty and internal climate variability (Fischer et al., 2013). Western Europe shows a consistent rise in future flood hazard (current 100-yr events could manifest every ~30 years in 2080s,  $S$  up to 70%), mainly as a result of a pronounced increase in average and extreme rainfall (Rojas et al., 2012). Such effects result in a 50-100% increase in future EAFE (Figure 2.4). A modest but significant decrease in river flood frequency is projected in Southern, Central and Eastern regions, in the latter because of the strong reduction in snowmelt induced river floods, which offsets the increase in average and extreme precipitation.



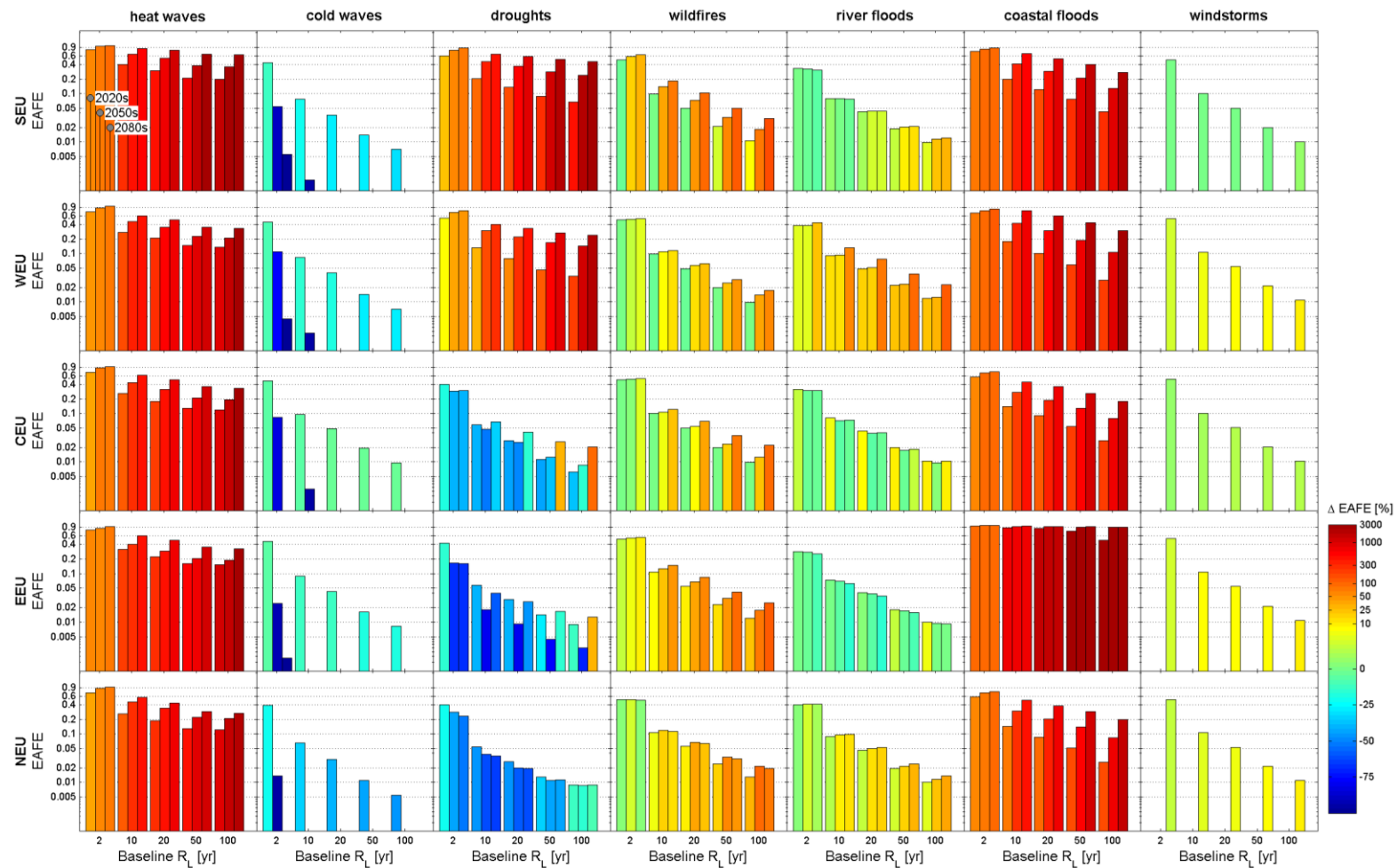
**Figure 2.3** Changes in frequency of climatic hazards. Baseline (x-axis) versus future (y-axis) hazard return periods for 2020s (green), 2050s (blue) and 2080s (red) for specific hazards. Return period values shown are the zonal median for different European regions of the grid-cell ensemble median return period of the experiments driven by the different climate realizations. Circle sizes represent the coefficient of variance (CV) amongst climate models and S values explicit the percentage of cells within a region with significant decrease/increase (-/+). Note that future scenarios with outstanding decrease/increase in frequency are out of plot margins (cold waves, droughts and coastal floods), projections of windstorm are only available for 2080s, significance analysis and climate variability have not been retrieved for coastal floods.

Coastal floods show a progressive and pronounced increase in recurrence along Europe's coastlines chiefly caused by sea level rise (current 100-yr event may manifest every 2 to 8 years, or even sub-annually in Eastern Europe, in the 2080s, Figure 2.3) and leading to strong increase in EAFE (Figure 2.4). Noteworthy is the pronounced increase in EAFE in Eastern Europe as a consequence of the rapid intensification of inundations over the Danube delta. Due to sea level rise the increase in frequency of occurrence of extreme coastal events is so pronounced in this region that current 100-year (and more frequent) events will happen sub-annually by the 2050s and 2080s, which explains why the curves for the 2050s and 2080s drop below the x-axis and are not visible.

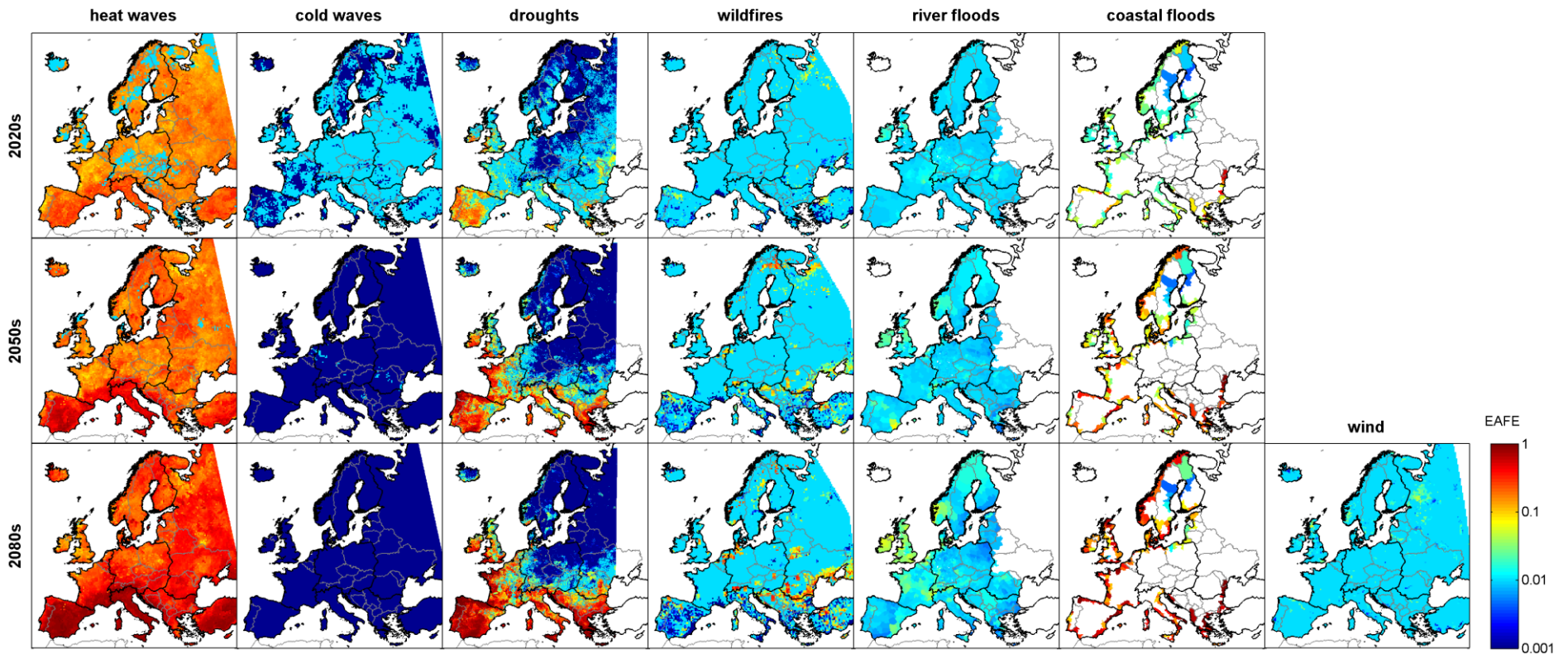
Evidence for changes in windstorms remains largely elusive ( $S < 16\%$ ) and with considerable inter-model spread for larger return levels (up to  $CV > 60\%$  for current 100-yr events, Figure 2.3). Areas with increases in windstorm hazard are mainly located in Western, Eastern and Northern Europe, while Southern regions present slight reductions in frequency as observed in previous studies (Nikulin et al., 2011; Outten and Esau, 2013). EAFE of windstorms show modest changes with respect to the baseline (up to  $\pm 10\%$ , Figure 2.4).

Interestingly, larger increases in EAFE can be observed at higher return levels and for long-term scenarios due to the progressive intensification of very extreme events. This occurs also in regions prevalently experiencing a reduction (or slight change) in future frequency of climate hazards, such as Central and Eastern Europe for droughts, Southern Europe for wildfires and Southern, Central and Northern Europe for floods. The apparent contradiction manifests where few localized areas experience a very large increase in frequency that outweighs the opposite tendency occurring in most of the region. The projected changes in single-hazard exposed fractions suggest that future hazard scenarios will considerably deviate from those observed in current climate, especially for climate hazards strongly linked to temperature rises (e.g., heat and cold waves, droughts and coastal floods).





**Figure 2.4** Changes in single-hazard Expected Annual Fraction Exposed. Baseline hazard return levels (on the x-axis) versus corresponding future EAFE (on the y-axis) for specific hazards. EAFE values shown are zonal averages for different European regions of the grid-cell ensemble median EAFE of the experiments driven by the different climate realizations. Bars refer to a future scenario period as labelled in the top-left panel. Colours reflect the relative change in region-average EAFE with respect to the baseline. Note that EAFE lower than 0.001 (e.g., for cold waves) are out of plot margins.



**Figure 2.5** Spatio-temporal patterns of 100-yr Expected Annual Fraction Exposed. Spatial and temporal variations of Expected Annual Fraction Exposed to 100-yr climate hazards. Note that values for river and coastal floods are aggregated at NUTS3 level (see Figure 1) to better visualize their effects. Values refer to the ensemble medians of experiments driven by the available climate models.

### 2.3.2 Changes in overall and concurrent exposures to climate hazards

Figure 2.6a shows the overall exposure to combinations of all hazards aggregated for each European region, expressed by the Overall Exposure Index that accounts for the overlapping of hazards. Spatio-temporal patterns of the 100-yr EAFE for OEI1, OEI2 and OEI3 are presented in Figure 2.6b. For all regions in Europe, the fraction exposed to at least one hazard, expressed by EAFE for OEI1, will progressively increase throughout this century, with the increase being more pronounced for higher return periods. In Southern Europe, about 76% of the area will be annually exposed to at least one climate hazard with a current 100-year intensity by the end of this century, more than a 15-fold increase compared to the present situation (currently nearly 5% of the area is expected to annually exposed to at least one hazard of this intensity). The distribution in space of the 100-yr EAFE for OEI1 (Figure 2.6b, left column) shows that by the end of this century in many areas in Southern Europe the whole territory will be annually exposed to at least one hazard of this intensity. This is mainly caused by the large increase in heat and drought hazard projected for the most southern regions of Europe. For the other regions in Europe, the fractions annually exposed and the increase therein with time are somewhat less pronounced, but still considerable: for Western, Central, Eastern and Northern Europe, about 50%, 36%, 31% and 29% of the territory, respectively, will by the end of this century be exposed annually to at least one hazard with a current 100-year intensity, corresponding to increases of 1021%, 732%, 614%, and 597%, respectively.

The EAFE for OEI2, expressing the fraction that is expected to be annually exposed to at least two hazards, shows even steeper increases with time in all regions of Europe. Again, the highest raise is projected for Southern Europe, with about 25% of the area that could be annually exposed to at least two hazards with a 100-year intensity by the end of this century, or nearly 250-fold the baseline value (which corresponds to approximately 0.1% in the different regions of Europe). The distribution in space of the 100-yr EAFE for OEI2 (Figure 2.6b, middle column) shows the highest values in most of Southern Europe and also further north along coasts and in river flood plains. For the other regions, increases in EAFE(100-yr) for

OEI2 are somewhat less pronounced but still very high, with rises of 9,500% for Western Europe, 2,100% for Central Europe, 1,400% for Eastern Europe and 1,000% for Northern Europe.

The results above for OEI1 and OEI2 show that the joint probability of areas to be annually exposed to multiple hazards is much smaller than for single hazards (due to the combination of single hazard probabilities), but that the increases in joint probability rise much sharper than for single hazards. This is because in many regions of Europe multiple climate hazards will occur more frequent under future climate. This is exemplified by the EAFE for OEI3. By the end of the century 0.7% of the area in Southern Europe is expected to be annually exposed to at least three hazards of a 100-year intensity. Albeit that this may seem small, this corresponds to a staggering increase of more than 70,000% (or 700-fold the current value). The projected increases in OEI3 for the other regions by the end of the century amount to 24,500% for Western Europe, 6,250% for Central Europe, 4,335% for Eastern Europe and 1,324% for Northern Europe.

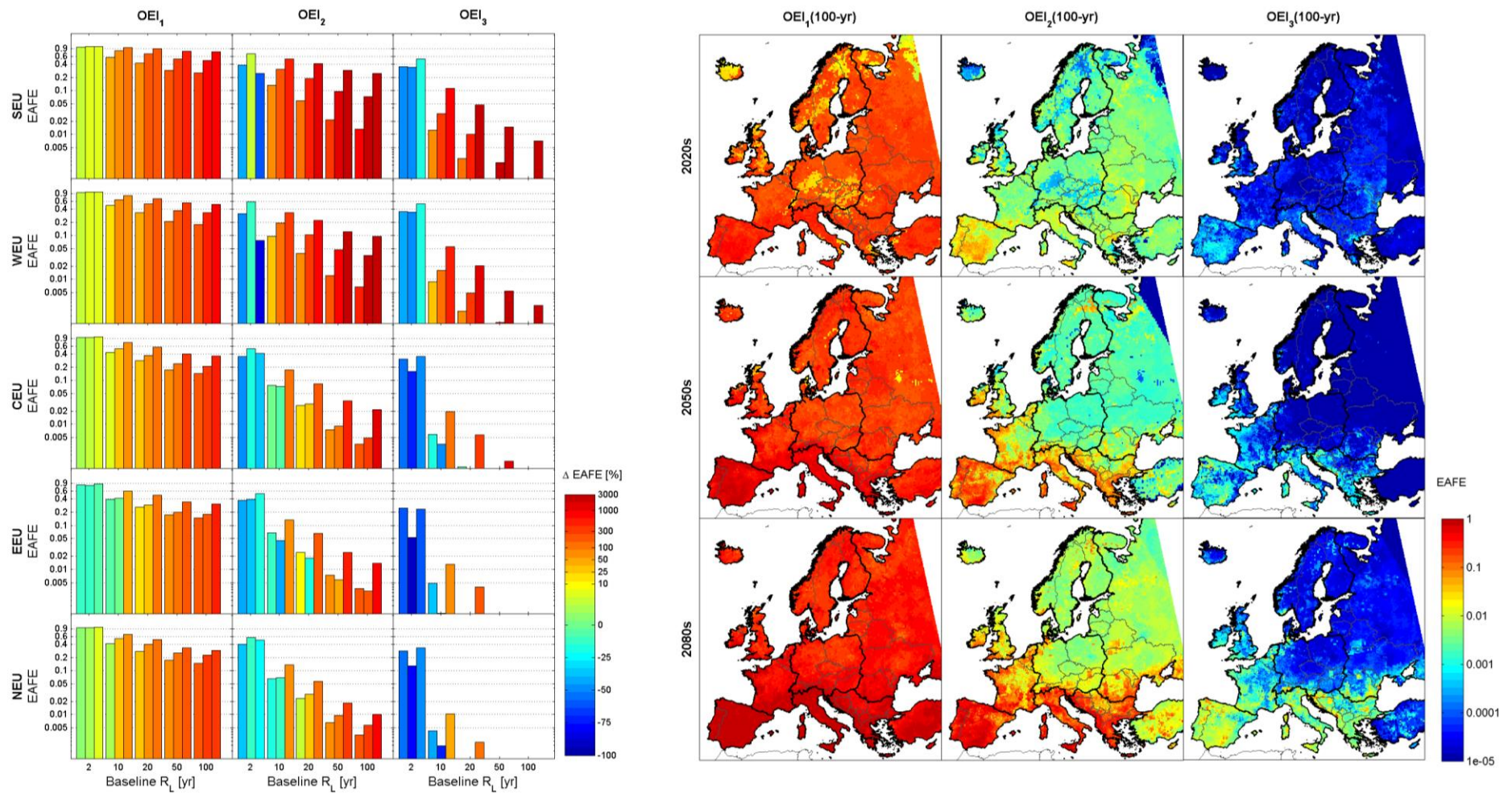
These results suggest that the entire Europe will likely face a progressive increase in overall exposure to climate extremes, with a prominent spatial gradient towards south-western regions (Figure 2.6b) and along coastlines and in flood plains. Heat waves, droughts and coastal flooding, which particularly strong increases in such regions, provide the most relevant contribution in the estimation of future OEI (Figure 2.5).

Spatial patterns of the Change Exposure Index (CEI) are presented in Figure 2.7b for the current 100-year event hazard intensity. The CEI maps represent the number of hazards that show moderate, strong and extreme (+20%, +100% and +1000%, respectively) increases in EAFE. For areas in dark blue (CEI = 0) none of the 7 hazards considered shows the threshold level increase in EAFE, whereas for areas in red (CEI = 4) four hazards reach the defined level of increase in EAFE. Regions with high CEI values reveal potential key hotspots that will be prone to an increase in exposure to multiple hazards. These are mainly located along coastlines and in floodplains in Southern and Western Europe where inland and coastal flooding will

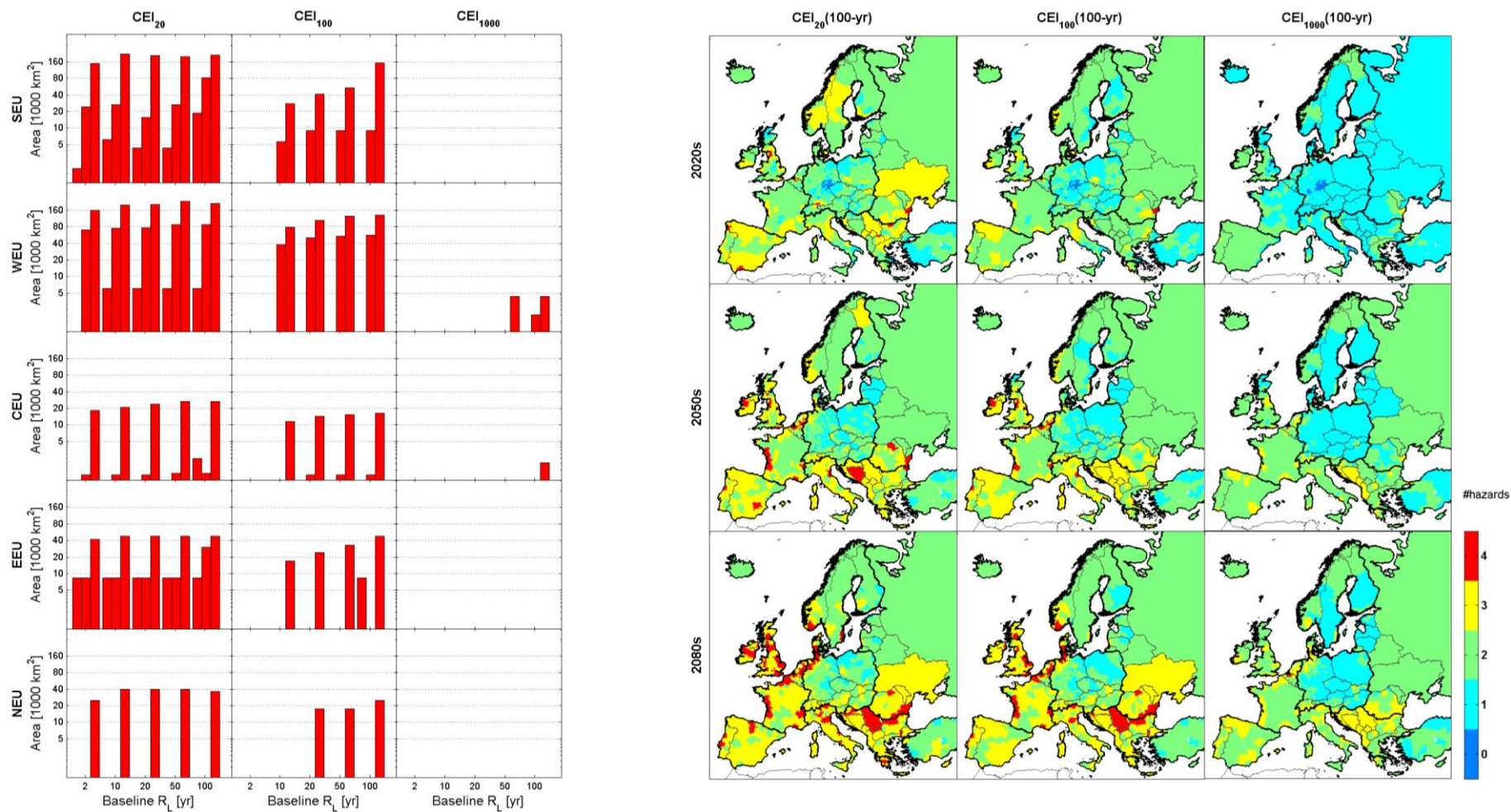
be likely relevant in combination with temperature-related hazards (see also hazard-specific contributions shown in Figure 2.8). More exposed regions include the British Isles, the North Sea area, north-western parts of the Iberian Peninsula, as well as parts of France, the Alps, Northern Italy and Balkan countries along the Danube River. These areas, even if they may present lower overall exposure to climate hazards compared to other regions in Europe (Figure 2.6), will be prone to the largest changes in exposure to multi-hazard, which potentially increases the presence of concurrent hazards and therefore results in larger risks.

Figure 2.7a shows for each European region the aggregated spatial extent experiencing pronounced increases in EAFE for at least four hazards, as expressed by CEI=4 (hence the areas coloured in red in Figure 2.7b), calculated for the different threshold levels of increase in EAFE and return periods between 2 and 100 years. It confirms that increases in hazards are more pronounced for higher return periods and for the long-term scenarios. Regions most prone to increases in multiple hazards are Southern and Western Europe.



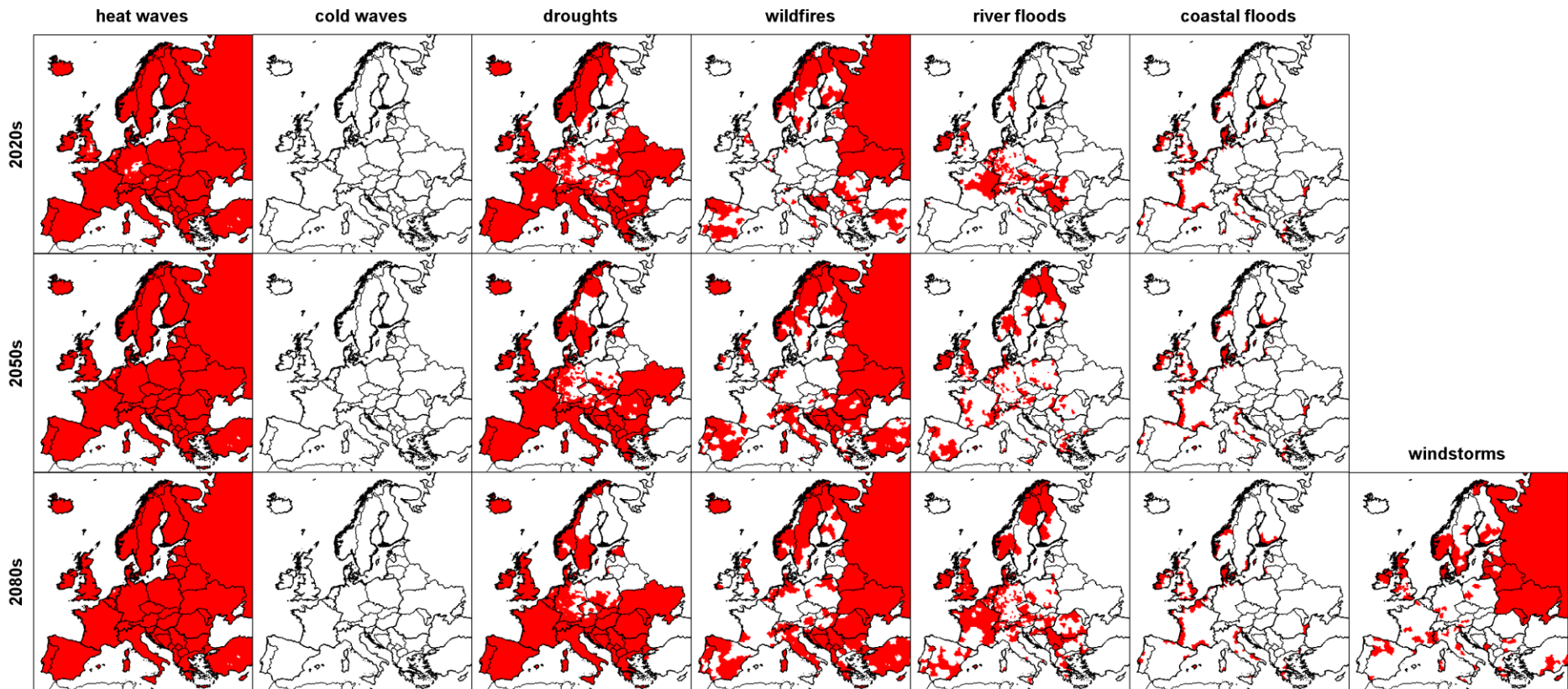


**Figure 2.6** Projections in Overall Exposure Index. Left (a) Baseline return levels (on the x-axis) versus corresponding future Expected Annual Fraction Exposed (EAFE) (on the y-axis) calculated as zonal average for different European regions resulting from the combination of all climate hazards accounting for the overlapping of one, two or three hazards (OEI<sub>1</sub>, OEI<sub>2</sub> and OEI<sub>3</sub>, respectively). Bars and colours visualized as in Figure 2.5; Right (b) spatio-temporal pattern of 100-yr EAFE for OEI<sub>1</sub>, OEI<sub>2</sub> and OEI<sub>3</sub>.



**Figure 2.7** Projections in Change Exposure Index. Left (a) Baseline return levels (on the x-axis) and corresponding area exposed to at least four hazards (CEI=4) with relative increases over 20%, 100% and 1000% with respect to the baseline (CEI<sub>20</sub>, CEI<sub>100</sub> and CEI<sub>1000</sub>, respectively) for different European regions; bars grouped as in Figure 2.5; Right (b) spatio-temporal patterns of CEI<sub>20</sub>, CEI<sub>100</sub> and CEI<sub>1000</sub> calculated for 100-yr events.





**Figure 2.8** Hazard-specific contributions to the Change Exposure Index calculation. NUTS3 regions whose relative increase in 100-yr EAFE is larger than 20% (in red).



## 2.4 Main limitations and knowledge gaps

Despite the depth of this study, results should be viewed in light of the potential uncertainty sources and caveats of the proposed methodology. The multi-hazard maps are dependent on the chosen set of climate hazard indicators: the use of diverse input hazards (e.g., hail, landslides) might lead to different findings. We argue that the set of hazards selected includes the most relevant hazards for Europe in terms of average annual losses and deaths (“NatCatSERVICE | Munich Re,” n.d.). Metrics used to represent the selected climate hazards are crucial for the resulting impact scenarios: changes in return periods depend on the time scale selected to characterize an event type, e.g. 1-day temperature extremes, weekly heatwaves or seasonal heat anomalies experience different changes in return periods (Perkins and Alexander, 2012; Trenberth et al., 2014). In our approach we focus on hazard-specific metrics of impact relevance that have been documented in recent literature. Details on the sensitivity analysis and calibration/validation exercises for each single hazard are reported in the references (Cid et al., 2014; Forzieri et al., 2014; M. Migliavacca et al., 2013; Outten and Esau, 2013; Rojas et al., 2012; Russo et al., 2014). We recognize that extreme value fitting may introduce additional uncertainty in the projections of climate hazards especially at high return periods. Recent studies, though, documented its secondary role with respect to the inter-model spread (Forzieri et al., 2014; Rojas et al., 2012).

We apply a conservative approach without accounting explicitly for hazard interrelations that could lead to greater impacts. Regions exposed to the overlap of multiple hazards and subject to concurrent increases in single-hazard EAFEs, however, are indicative of a more likely exacerbation of the overall impacts due to inter-hazard triggering relationships. Estimation of probabilities of coincidental or cascading events would require finer time resolution of hazard metrics (here annual or monthly) and a better knowledge of the inter-hazard physical interactions and coupled processes.

The socioeconomic scenarios driving GHG emissions, the sensitivity of the climate models to GHG concentrations and the specific hazard modelling utilized are subject

to uncertainty, and all are relevant in influencing the final multi-hazard assessment. The use of different climate model ensembles for each hazard may have introduced additional artefacts (Table 2.1). However, recent studies suggest that the reduced subsets utilized in this study for some hazards largely preserve main statistical properties of the initial 12-member ensemble (Russo et al., 2013). The use of identical - and possibly larger - ensembles could allow to better capturing climate-related uncertainties (Kharin et al., 2013; Sillmann et al., 2013). We used a different baseline and only one future time window for windstorms. New dedicated runs for windstorms for the remaining temporal periods were not feasible within this study. We understand that such diversity may limit the comparability with the other hazards; however, changes in extreme winds seem to be lower compared to the other climate hazards, hence the potential bias is expected to play a minor role. Analyses of the multi-hazard indices are performed using the ensemble median of all climate model combinations for each hazard as input because only one single GCM-RCM configuration is common amongst the hazards. While the median can be considered a robust estimate of single-hazard ensembles, this inevitably hampers the analysis of how single-hazard uncertainties (Figure 2.4) propagate to the combined metrics.

## 2.5 References

- Bedia, J., Herrera, S., Camia, A., Moreno, J.M., Gutiérrez, J.M., 2013. Forest fire danger projections in the Mediterranean using ENSEMBLES regional climate change scenarios. *Clim. Change* 122, 185–199. doi:10.1007/s10584-013-1005-z.
- Christidis, N., Jones, G.S., Stott, P.A., 2015. Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *Nat. Clim. Change* 5, 46–50. doi:10.1038/nclimate2468.
- Cid, A., Castanedo, S., Abascal, A.J., Menéndez, M., Medina, R., 2014. A high resolution hindcast of the meteorological sea level component for Southern Europe: the GOS dataset. *Clim. Dyn.* 43, 2167–2184. doi:10.1007/s00382-013-2041-0.
- Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Dilley, M., 2005. *Natural Disaster Hotspots: A Global Risk Analysis*. World Bank Publications.
- Fischer, E.M., Beyerle, U., Knutti, R., 2013. Robust spatially aggregated projections of climate extremes. *Nat. Clim. Change* 3, 1033–1038. doi:10.1038/nclimate2051.
- Fischer, E.M., Schär, C., 2010. Consistent geographical patterns of changes in high-impact European heatwaves. *Nat. Geosci.* 3, 398–403. doi:10.1038/ngeo866.
- Forzieri, G., Feyen, L., Rojas, R., Flörke, M., Wimmer, F., Bianchi, A., 2014. Ensemble projections of future streamflow droughts in Europe. *Hydrol Earth Syst Sci* 18, 85–108. doi:10.5194/hess-18-85-2014.
- Gill, J.C., Malamud, B.D., 2014. Reviewing and visualizing the interactions of natural hazards. *Rev. Geophys.* 52, 2013RG000445. doi:10.1002/2013RG000445.
- Hinkel, J., Nicholls, R.J., Vafeidis, A.T., Tol, R.S.J., Avagianou, T., 2010. Assessing risk of and adaptation to sea-level rise in the European Union: an application of DIVA. *Mitig. Adapt. Strateg. Glob. Change* 15, 703–719. doi:10.1007/s11027-010-9237-y.
- Kappes, M.S., Keiler, M., Elverfeldt, K. von, Glade, T., 2012. Challenges of analyzing multi-hazard risk: a review. *Nat. Hazards* 64, 1925–1958. doi:10.1007/s11069-012-0294-2.
- Kharin, V.V., Zwiers, F.W., Zhang, X., Wehner, M., 2013. Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Clim. Change* 119, 345–357. doi:10.1007/s10584-013-0705-8.

Kreibich, H., van den Bergh, J.C.J.M., Bouwer, L.M., Bubeck, P., Ciavola, P., Green, C., Hallegatte, S., Logar, I., Meyer, V., Schwarze, R., Thieken, A.H., 2014. Costing natural hazards. *Nat. Clim. Change* 4, 303–306. doi:10.1038/nclimate2182.

Lehner, B., Döll, P., Alcamo, J., Henrichs, T., Kaspar, F., 2006. Estimating the Impact of Global Change on Flood and Drought Risks in Europe: A Continental, Integrated Analysis. *Clim. Change* 75, 273–299. doi:10.1007/s10584-006-6338-4.

Lung, T., Lavalle, C., Hiederer, R., Dosio, A., Bouwer, L.M., 2013. A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change. *Global Environmental Change* 23, 522–536. doi:10.1016/j.gloenvcha.2012.11.009.

Migliavacca, M., Dosio, A., Camia, A., Houbourg, R., Houston-Durrant, T., Kaiser, J.W., Khabarov, N., Krasovskii, A.A., Marcolla, B., San Miguel-Ayanz, J., Ward, D.S., Cescatti, A., 2013. Modeling biomass burning and related carbon emissions during the 21st century in Europe. *J. Geophys. Res. Biogeosciences* 118, 2013JG002444. doi:10.1002/2013JG002444.

Migliavacca, M., Dosio, A., Kloster, S., Ward, D.S., Camia, A., Houbourg, R., Houston Durrant, T., Khabarov, N., Krasovskii, A.A., San Miguel-Ayanz, J., Cescatti, A., 2013. Modeling burned area in Europe with the Community Land Model. *J. Geophys. Res. Biogeosciences* 118, 265–279. doi:10.1002/jgrg.20026.

NatCatSERVICE, Munich Re, <http://www.munichre.com/natcatservice> (accessed 5.26.15).

Nicholls, R.J., Klein, R.J.T., 2005. Climate change and coastal management on Europe's coast, in: Vermaat, J., Salomons, W., Bouwer, L., Turner, K. (Eds.), *Managing European Coasts*, Environmental Science. Springer Berlin Heidelberg, pp. 199–226.

Nikulin, G., Kjellström, E., Hansson, U., Strandberg, G., Ullerstig, A., 2011. Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations. *Tellus A* 63, 41–55. doi:10.1111/j.1600-0870.2010.00466.x.

Outten, S.D., Esau, I., 2013. Extreme winds over Europe in the ENSEMBLES regional climate models. *Atmos Chem Phys* 13, 5163–5172. doi:10.5194/acp-13-5163-2013.

Pardaens, A.K., Lowe, J.A., Brown, S., Nicholls, R.J., de Gusmão, D., 2011. Sea-level rise and impacts projections under a future scenario with large greenhouse gas emission reductions. *Geophys. Res. Lett.* 38, L12604. doi:10.1029/2011GL047678.

Perkins, S.E., Alexander, L.V., 2012. On the Measurement of Heat Waves. *J. Clim.* 26, 4500–4517. doi:10.1175/JCLI-D-12-00383.1.

Rojas, R., Feyen, L., Bianchi, A., Dosio, A., 2012. Assessment of future flood hazard in Europe using a large ensemble of bias-corrected regional climate simulations. *J. Geophys. Res. Atmospheres* 117, D17109. doi:10.1029/2012JD017461.

- Rojas, R., Feyen, L., Watkiss, P., 2013. Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. *Global Environmental Change* 23, 1737–1751. doi:10.1016/j.gloenvcha.2013.08.006.
- Rummukainen, M., 2012. Changes in climate and weather extremes in the 21st century. *Wiley Interdiscip. Rev. Clim. Change* 3, 115–129. doi:10.1002/wcc.160.
- Russo, S., Dosio, A., Graversen, R.G., Sillmann, J., Carrao, H., Dunbar, M.B., Singleton, A., Montagna, P., Barbola, P., Vogt, J.V., 2014. Magnitude of extreme heat waves in present climate and their projection in a warming world. *J. Geophys. Res. Atmospheres* 119, 12,500–12,512. doi:10.1002/2014JD022098.
- Russo, S., Dosio, A., Sterl, A., Barbosa, P., Vogt, J., 2013. Projection of occurrence of extreme dry-wet years and seasons in Europe with stationary and nonstationary Standardized Precipitation Indices. *J. Geophys. Res. Atmospheres* 118, 7628–7639. doi:10.1002/jgrd.50571.
- Sillmann, J., Kharin, V.V., Zhang, X., Zwiers, F.W., Bronaugh, D., 2013. Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. *J. Geophys. Res. Atmospheres* 118, 1716–1733. doi:10.1002/jgrd.50203.
- Solomon, S., 2007. *Climate Change 2007 - The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC*. Cambridge University Press.
- Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. *Nat. Clim. Change* 4, 17–22. doi:10.1038/nclimate2067.

### 3 Vulnerability of critical infrastructures to climate hazards

#### 3.0 Key messages

- There is limited understanding of vulnerability of infrastructures to different hazards and quantitative information on the sensitivity of critical infrastructures to climate hazards is largely absent.
- Critical infrastructures are vulnerable to the various hazards in a myriad of ways. Some key vulnerabilities for each sector are exemplified in the Table 3.0 below.

**Table 3.0** Examples of main vulnerabilities of the sectors to the climate hazards

	Energy	Transport	Industry	Social
<b>Heat</b>	reduced power plant efficiency due to higher water temperature required for cooling	material degradation and buckling of roads, rails and bridges due to thermal expansion	increased cost for cooling and refrigeration	increased cost for cooling
<b>Cold</b>	structural damage to distribution lines due to ice and snow loads	buckling of roads, rails and bridges due to thermal contraction	water pipes vulnerable to frost/icing	increased cost of heating during cold episodes
<b>Drought</b>	reduction in hydropower potential and biofuel production	reduced navigability of rivers and channels	water quality degradation, reduction in usable water and increase in treatment costs	structural damages due to drought-induced subsidence and permafrost thawing
<b>Wildfire</b>	reduction in biofuel sources	deterioration of roads, railways and power lines	structural damages to industrial sites	destruction of social infrastructures
<b>Flood</b>	structural damages to energy production sites and transport networks	reduction of structural integrity of surface and subgrade material	structural damages to industrial sites, increasing cost for water treatment	structural damage to social infrastructures and reduction in operational services
<b>Windstorm</b>	disruption of transmission and distribution networks	structural damages to transport facilities	structural damages to industrial systems equipment	structural damages to social structures and facilities

- To ensure comparability in the multi-hazard and multi-infrastructure/investment context considered in CCMFF, qualitative sensitivities have been derived for the thematic priorities of the EU Cohesion Policy Funds (CPF) and for types of key infrastructures to the considered climate hazards by

integrating information from an extended literature review with a survey that was conducted among a pool of experts in the considered sectors.

- In the survey, 70% of the possible combinations of hazard (7) and infrastructures/investments (50) were considered sensitive by more than 80% of the respondents, while 40% of the themes are sensitive for more than 90% of the respondents. In general, the sensitivity is highest for inland floods, sea level rise and forest fires, whereas the sensitivity of infrastructures to drought seems less important.
- The expert survey generally corroborates the findings reported in the literature and the more robust findings of the survey correspond to higher consensus in the scientific community.
- Albeit that the derived sensitivity classes are subject to exposure, information and individual bias, and that infrastructure-specific vulnerability may show large variation depending on the institutional, economic, and technological context, they provide an indication of general sensitivities of different types of infrastructures and key economic assets to climate hazards and may help in orienting policy interventions for climate adaptation and resilience.

### 3.1 Introduction

An evaluation of the risk of a critical infrastructure or investment from a hazardous climate event requires a consideration of the element's vulnerability, further herein also referred to as sensitivity. We define vulnerability in accordance to the SREX report (IPCC, 2012) as the propensity or predisposition of the infrastructure to be adversely affected when exposed to a climate hazard. The potential degree to experience harm constitutes an internal characteristic of the affected infrastructure and is specific to the climate hazard.

Evaluating the effects of climate hazards on key economic assets is a complex issue because of incomplete scientific methodologies and limited understanding of vulnerability of infrastructures to different hazards. The most important approaches for the analysis of the physical vulnerability of infrastructures are the use of vulnerability curves, damage matrices or vulnerability indicators.

Vulnerability curves (frequently also referred to as damage, fragility, or risk curves) relate event intensity and resulting damages to a certain building type. While these functions offer continuous vulnerability information in relation to the degree of the hazard (for example, damage to an infrastructure for 1 m of flooding), they require extensive information on damaged buildings and are therefore typically only available for extensive and wide-spread processes like flooding (Kappes et al., 2012a). Also, albeit that there is a wide variety of flood damage functions in use internationally, they differ substantially in their approaches and economic estimates, and current methodologies for estimating infrastructural damage are not as well developed as methodologies for the estimation of damage to (residential) buildings (Jongman et al., 2012). Moreover, for other hazards like drought, impacts are much more difficult to quantify and link to specific events and their magnitude, hence damage functions more difficult to construct.

Vulnerability matrices provide discrete damage information for classified hazard intensities and are either based on observed damages or on rough appraisals. Despite the advantage of providing (semi-) quantitative information, damage



functions and matrices often relate damage with only one characteristic of the building, mainly the building type, hereby neglecting the properties of the element at risks (such as building age or number of floors). The method of vulnerability indicators, on the other hand, allows to integrating different building characteristics in the (qualitative) vulnerability description. However, whereas socio-economic indicators are more widely used to describe the multiple characteristics of humans, institutions and/or societies that contribute to their overall vulnerability, significantly less experience with vulnerability indicators has been acquired in the physical vulnerability context. Moreover, since vulnerability is primarily regarded as a characteristic of the element at risk, only in very few cases hazard-specific vulnerabilities are assessed in this way (Kappes et al., 2012b).

In the CCMFF project, rather than looking in very detail at a specific critical infrastructure in a particular setting, for which it is already very difficult to appraise its vulnerability, the aim is to evaluate potential impacts to types/classes of infrastructures and investments across a great territorial diversity with a wide variety of socio-economic settings and physical boundary conditions in Europe. This includes, for example, different building standards, positioning of the infrastructure in the landscape, its relation to the economy and depending sectors, as well as the existence of special protection measures (hard infrastructures like dikes or soft measures like early warning systems).

To ensure comparability in the multi-hazard and multi-infrastructure/investment context considered in CCMFF, a common method has to be adopted for the vulnerability assessment. We therefore derived general qualitative sensitivities for the thematic priorities of the EU Cohesion Policy Funds (CPF) and for types of key infrastructures to the considered climate hazards by integrating information from an extended literature review with a survey that was conducted among a pool of experts in the considered sectors. The performed analysis is an attempt to fill a gap in the scientific knowledge but also to provide a tractable database for assessing and comparing sensitiveness within future multi-hazard/multi-sector climate change impacts and adaptation studies.

## 3.2 Literature on climate sensitivity of infrastructures

It is not the aim of this report to provide an extensive overview of the literature related to potential impacts of climate extremes on infrastructures in different sectors. For a comprehensive overview we refer the reader to AR5 of the IPCC, (2014). Rather, we performed this review to understand what has been reported in the scientific literature about climate hazard sensitivities of critical infrastructures in order to supplement the expert survey (see section 4.3) in deriving vulnerability classes for types of infrastructures for the different climate hazards considered.

A summary of the literature for the different sectors and hazards is presented in Table 3.1, 3.2, 3.3 and 3.4. Studies looking at the sensitivity of multi-sectorial critical infrastructures to climate hazards are practically not existing. This observation may be explained by the need for transdisciplinary knowledge and collaboration for a review building on the existing literature in several sectors that is huge. The amount and detail of coverage in literature of these aspects varies strongly on the sector considered and the hazard.

For the energy sector, notwithstanding the variety of threats by climate extreme and their potential impacts on electricity generation and transmission systems, fuel infrastructure and transport systems, the range of the range of impacts modelled in the literature is still rather limited (IPCC, 2014). Most studies related to energy in relation to climate (hazards) have looked at climate impacts on changes in demand (typically related to changes in average temperature), whereas on the production side the majority of studies focus on renewable energy (hydropower, biomass) sources in relation to average climate changes, especially when compared to its share in the current installed capital/energy mix.

Studies on the impact of climate hazards on the transport sector to date have been mostly qualitative, and only few quantitative assessments are available. Recently three FP7 projects, EWENT (Extreme Weather impacts on European Networks of Transport - <http://ewent.vtt.fi>), ECCONET (Effects of climate change on the inland waterway networks - [www.econet.eu](http://www.econet.eu)) and WEATHER (Weather Extremes:

Assessment of Impacts on Transport and Hazards for European Regions - [www.weather-project.eu](http://www.weather-project.eu)), have studied impacts of weather phenomena to different aspects of the European transport systems. The main results of these projects are summarized in Michaelides et al., 2014) and several more detailed documents can be found on the project websites. Notwithstanding these and other recent advances, systematic and detailed knowledge on climate change vulnerability of and impacts on critical transport infrastructures remains limited in the literature (IPCC, 2014), especially with respect to climate extremes.

Research on the potential effects of climate hazards on industrial facilities and social (health and education) infrastructures is very limited, apart from some studies that focus on buildings in general.

Table 3.1, 3.2, 3.3 and 3.4 together with the paragraphs above show that many of the threats of extreme weather to different sectors are acknowledged and qualitatively described in the literature, but rather few quantitative assessment are available. Information on the sensitivity of infrastructures and economic assets in different sectors to climate hazards is not only scattered around many scientific disciplines, but also varies with local to regional boundary conditions that apply to the study. As such, there is no aggregated or global view allowing a comparison and application of a homogeneous methodological approach for assessing the sensitivity of infrastructures to climate hazards across Europe.

We therefore opted to construct a sensitivity matrix on the basis of a survey amongst experts (described in the next section), where the literature review serves to explain the channels through which the impacts are transmitted and to verify the robustness of the sensitivity matrix.

**Table 3.1** Overview of vulnerability (and impacts) of energy assets to climate hazards reported in literature

	<b>Heat waves</b>	<b>Cold</b>	<b>Droughts</b>	<b>Wildfires</b>	<b>River and coastal floods</b>	<b>Windstorms</b>
<b>Energy</b>	<p>Structural damages due to expansion of different materials (Pryor et al. 2010).</p> <p>Reduction of structural integrity due to melting permafrost (Ebinger, 2011, Cruz et al., 2013).</p> <p>Increased resistance on the power lines.</p> <p>Decrease in power plant efficiency due to higher water temperature required for cooling systems (van Vliet et al., 2012, van Vliet et al., 2013, Rubbelke et al., 2011, Chandramowli et al., 2014, EEA, 2012 ; Linnerud et al., 2011; Rübbelke, and Vögele, 2011).</p> <p>Reduction in biofuels sources (Moiseyev et al., 2011; Verkerk et al., 2011).</p> <p>Reduced performance of solar photovoltaic modules in hot weather as electrons movement is slower in hot materials (EEA, 2012).</p>	<p>Structural damages due to ice and snow loads overhead distribution lines (Bompard et al., 2013, McColl et al., 2012) and ice-induced changes in pipeline pressures (Humphrey et al, 2008).</p> <p>Increased corrosion on energy systems (Ebinger 2011; Cruz et al., 2013).</p> <p>Reduction in hydropower potential due to water freezing (Lehner et al. 2005; Mideska et al. 2010).</p> <p>Reduction in biofuels sources (Mideska et al., 2010).</p>	<p>Reduction of structural integrity due to melting of permafrost and drought-induced subsidence (Ebinger, 2011, Cruz et al., 2013).</p> <p>Deterioration of power systems caused by overexploitation of irrigation and water pumping (Rubbelke et al., 2011; Chandramowli et al., 2014; Klein et al., 2013).</p> <p>Decrease in power plant efficiency due to higher water temperature and lower water volumes required for cooling systems (Patt et al., 2013; Rubbelke et al., 2011; Paskal, 2010; Sieber, 2013; Arent et al., 2014; Mideksa, et al., 2010; Van Vliet, et al., 2013; Förster et al., 2010; Ebinger, 2011; EEA, 2012 ; Linnerud et al., 2011; Rübbelke, and Vögele, 2011).</p> <p>Deterioration of cooling systems due to excessive biological growth and clog water intages (Cruz et al., 2013, Sieber, 2013).</p> <p>Reduction in biofuels sources (Moiseyev et al., 2011; Verkerk et al., 2011).</p> <p>Reduction in hydropower potential due to reduced water volumes (van Vliet et al., 2012, van Vliet et al. 2013, Schaeffer et al. 2012, Lehner et al. 2005).</p>	<p>Damages to power systems equipment (Bompard et al., 2013)</p> <p>Reduction in biofuels sources (Boisvenue, 2005; Bompard et al., 2013).</p> <p>Damage to pipelines and electricity transmission lines from bushfires (IPCC, 2014).</p>	<p>Structural damages to energy production sites and transport networks due to direct impacts of overflows, reduced soil stability and induced mass movements (soil erosion, landslide, siltation) (Ebinger, 2011; Paskal et al., 2010; Brown et al., 2014; Bompard et al., 2013; Ebinger et al., 2011; Klein et al., 2013; Kovats et al., 2014; Brown, 2014; Chandramowli et al., 2014).</p> <p>Damages to power systems equipment due to debris and pollution in cooling water flows required (Sieber et al., 2013; Cruz et al.; 2013).</p> <p>Short-circuiting and power failure on electrical systems (Brown et al., 2014). Disable corrosion protection equipment and produce pitting (Humphrey et al., 2008; Cruz et al., 2013; Bompard et al., 2013).</p> <p>Reduction in biofuels sources (Mideska et al., 2010; Ebinger et al., 2011)</p> <p>Reduction in hydropower production due to increased silting of sediment into reservoirs due to increased erosion and sediment displacement.</p>	<p>Structural damages to power systems equipment and storage tanks due to wind pressure or debris impact (Pryor et al. 2010; Ebinger, 2011; Wilbanks et al., 2012; Bompard et al., 2013), Arent et al., 2014).</p> <p>Overloads of tidal and wave energy plants (Paskal, 2010).</p> <p>Disruption of electricity lines (transmission and distribution networks) and damages to cables due to falling trees (Bompard et al., 2013; Arent et al. 2014, McColl et al. 2012).</p> <p>Short-circuiting triggering possible fires especially with storage of liquid flammable hydrocarbons (Bompard et al., 2013; Sieber 2013; Ebinger 2011).</p> <p>Reduction in biofuels sources (Boisvenue, 2005; Bompard et al., 2013).</p> <p>Extreme storm gusts may damage wind turbines (EEA, 2012).</p>

**Table 3.2** Overview of vulnerability (and impacts) of transport assets to climate hazards reported in literature

	<b>Heat waves</b>	<b>Cold</b>	<b>Droughts</b>	<b>Wildfires</b>	<b>River and coastal floods</b>	<b>Windstorms</b>
<b>Transport</b>	<p>Buckling of roads, rails and bridges due to thermal expansion; structural material degradation; melting of asphalt and increased rutting and softening of pavement, signaling problems (Arent et al., 2014, Peterson et al. 2008, Jaroszweski et al. 2010; Mehrotra et al., 2011; Chinowski et al., 2012; Chinowsky et al., 2013; Mehrotra et al., 2011 ; Suarez, 2005 ; Peterson et al., 2008 ; Dobney et al., 2009 ; Eichhorst, 2009; Thornes et al., 2012 ; Cramer et al., 2014 ; Mills and Andrey , 2002 ; Molarius et al., 2011 ; Oslakovic et al., 2013, EEA, 2011; Nolte et al., 2011).</p> <p>Failures of power lines (Nemry et al., 2012).</p> <p>Overheating impacts on infrastructure equipment, lifetime reduction, reliability of the electronic and electric components (e.g., rail rolling stock equipment) (EEA, 2012);</p> <p>Slope instabilities due to the thawing of permafrost in alpine regions (EEA, 2012)</p>	<p>Buckling of roads, rails and bridges due to thermal contraction (Enei et al., 2011; Koetse et al., 2009; Oslakovic et al., 2013).</p> <p>Icing of aircraft wings and disruptions of airport functioning (Pejovic et al., 2009; Doll et al., 2013; Przuluski, 2012).</p> <p>Ice accumulation on vessels, decks, riggings, and docks (Molarius et al., 2013; Humphrey et al., 2008 ; Mehrotra et al., 2011).</p> <p>Boat traffic disrupted due to thick river ice cover (Schweighofer et al., 2014).</p>	<p>Reduced clearance under waterway bridges, reduced navigability of rivers and channels due to low level streamflows (Jonkeren et al., 2007; Jonkeren et al., 2013)</p> <p>Earthworks desiccation, increased abrasion of mechanical components (EEA, 2012)</p>	<p>Deterioration of roads, railways and power lines (Peterson et al., 2008).</p>	<p>Reduction of structural integrity of surface and subgrade material due to wave action and induced-mass movements (erosion, landslide, subsidence) (Wright et al., 2012; Peterson et al. 2008; Eichhorst, 2009; Jaroszweski et al., 2010; Arent et al., 2014; Nemry et al., 2012; Cramer et al., 2014).</p> <p>Scour on bridges and embankments, track and rail lineside equipment failure (Suarez, 2005; Humphrey et al., 2008; NRC, 2008 ; Peterson et al., 2008 ; Nemry et al., 2012 ; Eichhorst, 2009 ; Palin et al., 2013 ; Cramer et al., 2014 ; Mills and Andrey, ; 2002 ; Thornes et al., 2012 ; Molarius et al., 2011 ; Oslakovic et al., 2013).</p> <p>Structural damages to transport mode facilities (Hallegatte et al., 2011, Brown, 2014).</p> <p>Increased deterioration of infrastructures that lack a fouling-resistant design against salt water, Peterson et al., 2008).</p> <p>Disruption of transport vehicles (Koetse et al., 2009; Molarius et al., 2013).</p> <p>Reduced clearance under waterway bridges, reduced navigability of rivers and channels due to increased sedimentation (Jonkeren et al., 2007; Jonkeren et al., 2013; Humphrey et al., 2008; Molarius et al., 2013; Koetse et al., 2009; Arent et al., 2014; Eichhorst et al., 2009; Schweighofer et al.,2014).</p> <p>Drainage systems, tunnels, increased scour of bridges. Risk of weather-related delays in all modes of services (EEA, 2012)</p> <p>Damage to rail installations, catenary, all modes potential traffic disruption (EEA, 2012)</p>	<p>Structural damages to transport facilities (bridges, flyovers, electric tracks with overhead cables, train platforms, street lighting and signs) due to wind pressure or debris impact (Eichhorst, 2009; Enei et al., 2011; Molarius et al., 2011).</p> <p>Damage to rail installations, catenary, all modes potential traffic disruption (EEA, 2012)</p> <p>Short-circuiting along electrical cables (Burlando et al., 2010; Enei et al., 2011; Molarius et al., 2011)</p> <p>Obstruction of roads and rails due to fallen vegetation (Burlando et al., 2010; Molarius et al., 2011; Oslakovic et al., 2013).</p> <p>Air and boat traffic disrupted due to high turbulences (PWC, 2010; Kulesa et al., 2003).</p> <p>Piled shipping containers may tip over (PWC, 2010; TRB, 2008)</p> <p>Reduced clearance under waterway bridges, reduced navigability of rivers and channels due to floating debris (Jonkeren et al., 2013)</p> <p>Reduction in all transport modes (EEA, 2012)</p>

**Table 3.3** Overview of vulnerability (and impacts) of industrial assets to climate hazards reported in literature

	<b>Heat waves</b>	<b>Cold</b>	<b>Droughts</b>	<b>Wildfires</b>	<b>River and coastal floods</b>	<b>Windstorms</b>
<b>Industry</b>	<p>Enhanced degradation of materials and structures (Arent et al., 2014 ; Delpla et al., 2009; van Vliet et al., 2012; Tang et al., 2013)</p> <p>Structural damages to landfill due to increased methane production and potential leachate escape (Bebb et al., 2003).</p> <p>Increased cost for cooling and refrigeration.</p> <p>Higher treatment costs due to increase in distribution of vermin and pests (Bebb et al., 2003).</p> <p>Reduction in decomposition rate leading to lower operability and productivity (Bebb et al., 2003).</p>	<p>Water pipes vulnerable to frost/icing (Bebb et al., 2003; Whitehead et al., 2009; PWC, 2010)</p>	<p>Structural damages due to drought-induced subsidence and permafrost thawing (Tang et al., 2013; PWC, 2010)</p> <p>Water quality degradation, reduction in drinkable water and increase in treatment costs (Tang et al., 2013; Delpla et al., 2009; Whitehead et al., 2009; Cisneros et al., 2014; van Vliet et al., 2012)</p> <p>Reduction in decomposition rate leading to lower operability and productivity (Bebb et al., 2003).</p>	<p>Forest fires affect the viability of mining operations and potentially increases operating, transportation and decommissioning costs (IPCC, 2014)</p>	<p>Structural damages to industrial sites due to direct impacts of overflows, reduced soil stability and induced mass movements (soil erosion, landslide, siltation) (Burton et al., 2005; Ahmed, 2012; Cisneros et al., 2014; Cozzani et al., 2010; Krausmann et al., 2011).</p> <p>Increasing cost for water treatment due to release of pollutants into the drainage and sewer system when brownfields are exposed to overflows (Major et al., 2011).</p> <p>Overburden of drainage and sewer systems (Neuman et al., 2014; Delpla et al., 2009). Damages to transportation and transfer structures leading to disruption in water supply (Langeveld, 2013).</p> <p>Increased intrusion of salty water, damages for withdrawals, water quality degradation, wells pumping cut off, increasing cost for water treatment and reduction of water available for industrial purposes (Delpla et al., 2009; Ahmed, 2012; Major et al., 2011; Cozzani et al., 2010; Krausmann et al., 2011).</p>	<p>Structural damages to industrial systems equipment due to wind pressure or debris impact (Krausmann et al., 2011; Tannahill et al., 2011).</p> <p>Pipelines vulnerable to wind gust, strong winds may contribute to initiating unfavorable geodynamic processes and falling trees over the distribution system (Whitehead et al., 2009; Delpla, 2009; Wilbanks et al., 2012).</p>

**Table 3.4** Overview of vulnerability (and impacts) of social (education and health) assets to climate hazards reported in literature

	<b>Heat waves</b>	<b>Cold</b>	<b>Droughts</b>	<b>Wildfires</b>	<b>River and coastal floods</b>	<b>Windstorms</b>
<b>Social</b>	<p>Enhanced degradation of materials and structures (Hertin et al., 2003; Stewart et al., 2011).</p> <p>Higher dependence of people to water availability and quality (Pita et al., 2013)</p> <p>Overheating buildings, such as houses, hospitals, schools, (Crump et al., 2009; DCLG, 2012)</p>		<p>Structural damages due to drought-induced subsidence and permafrost thawing (Corti et al., 2009, 2011)</p> <p>Higher dependence of people to water availability and quality (Pita et al., 2013)</p> <p>Drought-induced soil subsidence and associated damage to dwellings (Corti et al., 2009)</p>		<p>Structural damage to social infrastructures and reduction in operational services (Carmichael et al., 2012; Hallegatte et al., 2011a)</p>	<p>Structural damages to education and health structures and facilities due to wind pressure or debris impact (Hallegatte et al., 2011b; Pita et al., 2013; Stewart et al., 2011).</p>

### 3.3 Expert survey

To derive a comparable vulnerability measure in the multi-hazard and multi-infrastructure/investment context considered in CCMFF a web-based survey was run amongst specialists, using the secured European Commission tool: EUSurvey (<http://ec.europa.eu/eusurvey>). In the survey the key economic assets and investments were grouped into the following sectors: (1) transport,, 2) energy, (3) information, industrial and social infrastructures and investments, (4) environmental/waste management and/or water treatment infrastructures, and (5) conservation of cultural and/or natural heritage. Based on the literature review, in a first screening of the allocations under the Cohesion Policy 2007-2013 programming period, 36 out of the 86 priority themes were considered not sensitive to climate hazards, so they were not retained in the survey (indicated without colour in Table 3.5). For each sector about 500 experts were inquired to complete the survey, including facility operators, authors and editorial boards of peer-reviewed journals in the field of climate change and sector-specific structural engineering. In the survey, sensitivity was defined as: “the degree an asset or system is affected when exposed to a climate hazard”. Experts assigned anonymously a degree of sensitivity (high, moderate, low, no) of sector-specific infrastructures to each of the 7 climate hazards considered. About 10% of the invited experts responded, resulting in a sample size of approximately 50 per investment/infrastructure type and hazard. The modes of the Likert distributions were considered representative of the sensitivities, and in case of low consensus amongst the experts and/or strong disagreement with reported impacts or sensitivities some adjustments were made based on the literature review.

The resulting sensitivity matrix for the Cohesion policy thematic priorities is shown in Table 3.5, for the critical infrastructures in Table 3.6. Green = no, yellow = low, orange = medium, and red = high sensitivity.

**Table 3.5** Sensitivities of CPF priority themes based on expert survey and literature Red = high, orange = medium, yellow = low, and green = no sensitivity. No color indicates the CPF priority themes that a priori were assumed to be not sensitive to climate hazards, hence was not included in the survey. DR = drought, FL = inland flooding; FF = forest fires; CL = cold; HE = heatwaves; SLR = sea level rise; and W = windstorms. (\*) CPF does not foresee investments in power plants so the sensitivity values for transmission/distribution are used instead).

Code	Thematic priority name	DR	FL	FF	CL	HE	SLR	WI
1	R&TD activities in research centres							
2	R&TD infrastructure and centres of competence	Orange	Orange	Orange	Yellow	Orange	Orange	Orange
3	Technology transfer and improvement of cooperation networks							
4	Assistance to R&TD, particularly in SMEs							
5	Advanced support services for firms and groups of firms							
6	Assistance to SMEs for the promotion of environmentally-friendly products							
7	Investment in firms directly linked to research and innovation							
8	Other investment in firms							
9	Other measures to stimulate research and innovation							
10	Telephone infrastructures (including broadband networks)	Yellow	Orange	Orange	Yellow	Yellow	Orange	Orange
11	Information and communication technologies	Yellow	Orange	Orange	Yellow	Yellow	Orange	Orange
12	Information and communication technologies (TEN-ICT)	Yellow	Orange	Orange	Yellow	Yellow	Orange	Orange
13	Services and applications for citizens							
14	Services and applications for SMEs							
15	Other measures							
16	Railways	Green	Orange	Orange	Orange	Orange	Orange	Yellow
17	Railways (TEN-T)	Green	Orange	Orange	Orange	Orange	Orange	Yellow
18	Mobile rail assets	Green	Yellow	Orange	Yellow	Yellow	Yellow	Yellow
19	Mobile rail assets (TEN-T)	Green	Yellow	Orange	Yellow	Yellow	Yellow	Yellow
20	Motorways	Green	Orange	Orange	Orange	Orange	Orange	Yellow
21	Motorways (TEN-T)	Green	Orange	Orange	Orange	Orange	Orange	Yellow
22	National roads	Green	Orange	Orange	Orange	Orange	Orange	Yellow
23	Regional/local roads	Green	Orange	Orange	Orange	Orange	Orange	Yellow
24	Cycle tracks	Green	Orange	Yellow	Orange	Orange	Orange	Yellow
25	Urban transport	Green	Orange	Yellow	Orange	Orange	Orange	Yellow
26	Multimodal transport	Green	Orange	Yellow	Orange	Orange	Orange	Yellow
27	Multimodal transport (TEN-T)	Green	Orange	Yellow	Orange	Orange	Orange	Yellow
28	Intelligent transport systems	Green	Orange	Yellow	Orange	Orange	Orange	Yellow
29	Airports	Green	Orange	Yellow	Orange	Yellow	Orange	Orange



30	Ports							
31	Inland waterways (regional and local)							
32	Inland waterways (TEN-T)							
33	Electricity*							
34	Electricity (TEN-E)*							
35	Natural gas*							
36	Natural gas (TEN-E)*							
37	Petroleum products*							
38	Petroleum products (TEN-E)*							
39	Renewable energy: wind							
40	Renewable energy: solar							
41	Renewable energy: biomass							
42	Renewable energy: hydroelectric, geothermal and other							
43	Energy efficiency, co-generation, energy management							
44	Management of household and industrial waste							
45	Management and distribution of water (drink water)							
46	Water treatment (waste water)							
47	Air quality							
48	Integrated prevention and pollution control							
49	Mitigation and adaption to climate change							
50	Rehabilitation of industrial sites and contaminated land							
51	Promotion of biodiversity and nature protection							
52	Promotion of clean urban transport							
53	Risk prevention							
54	Other measures to preserve the environment and prevent risks							
55	Promotion of natural assets							
56	Protection and development of natural heritage							
57	Other assistance to improve tourist services							
58	Protection and preservation of the cultural heritage							
59	Development of cultural infrastructure							
60	Other assistance to improve cultural service							
61	Integrated projects for urban and rural regeneration							
62	Development of life-long learning systems and strategies							
63	Design of innovative and more productive ways of organising work							

64	Development of special services for employment and training							
65	Modernisation and strengthening labour market institutions							
66	Implementing active and preventive measures on the labour market							
67	Measures encouraging active ageing and prolonging working life							
68	Support for self-employment and business start-up							
69	Measures to improve access to employment							
70	Specific action to increase migrants' participation in employment							
71	Integration and re-entry into employment for disadvantaged people							
72	Design, introduction and implementing of reforms in education							
73	Measures to increase participation in education and training							
74	Developing human potential in research & innovation							
75	Education infrastructure							
76	Health infrastructure							
77	Childcare infrastructure							
78	Housing infrastructure							
79	Other social infrastructure							
79	Other social infrastructure							
80	Promoting partnerships, pacts and initiatives							
81	Mechanisms for improving good policy and programme design							
82	Compensation of any additional costs due to accessibility							
83	Compensation of additional costs due to market forces							
84	Compensation of additional costs due to climate conditions							
85	Preparation, implementation, monitoring and inspection							
86	Evaluation and studies; information and communication							

**Table 3.6** Sensitivities of critical infrastructures based on expert survey and literature Red = high, orange = medium, yellow = low, and green = no sensitivity.

<b>ENERGY</b>	drought	flood	SLR	fire	cold	heat	wind
Nuclear power plants							
Coal fired power plants							
Gas fired power plants							
Oil fired power plants							
Electricity transmission/distribution							
Gas pipelines							
Wind							
Solar							
Biomass							
Hydro							
<b>TRANSPORT</b>	drought	flood	SLR	fire	cold	heat	wind
Rails							
Roads							
Airports							
Ports							
Inland Waterways							
<b>INDUSTRY</b>	drought	flood	SLR	fire	cold	heat	wind
Metals							
Chemical							
Refineries							
Minerals							
Water/waste management							
<b>SOCIAL</b>	drought	flood	SLR	fire	cold	heat	wind
Education							
Health							

In the survey, 70% of the possible combinations of hazard (7) and infrastructures/investments (50) were considered sensitive by more than 80% of the respondents while 40% of them are sensitive for more than 90% of the respondents. In general, the sensitivity is highest for inland floods, sea level rise and forest fires, whereas the sensitivity of infrastructures to drought seems less important.

The expert survey generally corroborates the findings reported in the literature and the more robust findings correspond to higher consensus in the scientific community. The consensus about the survey sensitiveness is linked to the number of referenced impacts found for droughts, flood and forest fires, while it is much less pronounced for heat waves, frost/snow/cold and wind. There is also clearly a relation between the number of impact channels inventoried in the literature and the average sensitivity assessed by experts, albeit that the number of channels does not give any information about the strength of a given channel nor the scale of the potential impacts.

We acknowledge different potential sources of bias in the survey:

- Exposure bias: respondents seem to sometimes confound (potentially unintentionally) exposure as part of the vulnerability when they indicate the level of sensitivity. The first evidence of the existence of such bias is the difference in sensitivity indicated by experts between sea-level rise/storm surges and floods for some investments (for instance telephone and broadband networks, high impact while for sea level rise/storm surges it is low, which can only be justified by a difference in exposure). Other evidence of such bias is the heterogeneity of answers from the survey for related infrastructures; for example, regional roads are estimated as more sensitive to frost/snow/cold and floods than motorways and national roads. Exposure bias was removed to the extent possible based on literature impacts and sensitivities.
- Information bias, both in the literature review and the survey: a general bias towards some more well-known and largely studied infrastructures vs. other ones to which the academic community has shed less light on (less studies on old technologies in energy production, apart from nuclear energy, especially compared to renewable energy). Some discrepancies between both assessment methods may also be the result of information bias. Impacts that are often discussed in the academic and grey literature (because associated with higher probability of occurrence or higher exposure) seem to be less acknowledged in the survey than in the review (meaning stronger bias in the

survey than in the literature review, potentially showing that this heuristic bias may be stronger when people try to gather expertise quickly to answer a survey online rather than when they write an article or choose a topic to study). For instance, the impact of droughts and heat waves on asphalt (both in the case of road transportation, which is very largely acknowledged by the literature, and of airports, the latter being associated with much less references) and on bridges is not well assessed by experts.

- Individual bias: The individual/personal representation of the overall impact of climate hazards and change was verified and shown to be very limited. We checked for individual bias by dropping the global representation of climate hazard impact within sectors, i.e. removing the average of all answers for each respondent, and this check led to the same results. Some heterogeneity between sector-specific samples (distinct panels of experts), however, may further bias the comparisons of results between sectors.

We further acknowledge that our approach has several limitations, including the following:

- Sensitivities for a given investment/infrastructure to a given hazard depend on the institutional and economic environment, especially on the upward and downward side of the production chain and thus on the dependency networks of critical infrastructure which are complex systems. Different degrees of interconnectivity of infrastructures indeed lead to different criticalness in case of a hazard (Kröger, 2008). Currently, there is, however, no satisfactory set of metrics or models that articulate the risk of failures, either naturally caused or human induced, for highly interdependent infrastructures.
- Technological heterogeneity among infrastructures may also have a great role in the sensitivity estimation. For example, power plants with closed circuit cooling systems are more efficient and less vulnerable to rising air temperatures.

- The life span of existing or planned infrastructure can influence its current and future vulnerability. For example, wind power systems have lower life spans making them more adaptable in the long run.

We implicitly consider in our survey exercise that experts are aware of the existing context (for instance the share of installed capital for a given technology of an infrastructure) and that they take this knowledge into account when answering the survey. Keeping these caveats in mind, our approach provides indications of general sensitivities of different types of infrastructures and key economic assets to climate hazards and may help in orienting policy interventions for climate adaptation and resilience. Further herein, when the vulnerability and exposure are combined with current climate hazards it is detailed how the qualitative sensitivity matrix is translated into quantitative estimates of impacts per sector.

### 3.4 References

Ahmed, D. Y., 2012. Potential Impacts of Climate Change on Waste Management in Ilorin city Nigeria. *Global Journal of Human-Social Science Research*, 12(6).

Araujo, M. B., Alagador D., Cabeza M., Nogues-Bravo D., Thuiller W., 2011. Climate change threatens European conservation areas. *Ecology Letters*, 14, 484–492.

Arent, D., Tol R., 2014. Key Economic Sectors and Services, Discussion paper, IPCC WGII AR5 Chapter 10.

Bebb, J., Kersey J., 2003. Potential impacts of climate change on waste management. Environment Agency.

Boisvenue, C., Running, S. W., 2006. Impacts of climate change on natural forest productivity - evidence since the middle of the 20th century. *Global Change Biology*, 12(5), 862–882.

Bompard, E., T. Huang, Y. Wu, and M. Cremenescu, 2013. Classification and trend analysis of threats origins to the security of power systems. *International Journal of Electrical Power & Energy Systems*, 50, 50–64.

Brimblecombe, P., C. M. Grossi, and I. Harris, 2011. Climate change critical to cultural heritage. *Survival and Sustainability*, pp. 195–205. Springer.

Brown, S., S. Hanson, and R. J. Nicholls, 2014. Implications of sea-level rise and extreme events around Europe: a review of coastal energy infrastructure. *Climatic Change*, 122, 81–95.

Burlando, M., A. Freda, C. Ratto, and G. Solari, 2010. A pilot study of the wind speed along the Rome-Naples HS/HC railway line. Part 1-Numerical modelling and wind simulations. *Journal of Wind Engineering and Industrial Aerodynamics*, 98(8), 392–403.

Burton, B., L. Gu, and Y. Yin, 2005. Overview of vulnerabilities of coastally-influenced conveyance and treatment infrastructure in greater Vancouver to climate change: Identification of adaptive responses. *World Water Congress 2005: Impacts of Global Climate Change - Proceedings of the 2005 World Water and Environmental Resources Congress*.

Campbell, A., V. Kapos, J. Scharlemann, P. Bubb, A. Chenery, L. Coad, B. Dickson, N. Doswald, M. Khan, F. Kershaw, 2009. Review of the literature on the links between biodiversity and climate change: impacts, adaptation and mitigation. Secretariat of the convention on biological diversity, Montreal. Technical Series, no. 42, p. 124.

Carmichael, C., G. Bickler, S. Kovats, D. Pencheon, V. Murray, C. West, and Y. Doyle, 2012. Overheating and Hospitals - What do we know? *Journal of Hospital Administration*, 2(1), DOI: 10.5430/jha.v2n1p1.

Corti, T., V. Muccione, P. Kollner-Heck, D. Bresch, and S.I. Seneviratne, 2009. Simulating past droughts and associated building damages in France. *Hydrology and Earth System Sciences*, 13(9), 1739-1747.

Chandramowli, S. N., and F. A. Felder, 2014. Impact of climate change on electricity systems and markets-A review of models and forecasts. *Sustainable Energy Technologies and Assessments*, 5, 62–74.

Chang, H., M. Lafrenz, I.-W. Jung, M. A. Figliozzi, R. Melgoza, D. Ruelas, D. Platman, and C. Pederson, 2011. Future Flooding Impacts on Transportation Infrastructure and Traffic Patterns Resulting from Climate Change. Discussion paper.

Chapman, L., J. A. Azevedo, and T. Prieto-Lopez, 2013. Urban heat & critical infrastructure networks: A viewpoint. *Urban Climate*, 3, 7–12.

Chatterton, J., C. Viviattene, J. Morris, E. C. Penning-Rowsell, and S. M. Tapsell, 2010. The costs of the summer 2007 floods in England. Discussion paper, Environment Agency.

Chinowsky, P., and C. Arndt, 2012. Climate Change and Roads: A Dynamic Stressor-Response Model. *Review of Development Economics*, 16(3), 448–462.

Chinowsky, P. S., J. C. Price, and J. E. Neumann, 2013. Assessment of climate change adaptation costs for the U.S. road network. *Global Environmental Change*, 23(4), 764 – 773.

Cisneros, B. E. J., and T. Oki, 2014. Freshwater Resources. Discussion paper, IPCC WGII AR5 Chapter 3.

Corti, T., V. Muccione, and P. Kollner-Heck, 2009. Simulating past droughts and associated building damages in France. *Hydrology and Earth System Sciences*, 13, 1739–1747.

Cozzani, V., M. Campedel, E. Renni, and E. Krausmann, 2010. Industrial accidents triggered by flood events: Analysis of past accidents. *Journal of Hazardous Materials*, 175(1-3), 501–509.

Cramer, W., and G. Yohe, 2014. Detection and Attribution of Observed Impacts,. Discussion paper, IPCC WGII AR5 Chapter 18.

Cruz, A. M., and E. Krausmann,. 2013. Vulnerability of the oil and gas sector to climate change and extreme weather events. *Climatic change*, 121, 41–53.

Crump, D., A. Dengel, and M. Swainson, 2009. Indoor Air Quality in Highly Energy Efficient Homes – A Review. NF18, National House-Building Council (NHBC) Foundation, IHS BRE Press, Bracknell, UK, 82 pp.

Damigos, D., 2012. Monetizing the impacts of climate change on the Greek mining sector. *Mitigation and Adaptation Strategies for Global Change*, 17(8), 865–878.



DCLG, 2012. Investigation into Overheating in Homes: Literature Review. UK Department of Communities and Local Government, London, UK, 124 pp.

Dell, J., P. Pasteris, et al., 2010. Adaptation in the oil and gas industry to projected impacts of climate change. SPE International Conference on Health Safety and Environment in Oil and Gas Exploration and Production. Society of Petroleum Engineers.

Delpla, I., A.-V. Jung, E. Baures, M. Clement, O. Thomas, 2009. Impacts of climate change on surface water quality in relation to drinking water production. *Environment International*, 35(8), 1225-1233.

Dobney, K., C. J., Baker, A. D. Quinn, and L. Chapman, 2009. Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east United Kingdom. *Meteorological Applications*, 16, 245–251.

Doll, C., C. Trinks, N. Sedlacek, V. Pelikan, T. Comes, and F. Schultmann, 2013. Adapting rail and road networks to weather extremes: case studies for southern Germany and Austria. *Natural Hazards*, 72(1), 63-85.

Ebinger, J. O. and W. Vegara, 2011. Climate impacts on energy systems: key issues for energy sector adaptation. World Bank Publications.

Eichhorst, U., 2009. Adapting urban transport to climate change, Sustainable transport : a sourcebook for policy-makers in developing cities, Vol. 5f, Dt. Ges. für Techn. Zusammenarbeit, 62 p.

Enei, R., C. Doll, N. Sedlacek, J. Kiel, N. Nesterova, L. Rudzikaite, A. Papanikolaou, V. Mitsakis, 2011. Vulnerability of transport systems. WEATHER project Deliverable 2.

Feyen, L., R. Dankers, K. Bodis, P. Salamon, J. I. Barredo, 2012. Fluvial flood risk in Europe in present and future climates. *Climatic Change*, 112(1), 47–62.

Ford, J., T. Pearce, J. Prno, F. Duerden, L. Berrang Ford, M. Beaumier, T. Smith, 2010. Perceptions of climate change risks in primary resource use industries: a survey of the Canadian mining sector. *Regional Environmental Change*, 10(1), 65–81.

Gibbons, J. H., 2012. Technology and innovation. In *Energy for Development* (pp. 141-148). Springer Netherlands.

Grossi, C., P. Brimblecombe, B. Menendez, D. Benavente, I. Harris, M. Déqué, 2011. Climatology of salt transitions and implications for stone weathering. *Science of the Total Environment*, 409(13), 2577–2585.

Hallegatte, S., J. Corfee-Morlot 2011a. Understanding climate change impacts, vulnerability and adaptation at city scale: an introduction. *Climatic Change*, 104, 1–12.

Hallegatte, S., N. Ranger, O. Mestre, P. Dumas, J. Corfee-Morlot, C. Herweijer, and R. M. Wood, 2011b. Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen. *Climatic change*, 104(1), 113–137.

Hanson, S., R. Nicholls, N. Ranger, S. Hallegatte, J. Corfee-Morlot, C. Herweijer, and J. Chateau, 2011. A global ranking of port cities with high exposure to climate extremes. *Climatic Change*, 104(1), 89–111.

Hertin, J., F. Berkhout, D. Gann, and J. Barlow, 2003. Climate change and the UK house building sector: perceptions, impacts and adaptive capacity. *Building Research and Information*, 31(3-4), 278–290.

Humphrey, N., et al., 2008. Potential impacts of climate change on US transportation. *Transportation Research News*, 256.

Hunt, A., and P. Watkiss, 2011. Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change*, 104(1), 13–49.

IPCC, 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field C.B., Barros V., Stocker T.F., Qin D., Dokken D.J., Ebi K.L., Mastrandrea M.D., Mach K.J., Plattner G.-K., Allen S.K., Tignor M., and Midgley P.M. (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

IPCC, 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

Jaroszweski, D., L. Chapman, and J. Petts, 2010. Assessing the potential impact of climate change on transportation: The need for an interdisciplinary approach. *Journal of Transport Geography*, 18(2), 331–335.

Jenkins, K., M. Gilbey, J. Hall, V. Glenis, and C. Kilsby, 2014. Implications of climate change for thermal discomfort on underground railways. *Transportation Research Part D: Transport and Environment*, 30(0), 1 – 9.

Jonkeren, O., P. Rietveld, and J. van Ommeren, 2007. Climate change and inland waterway transport: welfare effects of low water levels on the river Rhine. *Journal of Transport Economics and Policy*, pp. 387–411.

Jonkeren, O., P. Rietveld, J. van Ommeren, and A. te Linde, 2013. Climate change and economic consequences for inland waterway transport in Europe. *Regional Environmental Change*, pp. 1–13.

Jongman, B., Kreibich H., Apel H., Barredo J.I., Bates P.D., Feyen L., Gericke A., Neal J., Aerts J.C.J.H., Ward P.J., 2012. Comparative flood damage model assessment: Towards a European approach. *Natural Hazards and Earth System Science*, 12(12), 3733-3752.

Kappes M.S., Keiler M., von Elverfeldt K., Glade T., 2012a. Challenges of analyzing multi-hazard risk: a review. *Natural Hazards*, 64, 1925–1958. DOI 10.1007/s11069-012-0294-2.

Kappes M.S., Papathoma-Köhle M., Keiler M., 2012b. Assessing physical vulnerability for multi-hazards using an indicator-based methodology. *Applied Geography*, 32, 577-590.

Klein, D. R., M. Olonscheck, C. Walther, and J. P. Kropp, 2013. Susceptibility of the European electricity sector to climate change. *Energy*, 59(0), 183 – 193.

Koetse M.J., Rietveld P., 2009. The impact of climate change and weather on transport: an overview of empirical findings. *Transportation Research Part D*, 14,205–221.

Kovats, S., and R. Valentini, 2014. Regional Aspects: Europe. Discussion paper, IPCC WGII AR5 Chapter 23.

Krausmann, E., V. Cozzani, E. Salzano, E. Renni, E. Petrova, and M. Hailwood, 2011. Industrial accidents triggered by natural hazards: an emerging risk issue. *Natural Hazards and Earth System Sciences*, 11(3).

Kröger, W., 2008. Critical infrastructures at risk: A need for a new conceptual approach and extended analytical tools. *Reliability Engineering & System Safety*, 93(12), 1781-1787.

Kulesa, G., 2003. Weather and aviation: How does weather affect the safety and operations of airports and aviation, and how does FAA work to manage weather-related effects?. in *The Potential Impacts of Climate Change on Transportation*.

Langeveld, J., R. Schilperoort, and S. Weijers, 2013. Climate change and urban wastewater infrastructure: There is more to explore. *Journal of Hydrology*, 476(0), 112–119.

Lehnera, B., G. Czigob, and S. Vassoloa, 2005. The impact of global change on the hydropower potential of Europe: a model-based analysis. *Energy Policy*, 33, 839–855.

Lemmen, D. S., and F. J. Warren, 2004. Climate change impacts and adaptation: a Canadian perspective.

Linnerud, K., Mideska, T. K. and Eskeland, G. S., 2011. The impact of climate change on nuclear power supply. *The Energy Journal* 32(1), 149–168. doi:10.5547/ISSN0195-6574-EJ-Vol32-No1-6.

Loosemore, M., J. Carthey, V. Chandra, and A. M. Chand, 2011. Climate change risks and opportunities in hospital adaptation. *International Journal of Disaster Resilience in the Built Environment*, 2(3), 210–221.

Major, D. C., Leichenko, R. M., Johnson, K., & Linkin, M., 2013. Projecting future coastal flooding damages with climate change. *Review of Environment, Energy and Economics* (Re3).

McColl, L., E. J. Palin, H. E. Thornton, D. M. H. Sexton, R. Betts, and K. Mylne, 2012. Assessing the potential impact of climate change on the UK's electricity network. *Climatic Change*, 115(3-4), 821-835

Mehrotra, S., B. Lefevre, R. Zimmerman, H. Cercek, K. Jacob, and S. Srinivasan, 2011. Climate change and urban transportation systems. *Climate change and cities, First Assessment Report of the urban climate change research network*, pp. 145–177.

Michaelides S., Leviäkangas P., Doll C., Heyndrickx C., 2014. Foreward: EU-funded projects on extreme and high-impact weather challenging European transport systems. *Natural Hazards*, 72(1), 5-22.

Mideksa, T. K., and S. Kallbekken, 2010. The impact of climate change on the electricity market: a review. *Energy Policy*, 38(7), 3579–3585.

Mills, B., and J. Andrey, 2002. Climate change and transportation: potential interactions and impacts. *The Potential Impacts of Climate Change on Transportation*, [US] DOT Center for Climate Change and Environmental Forecasting (<http://climate.volpe.dot.gov/workshop1002/mills.doc>), pp. 77–88.

Mitsakis, E., A. Papanikolaou, G. Ayfadopoulou, J. Salanova, C. Doll, G. Giannopoulos, and C. Zerefos, 2013. An integrated framework for linking climate change impacts to emergency adaptation strategies for transport networks. *European Transport Research Review*, pp. 1–9.

Moiseyev, A., B. Solberg, A. M. I. Kallio, and M. Lindner, 2011. An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries. *Journal of Forest Economics*, 17(2), 197–213, Fuelwood, timber and climate change: Insights from the forest sector modeling.

Molarius, J. S., S. Toivonen, J. Keränen, J. Törnqvist, P. N. Juga, and J. Rauhala, 2011. Review on extreme weather impacts on transport systems. EWENT project Deliverable.

Molarius, R., V. Könönen, P. Leviäkangas, J. Rönty, A.-M. Hietajärvi, K. Oiva, et al., 2013. The extreme weather risk indicators (EWRI) for the European transport system. *Natural Hazards*, pp. 1–22.

National (US) Research Council (NRC), 2008. *Potential Impacts of Climate Change on US Transportation*, vol. 290. Transportation Research Board, Committee on Climate Change and US Transportation and National Research Council. Division on Earth and Life Studies.

Nemry, F., and H. Demirel, 2012. *Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures*. Publications Office.

Neumann, J. E., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J. B. Smith, W. Perkins, L. Jantarasami, et al., 2014. Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*, pp. 1–13.

Nokkala, M., P. Leviańkangas, and K. Oiva, 2012. The costs of extreme weather for the European transport system. Discussion paper, mimeo.

Nolte, R., Kamburow, C. and Rupp, J., 2011. ARISCC. Adaptation of Railway Infrastructure to Climate Change. Final Report. Institute for Future Studies and Technology Assessment (IZT), Berlin. <http://www.ariscc.org/index.php?id=103>.

Oslakovic, I.-S., A. Hartmann, and G. Dewulf, 2013. Risk Assessment Of Climate Change Impacts On Railway Infrastructure. proceedings of the Engineering Project Organization Conference Devil's Thumb Ranch, Colorado, July 9-11.

Oven, K. J., Curtis, S. E., Reaney, S., Riva, M., Stewart, M. G., Ohlemüller, R., & Holden, R., 2012). Climate change and health and social care: Defining future hazard, vulnerability and risk for infrastructure systems supporting older people's health care in England. *Applied Geography*, 33, 16-24.

Palin, E. J., H. E. Thornton, C. T. Mathison, R. E. McCarthy, R. T. Clark, and J. Dora, 2013. Future projections of temperature-related climate change impacts on the railway network of Great Britain. *Climatic change*, 120(1-2), 71–93.

Paskal, C., 2010. The vulnerability of energy infrastructure to environmental change. in *China and Eurasia Forum Quarterly*, vol. 8, pp. 149–163.

Patt, A., S. Pfenninger, and J. Lilliestam, 2013. Vulnerability of solar energy infrastructure and output to climate change. *Climatic change*, 121, 93–102.

Pearce, T. D., J. D. Ford, J. Prno, F. Duerden, J. Pittman, M. Beaumier, L. Berrang-Ford, and B. Smit, 2011. Climate change and mining in Canada. *Mitigation and Adaptation Strategies for Global Change*, 16(3), 347–368.

Pejovic, T., V. A. Williams, R. B. Noland, and R. Toumi, 2009. Factors affecting the frequency and severity of airport weather delays and the implications of climate change for future delays. *Transportation Research Record: Journal of the Transportation Research Board*, 2139(1), 97–106.

Peterson, T. C., M. McGuirk, T. G. Houston, A. H. Horvitz, and M. F. Wehner, 2008. Climate variability and change with implications for transportation. *Transportation Research Board*.

Pita, G. L., J.-P. Pinelli, K. R. Gurley, and S. Hamid, 2013. Hurricane vulnerability modeling: Development and future trends. *Journal of Wind Engineering and Industrial Aerodynamics*, 114, 96–105.

PricewaterhouseCoopers, 2010. Adapting to climate change in the infrastructure sectors, Maintaining robust and resilient infrastructure systems in the energy, transport, water and ICT sectors, November 2010, report.

Pryor, S., R. Barthelmie, and E. Kjellström, 2005. Potential climate change impact on wind energy resources in northern Europe: analyses using a regional climate model. *Climate Dynamics*, 25(7-8), 815–835.

Pryor, S. C., and R. J. Barthelmie, 2010. Climate change impacts on wind energy: A review. *Renewable and sustainable energy reviews*, 14, 430–437.

Przyluski, V., S. Hallegatte, F. Nadaud, R. Tomozeiu, C. Cacciamani, V. Pavan, and C. Doll, 2012. Weather Trends and Economy-Wide Impacts. Discussion paper, Deliverable 1 within the research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) European Commission, 7th framework programme.

Radovic, V., K. Vitale, and P. B. Tchounwou, 2012. Health facilities safety in natural disasters: experiences and challenges from South East Europe. *International journal of environmental research and public health*, 9(5), 1677–1686.

Riecken, D., and B. Lefebvre, 2009. Quels enjeux d'adaptation pour les villes? Leçons d'Hyderabad, ville à croissance rapide du centre de l'Inde du Sud. *Liaison énergie francophonie*, (OCT), 103–107.

Rübelke, D. and S. Vögele, 2011. Impacts of climate change on European critical infrastructures: The case of the power sector, *Environmental Science & Policy*, 14(1), 53-63.

Rübelke, D. and Vögele, S., 2011. Distributional Consequences of Climate Change Impacts on the Power Sector: Who gains and who loses? (CEPS Working Document No. 349). Centre for European Policy Studies. <http://www.ceps.eu/book/distributionalconsequences-climate-change-impacts-power-sectorwho-gains-and-who-loses>.

Schaeffer, R., A. S. Szklo, A. F. P. de Lucena, B. S. M. C. Borba, L. P. P. Nogueira, F. P. Fleming, A. Troccoli, M. Harrison, and M. S. Boulahya, 2012. Energy sector vulnerability to climate change: A review. *Energy*, 38(1), 1 – 12.

Schweighofer, J., 2014. The impact of extreme weather and climate change on inland waterway transport. *Natural Hazards*, 72(1), 23–40.

Sieber, J., 2013. Impacts of, and adaptation options to, extreme weather events and climate change concerning thermal power plants. *Climatic Change*, 121(1), 55–66.

Stewart, M. G., Wang, X., & Nguyen, M. N., 2011. Climate change impact and risks of concrete infrastructure deterioration. *Engineering Structures*, 33(4), 1326-1337.

Suarez, P., W. Anderson, V. Mahal, and T. Lakshmanan, 2005. Impacts of flooding and climate change on urban transportation: a systemwide performance assessment of the Boston Metro Area. *Transportation Research Part D: transport and environment*, 10(3), 231–244.

Tannahill, K., and C. A. Booth, 2011. Linkages of Waste Management Strategies and Climate Change Issues. *Solutions for Climate Change Challenges in the Built Environment*, 9, 207.

Tang, R., Clark, J. M., Bond, T., Graham, N., Hughes, D., & Freeman, C., 2013. Assessment of potential climate change impacts on peatland dissolved organic carbon release and drinking water treatment from laboratory experiments. *Environmental Pollution*, 173, 270-277.

Thornes, J., Rennie, M., Marsden, H., & Chapman, L., 2012. Climate Change Risk Assessment for the transport sector. UK 2012 climate change risk assessment.

van Vliet, M. T., J. R. Yearsley, F. Ludwig, S. Vögele, D. P. Lettenmaier, and P. Kabat, 2012. Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, 2(9), 676–681.

van Vliet, M. T. H., S. Vögele, and D. Rübberke, 2013. Water constraints on European power supply under climate change: impacts on electricity prices. *Environmental Research Letters*, 8(3), 035010.

Verkerk, P. J., P. Anttila, J. Eggers, M. Lindner, and A. Asikainen, 2011. The realisable potential supply of woody biomass from forests in the European Union. *Forest Ecology and Management*, 261(11), 2007–2015.

Whitehead, P., R. Wilby, R. Battarbee, M. Kernan, and A. J. Wade, 2009. A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal*, 54(1), 101–123.

Wilbanks, T., S. Fernandez, G. Backus, P. Garcia, K. Jonietz, P. Kirshen, M. Savonis, W. Solecki, L. Toole, et al., 2012. Climate change and infrastructure, urban systems. Discussion paper, and Vulnerabilities. Technical Report For The US Department of Energy in Support of the National Climate Assessment.

Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J. Smith, J.-M. Mayotte, A. Powell, L. Jantarasami, and W. Perkins, 2012. Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*, 17(8), 939–955.

## 4 Exposure: critical infrastructures and EU regional investments

### 4.0 Key messages

- Exposure refers to the inventory of the assets that may be affected by hazardous events. The assessment of exposure may address many classes of assets, their characteristics and geographical distribution. The value of an asset is function of its usefulness to an individual, group of individuals or the society as a whole.
- Two types of assets have been considered in this study: EU regional investments and current critical infrastructures in Europe.
- EU regional investments refer specifically to the investments under the Cohesion policy during the programming period 2007-2013 in the EU27. The funds allocated to European regions by the Cohesion policy are classified in 86 categories of expenditure. In this study, a total of 50 categories of expenditure were considered potentially vulnerable to natural hazards, which accounts for 53.1% of the 2007-2013 investment program, or roughly 185 billion Euros. Investments in transport and environment and tourism account for more than 75% of all vulnerable investments. Other vulnerable domains of investment are social, technology and communication and energy infrastructure. Regions in the South and Eastern parts of Europe are the main beneficiaries.
- A critical infrastructure is an asset which is essential for the maintenance of vital societal functions, health, safety, security, economic, or social well-being of people, as defined in the Council Directive 2008/114/EC. In this study, a total of 24 infrastructure types were considered including transport, energy, industry and social infrastructures.
- Data from various open and proprietary sources were collected to build a geodatabase storing both the location and key attributes of each critical infrastructure in vector format. The vector layers were then converted to raster layers and 'harmonized' using a procedure implemented in Geographical Information Systems to minimize potential data completeness issues and to allow the comparability between infrastructures of the same sector. The



harmonized infrastructure layers represent both the location of infrastructures and their 'intensity'. The intensity of a particular infrastructure type in a given location is a function of both the infrastructure's characteristics and its location, which defines its potential usefulness and value to society.

- The geo-database of critical infrastructures can be used to map the location of each infrastructure type in Europe. The spatial distribution of critical infrastructures varies considerably across Europe. For many types of infrastructures, there is a strong correlation between population density and the presence of infrastructures. For example, highly populated areas are generally well served by transport and social infrastructure. Some specific infrastructure types, however, are absent in many countries. For example, nuclear power plants are present in only a limited set of countries, and navigable inland waterways are mostly present in Central Europe.
- The presence of an infrastructure at a given location (exposure) does not necessarily imply that such infrastructure is at risk. To evaluate risk, the location of infrastructures needs to be combined with the probability of occurrence and intensity of a hazard and its vulnerability to the hazard (Chapter 5).

## 4.1 Introduction

Exposure refers to the people, property or any other interest that would be subject to a given hazardous event, and loss is a measure of its direct or indirect socio-economic consequences (Mileti 1999, UNDP 2004, Lerner-Lam 2007). Exposure is therefore a fundamental component of disaster risk (IPCC 2012). Disaster risk exists only when all its three components occur simultaneously in a given geographical area: climate/weather-driven hazardous events (hazard) and exposed assets that are vulnerable to those events (exposure and vulnerability). To illustrate, if there is a hazard occurring in a geographical area without any assets, no losses can be expected, and no stakes are at risk. Similarly, there is no risk if the assets exposed to a particular hazard are not vulnerable to it. Exposure and vulnerability are, therefore, tied closely. However, due to practical and methodological convenience, exposure and vulnerability are treated separately in this study.

The previous chapter focused on vulnerability, i.e. the propensity or predisposition of assets to be adversely affected (IPCC 2012). Vulnerability depends on the intrinsic characteristics of the assets that make them more or less sensitive to different types of hazardous events, in other words, the factors that contribute to loss, including the physical fragilities of buildings and infrastructure that may amplify losses (Lerner-Lam 2007). This chapter focus on exposure only, and refers specifically to the inventory of assets and their geographical distribution.

An ‘asset’ is anything that is useful to somebody or something<sup>9</sup>. Consequently, an asset always holds some sort of value, which often can be measured or expressed in monetary terms. Assets can be classified as material/physical (e.g. goods, infrastructure), financial (e.g. cash, investments), or intangible (e.g. know-how, culture). In agreement with DG CLIMA, two specific types of assets have been considered in this study:

- EU regional investments
- Critical infrastructures

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<sup>9</sup> According to Cambridge, Oxford and Collins dictionaries (consulted online in June 2015).

The EU regional investments refer to projects financed by the Cohesion policy (CP), also referred to as 'Regional policy'. The Cohesion policy is part of the multi-annual financial framework (MFF), which regulates the annual budgets of the European Union typically over periods of seven years. In the programming period 2007-2013, the Cohesion policy accounted for about 1/3 of the total MFF budget, and a similar share has been agreed for the on-going programming period (2014-2020).

The Cohesion policy is put into practice through 'operational programmes' (OPs), which are policy instruments that define the investment priorities for regions, countries, or trans-boundary regions. The Cohesion policy aims at kick-starting growth, employment, competitiveness, and development on a sustainable basis, and thus aiming to reduce economic, social and territorial disparities between regions. The Cohesion policy's funds are used in a range of domains of intervention, like infrastructure, environment, research and development, aid to the private sector, human resources, and technical assistance. Not all the domains of intervention and specific projects supported by the Cohesion policy are vulnerable to natural hazards. The objective is therefore to focus on those that are vulnerable to natural hazards and quantify the potential risks given future climate conditions.

Data regarding EU funded projects was made available by the Directorate-General for Regional and Urban Policy of the European Commission (DG REGIO), which manages the EU Cohesion policy. In this project, we used data regarding the Cohesion policy 2007-2013 only. Specific investment allocation data for the on-going programming period (2014-2020) were not available during the writing of this report. In section 4.2, we provide more details on the configuration of the Cohesion policy, and on the data used to quantify EU funded projects per region and per type of investment.

'Critical infrastructure' has been defined as "an asset, system or part thereof (...) which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions" (Council Directive 2008/114/EC). In this study we

selected a large set of infrastructure types that may classify as ‘critical’ according to the definition above. These broadly include transport, energy, industrial, environmental and social infrastructures. The objective was therefore to collect geospatial data on specific infrastructure types at the highest spatial resolution possible, for all the EU+EFTA countries. To our knowledge, this study has been the first one that attempted to collect and catalogue in the most complete, detailed and harmonized way data regarding critical infrastructures in the context of natural risk assessment at EU level. Section 4.3 describes in more detail the collected critical infrastructure data.

## **4.2 EU regional investments: Cohesion policy funds**

The basis for the current model of the Cohesion policy was laid in the 1988 reform. Since then, the structural funds were integrated into an overarching policy, with strategic guidelines defined by the Commission and strong involvement of Member States and regions that drafted operational and regional development plans on a multi-annual basis. Different strategic objectives were set for regions depending on their economic situation, but with particular emphasis on the lagging regions of the community (Manzella and Mendez 2009). Since then, a total of four multi-annual programs have been implemented: 1989-1993, 1994-1999, 2000-2006 and 2007-2013. The ongoing multi-annual program covers the period 2014-2020.

In the 2007-2013 programming period, the Cohesion policy was operationally structured in three different funds, each with specific objectives: The Cohesion Fund (CF), the European Social Fund (ESF), and the European Regional Development Fund (ERDF). The latter aims at strengthening economic and social cohesion in the European Union and specific measures consist of direct aid to small and medium enterprises (SMEs), co-financing of infrastructure linked to research and innovation, information and telecommunication, environment, energy and transport, and technical assistance measures. Actors in all regions of the EU can be funded by the ERDF. The European Social Fund supports actions that contribute to improve human capital and social integration in order to increase access to the labour market and

create opportunities for employment. Only the most developed EU regions (GDP/capita >90% of the EU average) are not eligible for ESF funding. Finally, the Cohesion Fund invests in key trans-European transport and energy networks, while improving the environment by increasing energy efficiency, renewable energy production, inter-modality and mass public transportation. Only the regions under the 'Convergence' objective (GDP/capita <75% of the EU average) are eligible for the CF.

A total of 347 billion Euros were distributed among the three funds, with 201 billion Euros allocated to the ERDF, 76 billion Euros to the ESF and 70 billion Euros to the CF. In terms of regional distribution, the regions under the 'Convergence' objective benefited the most, with a total of 283 billion euros allocated. While the total amount of the Cohesion policy represented a very small portion of the EU's GDP (~0.3%), in less developed regions, the yearly allocated investments can represent as high as 5% of their annual product.

As the manager of the Cohesion policy, the mission of the DG REGIO is, first, to ensure that the available financial instruments contribute to a sustainable economic, social and territorial cohesion by reducing disparities between the levels of development of regions and countries of the European Union, and furthermore to ensure that these objectives are not met at high environmental cost, and that potential negative impacts are foreseen and minimized. A study on direct and indirect land use impacts of the Cohesion policy has been done by the JRC at the request of the DG REGIO (Batista e Silva et al. 2013b). However, impacts of future weather and climate-driven hazardous events on EU investments have not been thoroughly assessed until this JRC study commissioned by the Directorate-General for Climate Action (DG CLIMA).

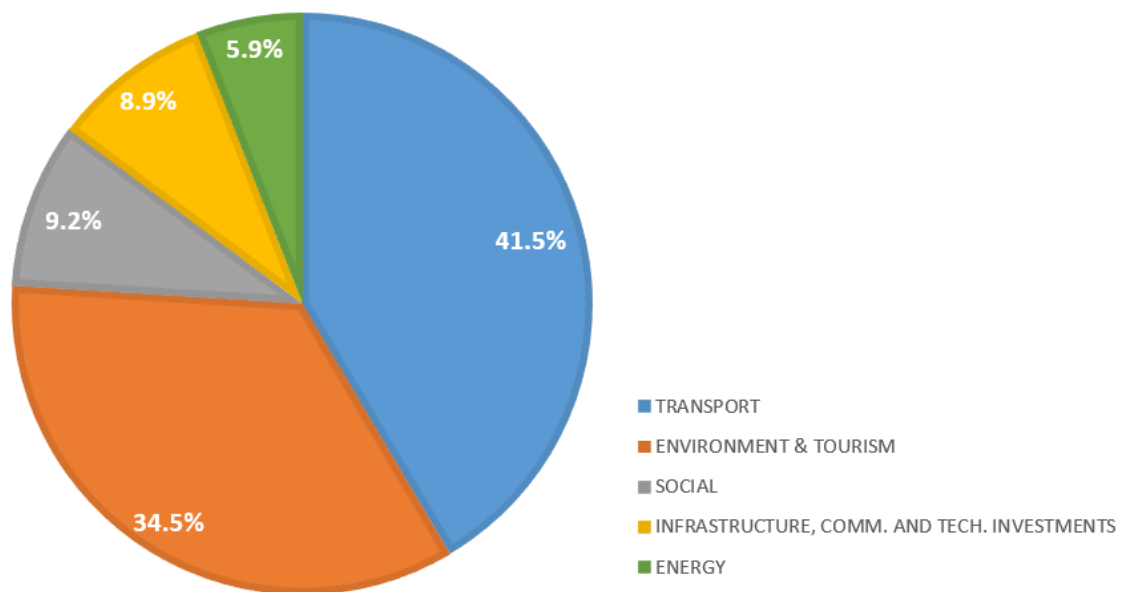
In this project, we used data regarding the Cohesion policy 2007-2013, which consisted of allocated investments per NUTS2 region (271 regions) and per category of expenditure (86 categories). The categories can be as specific as 'R&TD infrastructure', 'Support for self-employment and business start-up', 'Motorways', 'Multimodal transport', 'Ports', 'Renewable energy: solar', 'Integrated projects for

urban and rural regeneration', 'Promotion of natural assets', 'Education infrastructure', to mention just a few. The data was provided by DG REGIO in a matrix of investment allocations, with regions in rows and expenditure categories in columns.

Specific investment allocation data by the Cohesion policy for the 2014-2020 programming period were not available within the writing of this report, as many operational programs were still being finalized. Operational programs can be regional, thematic (national scope) and trans-boundary (multi-regional scope), and define the strategies for investment during the seven year programming period given: 1) the overarching EU's objectives of competitiveness and cohesion and 2) the specific regional and/or thematic goals. The OPs define in detail the share of each fund (ERDF + CF + ESF) that is used to support each objective and specific intervention. All summed together, the hundreds of OPs allow for a complete portrait of how the EU funds are expected to be used across regions and expenditure categories.

Not all the categories of expenditure are equally sensitive to natural hazards. The different sensitivity levels of investments to natural hazards have already been addressed in Chapter 3 of this report. However, a first screening was conducted to differentiate investment typologies that are more vulnerable to natural hazards from those that are not. In general, investments in infrastructure or any kind of physical assets were considered potentially vulnerable to natural hazards, while investments in immaterial actions like financial support to firms and to research and development, improvement of the human capital and social inclusion, strengthening of institutional capacity, technical assistance or direct compensations to outermost regions were considered not vulnerable. Investments targeted to make regions more resilient to environmental risks and climate change were not considered vulnerable by definition. According to this first screening, 50 expenditure categories out of 86 were considered potentially vulnerable to natural hazards, which accounts for 53.1% of the total Cohesion policy investments.

The potentially vulnerable expenditure categories were then grouped in 5 relevant sectors of investments, namely: transport, energy, environment and tourism, social infrastructure and information, communication and technology. The share of investments per each of these sectors is depicted in Figure 4.1. Investments in transport and environment and tourism represent more than 75% of the total vulnerable investments. Figure 4.2 shows the regional distribution of these investments, with a quite remarkable pattern of Southern and Eastern regions absorbing most of the investments. Because Croatia joined the EU in 2013, it did not benefit from the Cohesion policy for the period considered at its fullest. As such, Croatia was not included in the analysis on EU Regional Investments.



**Figure 4.1** Share of main vulnerable categories of EU regional investments under the Cohesion policy 2007-2013.

It is finally worth noting that data on specific projects were not available. The DG REGIO database has information for only a sample of large projects. Information on all specific projects, their nature, characteristics and precise locations would permit a much more accurate quantification of future expected damages due to natural hazards and changing climate conditions. However, such data are still very scattered and have not yet been systematized. Therefore, to what concerns exposed assets, only allocated investments per region and per category of expenditure have been considered. Moreover, these were assumed to be homogeneously distributed across each region's geographical extent. It was further assumed that allocated investments at the beginning of the program were implemented during the programs duration.



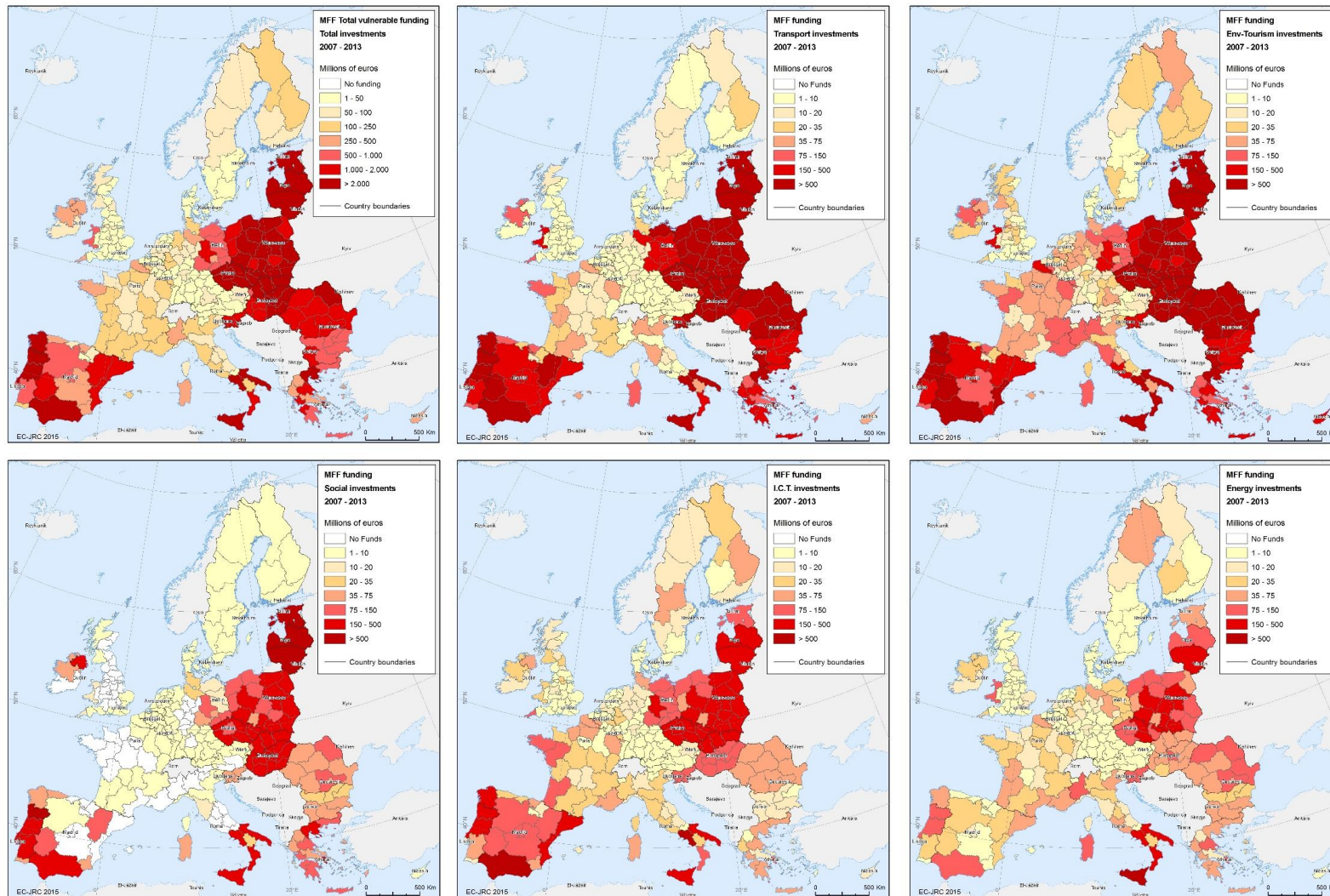


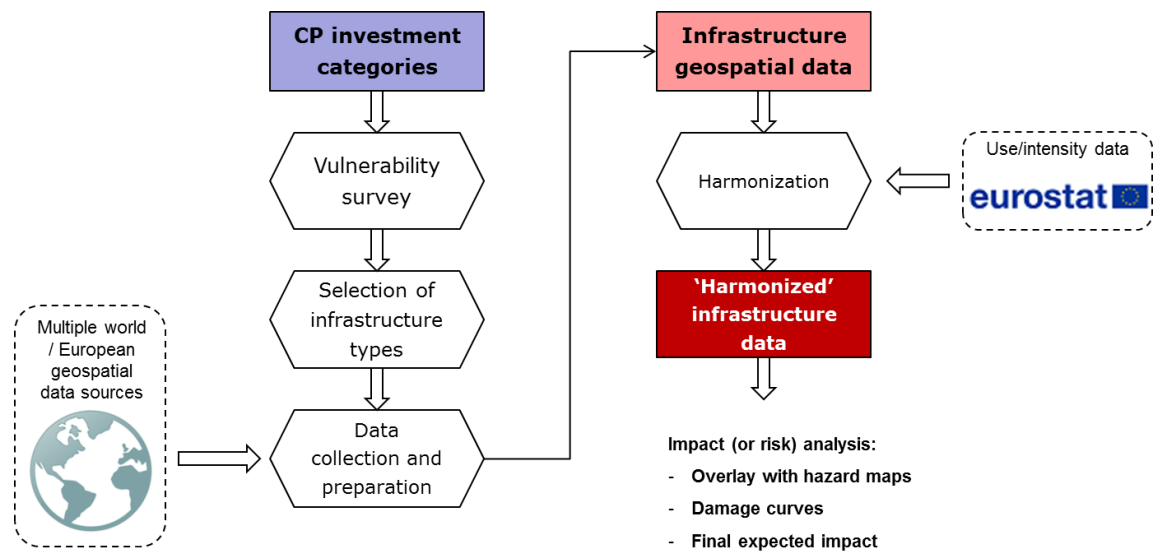
Figure 4.2 Regional distribution of Cohesion policy funds, per major type of investment

### 4.3 Critical infrastructures

As already mentioned in section 4.1, we took the definition of critical infrastructure from the Council Directive 2008/114/EC, which defines critical infrastructures as assets that are essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people. Such a broad definition encompasses necessarily many types of infrastructures.

The selection of infrastructure types to consider in this study was initially guided by the categories of investment of the Cohesion policy. As explained in section 4.2, a first qualitative screening was made to select the investment categories that were potentially vulnerable to natural hazards, which normally corresponded to physical infrastructure. From these infrastructure types we retained those that broadly fitted the definition of criticality. Although heavy industries are not directly targeted by EU investments, this type of infrastructure was added to the list due to their economic criticality. The results of the vulnerability survey were finally used to validate and adjust the selection. A total of 24 specific infrastructure types were finally considered in this study. These were then classified in four broad and meaningful sectors: transport infrastructure, energy infrastructure, industrial infrastructure, and social infrastructure (see Table 4.1).

A geographical database with the location of the different infrastructure types was constructed by compiling and preparing information gathered from multiple data sources (Marin Herrera et al., 2015). To allow consistency and comparability amongst the various infrastructure layers within sectors the data were further 'harmonized'. The 'harmonization' process is described in more detail in section 4.3.2. The final, harmonized infrastructure layers were used in the subsequent risk analysis, which is explained in detail in Chapter 5 of this report. A simplified scheme of this workflow is depicted in Figure 4.3.



**Figure 4.3** General workflow followed to collect and harmonize infrastructure geospatial data.

### 4.3.1 Data collection

A large part of this study was devoted to collecting detailed geospatial information of current critical infrastructures, as a one-stop-shop was not available. It actually became quite clear from the early stages of the project that information on infrastructures in Europe was rather scattered, with different sources available for different infrastructure types, or with different data sources providing data for the same infrastructure type.

The first step was therefore to seek and list all possible data sources for each infrastructure type, explore and learn about the main relevant characteristics of each data source and then select the optimal way to accurately represent the data. The following criteria were used to guide the selection of data sources:

- European geographical coverage: European data sources were preferred over national and worldwide sources to avoid, respectively, inconsistent data and low resolution levels;
- Data completeness: the highest stated or perceived data completeness was preferred;
- Data consistency: data sources with transparent and consistent mapping/reporting methodologies;
- Highest spatial resolution;

- Most recent data update;
- Large within-sector thematic coverage: Data sources which included data on the most infrastructure types within a sector.

The resulting geo-database consists of a set of layers in vector format, each representing one infrastructure type, covering the EU+EFTA countries. In the case of the energy infrastructure layers, additional information provided by the PLATTS database (proprietary database acquired by the European Commission) was kept, in particular the installed capacity of each power plant, the diameter of gas pipelines and the voltage of the electricity grid.

Table 4.1 summarizes the result of the process of infrastructure type selection, and their classification per major sector. The data sources, the original data structure, and the reference dates are specified for each infrastructure type as well.

**Table 4.1** List of infrastructures used in this study, sources used and reference dates.

Sector	Sub-sector	Infrastructure type	Data structure	Main sources	Reference date
Transport	Roads	Local roads	Vector (lines)	Open Street Map	2014
		Roads of national importance			
		Motorways			
	Other modes	Railways	Vector (lines)	GISCO + UNECE	
		Inland waterways			
		Ports	Vector (points)	CORINE Land Cover + GISCO	2006
Airports					
Energy	Non-renewable energy production	Coal power plants	Vector (points)	PLATTS	2013
		Gas power plants			
		Oil power plants			
		Nuclear power plants			
	Renewable energy production	Biomass and geothermal power plants	Vector (points)		
		Hydro power plants			
		Solar power plants			
		Wind power plants			
Energy transport	Electricity distribution / transmission	Vector (lines)			
	Gas pipelines				
Industry	Heavy industries	Metal industry	Vector (points)	EPRTR v7	2013
		Mineral industry			
		Chemical industry		Global Energy Observatory	2010
		Refineries			
	Water/waste treatment	Water and waste treatment	Vector (points)	EPRTR v7	2013
Social	Education	Education infrastructure	Vector (points)	Open Street Map	2014
	Health	Health infrastructure			

### 4.3.2 Harmonization

Despite the careful selection of data sources and the various checks carried out to evaluate the quality of the data, an exhaustive, quantitative validation of the data was outside the scope of this study. Nevertheless, there were some critical issues that had to be taken into account before overlaying the infrastructure data with the hazard information.

Data completeness was the first of those issues. First, some data sources have a limited scope. That is the case of the European Pollutant Release and Transfer Register (EPRTR) that was used to obtain the location of most of the industrial

infrastructures. The scope of EPRTR is to monitor pollution levels from the largest emitters, thus ignoring smaller ones. Second, it cannot be guaranteed that data sources such as the Open Street Map (OSM) contain each and every infrastructure location as found in reality at a given time. Moreover, as a voluntary geographical information project, the degree of completeness of the OSM can vary considerably from country to country and even from region to region. Finally, even proprietary, more structured and consistent data sources such as PLATTS do not report the degree of completeness of their databases.

Another issue relates to the comparability between different types of infrastructure within the same sector. For example, in terms of impacts in the transport sector, how can a port (which is represented as a point feature in a Geographical Information System (GIS)), be compared to 1 Km of road (which is represented as line feature in a GIS)? Or how can 1 Km of motorway be compared to 1 Km of local road? The same applies to the other sectors: how can a metal industry be compared to a refinery, or a hospital to a school? A more general question is: how can impacts of a given hazardous event on two different infrastructure types be compared using a sufficiently straightforward and generic methodology, applicable to all Europe?

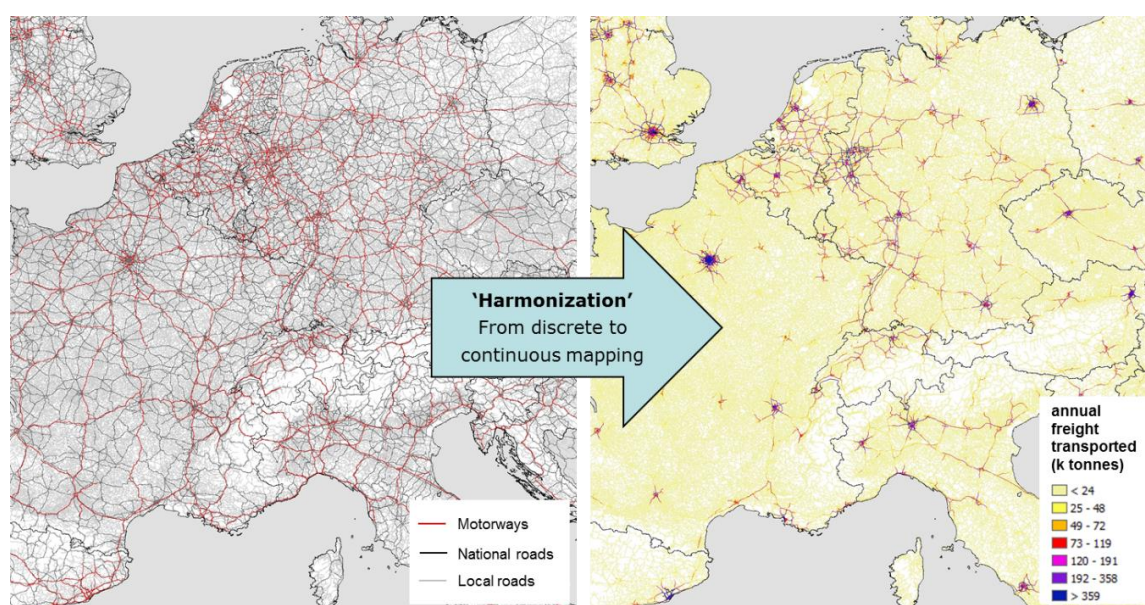
To allow a consistent impact framework, infrastructure types belonging to the same sector thus required a data transformation process to bring them to a level of comparability, in which their relative importance could be evaluated. To illustrate, rather than describing transport infrastructures by their typologies (categorical, discrete data), they would have to be described in terms of their actual usage or value. This data transformation process is hereinafter referred as 'harmonization'. The harmonization required, first and foremost, a conversion from vector to raster data structure, with a cell size of 1 Km x 1 Km. Subsequently, an 'intensity' measurement was assigned to each raster cell of each individual infrastructure type, with the intensity measurement varying per sector, as reported in Table 4.2.

Figure 4.4 illustrates the procedure applied to the road infrastructures, showing the transformation from discrete and categorical vector data to a raster and continuous data, with intensity values assigned to individual raster cells (locations). Locations

with higher intensity values are assumed to suffer higher impacts in case of a hazardous event.

**Table 4.2** Intensity variables used.

Sector	Variable	Unit
Transport infrastructure	Annual freight transported	k tonnes
Energy infrastructure	Electricity produced / transported	k tonnes oil equivalent (ktoe)
Industry infrastructure	Annual turnover	Million EUR (MEUR)
Social infrastructure	Annual expenditure	Million EUR (MEUR)



**Figure 4.4** Illustration of the 'harmonization' process: from categorical information to a continuous indicator of intensity.

In all cases, the intensity data was collected from Eurostat<sup>10</sup> at national level, for a series of the five most recent years available (typically 2009-2013). The entire series was averaged to avoid potential data artifacts, and the resulting values were finally assigned to infrastructures. The implicit and desirable outcome of this procedure is that impacts of a hazardous event on infrastructures differ depending on the different 'intensity' values of the infrastructures (apart from differences in impact due to varying degrees of vulnerability for different infrastructure types).

<sup>10</sup> Data collection conducted in early 2015, from Eurostat's online database.



Two assignment methods were used:

- Direct assignment
- Downscaling

The direct assignment is the most accurate way to assign an intensity value to infrastructures. However, this method was only applied to ports and airports, for which Eurostat data were available in detail. This allowed a reliable measurement of the usage in terms of annual freight transported for each port and airport.

The downscaling procedure consisted of disaggregating the national intensity values of each infrastructure type (e.g. annual turnover of the metal industry, or total electricity production from nuclear power plants) to the locations of those infrastructures within the respective country. It is worthwhile noting that the downscaling procedure minimized the impact of geospatial data incompleteness issues, as the total intensity of a given infrastructure type in a given country was preserved within that country. This means that even if an important power plant of a given country is missing from the geo-database, the total produced electricity in that country is kept, as it is redistributed among all the other power plants. This does not solve the problem of missing infrastructure in a particular location within a country, but allows aggregated impacts between countries to be reasonably compared.

The generic downscaling approach can be described by equation 4.1:

$$I_{j,i} = V_{j,c} * \left( \frac{w_{i,j}}{\sum_i w_{i,j}} \right) \quad [4.1]$$

where

$I_{j,i}$  = intensity of infrastructure j in pixel i

$V_{j,c}$  = total intensity of infrastructure j (or volume) in country c, as reported by Eurostat at national level.

w = weight = f(j)



for  $j = \text{roads}$ ,  $w_{i,j} = f(\text{length}_{i,j}, \text{capacity}_{i,j}, \text{nr. of people}_{i,j})$ , with capacity of motorways = 5, capacity of national road = 3, capacity of local roads = 2, and nr. of people in a predefined radius around  $i$ <sup>11</sup>.

for  $j = \text{rails or inland water ways}$ ,  $w_{i,j} = f(\text{length}_{i,j}, \text{average flow from exogenous model}_{i,j})$ <sup>12</sup>

for  $j = \text{energy production}$ ,  $w_{i,j} = f(\text{installed capacity}_{i,j})$ <sup>13</sup>

for  $j = \text{electricity grid}$ ,  $w_{i,j} = f(\text{length}_{i,j}, \text{voltage}_{i,j})$ <sup>4</sup>

for  $j = \text{gas pipelines}$ ,  $w_{i,j} = f(\text{length}_{i,j}, \text{pipeline diameter}_{i,j})$ <sup>4</sup>

for  $j = \text{industry}$ ,  $w_{i,j} = f(\text{nr. of facilities}_{i,j})$

for  $j = \text{social infrastructure}$ ,  $w_{i,j} = f(\text{nr. of potential users}_{i,j}) = \text{nr of people in predefined radius} / \text{nr infrastructures in radius}$

One major advantage of the harmonization approach is that it allows the summation of intensities from different infrastructure types  $j$  of the same sector  $s$ :

$$I_{s,i} = \sum_j I_{i,j} \text{ with } j \in s \quad [4.2]$$

In summary, the described harmonization procedure was applied to each individual infrastructure type, thus allowing to

- minimize incompleteness of the geospatial data sources;
- compare different types of infrastructures in the same unit of measure, and, consequently,
- merge different infrastructure types into four more significant sectors: transport, energy, industry, social infrastructure.

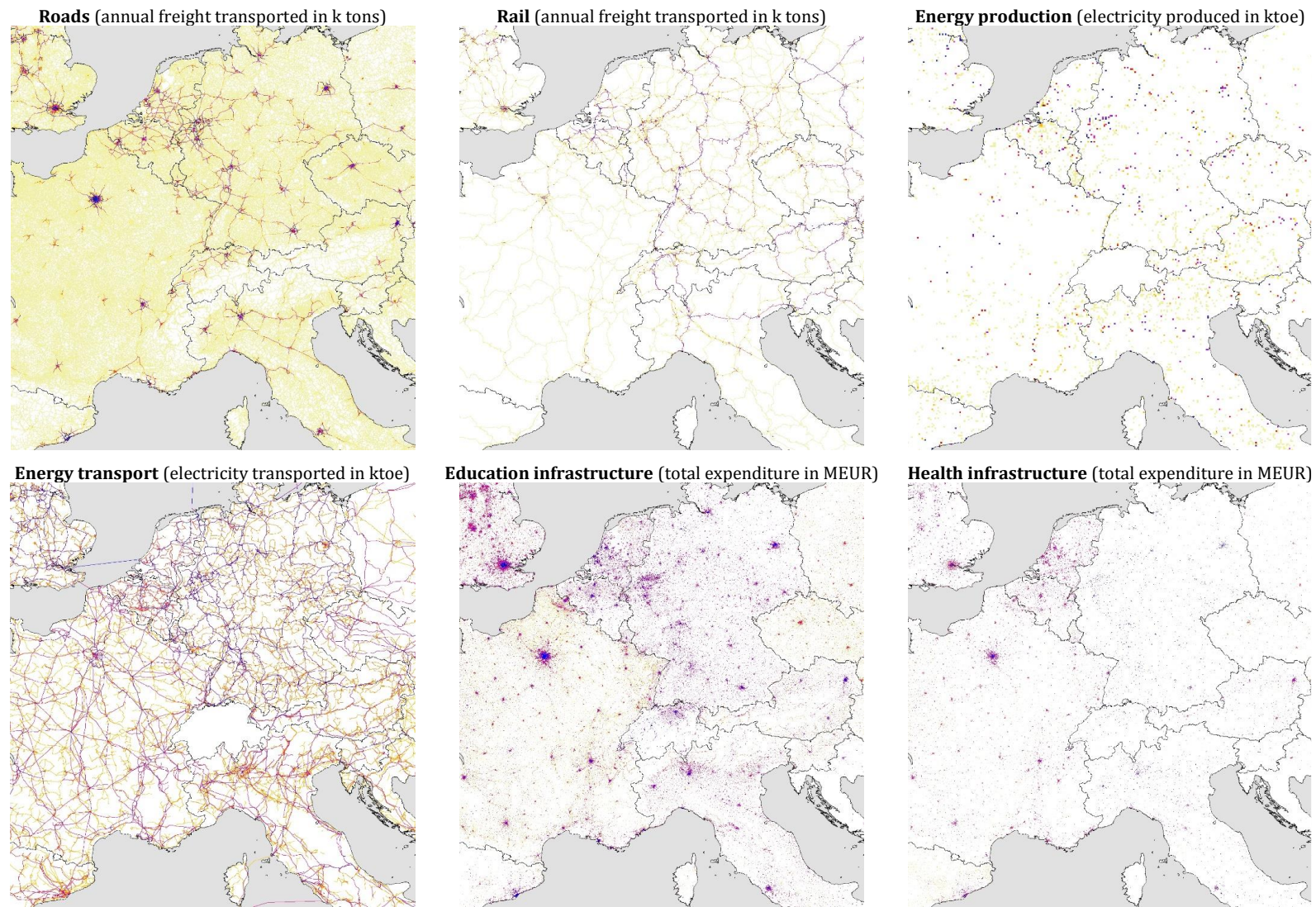
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<sup>11</sup> Population distribution taken from the JRC population grid map at 100 x 100m resolution 2006. See Batista e Silva et al. (2013).

<sup>12</sup> TRANSTOOLS model (JRC-IPTS). Documentation available online: [http://energy.jrc.ec.europa.eu/transtools/TT\\_model.html](http://energy.jrc.ec.europa.eu/transtools/TT_model.html).

<sup>13</sup> As reported by the PLATTS energy geo-database.

Figure 4.5 shows some examples of harmonized infrastructure layers. After the harmonization procedure, the layers can be combined with hazard data to derive an impact measured in the same units as of the harmonized layers. The translation to actual monetary losses can be finally achieved by applying cost coefficients (or cost curves) which link the estimated impacts (harmonized layers \* hazard) with actual observed losses due to natural hazards. This is explained thoroughly in Chapter 5.



**Figure 4.5** Examples of harmonized infrastructure layers.

#### **4.4 Main limitations and challenges**

One setback in this study was the delay in the preparation of the operational programs for the programming period 2014-2020, which prevented access to detailed regional and sector allocations of the European Structural and Investment Funds (ESIF). Therefore, and contrary to what had been initially planned, only the 2007-2013 regional investments were considered in this study. Impacts of natural hazards on the ESIF for the period 2014-2020 depend intrinsically on its geographical and sector distribution, which, at the time of this project, were largely unknown.

An important limitation of the analysis carried out to assess risk of EU regional investments is related to the assumption that investments were homogeneously distributed within NUTS2 regions. In reality, investments in regions may have marked spatial patterns, or target very specific locations within regions, depending of course on the type of investment. However, micro-data on past financed projects are extremely scattered and have not yet been systematized and published by the European Commission, which prevented a more spatially precise analysis.

The current stock of critical infrastructures has been assessed by using the most complete and up-to-date data sources. However, the exposure of future infrastructure was not addressed in this study, and remains still one of the main challenges in the evaluation of future risk. The location of future stock of infrastructures would require a more sophisticated approach based on trend analysis, or modelling/simulation. Lung et al. (2013), for example, have used results from a land use model (Lavalle et al. 2011) which projected future locations of forest and industrial/commercial areas.

Another limitation concerns the lack of information on the completeness level of the geographical data sources used in this study. Potential incompleteness was partially addressed by the harmonization procedure (see section 4.3.2), which, however, did not prevent underestimation of exposure at site-specific level when infrastructure

data were missing. As obvious at it may seem, the quality of input data affects significantly the reliability of the final risk estimates, yet, an actual assessment of the input data quality is not straightforward, and its influence on the accuracy of the final impact results remains unknown.

Various authors have emphasized the importance of population data to assess exposure and risk (e.g. National Research Council 2007a, Freire 2010). Although the focus of this study was essentially on investments and critical infrastructure, the information on the current and future location of people is essential to estimate the number of users of infrastructure, and the potential indirect losses resulting from damaged infrastructure. In an attempt to assess global exposure and vulnerability towards natural hazards, Peduzzi et al. (2009) have used population distribution as a proxy of exposure and various socio-economic factors were used as a measure of vulnerability. However, the location of people per age and social strata, and across different time-frames is still nowadays a key challenge in most countries.

## 4.5 References

Batista e Silva F., Gallego J. and Lavalle C., 2013a. A high-resolution population grid map for Europe. *Journal of Maps*, 9, 16-28.

Batista e Silva F., Lavalle C., Jacobs-Crisioni C., et al., 2013b. Direct and indirect land use impacts of the EU cohesion policy - Assessment with the Land Use Modelling Platform. Luxembourg: Publications office of the European Union.

Freire S., 2010. Modeling of Spatiotemporal Distribution of Urban Population at High Resolution – Value for Risk Assessment and Emergency Management. In: M. Konecny et al. (Eds.) *Geographic Information and Cartography for Risk and Crisis Management*, Lecture Notes in Geoinformation and Cartography. Springer, Berlin.

IPCC, 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Lavalle C., Baranzelli C., Batista e Silva F., Mubareka S., Rocha Gomes C., Koomen E., Hilferink M., 2011. A high resolution land use/cover modeling frame work for Europe: introducing the EU-ClueScanner100 model. In: Murgante B., Gervasi O., Iglesias A., Taniar D., Apduhan B.O. (Eds.) *Computational Science and its Applications – ICCSA 2011 International Conference Santander, Spain, June 2011, Proceedings Part 1*. Springer, Berlin, Heidelberg, pp. 60–75.

Lerner-Lam A., 2007. Assessing global exposure to natural hazards: Progress and future trends. *Environmental Hazards*, 7, 10-19.

Lung T., Lavalle C., Hiederer R., Dosio A., Bouwer L.M., 2013. A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change. *Global Environmental Change*, 23, 522-536.

Manzella G.P. and Mendez C., 2009. The turning points of the EU Cohesion policy. Working paper.

Marin Herrera M., Batista e Silva F., Bianchi A., Barranco R., Lavalle C., 2015. A geographical database of infrastructures in Europe. JRC Technical Report.

Mileti D.S., 1999. *Disaster by Design: a Reassessment of Natural Hazards in the United States*. Joseph Henry Press, Washington, DC, 351pp.

National Research Council, 2007a. *Tools and Methods for Estimating Population at Risk from Natural Disasters and Complex Humanitarian Crises*. Washington, DC: The National Academies Press.

National Research Council, 2007b. *Successful Response Starts with a Map: Improving Geospatial Support for Disaster Management*. Washington, DC: The National Academies Press.

Official Journal of the European Union. Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection.

Peduzzi P., Dao H., Herold C., Mouton F., 2009. Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index. *Natural Hazards and Earth System Sciences*, 9, 1149-1159.

United Nations Development Program, 2004. *Reducing Disaster Risk: A Challenge for Development*. UNDP Bureau for Crisis Prevention and Recovery, New York, 146 pp.

## 5 Multi-hazard risk assessment in Europe under climate change

### 5.0 Key messages

#### Critical infrastructures

- Multi-hazard multi-sector impacts
  - Europe will face a significant increase in multi-hazard multi-sector damages in the coming decades. Current damages of 3.4 billion €/year in the EU+ (EU28 + Switzerland, Norway and Iceland) are projected to triple by the 2020s, multiply six-fold by mid-century, and rise up to 38 billion €/year by the 2080s (undiscounted and no socio-economic changes assumed). These numbers reflect only the (combined) damages from the 7 climate hazards to the sectors considered in this study, hence they do not reflect the total damages of these hazards to society.
  - Indicative estimates of total damages from the 7 climate hazards to society could rise from currently 12 billion €/year to nearly 80 billion €/year by the end of this century.
  
- Sector impacts
  - The strongest increase in multi-hazard damages is projected for the energy sector, for which the baseline expected annual damage (EAD) of 0.5 billion €/year could rise to 2.0, 4.4, and 8.2 billion €/year (or increases in EAD of 394%, 860% and 1,612%) by the 2020s, 2050s and 2080s, respectively.
  - A comparable trend can be observed for the transport sector, for which the baseline EAD of 0.8 billion €/year is expected to reach nearly 12 billion €/year (increase of 1,496%) by the end of this century.
  - For industry, which shows the largest damages amongst the sectors considered, current EAD of 1.5 billion €/year is estimated to surpass 16 billion €/year by the 2080s, corresponding to a 10-fold increase.



- For the social sector, the rising trend in damages is less pronounced, but current EAD of 0.6 billion €/year could still more than double by the end of this century due to climate change.
- Hazard contributions
  - Aggregated over the four sectors, current climate hazard damages relate mostly to river floods (44%) and windstorms (27%). Their relative contribution to the total damage diminishes rapidly in time. The shares of drought and heat strongly rise, covering more than 70% of climate hazard damages by the end of the century (vs 12% in present times).
  - The contribution of wildfires and coastal floods is low, albeit that a strong increase in coastal flood damages is projected in the coming century.
  - The contribution of cold waves is also low and cold-related damages in Europe could completely disappear with global warming.
  - Hazard-contributions vary amongst the sectors. For the social sector, damages from windstorms and inland flooding will remain important. The industry and energy sector will be most impacted by droughts, with 56% and 67%, respectively, of sector damages relating to droughts by the end of this century. For the transport sector, on the other hand, heatwaves will largely dominate future damages (92% of total damages by 2080s).
- Regional impacts
  - For EU+ as a whole, the share of GDP at risk rises progressively from 0.03% now to 0.28% by the end of century. Southern and south-eastern countries will be most impacted. For Bulgaria (0.40%), Romania (0.45%), Italy (0.49%) and Slovenia (0.56%) damages remain below or close to 0.5% of GDP, whereas for Portugal (0.77%), Spain (0.87%) and Croatia (0.97%) damages could reach nearly 1% of GDP.

## EU Cohesion Policy investments

- Multi-hazard multi-sector impacts
  - Annual damages to EU regional investments will rise rapidly from 146 million €/year, or 0.04% of the total 2007-2013 regional investments, to 556 million €/year (382% baseline EAD) or 0.16% of total investments by the 2020s. By the 2050s damages further climb to 1,109 million €/year (761% baseline EAD) or 0.32% of total investments, and by the end of this century the annual risk amounts to 1,703 million €/year (1,168% baseline EAD) or 0.49% of total investments.
  
- Hazard contributions
  - Floods is currently the most damaging hazard to EU regional investments, accounting for about half (51%) of total impacts, followed by drought (26%) and heat waves (10%).
  - Drought damages increase significantly, from 38 million €/year now to 888 million €/year by the 2080s (2,315% baseline EAD), and form the largest share of future damages (52% by the end of the century).
  - The strongest relative increase in damages, however, is projected for heatwaves and coastal flooding (increases both around +4,500%). As a result heatwaves will become the second damaging hazard to EU structural investments (40% of total damages by 2080s).
  - Damages due to cold waves will evanesce in the coming decades, whereas damages due to wind, floods and fires show more moderate increases, with absolute damages rising this century by 10%, 30% and 50%, respectively.
  
- Sector impacts
  - Currently 48% of hazard impacts relate to transport investments, and 37% to the environment and tourism sector. Annual damages in the transport sector rise by 722% from 70 million €/year in the baseline to 573 million €/year by the 2080s. For the environment and tourism sector damages increase at a

rate double as high (+1,619%) from 55 million €/year now to 940 million €/year by the end of the century. Hence, this sector will under future climate account for more than half of the total hazard damages (55% vs 34% for the transport sector) to EU investments.

- Damages in the energy sector increase by more than tenfold (+1,077%), from 13 million €/year in the baseline to 157 million €/year by the 2080s.
- Impacts in the ICT and social sector are smaller and show less pronounced increases. Where damages to ICT investments are expected to rise by 160% from 1.9 to 5 million €/year by the 2080s, an increase of 363% from 6 to 28 million €/year is projected for the social sector.
- Regional impacts
  - Where by the 2080s multi-hazard multi-sector expected annual losses for the whole EU27 may correspond to 0.49% of total investments, in regions of the Iberian and Balkan Peninsulas impacts can amount to 3% of investments.
  - When looking at sector level, relative impacts can even be substantially higher in some parts of Europe. For the transport sector, by the end of the century expected annual losses to investments rise to about 5% of the transport investments for Latvia, Romania, Bulgaria and regions of Spain. For the energy and the environment and tourism sectors, expected yearly losses by the 2080s may rise up to, or locally exceed, 1/10 of the total sector investment in south-west and south-east regions of the EU. For the social and ICT sectors expected annual losses at regional scale remain mostly below 1% and 0.5% of sector investments, respectively.

## 5.1 Introduction

The projected increases in exposure to multiple climate hazards in many regions of Europe, as shown in the hazard assessment of this work (see Chapter 2), emphasize the relevance of a multi-hazard risk assessment to comprehensively quantify potential impacts of climate change and develop suitable adaptation strategies. In this context, quantifying the future impacts of climatic extremes on critical economic sectors, both in terms of critical infrastructures and EU-funded investments, is crucial due to their key role for human wellbeing and their effects on the overall economy.

As detailed in Chapter 4 of this report, critical infrastructures describe the existing assets and systems that are essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact as a result of the failure to maintain those functions. EU regional investments refer to the investments under the Cohesion policy during the programming period 2007-2013 in the EU27, aimed to specific regional development projects or actions. Of particular relevance in relation to potential climate change impacts in Europe are the transport, energy, industry, social, environment and tourism, and ICT sectors.

Evaluating the effects of multiple climate hazards on infrastructures and investments is a complex task because of incomplete scientific methodologies and limited understanding of vulnerability of infrastructures (see Chapter 3). Existing direct cost assessment methods generally focus on specific hazards or sectors by the use of susceptibility curves derived analytically under specific conditions (Ciscar et al., 2011; Meyer et al., 2013). Difficulties in establishing comparisons across hazards and sectors remain particularly relevant (Kappes et al., 2012). The recently developed InterSectoral Impact Model Intercomparison Project (ISI-MIP) offers a framework for comparing multiple climate impact models within and across different sectors based on a common set of climate and socioeconomic scenarios, providing a quantitative estimate of impacts and uncertainties (Warszawski et al.,

2014). While this open archive represents an unprecedented opportunity and a significant step forward to a better understanding of the potential impacts of climate change, systematic and detailed knowledge of the risk imposed by multiple climate extremes is still lacking.

This work provides the first comprehensive multi-hazard multi-sector risk assessment for Europe under climate change and identifies the most vulnerable regions throughout the 21<sup>st</sup> century. We focus on seven climate hazards (see Chapter 2) including heat and cold waves, wildfires, droughts, river and coastal floods and windstorms. Expected impacts to industry, energy, transport, social, environment and tourism, and ICT infrastructures and EU regional investments are investigated under current and future climate conditions. Although these sectors do not cover the full range of possible societal and environmental climate-hazard impacts, they include crucial aspects of livelihoods for Europe. Cost estimates reported here refer mostly to direct damages to infrastructures due to physical contact with the hazard and to a lesser extent also include damages related to the reduction in primary sources and productivity (see sections 5.2.4 and 5.3.3). The methodology integrates a set of high-resolution climate hazard projections (Chapter 2), a detailed representation of sectorial physical assets and productive systems and investments (Chapter 4), and a qualitative appraisal of their sensitivity based on expert view and literature review (Chapter 3). The three above-mentioned components have been combined in a vulnerability framework with recorded damages from climate disasters in order to derive quantitative estimates of risk. We then derive a comprehensive and comparable set of climate hazard cost figures for different sectors in the EU28 + Switzerland, Norway and Iceland (further denoted herein as EU+). Results are presented in spatial maps as well as aggregated for five European regions to simplify interpretation, analogously to the presentation in the hazard chapter (Chapter 2): Southern (SEU), Western (WEU), Central (CEU), Eastern (EEU) and Northern (NEU) Europe (see Figure 1.2). For clarity of presentation, after the description of the methods we first detail the impacts on the present stock of critical economic infrastructures, which allow a better interpretation of the potential impacts of climate change on the current socio-economic system, and then we synthesize the risk to EU regional investments.

## 5.2 Methods

The risk assessment focuses on direct tangible damages related to the impacts to physical assets, the disruption of productivity and loss of primary sources due to climate hazards. Expected Annual Damages are obtained from the combination of climate hazard, exposed infrastructures and investments, and the vulnerability of exposed assets (IPCC, 2012) and are expressed in 2010 € assuming no socio-economic change in future scenarios. In other words, we have modelled the economic effects of future climate change on the current economy (quasi static analysis).

The three main components that are utilized here for the risk assessment, namely climate hazard (Chapter 2), exposure (Chapter 4) and sensitivity of exposed assets (Chapter 3), are already amply discussed in their respective chapter. They are recalled here briefly for clarity and then we detail how they are combined in a coherent risk framework to translate impact scenarios into quantitative estimates of damage based on recorded loss data.

### 5.2.1 Hazards

The risk analysis focuses on seven critical climate hazards for Europe: heat and cold waves, river and coastal floods, streamflow droughts, wildfires and windstorms. Climate hazard indicators were derived for the baseline (1981-2010), 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100) for an ensemble of bias-corrected climate projections obtained from different regional climate model simulations under the A1B emissions scenario. Hazard magnitude levels ( $H_L$ ) are classified based on the probability of occurrence of events in current climatology; given  $T_R$  as return period corresponding to  $H_L$ , we assign the intensity class to the  $H_L$  event according to the Table 5.1.

The fraction of a given area that is expected to be annually exposed to a hazard of  $H_L$  magnitude – the Expected Annual Fraction Exposed (EAFE) – was derived for each scenario period. More details can be found in Chapter 2.

**Table 5.1** Classification of hazard intensity class based on probability thresholds

<b>Hazard intensity class (<math>H_L</math>)</b>	<b>Probability threshold</b>
very high	$T_R \geq 100\text{yr}$
high	$100\text{yr} > T_R \geq 50\text{yr}$
moderate	$50\text{yr} > T_R \geq 20\text{yr}$
low	$20\text{yr} > T_R \geq 10\text{yr}$
very low	$10\text{yr} > T_R \geq 2\text{yr}$
no hazard	$2\text{yr} < T_R$

### 5.2.2 Exposure

Exposure is described by two sets of GIS layers that refer to critical infrastructures and EU regional investments, respectively. The first set represents the present stock of transport, industry, energy and social infrastructures; the second set comprehends EU regional investments under the 2007-2013 period in the sectors transport, environment and tourism, energy, social, and information, communication and technology.

In order to allow intra-sector comparability between different types of infrastructures and to overcome possible incompleteness in the source databases, the original infrastructure data have been harmonized by assigning sector-specific intensity measurement to each infrastructure. Intensity values were obtained from EUROSTAT and assumed correlated to the economic value of the asset and its productivity. We assume no changes in exposed infrastructures along the century. EU regional investments are already expressed in a common unit (€) and do not require additional processing. More details are reported in Chapter 4.

### 5.2.3 Sensitivity

A web-based survey was set up amongst specialists to assess the climate sensitivity of critical economic infrastructures and investments. Here, sensitivity refers to what degree the asset or system is affected when exposed to a climate hazard. For each sector a sample of ~50 experts (vs. potential 500 respondents) was collected from private companies, authors and editorial boards of peer-reviewed journals in the field of climate change and sector-specific structural engineering. Experts assigned anonymously a degree of sensitivity (high, moderate, low, no) to infrastructures and investments with respect to each climate hazard. The distribution modes retrieved from the survey have been combined with vulnerability information obtained from literature in order to derive a representative set of sensitivities ( $S$ ). More details are described in Chapter 3.

### 5.2.4 Multi-hazard risk framework

For each hazard and the different infrastructure types considered, every grid cell where an infrastructure is located was labelled by a set of potential risk levels (very high, high, moderate, low, very low, no). They express how much of the infrastructure type in a particular cell is subject to certain levels of risk, which are based on the combination of the sensitivity of the infrastructure type and the hazard magnitude, as expressed by a pre-defined risk matrix ( $M$ ) (Figure 5.1). The infrastructure asset expected to be annually exposed to a given risk level  $R_L$  - the Expected Annual Asset Exposed EAAE - is then calculated as follows:

$$EAAE(R_L) = \sum_{\substack{H_L \Rightarrow \\ M[EAFE(H_L), S] = R_L}} EAFE(H_L) \cdot I \quad [5.1]$$

where the sum runs over all  $H_L$  magnitudes that in combination with the sensitivity  $S$  lead to the risk level  $R_L$  in the risk matrix  $M$ .  $I$  refers to the exposed asset (harmonized infrastructure layer or EU regional investment).



			SENSITIVITY				RISK LEVEL	
			No	Low	Med	High	VH	Very High
<b>H A Z A R D</b>	rp > 100 yr	Very high (VH)	<b>N</b>	<b>M</b>	<b>H</b>	<b>VH</b>	<b>H</b>	<b>High</b>
	50 yr < rp < 100 yr	High (VH)	<b>N</b>	<b>M</b>	<b>M</b>	<b>H</b>	<b>M</b>	<b>Medium</b>
	20 yr < rp < 50 yr	Moderate (M)	<b>N</b>	<b>L</b>	<b>M</b>	<b>M</b>	<b>L</b>	<b>Low</b>
	10 yr < rp < 20 yr	Low (L)	<b>N</b>	<b>L</b>	<b>L</b>	<b>M</b>	<b>VL</b>	<b>Very Low</b>
	2yr < rp < 10 yr	Very Low (VL)	<b>N</b>	<b>VL</b>	<b>L</b>	<b>L</b>	<b>N</b>	<b>No</b>
	rp < 2 yr	No (N)	<b>N</b>	<b>N</b>	<b>N</b>	<b>N</b>		

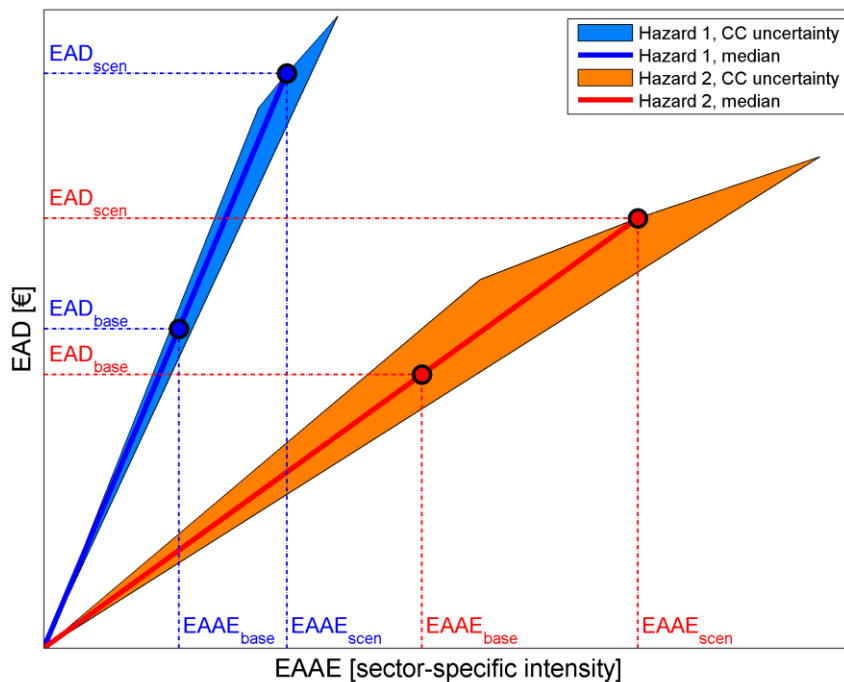
**Figure 5.1** Risk matrix *M*

The cumulated EAAE under very high and high risk level is considered linearly correlated to the corresponding damages. Note that this implies that for highly sensitive infrastructures and investments, hazard events with a 50-yr return period or higher are considered to contribute to the damage, whereas for moderately sensitive infrastructures and investments only 100-year or more extreme events result in damages. The EAAE-EAD relations are retrieved at sector and NUTS2 level for the baseline (base) and propagated for the future scenarios (scen) (Figure 5.2) based on the following equation:

$$EAD_{scen} = \frac{EAAE_{scen}}{EAAE_{base}} \cdot EAD_{base} \quad [5.2]$$

The implementation of Equation 5.2 is described in the following lines for the analysis of the impacts on critical infrastructures. After that we detail the application for the EU regional investments.

EAAE refers to the amount of asset at risk for a given sector and is expressed according to the sector-specific intensity value as defined by the harmonization process. As shown in Equation 5.1, EAAE values are obtained by combining exposure intensity values with hazard information. The latter, expressed by EAFE, varies amongst climate realizations, which explains the uncertainty bounds shown in Figure 5.2.



**Figure 5.2** Scheme of calculation for the EAAE-EAD relations in a two hazards case

Baseline annual damages ( $EAD_{base}$ ) are obtained for each hazard and sector at NUTS2 level by the integration of multiple disaster datasets (EMDAT, Munich RE) and economic statistics (EUROSTAT). More than 1100 disaster loss records for climate-related hazards that occurred in the 1981-2010 period have been collected from EMDAT. Information for each disaster include: hazard type, country, year and loss estimate (direct damages to asset and production interruption expressed in US \$ in the value of the year of occurrence). All data have been converted into €2010 using the country Harmonized Index of Consumer Prices derived from EUROSTAT. The resulting overall losses are compared with the estimates provided by Munich Re for Europe over the same period. Munich Re recorded an overall damage that is 30% larger than that derived from EMDAT, which can be imputable to minor events that are not reported in EMDAT. The 30% residual damages were, for each European region, disaggregated amongst hazards based on the hazard damage shares (for that region) derived from EMDAT statistics. Within each region the residual minor damages were further distributed amongst countries based on national GDP values. As such, baseline damage values were obtained for each of the 7 hazards for each country.

It is important to note that the baseline damages derived per country for each hazard reflect the total damage (as reported in the EMDAT and Munich Re databases) in that country due to the specific hazard. This total damage relates to impacts in all sectors, hence not only to critical infrastructures in the sectors considered in this study. For example, for droughts a considerable share of the damages typically relate to agricultural losses, which are not considered herein. To account for this, the hazard-specific country baseline damages have been distributed over sectors in each country based on the national shares of the monetary value of sector-specific capital stock and gross value added, and their sensitivity to the considered hazard. The shares of the total (reported) climate damages that relate to critical infrastructures considered in this work differ strongly between hazards: 28% for coastal flooding, 90% for cold, 45% for drought, 14% for fire, 28% for flood, heat for 67%, and 21% for windstorms. This means that for wildfires, for example, 86% of the damages relate to other assets/sectors than the critical infrastructures considered here, such as forests and nature (~35% of fire damages), or residential buildings (~30% of fire damages). For windstorms, inland and coastal flooding, large shares (up to 50%) also relate to residential infrastructures that are not included in our study.

Finally, hazard-specific damages to each sector in a country were disaggregated to NUTS2 level based on NUTS2 GDP shares within a country. Baseline EAD for EU regional investments have been obtained by rescaling the EAD values retrieved for the sector-specific critical infrastructures based on the share of the EU regional investments to the total capital stock and gross value added for each sector.

Baseline and future EAD values were calculated separately for all climate experiments, scenario periods and climate hazards. Multi-hazard damages are obtained by summing up single-hazard multi-model median EAD values under the assumption of static vulnerability (complete post-event recovery) and independent hazards (no hazard interrelations).

## 5.3 Results

### 5.3.1 Impacts to critical infrastructures

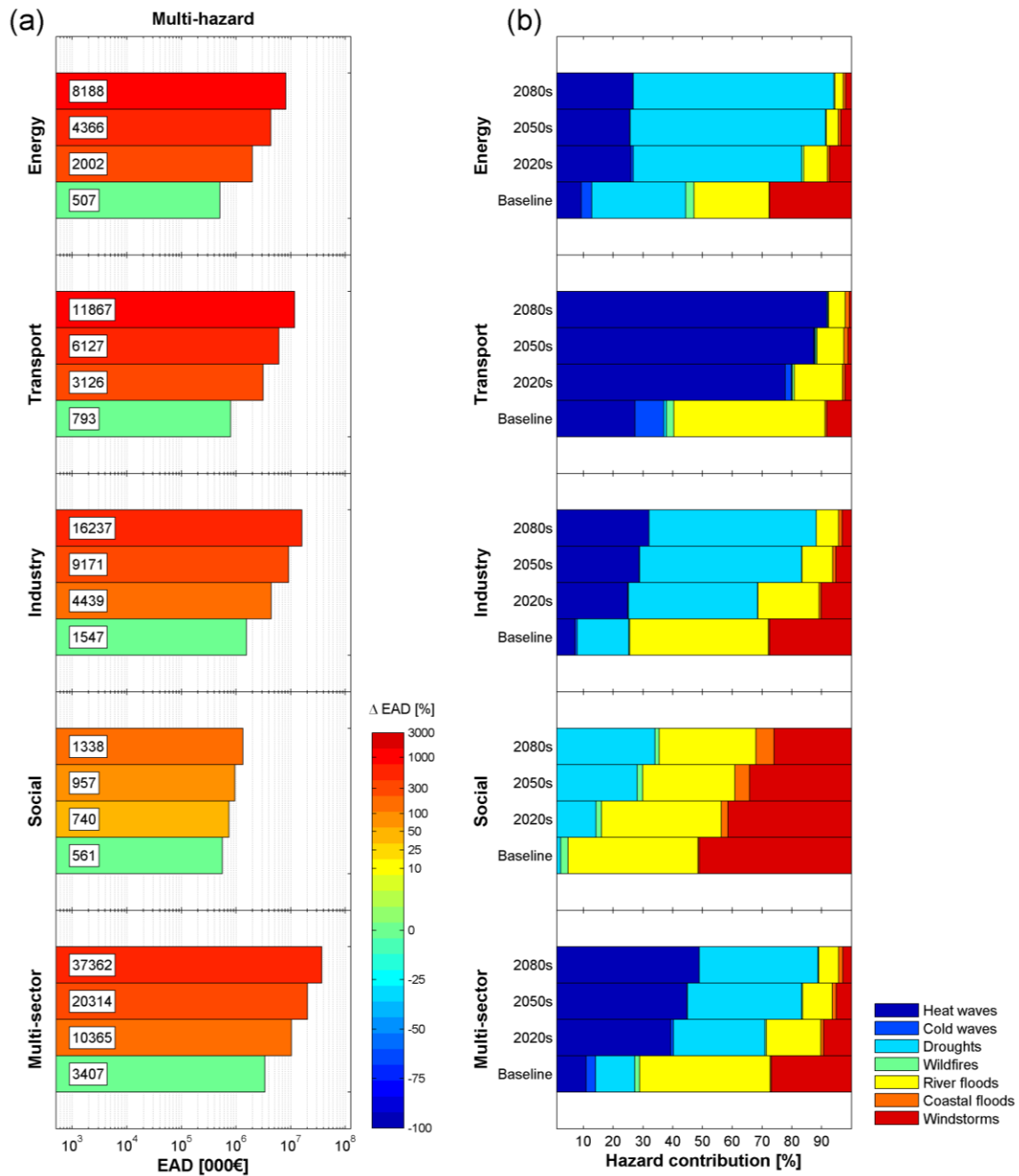
Here we present how climatic extremes are projected to affect critical infrastructures in the energy, transport, industry and social sector in the coming decades up to the end of the century. Impacts are estimated for EU28 as well as for Switzerland, Norway and Iceland, together further referred to as EU+. Damages reported further herein reflect median ensemble results, are undiscounted and expressed in 2010 € assuming no socio-economic change in future scenarios (only account for climate change). When reporting multi-hazard damages, for wind, where projections of hazard are not available for 2020 and 2050, damages for these periods were obtained by linearly interpolating between the baseline and the 2080s. Further note that the modelling domain of the flood and drought analysis do not include Cyprus and Malta, where Cyprus is also not included in the coastal flood domain. Hence no damages are reported for these hazards in Cyprus and Malta.

#### 5.3.1.1 Multi-hazard damages in Europe

Figure 5.3a shows the evolution in time of the multi-hazard EAD aggregated at European level (EU+) for each economic sector and the sectors combined, both in terms of magnitude and relative change with respect to the baseline. Results show that Europe will face a significant increase in multi-hazard multi-sector EAD in the coming decades. Baseline damages of 3.4 billion €/year are projected to triple by the 2020s, multiply six-fold by mid-century, and rise up to 38 billion €/year by the 2080s. These numbers reflect only the (combined) damages from the 7 climate hazards to the sectors considered in this study, hence they do not reflect the total damages of these hazards to society. Based on the shares of damages that relate to the infrastructures considered herein to the total (reported) climate damage (28% for coastal flooding, 90% for cold, 45% for drought, 14% for fire, 28% for flood, 67% for heat, and 21% for windstorms, see first paragraph page 102 of Section 5.2.4), and assuming that changes in the remaining damages follow the same trend, total damages from the 7 climate hazards to society could rise from currently 12 billion €/year to nearly 80 billion €/year by the end of this century. We further stress that

the myriad of climate change impacts go far beyond those of the 7 climate hazards considered herein; hence, it should be kept in mind that the damages presented here only reflect a fraction of the potential climate change damages to society.

Multi-hazard damages to the individual sectors evidently also show strong rises in time, with the actual degree and pace of change depending on the sector sensitivity to the different hazards and the rate and magnitude of change of the latter. The strongest increase in multi-hazard damages is projected for the energy sector, for which the baseline EAD of 0.5 billion €/year could rise to 2, 4.4, and 8.2 billion €/year (or increases in EAD of 394%, 860% and 1,612%) by the 2020s, 2050s and 2080s, respectively. A comparable trend can be observed for the transport sector, for which the baseline EAD of 0.8 billion €/year is expected to reach nearly 12 billion €/year (increase of 1,496%) by the end of this century. For industry, which shows the largest damages amongst the sectors considered, current EAD of 1.5 billion €/year is estimated to surpass 16 billion €/year by the 2080s, corresponding to a 10-fold increase. For the social sector, the rising trend in damages is less pronounced, but current EAD of 0.6 billion €/year could still more than double by the end of this century due to climate change.



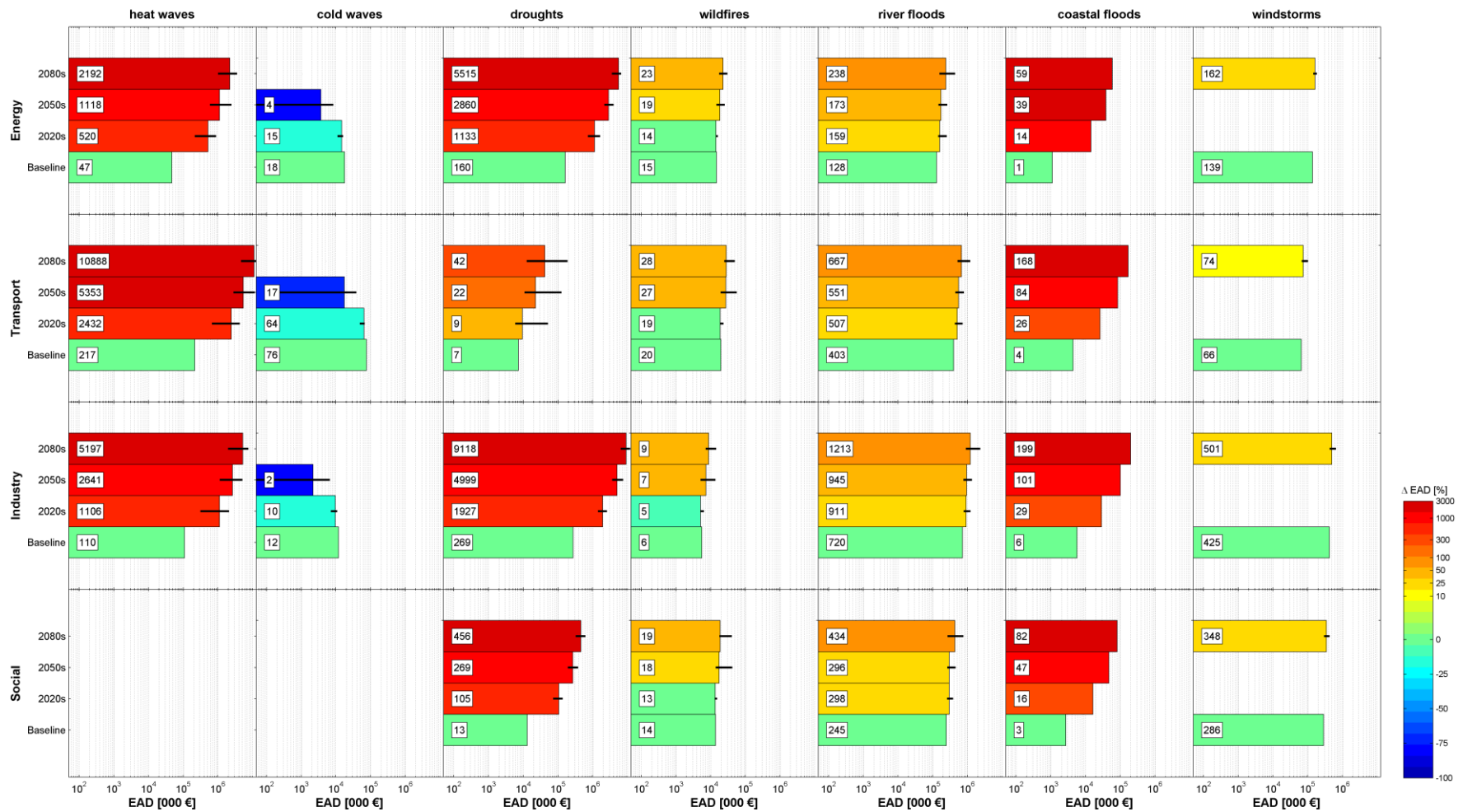
**Figure 5.3** Multi-hazard risk aggregated at European level (EU+) for each time period and sector of critical economic infrastructures: a) Expected Annual Damages: Bar length indicates the ensemble median – also reported in numerical labels in millions – where colours reflect the relative change in EAD with respect to the baseline; b) distribution of damages over the 7 hazards.

The hazard contribution (in time) to the total and sector damages is presented in Figure 5.3b. Aggregated over the four sectors, current climate hazard damages relate mostly to river floods (44%) and windstorms (27%). The relative contribution to the total damage of these two hazards diminishes rapidly in time, whereas the

shares of drought and heat damages strongly rises due to their more pronounced increase in view of climate change compared to the other hazards. Heat waves and droughts will likely cover more than 70% of climate hazard damages by the end of the century (vs 12% in the baseline period). This suggests that drastic changes in damage scenarios could manifest not only in terms of the magnitude of damage, but also in typologies of impacts. The contribution of wildfires and coastal floods is low, albeit that a strong increase in coastal flood damages is projected in the coming century. The low contribution of coastal flood damages may relate to the fact that in EMDAT there is no specific entry for coastal floods, and coastal flood events can be reported under storms or floods. So likely part of the coastal flood damages is reflected in the inland flood and windstorm damages. The contribution of cold waves is also low and cold-related damages in Europe could completely disappear with global warming. Hazard-contributions vary amongst the different sectors. For the social sector, damages from windstorms and inland flooding will remain important. The industry and energy sector will be most impacted by droughts, with 56% and 67%, respectively, of the sector damages relating to droughts by the end of this century. For the transport sector, on the other hand, heatwaves will largely dominate future damages (92% of total damages by 2080s). It is important to note that a decrease in the share of the damage of a specific hazard to the total multi-hazard damage does not imply that in absolute terms the damage due to this hazard will be lower.

#### 5.3.1.2 Impacts in the energy, transport, industry and social sector

Figure 5.4 shows baseline and projected EADs both in terms of magnitude and relative change aggregated at European level for each sector and climatic hazard. Each horizontal bar reflects a different time period, while the whiskers describe the inter-model spread (i.e., reflects the climate uncertainty). It is complemented by Figure 5.5 that displays the marginal contribution of infrastructures within a sector to the total hazard-induced damage ( $EAD_{IMC}$ ) for that sector.



**Figure 5.4** EAD to critical infrastructures aggregated at European level (EU+) for each hazard, time period and sector. Bar length indicates the ensemble median – also reported in numerical labels in millions – while the whiskers correspond to the 10 and 90 percentiles of the ensemble distribution. Colours reflect the relative change in EAD with respect to the baseline.



Results suggest that energy infrastructures will be increasingly affected by heat waves and droughts, up to 2,192 and 5,515 million €/year, respectively, by the end of the century, or approximately 4,700% and 3,400% of baseline damages. Fossil-fuel and nuclear power plants could be seriously affected by the decrease in efficiency due to higher air and water temperatures and periods of lower water volumes for cooling systems (Linnerud et al., 2011; Rübhelke and Vögele, 2011; van Vliet et al., 2012). Hydropower production could also be negatively impacted by more frequent low flow conditions (Lehner et al., 2005). System deterioration due to excessive biological growth and clog water intakes and a reduction of the structural integrity due to melting permafrost and drought-induced subsidence could further endanger physical infrastructures (Cruz and Krausmann, 2013; Ebinger, 2011). River and coastal flood impacts in the energy sector could amount up to 300 million €/year by the 2080s, or an increase of 130% compared to baseline flood damages (relative increases with respect to baseline of ~85% and 5,900%, respectively, for inland and coastal flooding). Impacts on electricity transport systems will be relevant likely due to short-circuiting, power failure and enhanced corrosion (Brown et al., 2013; Cruz and Krausmann, 2013). Structural damages to energy production sites due to direct impacts of flood flows may be also critical (Brown et al., 2013; Chandramowli and Felder, 2014; Cruz and Krausmann, 2013; Ebinger, 2011). Windstorms could increasingly endanger energy infrastructures, with damages reaching 162 million €/year by the 2080s, nearly a 20% increase with respect to baseline damages. This is mostly related to the disruption of transmission/distribution electricity lines due to fallen trees or wind gusts (94% EAD<sub>IMC</sub>) (Ebinger, 2011; Sieber, 2013). Wildfire impacts on the energy sector could rise with 50% by the end of the century, amounting to 27 million €/year. Fires result in potential failures of the power system mainly due to damages to transmission and distribution equipment such as electricity lines and gas pipelines (92% EAD<sub>IMC</sub>) (Bompard et al., 2013). Future impacts of cold waves are expected to decrease rapidly and they will fully disappear by 2080s. Residual damages along the twenty-first century will prevalently disrupt the electricity transport network (93% EAD<sub>IMC</sub>) due to ice and snow loads overhead distribution lines (Bompard et al., 2013; McColl et al., 2012).

Transport infrastructures could be strongly affected by heat waves in the future, with damages showing a ~5,000% increase to amount to nearly 11 billion €/year by the end of the century. Roads and rails will likely be the most threatened (89% and 11% EAD<sub>IMC</sub>, respectively) due to melting of asphalt, increased rutting and softening of pavement and buckling of rails (Chinowsky et al., 2013; Dobney et al., 2009; Palin et al., 2013). Drought-related damages in the transport sector could rise up to 42 million €/year, corresponding to 6-fold the baseline value, due to the reduced navigability of rivers and channels (Jonkeren et al., 2013, 2008, 2007). Impacts of river and coastal floods may increase up to 835 million €/year by 2080s, a doubling of the current damages, affecting prominently roads and rails due to the reduction of structural integrity of surface and subgrade material deteriorated by the wave action and induced-mass movements, scour on bridges and embankments, disruption of transport vehicles and facilities (Koetse and Rietveld, 2009; Suarez et al., 2005; Wright et al., 2012). Inland waterways could be increasingly affected by inland floods (9% EAD<sub>IMC</sub>) due to a reduced navigability of rivers and channels (Koetse and Rietveld, 2009; Love et al., 2010), while port infrastructures are impacted by coastal floods (32% EAD<sub>IMC</sub>) due to wave action and a deterioration of infrastructures that lack a fouling-resistant design against salt water (Hallegatte et al., 2010). Projected damages of wind extremes on the transport sector rise by little over 10% to 74 million €/year and relate mainly to wind pressure or debris impact on transport facilities and transport interruption (Doll et al., 2014; Molarius et al., 2013). Damages to transport systems due to wildfires could rise from 20 to 28 million €/year and will affect prevalently roads and rails (93% and 7% EAD<sub>IMC</sub>, respectively) due to the deterioration of materials. Damages of cold waves, currently around 76 million €/year, will considerably fall with time and become negligible by the end of this century. They affect pre-eminently roads due to bucking of asphalt, airport functioning due to icing of aircraft wings, and port infrastructures due to ice accumulation on vessels and deck, as well as the freezing of sea water (Doll et al., 2014; Koetse and Rietveld, 2009; Molarius et al., 2013; Pejovic et al., 2009; Schweighofer, 2013).

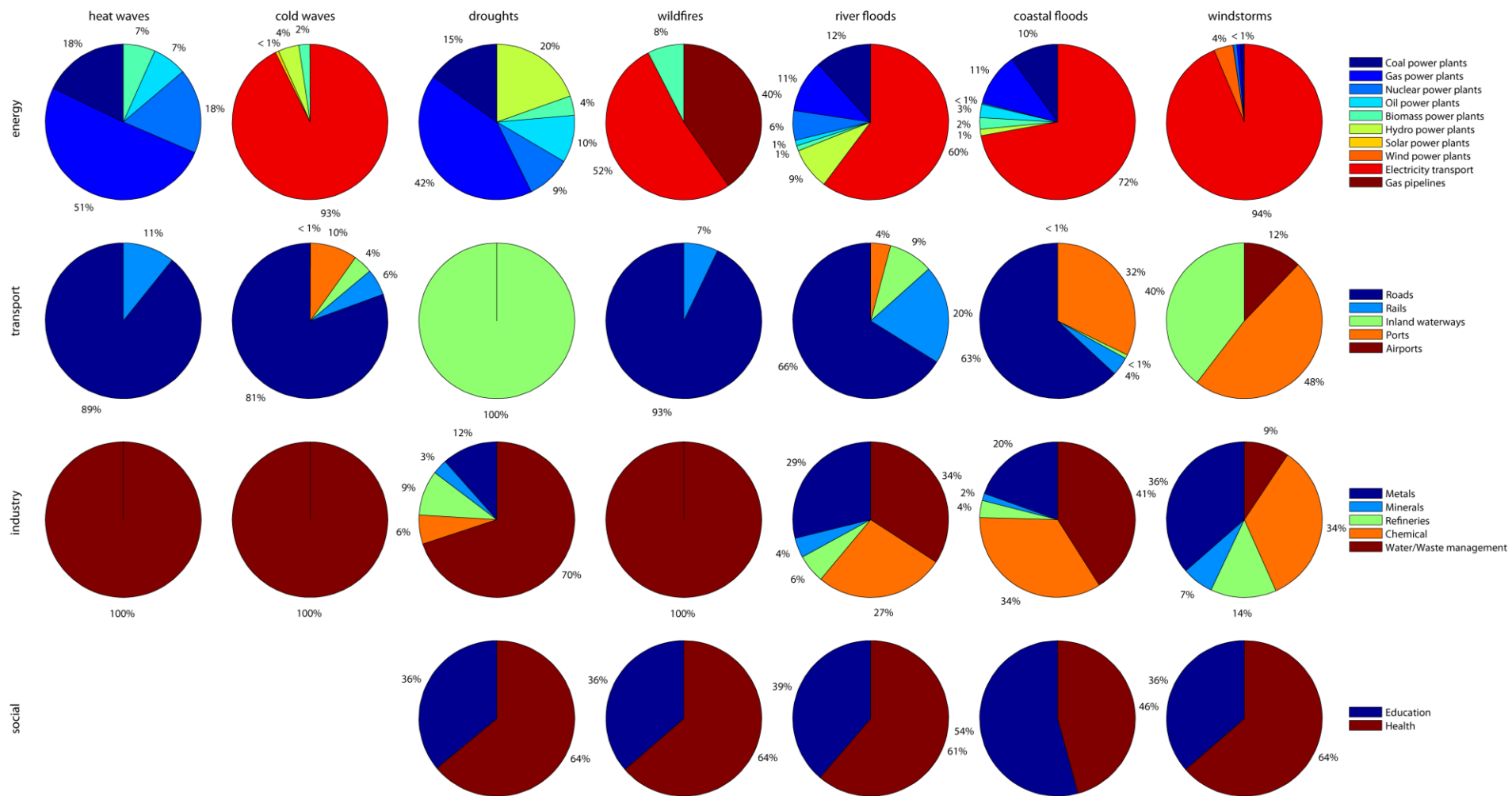


Figure 5.5 Distribution of hazard impacts over infrastructures types per sector, calculated over 2011-2100.

Industry infrastructures could be strongly affected by heat waves and droughts in the future, with expected annual damages rising up to 5,197 (+4,600%) and 9,118 (+3,300%) million €/year by 2080s, respectively. Waste management systems will be largely prone to increased methane production and potential leachate escape from brownfields and a reduction in decomposition rate leading to lower operability and productivity (Tannahill and Booth, 2012). Water management systems will be likely subject to prolonged periods of water shortage and increasing freshwater degradation with corresponding higher costs for water and its treatment (van Vliet et al., 2012). River and coastal flood impacts are expected to double to 1,412 million €/year for the industry sector. They affect predominantly water management systems due to an increasing cost for water treatment required to face the increased release of pollutants from flooded brownfields and augmented intrusion of salt water (Delpla et al., 2009; Langeveld et al., 2013; Sir, 2012). Chemical, metal, and mineral industries and refinery sites are also affected by the direct contact with flood water (Cozzani et al., 2010; Krausmann et al., 2011). Total windstorm damages are expected to slightly increase up to 501 million €/year. Wind pressure and debris impact similarly endanger all industry infrastructures (Krausmann et al., 2011). Wildfires impacts will likely rise to 9 million €/year by 2080s, mainly affecting waste management systems due to possible system failure. Cold waves mainly affect water management systems due to the possible disruption of water pipes vulnerable to icing (Whitehead et al., 2009) but results show a strongly decreasing trend in cold related damages to industry.

For the social sector no damages are obtained for heat and cold waves, as the sensitivity (derived from the survey and literature) of education and health infrastructures to the considered hazards is low. Damages in the social sector for the other hazards show mostly similar marginal contributions for education and health infrastructures, with slightly larger impacts for the latter. Drought induced damages could rise significantly from 13 to 456 million €/year, mainly as a result of increased structural damages due to drought-induced subsidence (Corti et al., 2011, 2009). River and coastal flood impacts will roughly double to 516 million €/year by the 2080s. Damages include direct damages to infrastructures from contact with flood water, including the reduced structural integrity of buildings due to wave action and

reduced soil stability (Carmichael et al., 2012; Hallegatte et al., 2010; Oven et al., 2012; Radovic et al., 2012). Damages related to windstorms and wildfires show a modest increase of 22% (348 million €/year) and 36% (19 million €/year), respectively, by the end of the century. Such impacts could be largely related to structural damages to social infrastructures due to wind pressure or debris impacts and fires-related failures (Stewart et al., 2011).

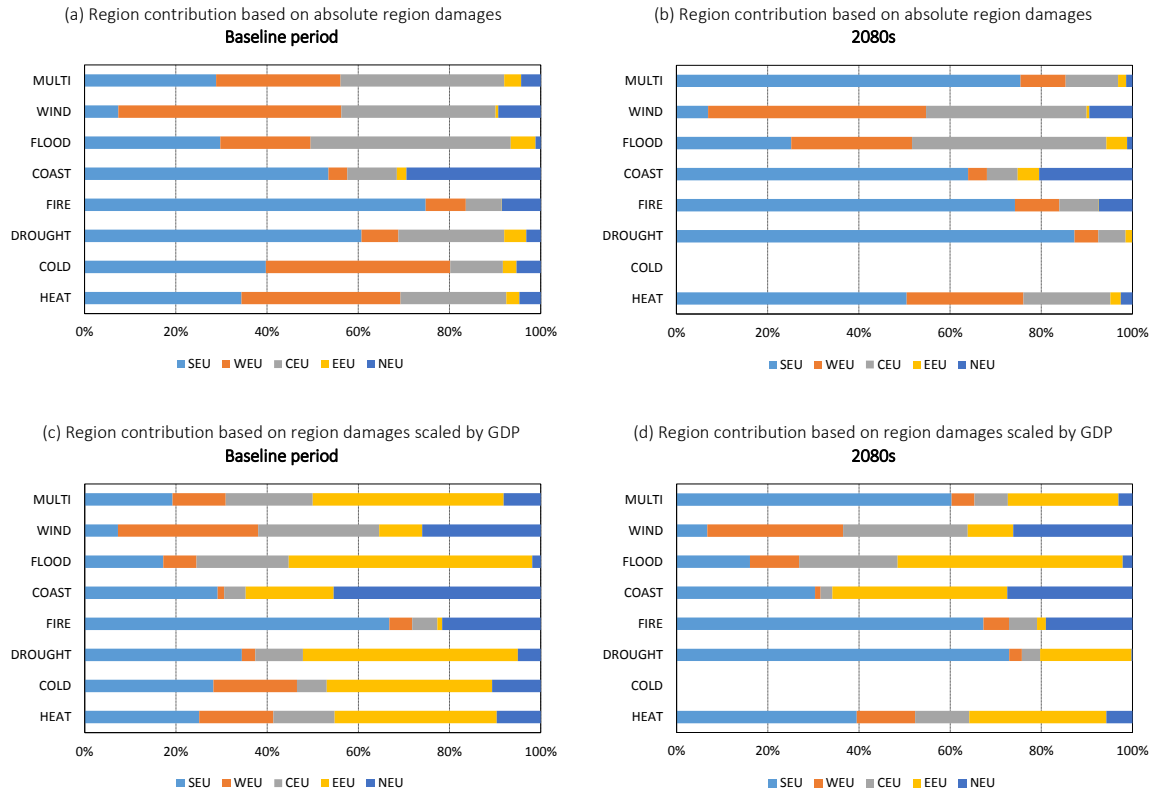
The inter-model spreads shown by whiskers in Figure 5.4 quantify the potential effects of climate variability on the resulting uncertainty of EAD estimates. This is largely driven by the influence of climate variability on climate hazard indicators (see Figure 2.1 in Chapter 2 on hazards) and further modulated by the spatial distribution of exposed infrastructures and their specific vulnerability. This results in a larger spread in the risk scenarios for climate hazards whose projections are more uncertain, such as floods, especially in areas with many exposed assets and a high sensitivity to the hazard. The relevant inter-model spread of EAD estimates reinforces the advantage of an ensemble-based approach for obtaining statistically robust projections of future risk.

### 5.3.1.3 Regional impacts to critical infrastructures

The aggregated results presented above mask the strong geographical differences in impacts across Europe for different hazards. Regional impacts depend on the spatial variations in the frequency of occurrence and magnitude of a hazard, the latter connected in turn to regional climate conditions and changes therein, as well as on the spatial distribution of assets and regional welfare. Figure 5.6 displays for each hazard and the hazards combined the relative distribution of multi-sector EAD over European regions for the baseline and by the end of this century. The upper two plots represent region contributions based on absolute damages per region. Results show that in absolute terms, most of the current and future climate hazard damages are largely concentrated in Southern (SEU), Western (WEU) and Central (CEU) Europe regions (see Figure 1.2). This, however, is in large part due to the areal extension of the macro regions considered herein, with the Eastern Europe (EEU)

region for example having a much smaller spatial domain compared to the other regions. The bottom two plots in Figure 5.6 therefore represent region contributions based on damages scaled by region GDP. They show that current multi-hazard damages are in relative terms highest in EEU, followed by SEU and CEU, whereas WEU and the Northern Europe (NEU) region are relatively least impacted. The most noticeable change due to climate change is the strong increase in relative damage load in SEU in the coming decades. This relates mainly to the much stronger increase in this region of damages from heat waves and especially droughts compared to other regions. The spatial distribution across Europe of the damages of the other hazards are more stable under climate change, whereas cold-related damages tend to disappear everywhere in Europe. Relative windstorm damages are and will remain highest in WEU, CEU and NEU, where relative fire impacts are and will remain by far the highest in SEU. For inland flooding the relative impacts are highest in EEU and CEU under current and future climate, whereas for coastal flooding EEU, NEU and SEU will show the highest relative impacts.

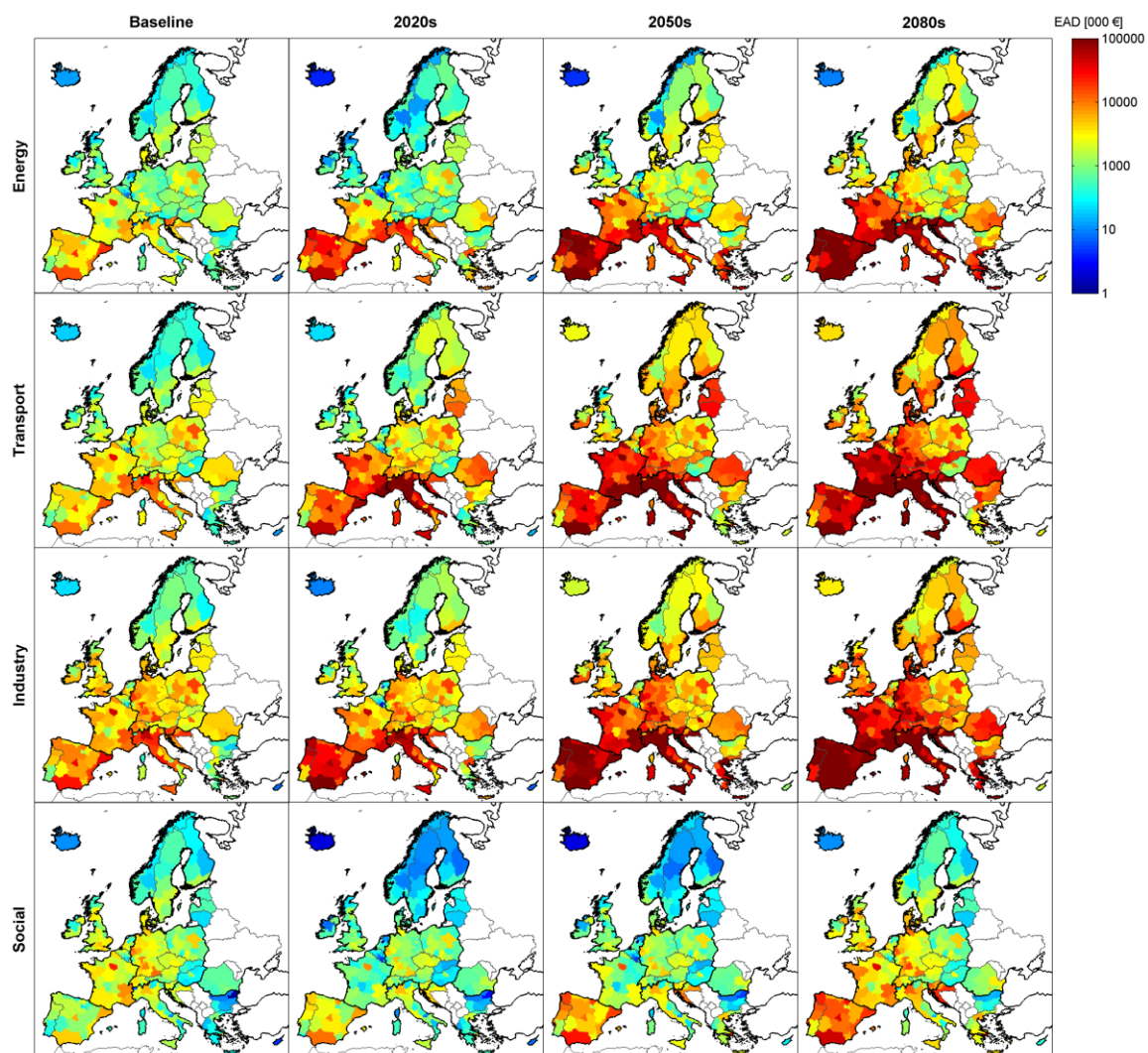
The hazard-specific shares at regional scale mask further local variations in risk patterns and dominant hazards. River and coastal floods, for example, will remain the most critical hazard in many floodplains and coastal stretches of Western, Central and Eastern Europe, including the British Isles, Poland, Czech Republic, Bulgaria, Romania and northern coastlines of the Iberian Peninsula.



**Figure 5.6** Distribution of multi-sector EAD by regions calculated for the baseline (left) and 2080s (right). Upper row represents region contributions based on absolute damage per region, bottom row represents region contributions based on damages scaled by region GDP.

More detailed space-time variations in impacts are visualized in the pan-European maps of multi-hazard EAD for the different sectors and time windows displayed in Figure 5.7. Although all regions of Europe are projected to experience a progressive increase in multi-hazard EAD, a prominent spatial gradient of increasing EAD towards southern regions of Europe becomes apparent with time for all sectors considered. The trend first manifests mainly in the Iberian Peninsula, south of France, Italy, Slovenia and Croatia, to expand towards the adjacent regions north, east and west as time proceeds. The most southern regions of Europe will progressively be much larger affected by future climate extremes compared to the rest of Europe. This is exemplified by the strong increase in relative and absolute damage shares of SEU to the total European damages during this century (see Figure 5.6). A large part of the north-south gradient in damages relates to droughts. This hazard will strongly intensify in southern parts of Europe, whereas in northern regions droughts will become less severe and occur less frequent with climate

change. As such, for sectors sensitive to this hazard, namely the energy, industry and to a lesser extent the social sector, drought-induced damages will strongly increase in the south and decrease in the north of Europe. For the transport sector only inland navigation is sensitive to droughts. As this mode of transport is hardly utilized in southern and northern parts of Europe, the north-south damage gradient is somewhat less pronounced for the transport sector. Heatwaves also contribute to the north-south gradient but to a lesser extent than droughts, as heatwave damages are projected to rise significantly all over Europe.



**Figure 5.7** Multi-hazard risk scenarios for critical infrastructures in the energy, transport, industry and social sector.



Multi-hazard and multi-sector EAD values normalized by country GDP are shown in Table 5.2 for European countries. Higher shares of GDP at risk indicate larger impacts on the country overall economy and a higher potential of cross-sectorial shocks. Currently (baseline period), for EU+ the share of GDP at risk amounts to 0.03%, where for most countries less than 0.06% of GDP is at risk. Note that these figures do not reflect total potential climate damages to the economy, rather they represent the damages induced by the 7 climate hazards to critical infrastructures in the energy, transport, industry and social sector. For EU+ the share of GDP at risk rises progressively to 0.28% by the end of century. There are, however, strong variations in the shares of GDP at risk within Europe, confirming earlier observations of the spread of climate hazards damages across Europe. Countries in northern Europe (with the exception of Denmark), the Benelux, the British Isles, as well as Poland and the Czech Republic show the lowest share of GDP at risk, with damages remaining below 0.1% of GDP up to the end of the century. Impacts by the end of the century remain below 0.2% of GDP in Germany (0.10%), Denmark (0.11%), Austria (0.14%), Hungary (0.15%), Lithuania (0.15%) and Switzerland (0.18%). Also Latvia (0.2%), France (0.23%), Estonia (0.25%) and Slovakia (0.27%) have damage shares below the European average. Southern and south-eastern countries will be most impacted. For Bulgaria (0.40%), Romania (0.45%), Italy (0.49%) and Slovenia (0.56%) damages remain below or close to 0.5% of GDP, whereas for Portugal (0.77%), Spain (0.87%) and Croatia (0.97%) damages could climb to nearly 1% of GDP by the 2080s. For Cyprus three (coastal and inland floods, and droughts) hazards are not modelled and for Malta two (floods and droughts), hence no damages for these hazards are reported for these countries. However, based on regional patterns of impacts it can be expected that the damages in these countries could represent a considerably larger share of the GDP as those reported in Table 5.2.

**Table 5.2** Percentage of GDP at risk expressed by multi-hazard damage normalized by country GDP.  
 \*Note that for Cyprus (coastal and inland floods, and droughts) and Malta (floods and droughts) some hazards are not modelled hence no damages are reported for these countries.

Country	baseline	2020s	2050s	2080s
AT	0.02%	0.03%	0.07%	0.14%
BE	0.02%	0.02%	0.03%	0.06%
BG	0.04%	0.11%	0.17%	0.40%
CH	0.03%	0.04%	0.11%	0.18%
CY*	0.00%	0.00%	0.03%	0.04%
CZ	0.05%	0.06%	0.06%	0.08%
DE	0.02%	0.03%	0.06%	0.10%
DK	0.03%	0.04%	0.07%	0.11%
EE	0.04%	0.07%	0.20%	0.25%
ES	0.04%	0.15%	0.45%	0.87%
FI	0.01%	0.02%	0.04%	0.06%
FR	0.02%	0.05%	0.13%	0.23%
GR	0.02%	0.07%	0.51%	0.68%
HR	0.04%	0.09%	0.34%	0.97%
HU	0.05%	0.04%	0.10%	0.15%
IE	0.01%	0.01%	0.03%	0.03%
IS	0.01%	0.01%	0.05%	0.07%
IT	0.03%	0.12%	0.28%	0.49%
LT	0.03%	0.07%	0.14%	0.15%
LU	0.01%	0.02%	0.02%	0.04%
LV	0.05%	0.09%	0.20%	0.20%
MT*	0.00%	0.11%	0.12%	0.14%
NL	0.01%	0.01%	0.02%	0.03%
NO	0.01%	0.01%	0.02%	0.03%
PL	0.06%	0.06%	0.06%	0.06%
PT	0.03%	0.15%	0.45%	0.77%
RO	0.08%	0.15%	0.21%	0.45%
SE	0.01%	0.02%	0.04%	0.06%
SI	0.05%	0.08%	0.18%	0.56%
SK	0.03%	0.03%	0.11%	0.27%
UK	0.02%	0.02%	0.03%	0.05%
EU+	0.03%	0.08%	0.15%	0.28%

### 5.3.2 Impacts on EU investments of 2007-2013 programming period

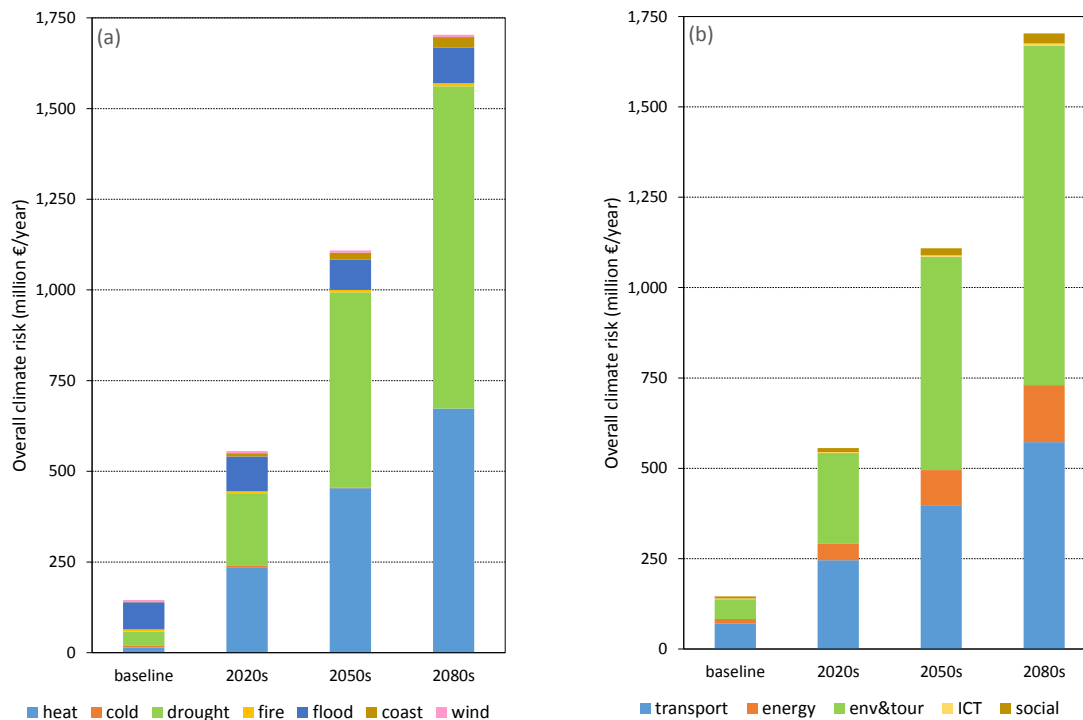
Here we present how the 7 climate hazards are projected to impact EU regional investments in the transport, energy, environment and tourism, ICT, and social sector in the coming decades up to the end of the century. Investments relate to the programming period 2007-2013 in the EU27. Damages reflect median ensemble results, are undiscounted and expressed in 2010 € assuming. Note again that impacts in Cyprus and Malta may be underestimated as they are not included in all model domains of the hazard analyses.

#### 5.3.2.1 Multi-hazard multi-sector impacts for EU27

Figure 5.8 shows the evolution in time of overall climate risk of the EU27 Structural Investments for 2007-2013, with a breakdown of the total climate risk in (a) multi-sector EAD per hazard and (b) multi-hazard EAD per sector. The EU27 baseline EAD amounts to 146 million €/year, or 0.04% of the total EU regional investments of 342 billion € for the period 2007-2013. Damages rise rapidly due to climate change and reach 556 million €/year (382% baseline EAD) or 0.16% of total investments by the 2020s. By the 2050s damages further climb to 1,109 million €/year (761% baseline EAD) or 0.32% of total investments, and by the end of this century the annual risk amounts to 1,703 million €/year (1,168% baseline EAD) or 0.49% of total investments.

The breakdown per hazard (Figure 5.8a) shows that currently floods is the most damaging hazard, accounting for about half (51%) of total hazard damages, followed by drought (26%) and heat waves (10%). Cold, fire and wind each have a share of 4%, whereas coastal floods contribute to the total damages for 0.5%. Drought damages increase significantly, from 38 million €/year now to 888 million €/year by the 2080s (2,315% baseline EAD), and form the largest share of future damages (52% by the end of the century). The strongest relative increase in damages, however, is projected for heatwaves and coastal flooding (increases both around +4,500%). As a result heatwaves will become the second damaging hazard to EU structural investments (40% of total damages by 2080s). Damages due to cold

waves will evanesce in the coming decades, whereas damages due to wind, floods and fires show more moderate increases, with absolute damages rising this century by 10%, 30% and 50%, respectively. Their relative contribution to the total damages logically reduces due to the pronounced increase in heatwave, drought and coastal flooding damages.



**Figure 5.8** Overall climate risk of 2007-2013 EU27 Structural Investments: breakdown of total climate risk in (a) multi-sector EAD per hazard, and (b) multi-hazard EAD per sector.

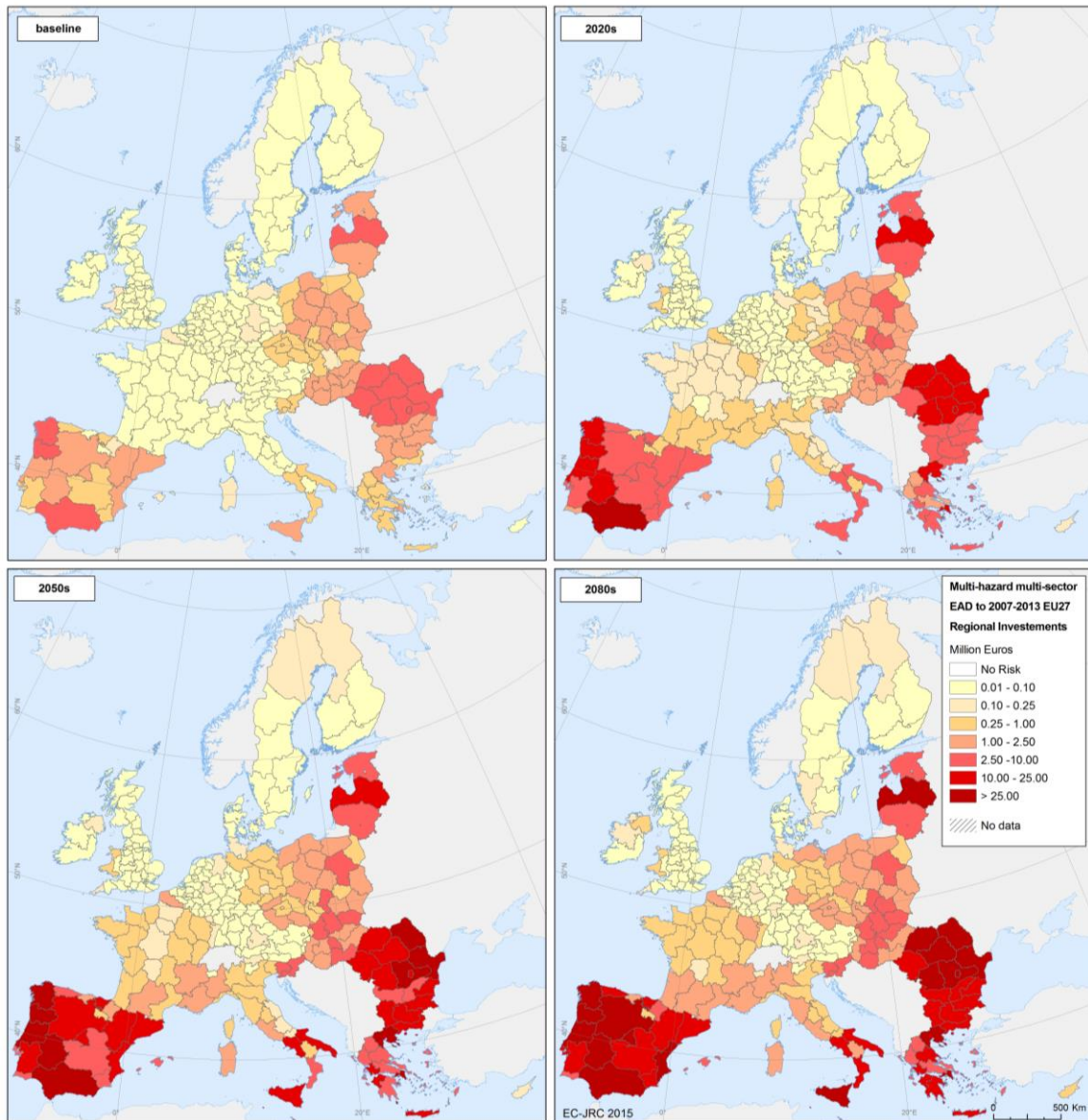
The breakdown of damages per sector (Figure 5.8b) shows that currently 48% of hazard impacts relate to the transport sector, and 37% to the environment and tourism sector. Annual damages in the transport sector rise by 722% from 70 million €/year in the baseline to 573 million €/year by the 2080s. This value corresponds to 0.77% of total transport allocations. For the environment and tourism sector damages increase at a rate double as high (+1,619%) from 55 million €/year now to 940 million €/year by the end of the century. Hence, this sector will under future climate account for more than half of the total hazard damages (55% vs 34% for the transport sector) to EU investments because of its larger sensitivity to the dominating hazards (droughts and heatwaves). The damage level reached by the

2080s represents 1.52% of the total EU regional investments in this sector. Damages in the energy sector increase by more than tenfold (+1,077%), with energy EAD rising from 13 million €/year in the baseline to 157 million €/year by the 2080s. The latter corresponds to 1.49% of EU regional energy allocations. The rise for the energy sector is similar as that for the overall losses, and as such the share of the energy damages to the total damages (around 9%) remains fairly constant in time. Impacts in the ICT and social sector are smaller, with an EAD of 1.9 and 6 million €/year, respectively, for the baseline period. They also show less pronounced increases compared to the other sectors. Where damages to ICT investments are expected to rise by 160% up to 5 million €/year by the 2080s, an increase of 363% up to 28 million €/year is projected by that period for the social sector. The damages for these sectors also represent a smaller share of the ICT and social investments, with impacts by the end of the century totaling 0.03% and 0.17% of EU allocations for 2007-2013 in these sectors.

Note that the rates of change in damage per sector can deviate from those observed for the critical infrastructures. This is because EU investments may be aimed at different priority themes than those considered in the spatial layers of critical infrastructures. For the energy sector, for example, a large share of the damages for the critical infrastructures relates to fossil-fuel and nuclear power plants (see Figure 5.5), to which EU regional investments are not targeted.

#### 5.3.2.2 Regional impacts on CPF investments

The spatial distribution of the absolute impacts across the EU27 is presented in Figure 5.9. The highest absolute damages to EU regional investments under the 2007-2013 period are projected for the Iberian Peninsula, Southern Italy, the EU27 countries in the Balkan Peninsula, and the Baltic States. In these regions damages to investments could amount to tens of millions on an annual basis, locally sometimes more than hundred million (e.g., regions of Andalucía and Galicia), by the end of this year. This spatial pattern is largely driven by the large allocation of funds to these regions (see Figure 4.2) and further modulated by the changes in hazard patterns.

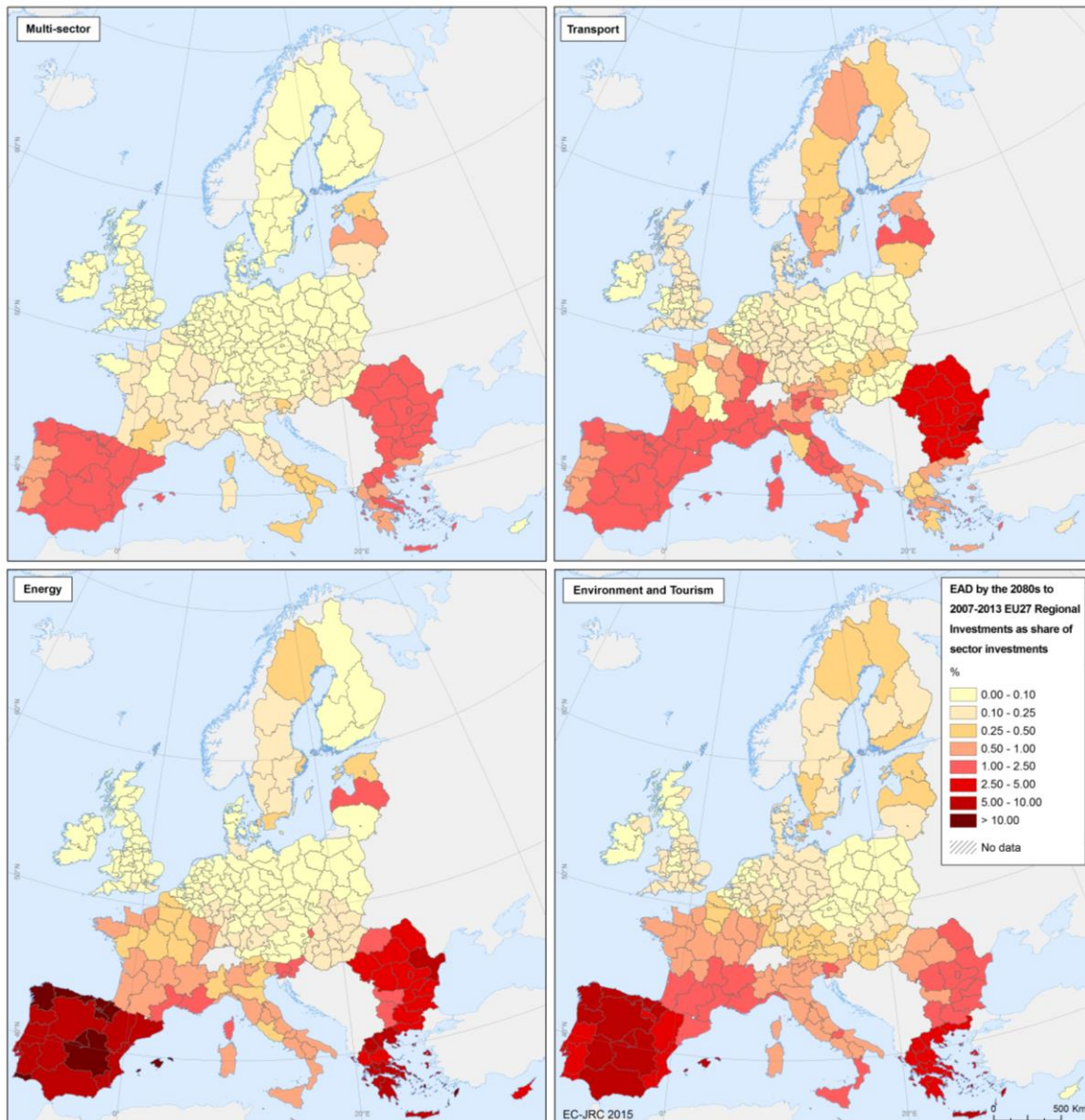


**Figure 5.9** Spatial distribution of multi-hazard multi-sector EAD to 2007-2013 EU27 regional investments: (a) baseline, (b) 2020s, (c) 2050s and (d) 2080s.

Impacts expressed as a share of the investments are shown in Figure 5.10 for the 2080s. The multi-hazard multi-sector expected annual losses (Figure 5.10a), which for the whole EU27 correspond to 0.49% of total investments (see section 5.3.2.1), can reach up to 3% in isolated regions of the Iberian and Balkan Peninsulas. Hence, in these regions total damages accumulated over a 30-year period would nearly sum up to the total investments. In most of north (apart from the Baltic States) and central (in terms of latitude, from British Isles to Poland) Europe, total expected annual damages remain below 0.1% of total investments.

When looking at sector level, relative impacts can even be substantially higher in some parts of Europe. For the transport sector (Figure 5.10b), by the end of the century expected annual losses to investments rise to about 5% of the transport investments for Latvia, Romania, Bulgaria and regions of Spain. At this rate the cumulated losses to the investment could equal the size of the investment after 20 years. For the energy (Figure 5.10c) and the environment and tourism (Figure 5.10d) sectors, annual loss shares (with respect to sector investments) could go even up to 10% and higher, or an expected yearly loss of more than 1/10 of the total sector investment, for regions in the southwest and southeast of the EU. For the social and ICT sectors, expected annual losses at regional scale remain mostly below 1% and 0.5% of sector investments, respectively.





**Figure 5.10** Spatial distribution by 2080s of multi-hazard multi-sector EAD to 2007-2013 EU27 regional investments expressed as a share of sector investments: (a) multi-sector, (b) transport, (c) energy, (d) environment and tourism.

## 5.4 Main limitations and knowledge gaps

We recognize that our risk estimates are subject to uncertainty due to methodological and data aspects that should be considered in addition to those described for the climate hazard, sensitivity and exposure components, already discussed in Chapter 2, 3 and 4, respectively.



Our multi-hazard risk framework is built on the propagation of baseline damages to future scenarios according to variations in the frequency of extreme events and the spatial distribution of exposed assets/investments. At present, our understanding of long-term climate risks is limited by the lack of in-depth knowledge on the impacts of climate hazards due to the absence of harmonised loss data recording. Baseline damages for this project are retrieved from hazard loss databases (EMDAT and MunichRe). As the data that populate these databases originate from different sources and are collected by multiple actors, their loss figures should be viewed in light of their potential biases (Gall et al., 2009). The databases may under-represent certain hazard types depending on their purpose and the audience, as well as on the type of impacts and how they are perceived (e.g., flood impacts are much more visible than heat impacts). A prominent example is the notoriously underestimation of droughts (Svoboda et al., 2002), being an insidious, slow-onset climate hazard inducing a wide range of impacts that affect many sectors of the economy. Also, coastal flooding events may be reported under floods or storms in general, therefore leading to an underestimation of coastal flood impacts. Furthermore, different threshold criteria used across EMDAT and MunichRe for data recording may result in disparities in collected disaster information (e.g., exclusion of small-scale events in EMDAT). Changes in political geography may affect how hazard loss data are reproduced in space and time. Loss data are reported in EMDAT and MunichRe according to the political geography at the time of the event. Boundary changes that have occurred in the last three decades (e.g., Germany, Balkan countries) may have affected the spatial accuracy of baseline loss data.

Disaster risk databases mostly record direct damages at the time of occurrence or direct aftermath of the hazard event. Possible indirect, inter-sectorial effects and intangible damages, which may considerably amplify the impacts of hazards, are typically not considered in damage recording. This may lead to potential underestimation of the impacts of climate extremes on the investigated sectors. The estimates of baseline and future climate risk impacts reported herein are fully conditional on the reported country damages in EMDAT and the aggregated Munich Re damage figures. Hence, any deviations of the reported damages from the true impacts are inherently translated into our damage estimates.

The national recorded hazard damages retrieved from the disaster databases have been disaggregated across sectors and NUTS2 regions based on the regional societal and economic structure as represented by EUROSTAT statistics and the sensitivities to the specific hazards derived from the survey and literature. The assumptions beyond the proposed disaggregation of losses represent potential sources of uncertainty resulting from the incomplete knowledge about the true sectorial-specific impacts and their spatialization (Meyer et al., 2013). Although reasonable assumptions have been formulated, such epistemic uncertainties are difficult to assess.

In this study, we assume independent hazards and static vulnerability. However, hazards may induce or reinforce other hazards, they may overlap spatially and temporally, as observed in Chapter 2, influencing not only the overall hazard level, but also the vulnerability of elements at risk through possible hazard interrelations or cascade effects (Kappes et al., 2012). The fragility of a certain asset could be largely intensified when subject to simultaneous or cascade impacts of several hazards (Lee and Rosowsky, 2006). While we recognize the relevance of the effects of overlapping hazards on the vulnerability of elements at risks, very few studies on this topic are available in literature (Kappes et al., 2012). The scarcity of observational relations linking variations in multi-hazard impacts on vulnerability does not allow a reliable integration of such effects in large-scale predictive systems.

The way observed damages are integrated in the methodology is by assuming for the baseline that they relate to events that happen every 50-years or less frequent for highly sensitive infrastructures and every 100-years or less frequent for infrastructures with medium sensitivity. For future time windows, we then translate changes in this high-end tail of the frequency distribution to project future damages. In principle, it is possible that for certain hazards more frequent (i.e., less extreme) events induce damages, or that impacts are avoided or minimized for more extreme events (e.g., very high flood protection standards in the Netherlands). This implies that we assume that the changes in the part of the frequency distribution that we

consider to be linked with the damages are representative for the true changes in the frequency of damaging events.

Climate-change impact uncertainties are quantified in this study solely in terms of the spread induced by the climate-model projections, and do not account for all the sources of uncertainty detailed above. We recognize that the impact-model spread of our damage projections can be comparable to, or even larger than, the spread introduced by the different climate models considered (Piontek et al., 2014). However, whereas for (some) climate hazards (in certain regions) there exists uncertainty in both the direction and magnitude of change, uncertainty in the impact assessment only affects the magnitude of the impact and of the change therein.

## 5.5 References

- Bompard, E., Huang, T., Wu, Y., Cremenescu, M., 2013. Classification and trend analysis of threats origins to the security of power systems. *Int. J. Electr. Power Energy Syst.* 50, 50–64. doi:10.1016/j.ijepes.2013.02.008
- Brown, S., Hanson, S., Nicholls, R.J., 2013. Implications of sea-level rise and extreme events around Europe: a review of coastal energy infrastructure. *Clim. Change* 122, 81–95. doi:10.1007/s10584-013-0996-9
- Carmichael, C., Bickler, G., Kovats, S., Pencheon, D., Murray, V., West, C., Doyle, Y., 2012. Overheating and Hospitals - What do we know? *J. Hosp. Adm.* 2, p1. doi:10.5430/jha.v2n1p1
- Chandramowli, S.N., Felder, F.A., 2014. Impact of climate change on electricity systems and markets – A review of models and forecasts. *Sustain. Energy Technol. Assess.* 5, 62–74. doi:10.1016/j.seta.2013.11.003
- Chinowsky, P.S., Price, J.C., Neumann, J.E., 2013. Assessment of climate change adaptation costs for the U.S. road network. *Glob. Environ. Change* 23, 764–773. doi:10.1016/j.gloenvcha.2013.03.004
- Ciscar, J.-C., Iglesias, A., Feyen, L., Szabó, L., Regemorter, D.V., Amelung, B., Nicholls, R., Watkiss, P., Christensen, O.B., Dankers, R., Garrote, L., Goodess, C.M., Hunt, A., Moreno, A., Richards, J., Soria, A., 2011. Physical and economic consequences of climate change in Europe. *Proc. Natl. Acad. Sci.* 108, 2678–2683. doi:10.1073/pnas.1011612108
- Corti, T., Muccione, V., Köllner-Heck, P., Bresch, D., Seneviratne, S.I., 2009. Simulating past droughts and associated building damages in France. *Hydrol Earth Syst Sci* 13, 1739–1747. doi:10.5194/hess-13-1739-2009
- Corti, T., Wüest, M., Bresch, D., Seneviratne, S.I., 2011. Drought-induced building damages from simulations at regional scale. *Nat Hazards Earth Syst Sci* 11, 3335–3342. doi:10.5194/nhess-11-3335-2011
- Cozzani, V., Campedel, M., Renni, E., Krausmann, E., 2010. Industrial accidents triggered by flood events: Analysis of past accidents. *J. Hazard. Mater.* 175, 501–509. doi:10.1016/j.jhazmat.2009.10.033
- Cruz, A.M., Krausmann, E., 2013. Vulnerability of the oil and gas sector to climate change and extreme weather events. *Clim. Change* 121, 41–53. doi:10.1007/s10584-013-0891-4
- Delpla, I., Jung, A.-V., Baures, E., Clement, M., Thomas, O., 2009. Impacts of climate change on surface water quality in relation to drinking water production. *Environ. Int.* 35, 1225–1233. doi:10.1016/j.envint.2009.07.001

- Dobney, K., Baker, C.J., Quinn, A.D., Chapman, L., 2009. Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east United Kingdom. *Meteorol. Appl.* 16, 245–251. doi:10.1002/met.114
- Doll, C., Klug, S., Enei, R., 2014. Large and small numbers: options for quantifying the costs of extremes on transport now and in 40 years. *Nat. Hazards* 72, 211–239. doi:10.1007/s11069-013-0821-9
- Ebinger, J.O., 2011. *Climate Impacts on Energy Systems: Key Issues for Energy Sector Adaptation*. World Bank Publications.
- Gall, M., Borden, K.A., Cutter, S.L., 2009. When Do Losses Count? *Bull. Am. Meteorol. Soc.* 90, 799–809. doi:10.1175/2008BAMS2721.1
- Hallegatte, S., Ranger, N., Mestre, O., Dumas, P., Corfee-Morlot, J., Herweijer, C., Wood, R.M., 2010. Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen. *Clim. Change* 104, 113–137. doi:10.1007/s10584-010-9978-3
- Jonkeren, O., Ommeren, J. van, Rietveld, P., 2008. Effects of low water levels on the river Rhine on the inland waterway transport sector, in: Hansjürgens, B., Antes, R. (Eds.), *Economics and Management of Climate Change*. Springer New York, pp. 53–64.
- Jonkeren, O., Rietveld, P., Ommeren, J. van, 2007. Climate Change and Inland Waterway Transport: Welfare Effects of Low Water Levels on the River Rhine. *J. Transp. Econ. Policy* 41, 387–411.
- Jonkeren, O., Rietveld, P., Ommeren, J. van, Linde, A. te, 2013. Climate change and economic consequences for inland waterway transport in Europe. *Reg. Environ. Change* 14, 953–965. doi:10.1007/s10113-013-0441-7
- Kappes, M.S., Keiler, M., Elverfeldt, K. von, Glade, T., 2012. Challenges of analyzing multi-hazard risk: a review. *Nat. Hazards* 64, 1925–1958. doi:10.1007/s11069-012-0294-2
- Koetse, M.J., Rietveld, P., 2009. The impact of climate change and weather on transport: An overview of empirical findings. *Transp. Res. Part Transp. Environ.* 14, 205–221. doi:10.1016/j.trd.2008.12.004
- Krausmann, E., Cozzani, V., Salzano, E., Renni, E., 2011. Industrial accidents triggered by natural hazards: an emerging risk issue. *Nat Hazards Earth Syst Sci* 11, 921–929. doi:10.5194/nhess-11-921-2011
- Langeveld, J.G., Schilperoort, R.P.S., Weijers, S.R., 2013. Climate change and urban wastewater infrastructure: There is more to explore. *J. Hydrol.* 476, 112–119. doi:10.1016/j.jhydrol.2012.10.021
- Lee, K.H., Rosowsky, D.V., 2006. Fragility analysis of woodframe buildings considering combined snow and earthquake loading. *Struct. Saf.* 28, 289–303. doi:10.1016/j.strusafe.2005.08.002

Lehner, B., Czisch, G., Vassolo, S., 2005. The impact of global change on the hydropower potential of Europe: a model-based analysis. *Energy Policy* 33, 839–855. doi:10.1016/j.enpol.2003.10.018

Linnerud, K., Mideksa, T.K., Eskeland, G.S., 2011. The Impact of Climate Change on Nuclear Power Supply. *Energy J.* 32. doi:10.5547/ISSN0195-6574-EJ-Vol32-No1-6

Love, G., Soares, A., Püempel, H., 2010. Climate Change, Climate Variability and Transportation. *Procedia Environ. Sci., World Climate Conference - 3 1*, 130–145. doi:10.1016/j.proenv.2010.09.010

McColl, L., Palin, E.J., Thornton, H.E., Sexton, D.M.H., Betts, R., Mylne, K., 2012. Assessing the potential impact of climate change on the UK's electricity network. *Clim. Change* 115, 821–835. doi:10.1007/s10584-012-0469-6

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J.C.J.M., Bouwer, L.M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfuertscheller, C., Poussin, J., Przyluski, V., Thielen, A.H., Viavattene, C., 2013. Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps. *Nat Hazards Earth Syst Sci* 13, 1351–1373. doi:10.5194/nhess-13-1351-2013

Molarius, R., Könönen, V., Leviäkangas, P., Zulkarnain, Rönty, J., Hietajärvi, A.-M., Oiva, K., 2013. The extreme weather risk indicators (EWRI) for the European transport system. *Nat. Hazards* 72, 189–210. doi:10.1007/s11069-013-0650-x

Oven, K.J., Curtis, S.E., Reaney, S., Riva, M., Stewart, M.G., Ohlemüller, R., Dunn, C.E., Nodwell, S., Dominelli, L., Holden, R., 2012. Climate change and health and social care: Defining future hazard, vulnerability and risk for infrastructure systems supporting older people's health care in England. *Appl. Geogr., The Health Impacts of Global Climate Change: A Geographic Perspective* 33, 16–24. doi:10.1016/j.apgeog.2011.05.012

Palin, E.J., Thornton, H.E., Mathison, C.T., McCarthy, R.E., Clark, R.T., Dora, J., 2013. Future projections of temperature-related climate change impacts on the railway network of Great Britain. *Clim. Change* 120, 71–93. doi:10.1007/s10584-013-0810-8

Pejovic, T., Williams, V., Noland, R., Toumi, R., 2009. Factors Affecting the Frequency and Severity of Airport Weather Delays and the Implications of Climate Change for Future Delays. *Transp. Res. Rec. J. Transp. Res. Board* 2139, 97–106. doi:10.3141/2139-12

Piontek, F., Müller, C., Pugh, T.A.M., Clark, D.B., Deryng, D., Elliott, J., González, F. de J.C., Flörke, M., Folberth, C., Franssen, W., Frieler, K., Friend, A.D., Gosling, S.N., Hemming, D., Khabarov, N., Kim, H., Lomas, M.R., Masaki, Y., Mengel, M., Morse, A., Neumann, K., Nishina, K., Ostberg, S., Pavlick, R., Ruane, A.C., Schewe, J., Schmid, E., Stacke, T., Tang, Q., Tessler, Z.D., Tompkins, A.M., Warszawski, L., Wisser, D., Schellnhuber, H.J., 2014. Multisectoral climate impact hotspots in a warming world. *Proc. Natl. Acad. Sci.* 111, 3233–3238. doi:10.1073/pnas.1222471110.

Radovic, V., Vitale, K., Tchounwou, P.B., 2012. Health Facilities Safety in Natural Disasters: Experiences and Challenges from South East Europe. *Int. J. Environ. Res. Public Health* 9, 1677–1686. doi:10.3390/ijerph9051677

Rojas, R., Feyen, L., Watkiss, P., 2013. Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. *Global Environmental Change* 23, 1737–1751. doi:10.1016/j.gloenvcha.2013.08.006

Rübbelke, D., Vögele, S., 2011. Impacts of climate change on European critical infrastructures: The case of the power sector. *Environ. Sci. Policy* 14, 53–63. doi:10.1016/j.envsci.2010.10.007

Schweighofer, J., 2013. The impact of extreme weather and climate change on inland waterway transport. *Nat. Hazards* 72, 23–40. doi:10.1007/s11069-012-0541-6

Sieber, J., 2013. Impacts of, and adaptation options to, extreme weather events and climate change concerning thermal power plants. *Clim. Change* 121, 55–66. doi:10.1007/s10584-013-0915-0

Sir, D.Y.A.A., 2012. Potential Impacts of Climate Change on Waste Management in Ilorin city Nigeria. *Glob. J. Hum.-Soc. Sci. Res.* 12.

Spengler, J.D., Chen, Q., 2000. Indoor Air Quality Factors in Designing a Healthy Building. *Annu. Rev. Energy Environ.* 25, 567–600. doi:10.1146/annurev.energy.25.1.567

Stewart, M.G., Wang, X., Nguyen, M.N., 2011. Climate change impact and risks of concrete infrastructure deterioration. *Eng. Struct.* 33, 1326–1337. doi:10.1016/j.engstruct.2011.01.010

Suarez, P., Anderson, W., Mahal, V., Lakshmanan, T.R., 2005. Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the Boston Metro Area. *Transp. Res. Part Transp. Environ.* 10, 231–244. doi:10.1016/j.trd.2005.04.007

Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., Rippey, B., Tinker, R., Palecki, M., Stooksbury, D., Miskus, D., Stephens, S., 2002. The Drought Monitor. *Bull. Am. Meteorol. Soc.* 83, 1181–1190.

Tannahill, K., Booth, C.A., 2012. Linkages of Waste Management Strategies and Climate Change Issues, in: Booth, C.A., Hammond, F.N., Lamond, J.E., Proverbs, D.G. (Eds.), *Solutions to Climate Change Challenges in the Built Environment*. Wiley-Blackwell, pp. 207–221.

Van Vliet, M.T.H., Yearsley, J.R., Ludwig, F., Vögele, S., Lettenmaier, D.P., Kabat, P., 2012. Vulnerability of US and European electricity supply to climate change. *Nat. Clim. Change* 2, 676–681. doi:10.1038/nclimate1546.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., Schewe, J., 2014. The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework. *Proc. Natl. Acad. Sci.* 111, 3228–3232. doi:10.1073/pnas.1312330110.

Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M., Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality. *Hydrol. Sci. J.* 54, 101–123. doi:10.1623/hysj.54.1.101.

Wright, L., Chinowsky, P., Strzepek, K., Jones, R., Streeter, R., Smith, J.B., Mayotte, J.-M., Powell, A., Jantarasami, L., Perkins, W., 2012. Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitig. Adapt. Strateg. Glob. Change* 17, 939–955. doi:10.1007/s11027-011-9354-2.



## 6 Climate resilient critical infrastructures and investments

### 6.0 Key messages

#### General

- A wide range of adaptation strategies exists, ranging from hard (capital-intensive, large, complex, inflexible technology and engineering) to soft (prioritization of natural capital, community control, simplicity and appropriateness) measures.
- In view of uncertain climate change, preference for no- or low-regret measures, the inclusion of a safety margin and reversible strategies.
- Quantitative assessments for appraising costs and effectiveness are limited, comprehensive frameworks largely absent.
- There is large uncertainty about the costs and appropriateness of various measures and additional studies are needed to fill the existing gaps and explore costs and appropriateness of measures, the optimal timing of action and the sensitivity of results to assumptions and uncertainties about future extreme events and costing methods.

#### Critical infrastructures

- Indicative estimates show that for EU+ (EU28 + Switzerland, Norway and Iceland) the total accumulated benefits (or avoided damages) amount to 100 billion € when adapting critical infrastructures against short term climate changes (up to 2040), with an accumulated cost of 39 billion €. Costs incurred now could amount to 12 billion €, or 0.1% of EU+ 2010 GDP, plus a yearly operational and maintenance (O&M) cost of nearly 1 billion €. Expected annual benefits of these investments would amount to 3.3 billion €.
- The investments for adaptation required to face changes in climate also in the medium term (including the 2050s) would amount to an upfront capital cost of

54 billion €, or 0.4% of EU+ 2010 GDP, and an annual O&M cost of 2.1 billion €, with expected annual benefits growing to 11.9 billion € by the 2050s.

- For making infrastructures climate resilient up to the end of the century, the total cost rises to 461 billion €, of which 138 billion € capital cost to be incurred now (about 1% of EU+ 2010 GDP) and O&M costs of nearly 3.6 billion €/year. This would yield total accumulated benefits or avoided damages of 1,152 billion € from now up to the end of this century, with expected annual benefits reaching 23 billion € by the 2080s.
- Adaptation costs will not fall equally across Europe. Some countries in Europe will potentially have to invest a significant share of their current GDP to abate the future impacts from climate hazards on critical infrastructures – notably Greece, Croatia, Portugal and Spain.

#### EU Regional Investments

- The cost of making CPF investments resilient against climate up to 2040 may amount to 1.1% of total CPF allocations, which grows to 6.2% and 10.4% for medium to long term climate changes, respectively.
- There are considerable variations in adaptation requirements for different sectors, both in terms of overall magnitude and distribution across regions.
- The sectors with the highest relative adaptation costs are the transport, energy, and environment/tourism sectors. For these sectors, several regions in southern and south-eastern Europe, but also some in France, can face short-term adaptation costs up to 10% of the sector investments, in localized regions in the Iberian and Balkan Peninsulas even up to 25% and more.

## 6.1 Introduction

As critical infrastructures and key economic assets typically have long operational lifetimes they are subject not only to the existing climate but also to climate variations over their life span. The hazard and risk parts of this report have shown that much of the existing infrastructure and planned future investments will be increasingly put at risk by extreme climate events in many regions of Europe due to climate change. In order to mitigate impacts of climate change in the coming decades it is therefore needed to increase the resilience of both existing infrastructures and new investments to more frequent and intense climate hazards.

The need to adapt for lowering the risks posed by unavoidable climate changes has in recent years received increased attention in the scientific and policy debate (e.g., EU Strategy on Adaptation). Adaptation to climate change can be a challenging activity as it must consider the full context in which adaptation takes place. Apart from the complexity and uncertainty of the factors that define (future) climate risks and vulnerability, adaptation requires technical know-how, substantial funding, adequate institutional structures and political will that can be constrained by limited physical, financial, institutional, political, cultural, and individual capacities to deal with climate-related changes and hazards.

It is not the goal of this report to provide an extensive review of all possible adaptation options for key infrastructures in the different sectors, which are bountiful. Rather, the aim of the CCMFF project is to take stock at a minimum of the available evidence on the costs of climate proofing critical infrastructures and investments and to provide a methodology and first assessment of the additional investments needed to climate proof investments in different regions of Europe.

## 6.2 Climate hazard mitigation measures

Adaptation options vary depending on the type of hazard and infrastructure. In general, they can be grouped into nine categories as presented in Table 6.1 (Bouwer et al., 2014), although that other ways exist to classify the large variety of options.

**Table 6.1** Comprehensive Categories of climate hazard mitigation measures (from Bouwer et al., 2014).

Category	Main goal	Main approach	Examples
Risk management planning, land-use planning, and climate adaptation	Vulnerability and exposure reduction	Regulation, legislation, communication, economic instruments	Spatial planning; zoning; adaptation strategies
Hazard modification	Hazard reduction	Technical, engineering	Cloud seeding; explosives for avalanches; retention areas for floods
Infrastructure	Hazard reduction	Technical, engineering	Reservoirs; dams; dikes; slope stabilization
Mitigation measures (stricto sensu)	Vulnerability reduction	Technical, economic instruments	Water conservation programs; hazard-proof building; reforestation
Communication (in advance of events)	Vulnerability reduction	Regulation, legislation, communication,	Education of public; hazard and risk maps; information on adequate behavior; experts' training
Monitoring and early warning systems (just before events)	Hazard reduction and vulnerability reduction	Technical, engineering, communication	Hydrological and meteorological monitoring; flood forecasting; extreme weather warning
Emergency response and evacuation	Vulnerability reduction	Technical, regulation, legislation, communication	Evacuation; emergency services and aid; response and recovery operations
Financial incentives	Vulnerability reduction	Regulation, legislation, communication, economic instruments	Finance institutions; subsidies; prerequisites for insurance coverage
Risk transfer	Vulnerability reduction and quick recovery	Regulation, legislation, economic instruments	Insurance; relief funds; donations; compensation

The first category includes risk management planning, land-use planning, and climate adaptation aimed at reducing exposure and vulnerability. Land use planning and management is increasingly recognized to play a crucial role in climate risk reduction (Serrao-Neumann et al., 2015). Categories 2 (hazard modification) and 3 (infrastructure) target a reduction of the hazard with measures that are typically taken at national or regional level (e.g., flood protection measures at catchment scale). Category 4 (mitigation measures stricto sensu) comprises small-scale measures applied at the local (community, company or household) level to reduce vulnerability. Communication measures (Category 5) in advance of an event can take place at all administrative levels. This includes, for example, flood risk maps by EU member states in compliance with the EU Flood Directive (EC, 2007), but also local information campaigns. Monitoring and early warning systems (Category 6) are typically operated by a central government organization that coordinates all related activities, for instance, for a coast or river basin. Supranational systems also

exist, like the European Drought Observatory and European Flood Awareness System that have been developed at the JRC. Whereas the measures under Categories 1 to 6 can be considered pre-event risk reduction measures, emergency response and evacuation (Category 7) take place during and in the immediate aftermath of the event. Finally, financial incentives (Category 8) can be used as stimuli for pre-event risk-reducing measures, whereas risk transfer measures (Category 9) allow post-event compensation of losses (adapted from Bouwer et al., 2014).

For critical infrastructures and key economic investments in specific, several documents provide overviews of possible risk reduction options for the energy and transport sector. For the energy sector, Table 10-1 and Table 10-2 of Chapter 10 of WGIIAR5 (Arent et al., 2014) describe the range of adaptation options for energy supply, and pipelines and the electricity grid, respectively. In general, more robust design specifications will allow structures to withstand more extreme conditions. In some circumstances, it may also be necessary to consider relocating or retrofitting extremely vulnerable existing infrastructure. Furthermore, decentralized generation systems (renewables) may reduce the need for large facilities in high-risk areas. For the transport sector, overviews of adaptation challenges and options across transport modes are, for example, provided in “Adaptation of transport to climate change in Europe” (EEA, 2014) and Doll et al. (2011). Adaptation options for transport includes engineering (structural) measures (subsurface conditions, material specifications, cross section and standard dimensions, drainage and erosion, and protective engineering structures), as well as non-engineering strategies (maintenance planning and early warning, alignment, master planning and land use planning, and environmental management). For other critical infrastructures (e.g., industry and social infrastructures) information is more scarce and fragmented.

In general, especially in view of uncertain climate change, it is suggested in literature that adaptation options preferably have the following characteristics:

- No or low regret strategies that yield development benefits regardless of the nature and extent of changes in climate.
- Include a safety margin to increase the robustness.
- Should be reversible rather than irreversible.
- Take into account synergies and conflicts between different options and between adaptation and mitigation.
- Soft adaptation measures are often more flexible and better able to manage uncertainty than hard adaptation strategies.

### **6.3 Costs and effectiveness of adapting to climate change**

There are many approaches to arriving at a priority setting for alternative adaptation options. To make optimal use of limited resources for investments in climate impact mitigation, information about the cost and the appropriateness and effectiveness of a range of adaptation options is needed.

Whereas many studies have described qualitatively the wide range of potential adaptation options, the literature on the costing of these measures and their value for reducing impacts of natural hazards (to critical infrastructures) is limited and fragmented. Comprehensive frameworks for addressing costs and benefits of adaptation options are largely absent due to several reasons. Adaptation measures are very diverse and usually take place at the local level with diverse regulatory, legal and governance settings. These determine the type of measures chosen and level of investments as well as the scale at which the measures are implemented and the associated costing framework (Bouwer et al., 2014). Costs and benefits in various studies are difficult to compare as they are represented in a variety of ways. They can cover (a combination of) direct, indirect and intangible aspects, and can be presented on an annual basis or accumulated over time, discounted or undiscounted, and in absolute terms or as share of GDP. Many studies on adaptation fail to provide a quantification of the benefits, rather instead assume that certain types of impacts should be avoided. Benefits also often take place long after costs

are made and are more unpredictable as they depend on the possible occurrence of extreme events over the lifetime of the infrastructure.

### **6.3.1 Indicative costs of adapting infrastructures to climate change**

The decision on the implementation of the optimal measure in a specific setting would require a detailed analysis of the costs and efficiency of a range of measures, as well as the consideration of non-monetary and non-market consequences, and of the equity impacts of alternative actions (Chambwera et al., 2014). A number of these items pose challenges for measurement and certainly for monetization. Within the current modelling framework it is not possible to undertake a detailed multi-metric evaluation of potential adaptation measures across Europe. Hence, we do not provide a formal cost-benefit or multi-criteria analysis but instead surveyed the literature on cost and benefits of adaptation options related to infrastructures. Few studies have reported figures about benefits and costs of risk mitigation strategies across Europe, covering different regions, types of hazards, infrastructures, measures, accounting and appraisal approaches. These studies indicate that the uncertainty about the costs and benefits is large, but that many adaptation options could have high benefits when compared to costs, although capital investments can be large.

The studies reviewed (see Table 6.2) provided a range of benefit to cost ratio (BCR) between 9 and 0.4, with an average value of 2.5. These BCR values have been used herein to provide indicative estimates (order of magnitude) of the potential cost of adaptation, similar as done by Rojas et al. (2013) for appraising flood adaptation costs. Ideally, adaptation would offset the increased risk from climate change, reducing future risk levels to equal current ones. In that case, the direct benefits of adaptation (apart from potential co-benefits such as enhancing development) equal the potential avoided adverse impacts, i.e., the increase in damages from the present to the future in the case of no adaptation. However, the theory and the evidence suggest that adaptation cannot generally overcome all climate change impacts and that some adaptation may not be physically possible or economically worthwhile (Parry et al., 2009). We assume that the unavoidable or residual damages from

climate change that take place even with adaptation equal 25% of the increased risk, hence the benefits of adaptation represent 75% of the potential avoided damages. The latter are obtained as a difference in the damages to infrastructures between the future time period and the present (baseline).

To derive indicative costs of adaptation, the literature-based BCR values were combined with the projected benefits. Table 6.3 shows the indicative estimates of adaptation costs per country and for the EU+ (EU28 + Switzerland, Norway and Iceland) for the multi-hazard multi-sector analysis. Costs are provided for the three time periods and should be interpreted as follows. For the 2020s (period 2011-2040), the values reflect adaptation costs assuming that adaptation would only take into account the projected changes in hazard in the short term (up to 2040, or adapting to short term changes). Cost estimates for the 2050s (2041-2070) are based on expected annual damages from now up to 2070, hence assume that adaptation considers also medium term projected climate changes. For the last period (2080s), adaptation costs take into consideration the changes in climate hazard and consequent damages up to the end of the century. Note that all estimates reported assume no discounting and no socio-economic changes.

The total accumulated cost of adaptation (columns 2-4 of Table 6.3) reflects the total amount that should be invested in adaptation to achieve a 75% reduction in climate related risk (whereas the residual 25% is assumed as unavoidable impacts of climate change). For the EU+, the total accumulated cost for short-term climate change adaptation amounts to 39 billion €, which grows to 461 billion € when proofing infrastructures against long-term climate change. These costs will result in total accumulated benefits (or avoided damages) of 98 billion € by 2040 and 1,152 billion € by the end of this century.



**Table 6.2** Benefit to cost ratios (BCR) of adaptation measures reported in literature.

<b>Adaptation measure</b>	<b>BCR (avg and range)</b>	<b>Region</b>	<b>Reference</b>
<b>Infrastructures</b>			
Prevention of storm damage to buildings	2.7 (1.3 - 4.8)	Germany	Tröltzsch et al. (2012)
Local structural protection	1.7	Austria	Holub and Fuchs (2008)
<b>Industry</b>			
Awareness raising for companies	5.3 (1.0 - 9.7)	EU	Hjerp et al. (2012)
<b>Energy</b>			
Adaptation of electricity grids	5.1	EU26, without Malta	Hjerp et al. (2012)
High efficiency ventilation	1.8	EU26, without Malta	Hjerp et al. (2012)
<b>Transport</b>			
Improved road pavement materials and design standards	3	Germany and Austria	Doll et al. (2014)
Adapting tracks to higher temperatures	2 (0.34 - 9)	EU	Hjerp et al. (2012)
Adapting roads to higher temperatures	0.4 (0.2 - 0.9)	EU	Hjerp et al. (2012)
Adapting roads to increase in precipitation	0.5 (0.1 - 1.9)	EU	Hjerp et al. (2012)
Transport and spatial planning: general protection measures	1.3	EU	Doll et al. (2011)
Transport and spatial planning: network redesign	1.2	EU	Doll et al. (2011)
Infrastructure measures: incentives and information	2.4	EU	Doll et al. (2011)
Infrastructure measures: supervision and maintenance	1.2	EU	Doll et al. (2011)
Infrastructure measures: investments	1.5	EU	Doll et al. (2011)
Vehicle technologies: detection and communication	1.2	EU	Doll et al. (2011)
Vehicle technologies: vehicle engineering	1.9	EU	Doll et al. (2011)
Vehicle technologies: maintenance	1	EU	Doll et al. (2011)
Service operations: raising preparedness	1.4	EU	Doll et al. (2011)
Service operations: co-operation strategies	3.8	EU	Doll et al. (2011)
Service operations: system redesign	0.7	EU	Doll et al. (2011)
<b>Cross-cutting</b>			
Building dykes and beach nourishment	2.5	Germany	Tröltzsch et al. (2012)
Storm retention reservoirs	3.5 (0.5-9.4)	EU	Hjerp et al. (2012)
Action plan on Flood Defence for Rhine River	3.4	River Rhine (Germany)	Petrascheck (2003)
Flood and coastal risk management in England	7.5 (4 - 11)	UK	EA (2009)
Flood risk management plan in Belgium	4.1	Scheldt Estuary (Belgium)	Broekx et al. (2011)
Early warning for flash floods	9	Germany	EWASE (2008)
Groins	3.2 (1.6-4)	Greece	Kontogianni et al. (2014)
Beach nourishment	2.1 (0.4-3.8)	Greece	Kontogianni et al. (2014)
Revetments and geotextiles	3.7 (3.3-3.9)	Greece	Kontogianni et al. (2014)
Bulkheads	3.3 (2.4-3.9)	Greece	Kontogianni et al. (2014)

The following two scenarios are then considered:

- 1) Scenario 1: adaptation costs reflect maintenance, operation and replacement costs distributed in time (assuming capital costs are distributed equally in time). Under this scenario two different strategies are further considered: a) strategy 1: incremental adaptation goals that only take into account climate change in the next 30-year period; and b) strategy 2: long term adaptation goals taking into account long term climatic conditions; and
- 2) Scenario 2: capital costs are incurred upfront and operation and maintenance (O&M) costs are spread equally in time.

Below results of the different combinations are detailed.

#### Scenario 1 – strategy 1

Columns 5-7 present the annual costs of adaptation for the three different time windows, assuming incremental steps of adaptation (only accounting for marginal climate impacts in next 30-year period). The annual cost to adapt infrastructures against short term climate change is 1.3 billion €/year for EU+ in the period from now up to 2040. In the 2050s, 4.7 billion € would need to be invested annually in adaptation to lower risks to current levels (assuming that 25% of the projected increase in risk is unavoidable), which further rises to 9.3 billion €/year between 2071 and 2100. There is a large variation in the cost of adaptation by country. These mirror the range of damage costs detailed in Chapter 5. Thus, countries with higher estimated damages will face higher adaptation costs. Expressed as a share of GDP, annual costs for incremental steps of adaptation grow from 0.01% now up to 0.07% by the end of the century for EU+.

#### Scenario 1 – strategy 2

Column 8 shows cost estimates assuming that adaptation strategies take into account long term climate changes with costs of adaptation distributed evenly over the 90 years (long term planning). In that case, annual expenditure for adaptation

from now up to 2100 would amount to 5.1 billion €/year, or approximately 0.04% of EU+ GDP. Comparison of these results with those of strategy 1 shows that incremental steps of adaptation may result in lower investments in the short term but higher investments on the longer term, hence the bulk of the burden is placed on future generations. This strategy may only be justifiable for infrastructures with short life times, for which impacts in the long run are not relevant.

## Scenario 2

Adaptation measures often involve substantial capital expenses (Sussman et al., 2014), which under scenario 1 were considered as part of the annual costs. Under this scenario it is assumed that capital costs reflect 30% of the total adaptation cost over its lifetime and that they are incurred now, whereas O&M costs (70% remaining costs) are spread equally in time. It is important to note that depending on the adaptation measure the share of capital costs to the total cost of adaptation may be higher (hard structural measures) or lower (soft adaptation measures).

Results under this scenario (columns 13 to 20 of Table 6.3) indicate that for EU+, taking into account short term projected changes in climate, costs incurred now would equal approximately 12 billion €, or approximately 0.1% of EU+ 2010 GDP, plus a yearly O&M cost of nearly 1 billion €. Expected annual benefits of these investments would amount to 3.3 billion €. This, however, would only make infrastructures resilient to climate up to 2040. The investments for adaptation required to face changes in climate also in the medium term (including the 2050s) would amount to an upfront capital cost of 54 billion €, or 0.4% of EU+ 2010 GDP, and an annual O&M cost of 2.1 billion €. Expected annual benefits would grow to 11.9 billion € by the 2050s. For making infrastructures climate resilient up to the end of the century, the capital cost rises to 138 billion € (about 1% of EU+ 2010 GDP) and O&M cost grow to nearly 3.6 billion €/year, with expected annual benefits reaching 23 billion € by the 2080s.

While it is obvious that adaptation costs and impacts will not fall equally across Europe, this does have important implications. The analysis of indicative adaptation costs by country (if incurred now) accounting for medium to long term climate effects indicates that some countries in Europe would potentially have to invest a significant share of their current GDP to abate the future impacts from climate hazards on critical infrastructures – notably Greece, Croatia, Portugal and Spain.

It is stressed that these indicative costs are subject to many factors, such as the shape of the marginal cost curve for increasing resilience against increasing extreme hazard intensity, the balance between soft and hard options, and the balance of capital and operating and maintenance costs, among others. Nonetheless, they suggest that adaptation (i.e., enhanced resilience) could be a highly cost-effective strategy, but that costs to be incurred could be considerable for several countries in Europe.

**Table 6.3** Estimated cost of adaptation for multi-hazard multi-sector analysis. No discounting, expressed in € 2010 constant prices or share of 2010 GDP, assuming no socio-economic change in future scenarios. ®Scenario 1, strategy 1; †Scenario 1, strategy 2; ♦Scenario 2.

Country	Accumulated total cost (in million €)			Annual total cost (in million €)				Annual total cost (share GDP)				Capital cost (in million €)			Capital cost (share GDP)			Annual O&M cost (in million €)	
	2020	2050	2080	2020®	2050®	2080®	2080†	2020®	2050®	2080®	2080†	2020♦	2050♦	2080♦	2020♦	2050♦	2080♦	2020♦	2080♦
AT	260	1,462	4,644	8.7	40	106	52	0.003	0.014	0.036	0.018	78	439	1,393	0.03	0.15	0.47	6.1	36
BE	7	610	1,962	0.2	20	45	22	0.000	0.005	0.012	0.006	2	183	589	0.00	0.05	0.16	0.2	15
BG	223	646	1,838	7.4	14	40	20	0.020	0.038	0.108	0.056	67	194	551	0.18	0.53	1.50	5.2	14
CH	543	3,683	9,634	18	105	198	107	0.004	0.024	0.045	0.024	163	1,105	2,890	0.04	0.25	0.66	13	75
CY	1	43	110	0.0	1.4	2.2	1.2	0.000	0.007	0.012	0.006	0	13	33	0.00	0.07	0.17	0.0	0.9
CZ	26	92	450	0.9	2.2	12	5.0	0.001	0.001	0.008	0.003	8	28	135	0.00	0.02	0.09	0.6	3.5
DE	1,839	11,374	29,518	61	318	605	328	0.002	0.012	0.023	0.013	552	3,412	8,856	0.02	0.13	0.34	43	230
DK	249	1,201	2,912	8.3	32	57	32	0.003	0.013	0.024	0.013	75	360	874	0.03	0.15	0.36	5.8	23
EE	40	245	517	1.3	6.8	9.1	5.7	0.009	0.046	0.062	0.039	12	73	155	0.08	0.50	1.05	0.9	4.0
ES	11,605	51,749	132,710	387	1,338	2,699	1,475	0.036	0.124	0.250	0.136	3,482	15,525	39,813	0.32	1.44	3.68	271	1,032
FI	127	587	1,453	4.2	15	29	16	0.002	0.008	0.015	0.009	38	176	436	0.02	0.09	0.23	3.0	11
FR	5,304	24,901	63,325	177	653	1,281	704	0.009	0.033	0.064	0.035	1,591	7,470	18,997	0.08	0.37	0.95	124	493
GR	1,095	11,067	24,483	36	332	447	272	0.016	0.147	0.198	0.120	328	3,320	7,345	0.15	1.47	3.25	26	190
HR	182	1,331	5,065	6	38	124	56	0.015	0.085	0.277	0.125	55	399	1,519	0.12	0.89	3.38	4	39
HU	0	472	1,395	0	17	31	16	0.000	0.017	0.031	0.016	0	142	419	0.00	0.14	0.43	0	11
IE	26	313	633	0.9	10	11	7.0	0.001	0.006	0.006	0.004	8	94	190	0.00	0.06	0.12	0.6	4.9
IS	0	38	98	0.0	1.3	2.0	1.1	0.000	0.013	0.020	0.011	0	11	29	0.00	0.11	0.29	0.0	0.8
IT	13,335	49,296	115,411	445	1,199	2,204	1,282	0.028	0.075	0.137	0.080	4,001	14,789	34,623	0.25	0.92	2.16	311	898
LT	89	350	655	3.0	8.7	10	7.3	0.011	0.031	0.036	0.026	27	105	196	0.10	0.38	0.70	2.1	5.1
LU	3	38	144	0.1	1.2	3.5	1.6	0.000	0.003	0.009	0.004	1	11	43	0.00	0.03	0.11	0.1	1.1
LV	72	318	569	2.4	8.2	8.4	6.3	0.013	0.046	0.047	0.035	22	95	171	0.12	0.53	0.95	1.7	4.4
MT	67	138	219	2.2	2.4	2.7	2.4	0.034	0.036	0.041	0.037	20	42	66	0.30	0.63	0.99	1.6	1.7
NL	34	644	1,570	1.1	20	31	17	0.000	0.003	0.005	0.003	10	193	471	0.00	0.03	0.07	0.8	12
NO	35	433	1,150	1.2	13	24	13	0.000	0.004	0.007	0.004	10	130	345	0.00	0.04	0.11	0.8	8.9
PL	43	203	453	1.4	5.3	8.3	5.0	0.000	0.001	0.002	0.001	13	61	136	0.00	0.02	0.04	1.0	3.5
PT	2,072	8,997	20,998	69	231	400	233	0.038	0.128	0.222	0.130	622	2,699	6,299	0.35	1.50	3.50	48	163
RO	847	2,323	6,629	28	49	144	74	0.022	0.039	0.113	0.058	254	697	1,989	0.20	0.55	1.57	20	52
SE	122	1,136	2,551	4.1	34	47	28	0.001	0.009	0.013	0.008	37	341	765	0.01	0.09	0.21	2.9	20
SI	106	543	2,217	4	15	56	25	0.010	0.040	0.154	0.068	32	133	665	0.09	0.45	1.84	2	17
SK	14	522	1,988	0.5	17	49	22	0.001	0.025	0.073	0.033	4	157	596	0.01	0.23	0.89	0.3	15
UK	214	2,232	7,158	7.1	67	164	80	0.000	0.004	0.009	0.004	64	670	2,147	0.00	0.04	0.12	5.0	56
<b>EU+</b>	<b>39,297</b>	<b>181,789</b>	<b>461,166</b>	<b>1,310</b>	<b>4,750</b>	<b>9,313</b>	<b>5,124</b>	<b>0.010</b>	<b>0.035</b>	<b>0.069</b>	<b>0.038</b>	<b>11,789</b>	<b>54,537</b>	<b>138,350</b>	<b>0.09</b>	<b>0.40</b>	<b>1.02</b>	<b>917</b>	<b>3,587</b>

### **6.3.2 Climate proofing EU investments**

The above shows that the implementation of adaptation measures, whether it be physical adjustments to infrastructures and buildings, or organizational, institutional and other soft response actions, may require substantial resources (Bouwer and Aerts 2006), especially in regions that will be most affected by climate change. The Cohesion Policy Funds (CPF) are a key financing instrument of the EU, distributing about a third (347 billion € for the period 2007-2013) of the EU budget across regions, based on economic and social indicators, with the aim to stimulate development especially in less prosperous regions in order to achieve economic and social cohesion. Even though that adaptation only became a serious policy concern for the EU after the definition of the thematic priorities of the CPF 2007-2013, some of the thematic priorities can be linked with adaptation. Especially since funding is available not only for hard infrastructures but also for human capital, institution and capacity building as well as technological development, which may be tailored towards increasing the adaptive capacity of regions.

We build on the work of Hanger et al. (2013) to appraise the amount of funding under CPF 2007-2013 that can be considered relevant to supporting adaptation-related aims. From the 86 thematic priorities, adaptation-related expenditure is assigned based on the Rio marker methodology developed by the Organization for Economic Cooperation and Development (OECD) for reporting climate-related development assistance (OECD, 2011). This method distinguishes between three categories of priority themes: the first category (climate change as principal objective) is weighted 100%, the second (climate change as significant objective) at 40% and the third (climate change not an objective) are assigned no weight. For priority themes of the first two categories that are also related to climate mitigation an equal share is assigned to mitigation and adaptation. Table 6.4 shows the priority themes that were retained in this analysis, with an indication of their relevance for climate change mitigation and/or adaptation. The sum of these contributions represents the climate adaptation potential of the EU CPF 2007-2013 investments (CPF-A).

**Table 6.4** CPF priority themes marked according to OECD ‘Rio marker’ system as ‘climate change as principal objective’ (100 %) or ‘climate change as significant objective’ (40 %); together with a classification into adaptation relevant (A), mitigation relevant (M), or mitigation and adaptation relevant (M&A), and the share of total CPF funding (in percentage of total “Structural and Cohesion Funds, SCF”) – from Hanger et al. (2013).

Code <sup>a</sup>	Priority theme description	100 %	40 %	% of total SCF
06	Assistance to SMEs for [...] environmentally-friendly products ...		M&A	0.73
16	Railways		M	1.20
17	Railways (TEN-T)		M	5.38
18	Mobile rail assets		M	0.16
19	Mobile rail assets (TEN-T)		M	0.20
24	Cycle tracks		M	0.18
25	Urban transport		M	0.52
28	Intelligent transport systems		M	0.32
39	Renewable energy: wind	M		0.23
40	Renewable energy: solar	M		0.31
41	Renewable energy: biomass	M		0.52
42	Renewable energy: hydroelectric, geothermal and other	M		0.33
43	Energy efficiency, co-generation and energy management	M		1.22
47	Air quality		M	0.30
48	Integrated prevention and pollution control		M	0.21
49	Mitigation and adaptation to climate change	M&A		0.09
51	Promotion of biodiversity and nature protection		M&A	0.79
52	Promotion of clean urban transport		M	1.79
53	Risk prevention		A	1.69
55	Promotion of natural assets		M&A	0.33
56	Protection and development of natural heritage		M&A	0.42
76	Health infrastructure		A	1.51
78	Housing infrastructure		M&A	0.23

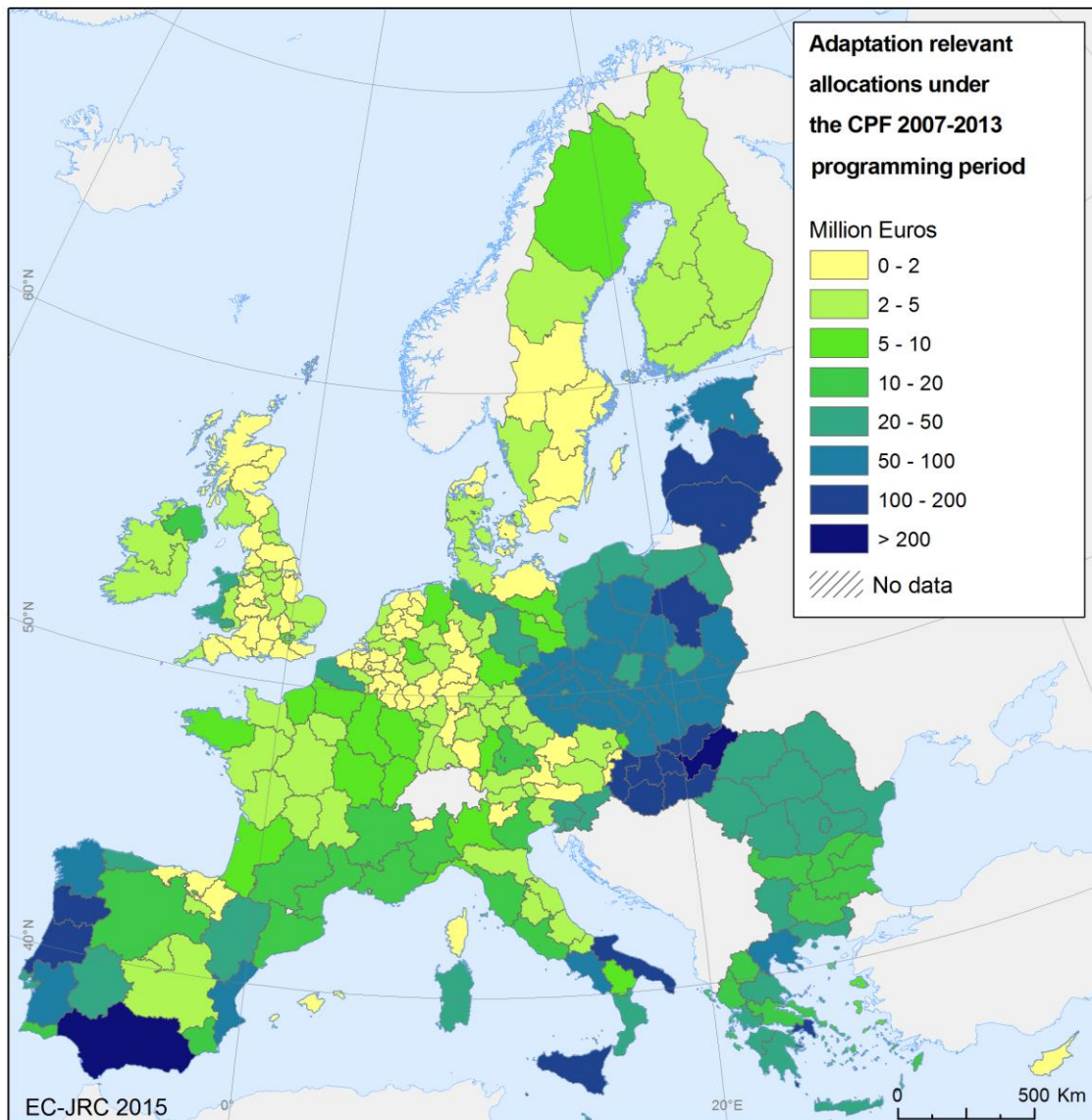
100 % = climate change as principal objective, 40 % = climate change as significant objective

*M* mitigation related, *A* adaptation related, *M&A* both mitigation and adaptation related

<sup>a</sup> According to Commission Regulation 1828/2006

The spatial distribution of CPF-A is presented in Figure 6.1. It shows highest adaptation-related allocations in regions of Spain, Portugal, Italy, Hungary, Poland and the Baltic States. Similar as for the distribution of CPF investments at risk (Figure 5.9) this pattern is largely driven by the total amount of allocations, as adaptation was not high on the agenda when the distribution amongst priority themes were agreed. Aggregated over EU27 CPF-A amounts to 6.2 billion €, or approximately 1.8% of the total allocations for 2007-2013. It should be noted that the EU allocations are indicative, proposed by the Member States and approved by the European Commission, hence may differ from actual spending. Ultimately the effectiveness of spending under each thematic priority can only be evaluated at the project level, for which no comprehensive data exist at the European level. Furthermore, the amounts earmarked for adaptation under the CPF 2007-2013 refer largely to environmental measures, which may not necessarily be effective in reducing the impacts to all the investments at risk.





**Figure 6.1** Adaptation relevant allocations (CPF-A, in million €) under the Cohesion policy during the 2007-2013 programming period (based on Hanger et al., 2013).

Specific investment allocation data for the on-going programming period (2014-2020) were not available during the writing of this report. However, in recent years the EU has made strong efforts for augmenting the profile of climate change in their budget and policies. This is expressed by the following recent actions.

- The European Council has set as political objective to earmark at least 20% of the entire EU budget for climate-relevant actions in the period 2014-2020<sup>14</sup>.

<sup>14</sup> Conclusions of the European Council (7/8 February 2013) as regards the Multiannual Financial Framework.

- The current programming period is the first in which climate considerations have been included. Major projects funded by ESIF will need to be screened against climate-related vulnerabilities during the preparation and implementation phase and necessary adaptation measures need to be reported<sup>15</sup>.
- For European and Structural Investment Funds (ESIF) there is now the specific requirement that adaptation to climate change is part of the horizontal principle of sustainable development<sup>16</sup>.
- One of the 11 thematic objectives under the new ESIF interventions includes specific measures for adaptation (Thematic Objective 5 – Promoting climate change adaptation, risk prevention and management)<sup>17</sup>.

To optimally allot funds for adaptation across the EU it is important to understand the regional distribution of impacts and adaptation costs, such that higher adaptation efforts can be targeted towards the most impacted regions. To provide an indication of expenditures required for climate proofing CPF investments across the EU27, we map in Figure 6.2 adaptation costs expressed as a share of the total 2007-2013 CPF allocations. These adaptation costs relate to the risks to EU investments and not to the total stock of infrastructure. The adaptation costs have been derived as follows. The difference in multi-hazard damages (EAD) between the baseline and 2020s have been accumulated over a 30-year period. This reflects the total increased climate risk over the next 30 years compared to the baseline. Hence, it is assumed here that the life span of the investment is limited to 30 years, and therefore only climate changes in the short term are accounted for. This means that for investments and infrastructures with longer life spans the risks may be underestimated. Similar as in the analysis for critical infrastructures, we further assume that with adaptation we can avoid 75% of the increase in risk (= benefits of adaptation) and apply a benefit-to-cost ratio (BCR) of 2.5 to get indicative numbers

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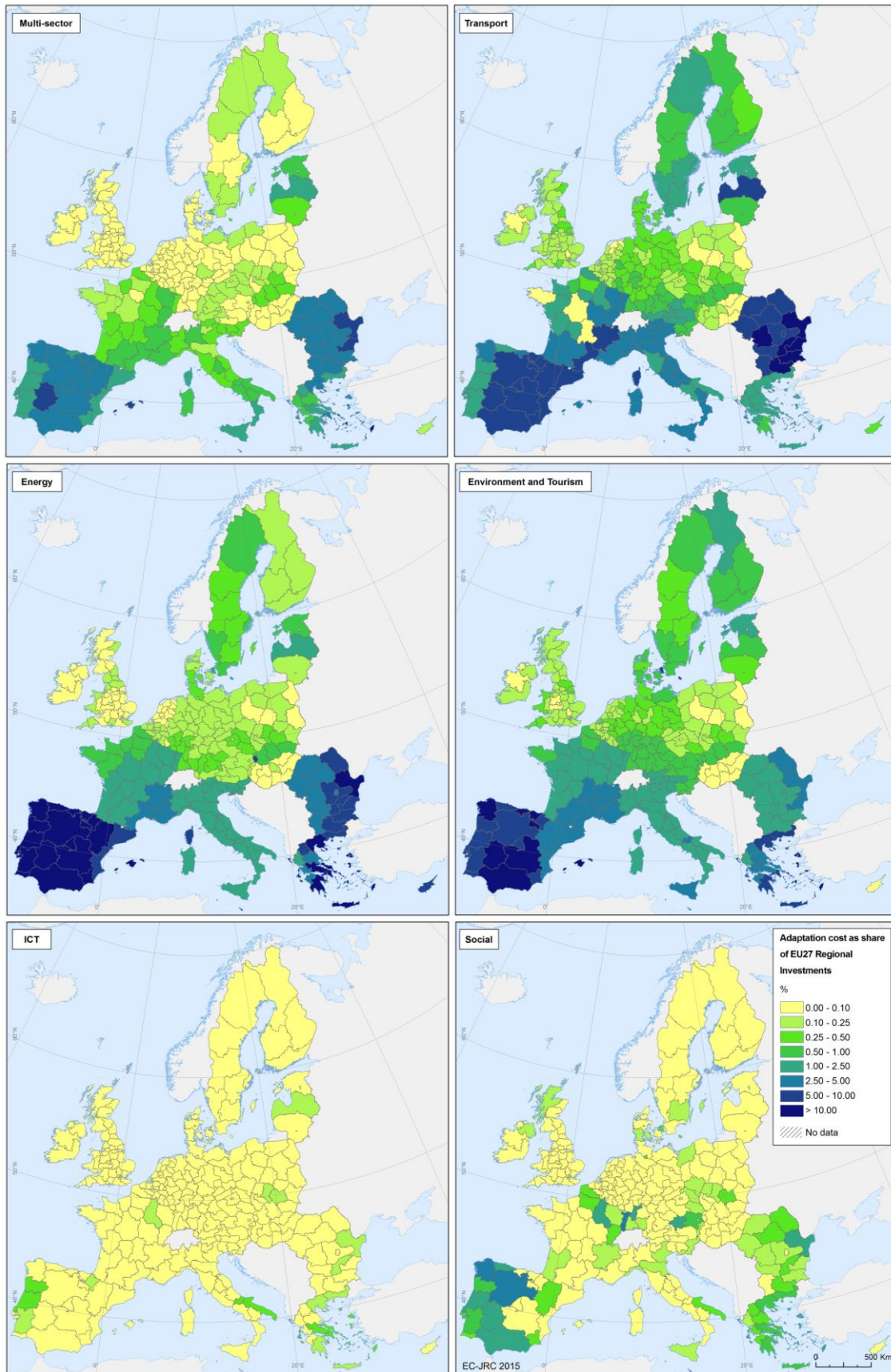
<sup>15</sup> Article 101 of Regulation (EU) No 1303/2013 of the European Parliament and of the Council of 17 December 2013; Commission Implementing Regulation (EU) 2015/207 – Annex II, Section F.8.

<sup>16</sup> Article 8 of Regulation (EU) No 1303/2013 of the European Parliament and of the Council of 17 December 2013.

<sup>17</sup> Article 9 of Regulation (EU) No 1303/2013 of the European Parliament and of the Council of 17 December 2013.

of the adaptation costs. In Figure 6.2 the latter are scaled by the total CPF allocations under the 2007-2013 programming period.

For EU27 the cost of proofing CPF investments against climate up to 2040 amounts to 1.1% of total CPF allocations. This implies that the total adaptation relevant allocations under the 2007-2013 programming period as derived by the method of Hanger et al. (2013) should be sufficient to cover adaptation costs to face short term climate changes. When climate change in the medium term (including the 2050s, results not shown here) is also accounted for, however, total costs for EU27 rise to 6.2%, whereas proofing investments against climate in the 2080s would require 10.4% of total allocations. The maps in Figure 6.2 show that there is a large heterogeneity across the EU in adaptation costs, which follow the distribution of risks to CPF investments as described in Chapter 5. For regions in the south and southeast the costs of climate proofing all investments against short term climate change can reach 5% of total allocations (Figure 6.2a). There also exists considerable variation in adaptation requirements for different sectors, both in terms of overall magnitude and distribution across regions. The sectors with the highest relative adaptation costs are the transport, energy, and environment/tourism sectors, with EU27 aggregated costs for short-term climate change adaptation between 2 and 3% of sector investments (for longer term climate change adaptation cost could rise to 20-30% of sector investments). For these sectors, several regions in southern and south-eastern Europe, but also some in France, can face short-term adaptation costs up to 10% of the sector investments, in localized regions in the Iberian and Balkan Peninsulas event up to 25% and more. The ranking of the three most impacted sectors in terms of adaptation requirements can be different for each region, depending on the amount of sector allocations, the prevalence of climate hazards and the sensitivity of the investment to the hazards. The costs for climate proofing are considerably lower for the ICT and social sectors, amounting for the EU27 to 0.05% and 0.28%, respectively, of sector investments when only considering short-term climate change. For the social sector, however, we see that locally in Spain but also in France short-term adaptation costs could reach nearly 5% of sector investments.



**Figure 6.2** Adaptation costs as share of CPF investments: (a) multi-sector, (b) transport, (c) energy, (d) environment and tourism, (e) ICT, and (f) social sector. Estimated adaptation costs only take into account short term climate changes.

We stress that the reported adaptation costs can be subject to large uncertainty. However, while these estimates are only indicative, they do highlight some important issues. The distribution in space and amongst sectors provides an indication of the regions and sectors that may face substantial efforts for climate proofing EU investments. The disproportionate distribution of economic costs – both adaptation and impacts – suggests that a better understanding of the regional and thematic distribution of costs could aid in targeting further EU investments such that cohesion policy also gains meaning as a burden sharing instrument for adaptation to climate change.



## 6.4 References

Arent, D.J., R.S.J. Tol, E. Faust, J.P. Hella, S. Kumar, K.M. Strzepek, F.L. Tóth, and D. Yan, 2014. Key economic sectors and services. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-708.

Bouwer L., Aerts J., 2006. Financing climate change adaptation. *Disasters* 30(1):49–63.

Bouwer, L.M., Papyrakis, E., Poussin, J., Pfuertscheller, C., Thielen, A.H., 2014. The costing of measures for natural hazard mitigation in Europe. *Natural Hazards Review*, 15 (4), art. no. 04014010.

Broekx, S., Smets, S., Liekens, I., Bulckaen, D., de Nocker, L., 2011. Designing a long-term flood risk management plan for the Scheldt estuary using a risk-based approach. *Natural Hazards*, 57(2), 245-266.

Chambwera, M., G. Heal, C. Dubeux, S. Hallegatte, L. Leclerc, A. Markandya, B.A. McCarl, R. Mechler, and J.E. Neumann, 2014. Economics of adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 945-977.

Doll, C., Klug S., Partzsch I., Enei R., Pelikan V., Sedlacek N., Maurer H., Rudzikaite L., Papanikolaou A., Mitsakis V., 2011. Adaptation strategies in the transport sector. FP7 project WEATHER Deliverable 4 ([www.weather-project.eu](http://www.weather-project.eu)).

Doll, C., Trinks C., Sedlacek N., Pelikan V., Comes T., Schultmann F., 2014. Adapting rail and road networks to weather extremes: Case studies for southern Germany and Austria. *Natural Hazards*, 72 (1), 63-85.

EA, 2009. Investing for the future: Flood and coastal risk management in England - A long-term investment strategy. UK Environment Agency. <http://publications.environment-agency.gov.uk/pdf/GEH00609BQDF-E-E.pdf>.

EWASE, 2008. CRUE Research report No. I-5: Effectiveness and Efficiency of Early Warning Systems For Flash Floods (EWASE). First CRUE ERA-Net Common Call Effectiveness and Efficiency of Non-structural Flood Risk Management Measures.

EEA, 2014. Adaptation of transport to climate change in Europe. EEA Report No 8/2014 ([www.eea.europa.eu/publications/adaptation-of-transport-to-climate](http://www.eea.europa.eu/publications/adaptation-of-transport-to-climate)).

EC, 2007. Directive 2007/60/EC of the European Parliament and of the Council. Technical Report. European Commission. Published in the Official Journal of the European Union, L 288/27, 6 November 2007, 8 pp. URL: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32007L0060:EN:NOT>.

European Council, 2006. Regulation (EC) No 1083/2006 laying down general provisions on the European Regional Development Fund, the European Social Fund and the Cohesion Fund and repealing Regulation (EC) No 1260/1999.

Hanger S., Haug C., Lung T., Bouwer L.M., 2013. Mainstreaming climate change in regional development policy in Europe: five insights from the 2007-2013 programming period. *Regional Environmental Change*, 15(6), 973-985.

Hjerp, P., Volkery A., Lückge H., Medhurst J., Hart K., Medarova-Bergstrom K., Tröltzsch J., McGuinn J., Skinner I., Desbarats J., Slater C., Bartel A., Frelid-Larsen A., ten Brink P., 2012. Methodologies for Climate Proofing Investments and Measures under Cohesion and Regional Policy and the Common Agricultural Policy, A report for DG Climate.

Holub M. and Fuchs S., 2008. Benefits of local structural protection to mitigate torrent-related hazards. In: Brebbia CA, Beritatos E, editors. *Risk Analysis VI, WIT Transactions on Information and Communication Technologies*, vol. 39. Southampton, U.K.: WIT Press, p. 401-411.

Kontogianni, A., Kontogianna C.H., Tourkoliasb D., Damigosc Skourtos M., 2014. Assessing sea level rise costs and adaptation benefits under uncertainty in Greece. *Environmental Science & Policy*, 37, 61-78.

OECD, 2011. Handbook on the OECD DAC climate markers. Paris

Parry M., Lowe J., Hanson C., 2009. Overshoot, adapt and recover. *Nature* 458, 1102-1103, <http://dx.doi.org/10.1038/4581102a>.

Petrascheck, A., 2003. The "Action plan on Flood Defence" of the International Commission for the Protection of the Rhine as an example for European Cooperation. Presentation at "Flood Prevention - an international exchange of experiences" Workshop, Bonn 5-6 Feb. 2003. <http://www.ecologic-events.de/floods2003/de/documents/ArminPetrascheck.PDF>.

Rojas, R., Feyen, L., Watkiss, P., 2013. Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. *Global Environmental Change* 23, 1737-1751. doi:10.1016/j.gloenvcha.2013.08.006

Serrao-Neumann, S., Crick, F., Harman, B., Schuch, G., Choy, D.L., 2015. Maximising synergies between disaster risk reduction and climate change adaptation: Potential enablers for improved planning outcomes. *Environmental Science and Policy*, 50, 46-61.

Sussman F., Krishnan N., Maher K., Miller R., Mack C., Stewart P., Shouse K., Perkins B., 2014. Climate change adaptation cost in the US: what do we know?, *Climate Policy*, 14:2, 242-282, DOI: 10.1080/14693062.2013.777604.

Tröltzsch J., Görlach B., Lückge H., Peter M., Sartorius C., 2012. Kosten und Nutzen von Anpassungsmaßnahmen an den Klimawandel. Analyse von 28 Anpassungsmaßnahmen in Deutschland. Dessau-Roßlau, Germany.



## Annex I Structure of CPF and CI risk maps

Maps representing (current and future) impacts of individual hazards on EU investments and critical economic assets are organized with the following tree structure

- CPF map collection
  - Single hazard maps
    - 1. Hazard 1
      - 1. Sector 1
        - 1. Time step 1
        - ⋮
        - 4. Time step 4
      - 2. Sector 2
      - ⋮
      - 6. Sector 6
    - 2. Hazard 2
    - ⋮
    - 7. Hazard 7
- Multi-hazard maps
  - 8. Multi-hazard
    - 1. Sector 1
      - 1. Time step 1
      - ⋮
      - 2. Time step 4
    - 2. Sector 2
    - ⋮
    - 6. Sector 6

➤ **Namefile**

➤ **Namefile**

**Figure Annex.3** CPF folder structure

- CI map collection
    - Single hazard maps
      - 1. Hazard 1
        - 1. Sector 1
          - 1. Time step 1
          - ⋮
          - 5. Time step 4
        - 2. Sector 2
        - ⋮
        - 5. Sector 5
      - 2. Hazard 2
      - ⋮
      - 7. Hazard 7
- **Namefile**
- Multi-hazard maps
  - 8. Multi-hazard
    - 1. Sector 1
      - 1. Time step 1
      - ⋮
      - 2. Time step 4
    - 2. Sector 2
    - ⋮
    - 6. Sector 6

➤ **Namefile**

**Figure Annex.4** CI folder structure

The CPF folder refers to Cohesion Fund investments (2007-2013) at risk, with damages expressed in Euro per NUTS2 region. A collection of maps have been produced for each single hazard as well as for the aggregation of all the hazards. The CPF single hazard folder contains maps that show the CPF themes at risk for each hazard and time slice. Maps are in different folders per hazard and for each sector (See Figure Annex.1)

The nomenclature of the files is as follows:

Namefile = Hazard number + Sector number + Time step number + "CPF" + Time step name + Hazard abbreviation + Sector abbreviation

- Hazard number/name = "1" for Cold wave, "2" for Drought, "3" for Wildfire, "4" for River floods, "5" for Heatwave, "6" for Coastal Flood and "7" for Windstorm.
- Sector number/name = "1" for Energy, "2" for Environment and Tourism, "3" for Information, Communication and Technology, "4" for Social, "5" for Transport, and "6" for Total.
- Time step number/name = "1" for ts1 (1981-2010, except Windstorm hazard that has used 1961-1990 as baseline), "2" for ts2 (2011-2040), "3" for ts3 (2041-2070) and "4" for ts4 (2071-2100)
- Hazard abbreviation = "C" for Cold wave, "D" for Drought, "F" for Wildfire, "RF" for River floods, "H" for Heatwave, "CF" for Coastal Flood and "W" for Windstorm.
- Sector abbreviation = "ENER" for Energy, "ENV\_TOUR" for Environment and Tourism, "ICT" for Information, Communication and Technology, "SOCIAL" for Social, "TRANS" for Transport, and "TOTAL" for the aggregation of all the sectors.

For instance, the namefile: "1.1.1 CPF\_ts1\_C\_ENER" corresponds to the single map of annual damages in EUR of CPF Energy allocations to Cold waves in the time step 1981-2010.

The CPF multi-hazard folder contains maps that show CPF themes at risk for the sum of all the hazards for each time slice. Maps are stored in different folders for each hazard.

The nomenclature of the files is as follows:

Namefile = Hazard number + Sector number + Time step number + “CPF” + Time step name + Hazard abbreviation + Sector abbreviation

- Hazard number/name = “8” for Multi-hazard
- Hazard abbreviation = “M” for Multi-hazard

For instance, the namefile = 7.2.4 CPF\_ts1\_M\_ENV\_TOUR corresponds to the multi-hazard map of annual damages in EUR of CPF Environment and Tourism to Multi-hazard in the time step 2071-2100.

The CI folder refers to the Critical Infrastructures (or Critical Economic Assets – CEA) under risk, with damages expressed in Euro per NUTS2 region. A set of maps have been created for each single hazard and the aggregation of all the hazards.

The CI single hazard folder contains maps that show the CI at risk for each hazard and time slice. Maps are stored in different folders for each hazard first and secondly for each sector (See Figure Annex.2)

The nomenclature of the files is as follows:

Namefile = Hazard number + Sector number + Time step number + “CEA” + Time step name + Hazard abbreviation + Sector abbreviation

- Hazard number/name = “1” for Cold wave, “2” for Drought, “3” for Wildfire, “4” for River floods, “5” for Heatwave, “6” for Coastal Flood and “7” for Windstorm.
- Sector number/name = “1” for Energy, “2” for Industrial, “3” for Social, “4” for Transport, and “5” for Total.

- Time step number/name = “1” for ts1 (1981-2010, except Windstorm hazard that takes 1961-1990), “2” for ts2 (2011-2040), “3” for ts3 (2041-2070) and “4” for ts4 (2071-2100)
- Hazard abbreviation = “C” for Cold wave, “D” for Drought, “F” for Wildfire, “RF” for River floods, “H” for Heatwave, “CF” for Coastal Flood and “W” for Windstorm.
- Sector abbreviation = “ENER” for Energy sector, “INDUSTRIAL” for Industrial facilities, “SOCIAL” for Social facilities, “TRANS” for Transport infrastructures, and “TOTAL” for the sum of all the sectors.

For instance, the namefile “1.2.1 CEA\_ts1\_C\_INDUSTRIAL” corresponds to the single map of annual damages in EUR of CEA Industrial allocations to Cold waves hazard from 1981 to 2010.

The CI multi-hazard folder contains maps that show CI at risk for the sum of all the hazards for each time slice. Maps are stored in different folders for each hazard.

The nomenclature of the files is as follows:

Namefile = Hazard number + Sector number + Time step number + “CEA” + Time step name + Hazard abbreviation + Sector abbreviation

Hazard number/name = “8” for Multi-hazard

Hazard abbreviation = “M” for Multi-hazard.

For instance, the namefile = 8.5.4 CEA\_ts4\_M\_TOTAL corresponds to the multi-hazard map of annual damages in EUR of CEA Total investments to Multi-hazard in the time step running from 2071 to 2100.

## Annex II CPF and CI risk maps

### 1A: CPF single hazard maps

Namefile	Caption
1.1.1.CPF_ts1_C_ENER	1.1.1 Annual Damages in Euros to CPF Energy allocations from Cold wave hazard in 1981-2010
1.1.2.CPF_ts2_C_ENER	1.1.2 Annual Damages in Euros to CPF Energy allocations from Cold wave hazard in 2011-2040
1.1.3.CPF_ts3_C_ENER	1.1.3 Annual Damages in Euros to CPF Energy allocations from Cold wave hazard in 2041-2070
1.1.4.CPF_ts4_C_ENER	1.1.4 Annual Damages in Euros to CPF Energy allocations from Cold wave hazard in 2071-2100
1.2.1.CPF_ts1_C_ENV_TOUR	1.2.1 Annual Damages in Euros to CPF Environment and Tourism allocations from Cold wave hazard in 1981-2010
1.2.2.CPF_ts2_C_ENV_TOUR	1.2.2 Annual Damages in Euros to CPF Environment and Tourism allocations from Cold wave hazard in 2011-2040
1.2.3.CPF_ts3_C_ENV_TOUR	1.2.3 Annual Damages in Euros to CPF Environment and Tourism allocations from Cold wave hazard in 2041-2070
1.2.4.CPF_ts4_C_ENV_TOUR	1.2.4 Annual Damages in Euros to CPF Environment and Tourism allocations from Cold wave hazard in 2071-2100
1.3.1.CPF_ts1_C_ICT	1.3.1 Annual Damages in Euros to CPF I.C.T. allocations from Cold wave hazard in 1981-2010
1.3.2.CPF_ts2_C_ICT	1.3.2 Annual Damages in Euros to CPF I.C.T. allocations from Cold wave hazard in 2011-2040
1.3.3.CPF_ts3_C_ICT	1.3.3 Annual Damages in Euros to CPF I.C.T. allocations from Cold wave hazard in 2041-2070
1.3.4.CPF_ts4_C_ICT	1.3.4 Annual Damages in Euros to CPF I.C.T. allocations from Cold wave hazard in 2071-2100
1.4.1.CPF_ts1_C_SOCIAL	1.4.1 Annual Damages in Euros to CPF Social allocations from Cold wave hazard in 1981-2010
1.4.2.CPF_ts2_C_SOCIAL	1.4.2 Annual Damages in Euros to CPF Social allocations from Cold wave hazard in 2011-2040
1.4.3.CPF_ts3_C_SOCIAL	1.4.3 Annual Damages in Euros to CPF Social allocations from Cold wave hazard in 2041-2070
1.4.4.CPF_ts4_C_SOCIAL	1.4.4 Annual Damages in Euros to CPF Social allocations from Cold wave hazard in 2071-2100
1.5.1.CPF_ts1_C_TRANS	1.5.1 Annual Damages in Euros to CPF Transport allocations from Cold wave hazard in 1981-2010
1.5.2.CPF_ts2_C_TRANS	1.5.2 Annual Damages in Euros to CPF Transport allocations from Cold wave hazard in 2011-2040
1.5.3.CPF_ts3_C_TRANS	1.5.3 Annual Damages in Euros to CPF Transport allocations from Cold wave hazard in 2041-2070
1.5.4.CPF_ts4_C_TRANS	1.5.4 Annual Damages in Euros to CPF Transport allocations from Cold wave hazard in 2071-2100
1.6.1.CPF_ts1_C_TOTAL	1.6.1 Annual Damages in Euros to CPF Total allocations from Cold wave hazard in 1981-2010
1.6.2.CPF_ts2_C_TOTAL	1.6.2 Annual Damages in Euros to CPF Total allocations from Cold wave hazard in 2011-2040

1.6.3.CPF_ts3_C_TOTAL	1.6.3 Annual Damages in Euros to CPF Total allocations from Cold wave hazard in 2041-2070
1.6.4.CPF_ts4_C_TOTAL	1.6.4 Annual Damages in Euros to CPF Total allocations from Cold wave hazard in 2071-2100
2.1.1.CPF_ts1_D_ENER	2.1.1 Annual Damages in Euros to CPF Energy allocations from Drought hazard in 1981-2010
2.1.2.CPF_ts2_D_ENER	2.1.2 Annual Damages in Euros to CPF Energy allocations from Drought hazard in 2011-2040
2.1.3.CPF_ts3_D_ENER	2.1.3 Annual Damages in Euros to CPF Energy allocations from Drought hazard in 2041-2070
2.1.4.CPF_ts4_D_ENER	2.1.4 Annual Damages in Euros to CPF Energy allocations from Drought hazard in 2071-2100
2.2.1.CPF_ts1_D_ENV_TOUR	2.2.1 Annual Damages in Euros to CPF Environment and Tourism allocations from Drought hazard in 1981-2010
2.2.2.CPF_ts2_D_ENV_TOUR	2.2.2 Annual Damages in Euros to CPF Environment and Tourism allocations from Drought hazard in 2011-2040
2.2.3.CPF_ts3_D_ENV_TOUR	2.2.3 Annual Damages in Euros to CPF Environment and Tourism allocations from Drought hazard in 2041-2070
2.2.4.CPF_ts4_D_ENV_TOUR	2.2.4 Annual Damages in Euros to CPF Environment and Tourism allocations from Drought hazard in 2071-2100
2.3.1.CPF_ts1_D_ICT	2.3.1 Annual Damages in Euros to CPF I.C.T. allocations from Drought hazard in 1981-2010
2.3.2.CPF_ts2_D_ICT	2.3.2 Annual Damages in Euros to CPF I.C.T. allocations from Drought hazard in 2011-2040
2.3.3.CPF_ts3_D_ICT	2.3.3 Annual Damages in Euros to CPF I.C.T. allocations from Drought hazard in 2041-2070
2.3.4.CPF_ts4_D_ICT	2.3.4 Annual Damages in Euros to CPF I.C.T. allocations from Drought hazard in 2071-2100
2.4.1.CPF_ts1_D_SOCIAL	2.4.1 Annual Damages in Euros to CPF Social allocations from Drought hazard in 1981-2010
2.4.2.CPF_ts2_D_SOCIAL	2.4.2 Annual Damages in Euros to CPF Social allocations from Drought hazard in 2011-2040
2.4.3.CPF_ts3_D_SOCIAL	2.4.3 Annual Damages in Euros to CPF Social allocations from Drought hazard in 2041-2070
2.4.4.CPF_ts4_D_SOCIAL	2.4.4 Annual Damages in Euros to CPF Social allocations from Drought hazard in 2071-2100
2.5.1.CPF_ts1_D_TRANS	2.5.1 Annual Damages in Euros to CPF Transport allocations from Drought hazard in 1981-2010
2.5.2.CPF_ts2_D_TRANS	2.5.2 Annual Damages in Euros to CPF Transport allocations from Drought hazard in 2011-2040
2.5.3.CPF_ts3_D_TRANS	2.5.3 Annual Damages in Euros to CPF Transport allocations from Drought hazard in 2041-2070
2.5.4.CPF_ts4_D_TRANS	2.5.4 Annual Damages in Euros to CPF Transport allocations from Drought hazard in 2071-2100
2.6.1.CPF_ts1_D_TOTAL	2.6.1 Annual Damages in Euros to CPF Total allocations from Drought hazard in 1981-2010
2.6.2.CPF_ts2_D_TOTAL	2.6.2 Annual Damages in Euros to CPF Total allocations from Drought hazard in 2011-2040
2.6.3.CPF_ts3_D_TOTAL	2.6.3 Annual Damages in Euros to CPF Total allocations from Drought hazard in 2041-2070
2.6.4.CPF_ts4_D_TOTAL	2.6.4 Annual Damages in Euros to CPF Total allocations from Drought hazard in 2071-2100

3.1.1.CPF_ts1_F_ENER	3.1.1 Annual Damages in Euros to CPF Energy allocations from Wildfire hazard in 1981-2010
3.1.2.CPF_ts2_F_ENER	3.1.2 Annual Damages in Euros to CPF Energy allocations from Wildfire hazard in 2011-2040
3.1.3.CPF_ts3_F_ENER	3.1.3 Annual Damages in Euros to CPF Energy allocations from Wildfire hazard in 2041-2070
3.1.4.CPF_ts4_F_ENER	3.1.4 Annual Damages in Euros to CPF Energy allocations from Wildfire hazard in 2071-2100
3.2.1.CPF_ts1_F_ENV_TOUR	3.2.1 Annual Damages in Euros to CPF Environment and Tourism allocations from Wildfire hazard in 1981-2010
3.2.2.CPF_ts2_F_ENV_TOUR	3.2.2 Annual Damages in Euros to CPF Environment and Tourism allocations from Wildfire hazard in 2011-2040
3.2.3.CPF_ts3_F_ENV_TOUR	3.2.3 Annual Damages in Euros to CPF Environment and Tourism allocations from Wildfire hazard in 2041-2070
3.2.4.CPF_ts4_F_ENV_TOUR	3.2.4 Annual Damages in Euros to CPF Environment and Tourism allocations from Wildfire hazard in 2071-2100
3.3.1.CPF_ts1_F_ICT	3.3.1 Annual Damages in Euros to CPF I.C.T. allocations from Wildfire hazard in 1981-2010
3.3.2.CPF_ts2_F_ICT	3.3.2 Annual Damages in Euros to CPF I.C.T. allocations from Wildfire hazard in 2011-2040
3.3.3.CPF_ts3_F_ICT	3.3.3 Annual Damages in Euros to CPF I.C.T. allocations from Wildfire hazard in 2041-2070
3.3.4.CPF_ts4_F_ICT	3.3.4 Annual Damages in Euros to CPF I.C.T. allocations from Wildfire 'Multi CEA'!M16hazard in 2071-2100
3.4.1.CPF_ts1_F_SOCIAL	3.4.1 Annual Damages in Euros to CPF Social allocations from Wildfire hazard in 1981-2010
3.4.2.CPF_ts2_F_SOCIAL	3.4.2 Annual Damages in Euros to CPF Social allocations from Wildfire hazard in 2011-2040
3.4.3.CPF_ts3_F_SOCIAL	3.4.3 Annual Damages in Euros to CPF Social allocations from Wildfire hazard in 2041-2070
3.4.4.CPF_ts4_F_SOCIAL	3.4.4 Annual Damages in Euros to CPF Social allocations from Wildfire hazard in 2071-2100
3.5.1.CPF_ts1_F_TRANS	3.5.1 Annual Damages in Euros to CPF Transport allocations from Wildfire hazard in 1981-2010
3.5.2.CPF_ts2_F_TRANS	3.5.2 Annual Damages in Euros to CPF Transport allocations from Wildfire hazard in 2011-2040
3.5.3.CPF_ts3_F_TRANS	3.5.3 Annual Damages in Euros to CPF Transport allocations from Wildfire hazard in 2041-2070
3.5.4.CPF_ts4_F_TRANS	3.5.4 Annual Damages in Euros to CPF Transport allocations from Wildfire hazard in 2071-2100
3.6.1.CPF_ts1_F_TOTAL	3.6.1 Annual Damages in Euros to CPF Total allocations from Wildfire hazard in 1981-2010
3.6.2.CPF_ts2_F_TOTAL	3.6.2 Annual Damages in Euros to CPF Total allocations from Wildfire hazard in 2011-2040
3.6.3.CPF_ts3_F_TOTAL	3.6.3 Annual Damages in Euros to CPF Total allocations from Wildfire hazard in 2041-2070
3.6.4.CPF_ts4_F_TOTAL	3.6.4 Annual Damages in Euros to CPF Total allocations from Wildfire hazard in 2071-2100
4.1.1.CPF_ts1_RF_ENER	4.1.1 Annual Damages in Euros to CPF Energy allocations from River Flood hazard in 1981-2010
4.1.2.CPF_ts2_RF_ENER	4.1.2 Annual Damages in Euros to CPF Energy allocations from River Flood hazard in 2011-2040
4.1.3.CPF_ts3_RF_ENER	4.1.3 Annual Damages in Euros to CPF Energy allocations from



	River Flood hazard in 2041-2070
4.1.4.CPF_ts4_RF_ENER	4.1.4 Annual Damages in Euros to CPF Energy allocations from River Flood hazard in 2071-2100
4.2.1.CPF_ts1_RF_ENV_TOUR	4.2.1 Annual Damages in Euros to CPF Environment and Tourism allocations from River Flood hazard in 1981-2010
4.2.2.CPF_ts2_RF_ENV_TOUR	4.2.2 Annual Damages in Euros to CPF Environment and Tourism allocations from River Flood hazard in 2011-2040
4.2.3.CPF_ts3_RF_ENV_TOUR	4.2.3 Annual Damages in Euros to CPF Environment and Tourism allocations from River Flood hazard in 2041-2070
4.2.4.CPF_ts4_RF_ENV_TOUR	4.2.4 Annual Damages in Euros to CPF Environment and Tourism allocations from River Flood hazard in 2071-2100
4.3.1.CPF_ts1_RF_ICT	4.3.1 Annual Damages in Euros to CPF I.C.T. allocations from River Flood hazard in 1981-2010
4.3.2.CPF_ts2_RF_ICT	4.3.2 Annual Damages in Euros to CPF I.C.T. allocations from River Flood hazard in 2011-2040
4.3.3.CPF_ts3_RF_ICT	4.3.3 Annual Damages in Euros to CPF I.C.T. allocations from River Flood hazard in 2041-2070
4.3.4.CPF_ts4_RF_ICT	4.3.4 Annual Damages in Euros to CPF I.C.T. allocations from River Flood hazard in 2071-2100
4.4.1.CPF_ts1_RF_SOCIAL	4.4.1 Annual Damages in Euros to CPF Social allocations from River Flood hazard in 1981-2010
4.4.2.CPF_ts2_RF_SOCIAL	4.4.2 Annual Damages in Euros to CPF Social allocations from River Flood hazard in 2011-2040
4.4.3.CPF_ts3_RF_SOCIAL	4.4.3 Annual Damages in Euros to CPF Social allocations from River Flood hazard in 2041-2070
4.4.4.CPF_ts4_RF_SOCIAL	4.4.4 Annual Damages in Euros to CPF Social allocations from River Flood hazard in 2071-2100
4.5.1.CPF_ts1_RF_TRANS	4.5.1 Annual Damages in Euros to CPF Transport allocations from River Flood hazard in 1981-2010
4.5.2.CPF_ts2_RF_TRANS	4.5.2 Annual Damages in Euros to CPF Transport allocations from River Flood hazard in 2011-2040
4.5.3.CPF_ts3_RF_TRANS	4.5.3 Annual Damages in Euros to CPF Transport allocations from River Flood hazard in 2041-2070
4.5.4.CPF_ts4_RF_TRANS	4.5.4 Annual Damages in Euros to CPF Transport allocations from River Flood hazard in 2071-2100
4.6.1.CPF_ts1_RF_TOTAL	4.6.1 Annual Damages in Euros to CPF Total allocations from River Flood hazard in 1981-2010
4.6.2.CPF_ts2_RF_TOTAL	4.6.2 Annual Damages in Euros to CPF Total allocations from River Flood hazard in 2011-2040
4.6.3.CPF_ts3_RF_TOTAL	4.6.3 Annual Damages in Euros to CPF Total allocations from River Flood hazard in 2041-2070
4.6.4.CPF_ts4_RF_TOTAL	4.6.4 Annual Damages in Euros to CPF Total allocations from River Flood hazard in 2071-2100
5.1.1.CPF_ts1_H_ENER	5.1.1 Annual Damages in Euros to CPF Energy allocations from Heatwave hazard in 1981-2010
5.1.2.CPF_ts2_H_ENER	5.1.2 Annual Damages in Euros to CPF Energy allocations from Heatwave hazard in 2011-2040
5.1.3.CPF_ts3_H_ENER	5.1.3 Annual Damages in Euros to CPF Energy allocations from Heatwave hazard in 2041-2070
5.1.4.CPF_ts4_H_ENER	5.1.4 Annual Damages in Euros to CPF Energy allocations from Heatwave hazard in 2071-2100
5.2.1.CPF_ts1_H_ENV_TOUR	5.2.1 Annual Damages in Euros to CPF Environment and Tourism allocations from Heatwave hazard in 1981-2010

5.2.2.CPF_ts2_H_ENV_TOUR	5.2.2 Annual Damages in Euros to CPF Environment and Tourism allocations from Heatwave hazard in 2011-2040
5.2.3.CPF_ts3_H_ENV_TOUR	5.2.3 Annual Damages in Euros to CPF Environment and Tourism allocations from Heatwave hazard in 2041-2070
5.2.4.CPF_ts4_H_ENV_TOUR	5.2.4 Annual Damages in Euros to CPF Environment and Tourism allocations from Heatwave hazard in 2071-2100
5.3.1.CPF_ts1_H_ICT	5.3.1 Annual Damages in Euros to CPF I.C.T. allocations from Heatwave hazard in 1981-2010
5.3.2.CPF_ts2_H_ICT	5.3.2 Annual Damages in Euros to CPF I.C.T. allocations from Heatwave hazard in 2011-2040
5.3.3.CPF_ts3_H_ICT	5.3.3 Annual Damages in Euros to CPF I.C.T. allocations from Heatwave hazard in 2041-2070
5.3.4.CPF_ts4_H_ICT	5.3.4 Annual Damages in Euros to CPF I.C.T. allocations from Heatwave hazard in 2071-2100
5.4.1.CPF_ts1_H_SOCIAL	5.4.1 Annual Damages in Euros to CPF Social allocations from Heatwave hazard in 1981-2010
5.4.2.CPF_ts2_H_SOCIAL	5.4.2 Annual Damages in Euros to CPF Social allocations from Heatwave hazard in 2011-2040
5.4.3.CPF_ts3_H_SOCIAL	5.4.3 Annual Damages in Euros to CPF Social allocations from Heatwave hazard in 2041-2070
5.4.4.CPF_ts4_H_SOCIAL	5.4.4 Annual Damages in Euros to CPF Social allocations from Heatwave hazard in 2071-2100
5.5.1.CPF_ts1_H_TRANS	5.5.1 Annual Damages in Euros to CPF Transport allocations from Heatwave hazard in 1981-2010
5.5.2.CPF_ts2_H_TRANS	5.5.2 Annual Damages in Euros to CPF Transport allocations from Heatwave hazard in 2011-2040
5.5.3.CPF_ts3_H_TRANS	5.5.3 Annual Damages in Euros to CPF Transport allocations from Heatwave hazard in 2041-2070
5.5.4.CPF_ts4_H_TRANS	5.5.4 Annual Damages in Euros of CPF Transport allocations from Heatwave hazard in 2071-2100
5.6.1.CPF_ts1_H_TOTAL	5.6.1 Annual Damages in Euros to CPF Total allocations from Heatwave hazard in 1981-2010
5.6.2.CPF_ts2_H_TOTAL	5.6.2 Annual Damages in Euros to CPF Total allocations from Heatwave hazard in 2011-2040
5.6.3.CPF_ts3_H_TOTAL	5.6.3 Annual Damages in Euros to CPF Total allocations from Heatwave hazard in 2041-2070
5.6.4.CPF_ts4_H_TOTAL	5.6.4 Annual Damages in Euros to CPF Total allocations from Heatwave hazard in 2071-2100
6.1.1.CPF_ts1_CF_ENER	6.1.1 Annual Damages in Euros to CPF Energy allocations from Coastal flood hazard in 1981-2010
6.1.2.CPF_ts2_CF_ENER	6.1.2 Annual Damages in Euros to CPF Energy allocations from Coastal flood hazard in 2011-2040
6.1.3.CPF_ts3_CF_ENER	6.1.3 Annual Damages in Euros to CPF Energy allocations from Coastal flood hazard in 2041-2070
6.1.4.CPF_ts4_CF_ENER	6.1.4 Annual Damages in Euros to CPF Energy allocations from Coastal flood hazard in 2071-2100
6.2.1.CPF_ts1_CF_ENV_TOUR	6.2.1 Annual Damages in Euros to CPF Environment and Tourism allocations from Coastal flood hazard in 1981-2010
6.2.2.CPF_ts2_CF_ENV_TOUR	6.2.2 Annual Damages in Euros to CPF Environment and Tourism allocations from Coastal flood hazard in 2011-2040
6.2.3.CPF_ts3_CF_ENV_TOUR	6.2.3 Annual Damages in Euros to CPF Environment and Tourism allocations from Coastal flood hazard in 2041-2070
6.2.4.CPF_ts4_CF_ENV_TOUR	6.2.4 Annual Damages in Euros to CPF Environment and

	Tourism allocations from Coastal flood hazard in 2071-2100
6.3.1.CPF_ts1_CF_ICT	6.3.1 Annual Damages in Euros to CPF I.C.T. allocations from Coastal flood hazard in 1981-2010
6.3.2.CPF_ts2_CF_ICT	6.3.2 Annual Damages in Euros to CPF I.C.T. allocations from Coastal flood hazard in 2011-2040
6.3.3.CPF_ts3_CF_ICT	6.3.3 Annual Damages in Euros to CPF I.C.T. allocations from Coastal flood hazard in 2041-2070
6.3.4.CPF_ts4_CF_ICT	6.3.4 Annual Damages in Euros to CPF I.C.T. allocations from Coastal flood hazard in 2071-2100
6.4.1.CPF_ts1_CF_SOCIAL	6.4.1 Annual Damages in Euros to CPF Social allocations from Coastal flood hazard in 1981-2010
6.4.2.CPF_ts2_CF_SOCIAL	6.4.2 Annual Damages in Euros to CPF Social allocations from Coastal flood hazard in 2011-2040
6.4.3.CPF_ts3_CF_SOCIAL	6.4.3 Annual Damages in Euros to CPF Social allocations from Coastal flood hazard in 2041-2070
6.4.4.CPF_ts4_CF_SOCIAL	6.4.4 Annual Damages in Euros to CPF Social allocations from Coastal flood hazard in 2071-2100
6.5.1.CPF_ts1_CF_TRANS	6.5.1 Annual Damages in Euros to CPF Transport allocations from Coastal flood hazard in 1981-2010
6.5.2.CPF_ts2_CF_TRANS	6.5.2 Annual Damages in Euros to CPF Transport allocations from Coastal flood hazard in 2011-2040
6.5.3.CPF_ts3_CF_TRANS	6.5.3 Annual Damages in Euros to CPF Transport allocations from Coastal flood hazard in 2041-2070
6.5.4.CPF_ts4_CF_TRANS	6.5.4 Annual Damages in Euros to CPF Transport allocations from Coastal flood hazard in 2071-2100
6.6.1.CPF_ts1_CF_TOTAL	6.6.1 Annual Damages in Euros to CPF Total allocations from Coastal flood hazard in 1981-2010
6.6.2.CPF_ts2_CF_TOTAL	6.6.2 Annual Damages in Euros to CPF Total allocations from Coastal flood hazard in 2011-2040
6.6.3.CPF_ts3_CF_TOTAL	6.6.3 Annual Damages in Euros to CPF Total allocations from Coastal flood hazard in 2041-2070
6.6.4.CPF_ts4_CF_TOTAL	6.6.4 Annual Damages in Euros to CPF Total allocations from Coastal flood hazard in 2071-2100
7.1.1.CPF_ts1_W_ENER	7.1.1 Annual Damages in Euros to CPF Energy allocations from Windstorm hazard in 1981-2010
7.1.4.CPF_ts4_W_ENER	7.1.4 Annual Damages in Euros to CPF Energy allocations from Windstorm hazard in 2071-2100
7.2.1.CPF_ts1_W_ENV_TOUR	7.2.1 Annual Damages in Euros to CPF Environment and Tourism allocations from Windstorm hazard in 1981-2010
7.2.4.CPF_ts4_W_ENV_TOUR	7.2.4 Annual Damages in Euros to CPF Environment and Tourism allocations from Windstorm hazard in 2071-2100
7.3.1.CPF_ts1_W_ICT	7.3.1 Annual Damages in Euros to CPF I.C.T. allocations from Windstorm hazard in 1981-2010
7.3.4.CPF_ts4_W_ICT	7.3.4 Annual Damages in Euros to CPF I.C.T. allocations from Windstorm hazard in 2071-2100
7.4.1.CPF_ts1_W_SOCIAL	7.4.1 Annual Damages in Euros to CPF Social allocations from Windstorm hazard in 1981-2010
7.4.4.CPF_ts4_W_SOCIAL	7.4.4 Annual Damages in Euros to CPF Social allocations from Windstorm hazard in 2071-2100
7.5.1.CPF_ts1_W_TRANS	7.5.1 Annual Damages in Euros to CPF Transport allocations from Windstorm hazard in 1981-2010
7.5.4.CPF_ts4_W_TRANS	7.5.4 Annual Damages in Euros to CPF Transport allocations from Windstorm hazard in 2071-2100

7.6.1.CPF_ts1_W_TOTAL	7.6.1 Annual Damages in Euros to CPF Total allocations from Windstorm hazard in 1981-2010
7.6.4.CPF_ts4_W_TOTAL	7.6.4 Annual Damages in Euros to CPF Total allocations from Windstorm hazard in 2071-2100

## **1B: CPF Multi-hazard maps**

Namefile	Caption
8.1.1 CPF_ts1_M_ENER	8.1.1 Annual Damages in Euros to CPF Energy allocations from Multi-hazards in 1981-2010
8.1.2 CPF_ts2_M_ENER	8.1.2 Annual Damages in Euros to CPF Energy allocations from Multi-hazards in 2011-2040
8.1.3 CPF_ts3_M_ENER	8.1.3 Annual Damages in Euros to CPF Energy allocations from Multi-hazards in 2041-2070
8.1.4 CPF_ts4_M_ENER	8.1.4 Annual Damages in Euros to CPF Energy allocations from Multi-hazards in 2071-2100
8.2.1 CPF_ts1_M_ENV_TOUR	8.2.1 Annual Damages in Euros to CPF Environment and Tourism allocations from Multi-hazards in 1981-2010
8.2.2 CPF_ts2_M_ENV_TOUR	8.2.2 Annual Damages in Euros to CPF Environment and Tourism allocations from Multi-hazards in 2011-2040
8.2.3 CPF_ts3_M_ENV_TOUR	8.2.3 Annual Damages in Euros to CPF Environment and Tourism allocations from Multi-hazards in 2041-2070
8.2.4 CPF_ts4_M_ENV_TOUR	8.2.4 Annual Damages in Euros to CPF Environment and Tourism allocations from Multi-hazards in 2071-2100
8.3.1 CPF_ts1_M_ICT	8.3.1 Annual Damages in Euros to CPF I.C.T. allocations from Multi-hazards in 1981-2010
8.3.2 CPF_ts2_M_ICT	8.3.2 Annual Damages in Euros to CPF I.C.T. allocations from Multi-hazards in 2011-2040
8.3.3 CPF_ts3_M_ICT	8.3.3 Annual Damages in Euros to CPF I.C.T. allocations from Multi-hazards in 2041-2070
8.3.4 CPF_ts4_M_ICT	8.3.4 Annual Damages in Euros to CPF I.C.T. allocations from Multi-hazards in 2071-2100
8.4.1 CPF_ts1_M_SOCIAL	8.4.1 Annual Damages in Euros to CPF Social allocations from Multi-hazards in 1981-2010
8.4.2 CPF_ts2_M_SOCIAL	8.4.2 Annual Damages in Euros to CPF Social allocations from Multi-hazards in 2011-2040
8.4.3 CPF_ts3_M_SOCIAL	8.4.3 Annual Damages in Euros to CPF Social allocations from Multi-hazards in 2041-2070
8.4.4 CPF_ts4_M_SOCIAL	8.4.4 Annual Damages in Euros to CPF Social allocations from Multi-hazards in 2071-2100
8.5.1 CPF_ts1_M_TRANS	8.5.1 Annual Damages in Euros to CPF Transport allocations from Multi-hazards in 1981-2010
8.5.2 CPF_ts2_M_TRANS	8.5.2 Annual Damages in Euros to CPF Transport allocations from Multi-hazards in 2011-2040
8.5.3 CPF_ts3_M_TRANS	8.5.3 Annual Damages in Euros to CPF Transport allocations from Multi-hazards in 2041-2070
8.5.4 CPF_ts4_M_TRANS	8.5.4 Annual Damages in Euros to CPF Transport allocations from Multi-hazards in 2071-2100
8.6.1 CPF_ts1_M_TOTAL	8.6.1 Annual Damages in Euros to CPF Total allocations from Multi-hazards in 1981-2010

8.6.2 CPF_ts2_M_TOTAL	8.6.2 Annual Damages in Euros to CPF Total allocations from Multi-hazards in 2011-2040
8.6.3 CPF_ts3_M_TOTAL	8.6.3 Annual Damages in Euros to CPF Total allocations from Multi-hazards in 2041-2070
8.6.4 CPF_ts4_M_TOTAL	8.6.4 Annual Damages in Euros to CPF Total allocations from Multi-hazards in 2071-2100

## **2A: CI single hazard maps**

Namefile	Caption
1.1.1 CI_ts1_C.ENER	1.1.1 Annual Damages in Euros to Critical Energy Infrastructures from Coldwaves hazard in 1981-2010
1.1.2 CI_ts2_C.ENER	1.1.2 Annual Damages in Euros to Critical Energy Infrastructures from Coldwaves hazard in 2011-2040
1.1.3 CI_ts3_C.ENER	1.1.3 Annual Damages in Euros to Critical Energy Infrastructures from Coldwaves hazard in 2041-2070
1.1.4 CI_ts4_C.ENER	1.1.4 Annual Damages in Euros to Critical Energy Infrastructures from Coldwaves hazard in 2071-2100
1.2.1 CI_ts1_C.INDUSTRIAL	1.2.1 Annual Damages in Euros to Critical Industry Infrastructures from Coldwaves hazard in 1981-2010
1.2.2 CI_ts2_C.INDUSTRIAL	1.2.2 Annual Damages in Euros to Critical Industry Infrastructures from Coldwaves hazard in 2011-2040
1.2.3 CI_ts3_C.INDUSTRIAL	1.2.3 Annual Damages in Euros to Critical Industry Infrastructures from Coldwaves hazard in 2041-2070
1.2.4 CI_ts4_C.INDUSTRIAL	1.2.4 Annual Damages in Euros to Critical Industry Infrastructures from Coldwaves hazard in 2071-2100
1.3.1 CI_ts1_C.SOCIAL	1.3.1 Annual Damages in Euros to Critical Social Infrastructures from Coldwaves hazard in 1981-2010
1.3.2 CI_ts2_C.SOCIAL	1.3.2 Annual Damages in Euros to Critical Social Infrastructures from Coldwaves hazard in 2011-2040
1.3.3 CI_ts3_C.SOCIAL	1.3.3 Annual Damages in Euros to Critical Social Infrastructures from Coldwaves hazard in 2041-2070
1.3.4 CI_ts4_C.SOCIAL	1.3.4 Annual Damages in Euros to Critical Social Infrastructures from Coldwaves hazard in 2071-2100
1.4.1 CI_ts1_C.TRANS	1.4.1 Annual Damages in Euros to Critical Transport Infrastructures from Coldwaves hazard in 1981-2010
1.4.2 CI_ts2_C.TRANS	1.4.2 Annual Damages in Euros to Critical Transport Infrastructures from Coldwaves hazard in 2011-2040
1.4.3 CI_ts3_C.TRANS	1.4.3 Annual Damages in Euros to Critical Transport Infrastructures from Coldwaves hazard in 2041-2070
1.4.4 CI_ts4_C.TRANS	1.4.4 Annual Damages in Euros to Critical Transport Infrastructures from Coldwaves hazard in 2071-2100
1.5.1 CI_ts1_C.TOTAL	1.5.1 Annual Damages in Euros to Total Critical Infrastructures from Coldwaves hazard in 1981-2010
1.5.2 CI_ts2_C.TOTAL	1.5.2 Annual Damages in Euros to Total Critical Infrastructures from Coldwaves hazard in 2011-2040
1.5.3 CI_ts3_C.TOTAL	1.5.3 Annual Damages in Euros to Total Critical Infrastructures from Coldwaves hazard in 2041-2070
1.5.4 CI_ts4_C.TOTAL	1.5.4 Annual Damages in Euros to Total Critical Infrastructures from Coldwaves hazard in 2071-2100

2.1.1 CI_ts1_D.ENER	2.1.1 Annual Damages in Euros to Critical Energy Infrastructures from Drought hazard in 1981-2010
2.1.2 CI_ts2_D.ENER	2.1.2 Annual Damages in Euros to Critical Energy Infrastructures from Drought hazard in 2011-2040
2.1.3 CI_ts3_D.ENER	2.1.3 Annual Damages in Euros to Critical Energy Infrastructures from Drought hazard in 2041-2070
2.1.4 CI_ts4_D.ENER	2.1.4 Annual Damages in Euros to Critical Energy Infrastructures from Drought hazard in 2071-2100
2.2.1 CI_ts1_D.INDUSTRIAL	2.2.1 Annual Damages in Euros to Critical Industry Infrastructures from Drought hazard in 1981-2010
2.2.2 CI_ts2_D.INDUSTRIAL	2.2.2 Annual Damages in Euros to Critical Industry Infrastructures from Drought hazard in 2011-2040
2.2.3 CI_ts3_D.INDUSTRIAL	2.2.3 Annual Damages in Euros to Critical Industry Infrastructures from Drought hazard in 2041-2070
2.2.4 CI_ts4_D.INDUSTRIAL	2.2.4 Annual Damages in Euros to Critical Industry Infrastructures from Drought hazard in 2071-2100
2.3.1 CI_ts1_D.SOCIAL	2.3.1 Annual Damages in Euros to Critical Social Infrastructures from Drought hazard in 1981-2010
2.3.2 CI_ts2_D.SOCIAL	2.3.2 Annual Damages in Euros to Critical Social Infrastructures from Drought hazard in 2011-2040
2.3.3 CI_ts3_D.SOCIAL	2.3.3 Annual Damages in Euros to Critical Social Infrastructures from Drought hazard in 2041-2070
2.3.4 CI_ts4_D.SOCIAL	2.3.4 Annual Damages in Euros to Critical Social Infrastructures from Drought hazard in 2071-2100
2.4.1 CI_ts1_D.TRANS	2.4.1 Annual Damages in Euros to Critical Transport Infrastructures from Drought hazard in 1981-2010
2.4.2 CI_ts2_D.TRANS	2.4.2 Annual Damages in Euros to Critical Transport Infrastructures from Drought hazard in 2011-2040
2.4.3 CI_ts3_D.TRANS	2.4.3 Annual Damages in Euros to Critical Transport Infrastructures from Drought hazard in 2041-2070
2.4.4 CI_ts4_D.TRANS	2.4.4 Annual Damages in Euros to Critical Transport Infrastructures from Drought hazard in 2071-2100
2.5.1 CI_ts1_D.TOTAL	2.5.1 Annual Damages in Euros to Total Critical Infrastructures from Drought hazard in 1981-2010
2.5.2 CI_ts2_D.TOTAL	2.5.2 Annual Damages in Euros to Total Critical Infrastructures from Drought hazard in 2011-2040
2.5.3 CI_ts3_D.TOTAL	2.5.3 Annual Damages in Euros to Total Critical Infrastructures from Drought hazard in 2041-2070
2.5.4 CI_ts4_D.TOTAL	2.5.4 Annual Damages in Euros to Total Critical Infrastructures from Drought hazard in 2071-2100
3.1.1 CI_ts1_F.ENER	3.1.1 Annual Damages in Euros to Critical Energy Infrastructures from Wildfire hazard in 1981-2010
3.1.2 CI_ts2_F.ENER	3.1.2 Annual Damages in Euros to Critical Energy Infrastructures from Wildfire hazard in 2011-2040
3.1.3 CI_ts3_F.ENER	3.1.3 Annual Damages in Euros to Critical Energy Infrastructures from Wildfire hazard in 2041-2070
3.1.4 CI_ts4_F.ENER	3.1.4 Annual Damages in Euros to Critical Energy Infrastructures from Wildfire hazard in 2071-2100
3.2.1 CI_ts1_F.INDUSTRIAL	3.2.1 Annual Damages in Euros to Critical Industry Infrastructures from Wildfire hazard in 1981-2010
3.2.2 CI_ts2_F.INDUSTRIAL	3.2.2 Annual Damages in Euros to Critical Industry Infrastructures from Wildfire hazard in 2011-2040

3.2.3 CI_ts3_F.INDUSTRIAL	3.2.3 Annual Damages in Euros to Critical Industry Infrastructures from Wildfire hazard in 2041-2070
3.2.4 CI_ts4_F.INDUSTRIAL	3.2.4 Annual Damages in Euros to Critical Industry Infrastructures from Wildfire hazard in 2071-2100
3.3.1 CI_ts1_F.SOCIAL	3.3.1 Annual Damages in Euros to Critical Social Infrastructures from Wildfire hazard in 1981-2010
3.3.2 CI_ts2_F.SOCIAL	3.3.2 Annual Damages in Euros to Critical Social Infrastructures from Wildfire hazard in 2011-2040
3.3.3 CI_ts3_F.SOCIAL	3.3.3 Annual Damages in Euros to Critical Social Infrastructures from Wildfire hazard in 2041-2070
3.3.4 CI_ts4_F.SOCIAL	3.3.4 Annual Damages in Euros to Critical Social Infrastructures from Wildfire hazard in 2071-2100
3.4.1 CI_ts1_F.TRANS	3.4.1 Annual Damages in Euros to Critical Transport Infrastructures from Wildfire hazard in 1981-2010
3.4.2 CI_ts2_F.TRANS	3.4.2 Annual Damages in Euros to Critical Transport Infrastructures from Wildfire hazard in 2011-2040
3.4.3 CI_ts3_F.TRANS	3.4.3 Annual Damages in Euros to Critical Transport Infrastructures from Wildfire hazard in 2041-2070
3.4.4 CI_ts4_F.TRANS	3.4.4 Annual Damages in Euros to Critical Transport Infrastructures from Wildfire hazard in 2071-2100
3.5.1 CI_ts1_F.TOTAL	3.5.1 Annual Damages in Euros to Total Critical Infrastructures from Wildfire hazard in 1981-2010
3.5.2 CI_ts2_F.TOTAL	3.5.2 Annual Damages in Euros to Total Critical Infrastructures from Wildfire hazard in 2011-2040
3.5.3 CI_ts3_F.TOTAL	3.5.3 Annual Damages in Euros to Total Critical Infrastructures from Wildfire hazard in 2041-2070
3.5.4 CI_ts4_F.TOTAL	3.5.4 Annual Damages in Euros to Total Critical Infrastructures from Wildfire hazard in 2071-2100
4.1.1 CI_ts1_RF.ENER	4.1.1 Annual Damages in Euros to Critical Energy Infrastructures from River Flood hazard in 1981-2010
4.1.2 CI_ts2_RF.ENER	4.1.2 Annual Damages in Euros to Critical Energy Infrastructures from River Flood hazard in 2011-2040
4.1.3 CI_ts3_RF.ENER	4.1.3 Annual Damages in Euros to Critical Energy Infrastructures from River Flood hazard in 2041-2070
4.1.4 CI_ts4_RF.ENER	4.1.4 Annual Damages in Euros to Critical Energy Infrastructures from River Flood hazard in 2071-2100
4.2.1 CI_ts1_RF.INDUSTRIAL	4.2.1 Annual Damages in Euros to Critical Industry Infrastructures from River Flood hazard in 1981-2010
4.2.2 CI_ts2_RF.INDUSTRIAL	4.2.2 Annual Damages in Euros to Critical Industry Infrastructures from River Flood hazard in 2011-2040
4.2.3 CI_ts3_RF.INDUSTRIAL	4.2.3 Annual Damages in Euros to Critical Industry Infrastructures from River Flood hazard in 2041-2070
4.2.4 CI_ts4_RF.INDUSTRIAL	4.2.4 Annual Damages in Euros to Critical Industry Infrastructures from River Flood hazard in 2071-2100
4.3.1 CI_ts1_RF.SOCIAL	4.3.1 Annual Damages in Euros to Critical Social Infrastructures from River Flood hazard in 1981-2010
4.3.2 CI_ts2_RF.SOCIAL	4.3.2 Annual Damages in Euros to Critical Social Infrastructures from River Flood hazard in 2011-2040
4.3.3 CI_ts3_RF.SOCIAL	4.3.3 Annual Damages in Euros to Critical Social Infrastructures from River Flood hazard in 2041-2070
4.3.4 CI_ts4_RF.SOCIAL	4.3.4 Annual Damages in Euros to Critical Social Infrastructures from River Flood hazard in 2071-2100
4.4.1 CI_ts1_RF.TRANS	4.4.1 Annual Damages in Euros to Critical Transport

	Infrastructures from River Flood hazard in 1981-2010
4.4.2 CI_ts2_RF.TRANS	4.4.2 Annual Damages in Euros to Critical Transport Infrastructures from River Flood hazard in 2011-2040
4.4.3 CI_ts3_RF.TRANS	4.4.3 Annual Damages in Euros to Critical Transport Infrastructures from River Flood hazard in 2041-2070
4.4.4 CI_ts4_RF.TRANS	4.4.4 Annual Damages in Euros to Critical Transport Infrastructures from River Flood hazard in 2071-2100
4.5.1 CI_ts1_RF.TOTAL	4.5.1 Annual Damages in Euros to Total Critical Infrastructures from River Flood hazard in 1981-2010
4.5.2 CI_ts2_RF.TOTAL	4.5.2 Annual Damages in Euros to Total Critical Infrastructures from River Flood hazard in 2011-2040
4.5.3 CI_ts3_RF.TOTAL	4.5.3 Annual Damages in Euros to Total Critical Infrastructures from River Flood hazard in 2041-2070
4.5.4 CI_ts4_RF.TOTAL	4.5.4 Annual Damages in Euros to Total Critical Infrastructures from River Flood hazard in 2071-2100
5.1.1 CI_ts1_H.ENER	5.1.1 Annual Damages in Euros to Critical Energy Infrastructures from Heatwave hazard in 1981-2010
5.1.2 CI_ts2_H.ENER	5.1.2 Annual Damages in Euros to Critical Energy Infrastructures from Heatwave hazard in 2011-2040
5.1.3 CI_ts3_H.ENER	5.1.3 Annual Damages in Euros to Critical Energy Infrastructures from Heatwave hazard in 2041-2070
5.1.4 CI_ts4_H.ENER	5.1.4 Annual Damages in Euros to Critical Energy Infrastructures from Heatwave hazard in 2071-2100
5.2.1 CI_ts1_H.INDUSTRIAL	5.2.1 Annual Damages in Euros to Critical Industry Infrastructures from Heatwave hazard in 1981-2010
5.2.2 CI_ts2_H.INDUSTRIAL	5.2.2 Annual Damages in Euros to Critical Industry Infrastructures from Heatwave hazard in 2011-2040
5.2.3 CI_ts3_H.INDUSTRIAL	5.2.3 Annual Damages in Euros to Critical Industry Infrastructures from Heatwave hazard in 2041-2070
5.2.4 CI_ts4_H.INDUSTRIAL	5.2.4 Annual Damages in Euros to Critical Industry Infrastructures from Heatwave hazard in 2071-2100
5.3.1 CI_ts1_H.SOCIAL	5.3.1 Annual Damages in Euros to Critical Social Infrastructures from Heatwave hazard in 1981-2010
5.3.2 CI_ts2_H.SOCIAL	5.3.2 Annual Damages in Euros to Critical Social Infrastructures from Heatwave hazard in 2011-2040
5.3.3 CI_ts3_H.SOCIAL	5.3.3 Annual Damages in Euros to Critical Social Infrastructures from Heatwave hazard in 2041-2070
5.3.4 CI_ts4_H.SOCIAL	5.3.4 Annual Damages in Euros to Critical Social Infrastructures from Heatwave hazard in 2071-2100
5.4.1 CI_ts1_H.TRANS	5.4.1 Annual Damages in Euros to Critical Transport Infrastructures from Heatwave hazard in 1981-2010
5.4.2 CI_ts2_H.TRANS	5.4.2 Annual Damages in Euros to Critical Transport Infrastructures from Heatwave hazard in 2011-2040
5.4.3 CI_ts3_H.TRANS	5.4.3 Annual Damages in Euros to Critical Transport Infrastructures from Heatwave hazard in 2041-2070
5.4.4 CI_ts4_H.TRANS	5.4.4 Annual Damages in Euros to Critical Transport Infrastructures from Heatwave hazard in 2071-2100
5.5.1 CI_ts1_H.TOTAL	5.5.1 Annual Damages in Euros to Total Critical Infrastructures from Heatwave hazard in 1981-2010
5.5.2 CI_ts2_H.TOTAL	5.5.2 Annual Damages in Euros to Total Critical Infrastructures from Heatwave hazard in 2011-2040
5.5.3 CI_ts3_H.TOTAL	5.5.3 Annual Damages in Euros to Total Critical Infrastructures from Heatwave hazard in 2041-2070



5.5.4 CI_ts4_H.TOTAL	5.5.4 Annual Damages in Euros to Total Critical Infrastructures from Heatwave hazard in 2071-2100
6.1.1 CI_ts1_CF.ENER	6.1.1 Annual Damages in Euros to Critical Energy Infrastructures from Coastal Flood hazard in 1981-2010
6.1.2 CI_ts2_CF.ENER	6.1.2 Annual Damages in Euros to Critical Energy Infrastructures from Coastal Flood hazard in 2011-2040
6.1.3 CI_ts3_CF.ENER	6.1.3 Annual Damages in Euros to Critical Energy Infrastructures from Coastal Flood hazard in 2041-2070
6.1.4 CI_ts4_CF.ENER	6.1.4 Annual Damages in Euros to Critical Energy Infrastructures from Coastal Flood hazard in 2071-2100
6.3.1 CI_ts1_CF.INDUSTRIAL	6.3.1 Annual Damages in Euros to Critical Industry Infrastructures from Coastal Flood hazard in 1981-2010
6.3.2 CI_ts2_CF.INDUSTRIAL	6.3.2 Annual Damages in Euros to Critical Industry Infrastructures from Coastal Flood hazard in 2011-2040
6.3.3 CI_ts3_CF.INDUSTRIAL	6.3.3 Annual Damages in Euros to Critical Industry Infrastructures from Coastal Flood hazard in 2041-2070
6.3.4 CI_ts4_CF.INDUSTRIAL	6.3.4 Annual Damages in Euros to Critical Industry Infrastructures from Coastal Flood hazard in 2071-2100
6.4.1 CI_ts1_CF.SOCIAL	6.4.1 Annual Damages in Euros to Critical Social Infrastructures from Coastal Flood hazard in 1981-2010
6.4.2 CI_ts2_CF.SOCIAL	6.4.2 Annual Damages in Euros to Critical Social Infrastructures from Coastal Flood hazard in 2011-2040
6.4.3 CI_ts3_CF.SOCIAL	6.4.3 Annual Damages in Euros to Critical Social Infrastructures from Coastal Flood hazard in 2041-2070
6.4.4 CI_ts4_CF.SOCIAL	6.4.4 Annual Damages in Euros to Critical Social Infrastructures from Coastal Flood hazard in 2071-2100
6.5.1 CI_ts1_CF.TRANS	6.5.1 Annual Damages in Euros to Critical Transport Infrastructures from Coastal Flood hazard in 1981-2010
6.5.2 CI_ts2_CF.TRANS	6.5.2 Annual Damages in Euros to Critical Transport Infrastructures from Coastal Flood hazard in 2011-2040
6.5.3 CI_ts3_CF.TRANS	6.5.3 Annual Damages in Euros to Critical Transport Infrastructures from Coastal Flood hazard in 2041-2070
6.5.4 CI_ts4_CF.TRANS	6.5.4 Annual Damages in Euros to Critical Transport Infrastructures from Coastal Flood hazard in 2071-2100
6.6.1 CI_ts1_CF.TOTAL	6.6.1 Annual Damages in Euros to Total Critical Infrastructures from Coastal Flood hazard in 1981-2010
6.6.2 CI_ts2_CF.TOTAL	6.6.2 Annual Damages in Euros to Total Critical Infrastructures from Coastal Flood hazard in 2011-2040
6.6.3 CI_ts3_CF.TOTAL	6.6.3 Annual Damages in Euros to Total Critical Infrastructures from Coastal Flood hazard in 2041-2070
6.6.4 CI_ts4_CF.TOTAL	6.6.4 Annual Damages in Euros to Total Critical Infrastructures from Coastal Flood hazard in 2071-2100
7.1.1 CI_ts1_W.ENER	7.1.1 Annual Damages in Euros to Critical Energy Infrastructures from Windstorm hazard in 1981-2010
7.1.4 CI_ts4_W.ENER	7.1.4 Annual Damages in Euros to Critical Energy Infrastructures from Windstorm hazard in 2071-2100
7.2.1 CI_ts1_W.INDUSTRIAL	7.2.1 Annual Damages in Euros to Critical Industry Infrastructures from Windstorm hazard in 1981-2010
7.2.4 CI_ts4_W.INDUSTRIAL	7.2.4 Annual Damages in Euros to Critical Industry Infrastructures from Windstorm hazard in 2071-2100
7.3.1 CI_ts1_W.SOCIAL	7.3.1 Annual Damages in Euros to Critical Social Infrastructures from Windstorm hazard in 1981-2010
7.3.4 CI_ts4_W.SOCIAL	7.3.4 Annual Damages in Euros to Critical Social

	Infrastructures from Windstorm hazard in 2071-2100
7.4.1 CI_ts1_W.TRANS	7.4.1 Annual Damages in Euros to Critical Transport Infrastructures from Windstorm hazard in 1981-2010
7.4.4 CI_ts4_W.TRANS	7.4.4 Annual Damages in Euros to Critical Transport Infrastructures from Windstorm hazard in 2071-2100
7.5.1 CI_ts1_W.TOTAL	7.5.1 Annual Damages in Euros to Total Critical Infrastructures from Windstorm hazard in 1981-2010
7.5.4 CI_ts4_W.TOTAL	7.5.4 Annual Damages in Euros to Total Critical Infrastructures from Windstorm hazard in 2071-2100

## **2B: CI Multi-hazard maps**

Namefile	Caption
8.1.1 CI_ts1_M.ENER	8.1.1 Annual Damages in Euros to Critical Energy Infrastructures from Multi-hazards in 1981-2010
8.1.2 CI_ts2_M.ENER	8.1.2 Annual Damages in Euros to Critical Energy Infrastructures from Multi-hazards in 2011-2040
8.1.3 CI_ts3_M.ENER	8.1.3 Annual Damages in Euros to Critical Energy Infrastructures from Multi-hazards in 2041-2070
8.1.4 CI_ts4_M.ENER	8.1.4 Annual Damages in Euros to Critical Energy Infrastructures from Multi-hazards in 2071-2100
8.2.1 CI_ts1_M.INDUSTRIAL	8.2.1 Annual Damages in Euros to Critical Industry Infrastructures from Multi-hazards in 1981-2010
8.2.2 CI_ts2_M.INDUSTRIAL	8.2.2 Annual Damages in Euros to Critical Industry Infrastructures from Multi-hazards in 2011-2040
8.2.3 CI_ts3_M.INDUSTRIAL	8.2.3 Annual Damages in Euros to Critical Industry Infrastructures from Multi-hazards in 2041-2070
8.2.4 CI_ts4_M.INDUSTRIAL	8.2.4 Annual Damages in Euros to Critical Industry Infrastructures from Multi-hazards in 2071-2100
8.3.1 CI_ts1_M.SOCIAL	8.3.1 Annual Damages in Euros to Critical Social Infrastructures from Multi-hazards in 1981-2010
8.3.2 CI_ts2_M.SOCIAL	8.3.2 Annual Damages in Euros to Critical Social Infrastructures from Multi-hazards in 2011-2040
8.3.3 CI_ts3_M.SOCIAL	8.3.3 Annual Damages in Euros to Critical Social Infrastructures from Multi-hazards in 2041-2070
8.3.4 CI_ts4_M.SOCIAL	8.3.4 Annual Damages in Euros to Critical Social Infrastructures from Multi-hazards in 2071-2100
8.4.1 CI_ts1_M.TRANS	8.4.1 Annual Damages in Euros to Critical Transport Infrastructures from Multi-hazards in 1981-2010
8.4.2 CI_ts2_M.TRANS	8.4.2 Annual Damages in Euros to Critical Transport Infrastructures from Multi-hazards in 2011-2040
8.4.3 CI_ts3_M.TRANS	8.4.3 Annual Damages in Euros to Critical Transport Infrastructures from Multi-hazards in 2041-2070
8.4.4 CI_ts4_M.TRANS	8.4.4 Annual Damages in Euros to Critical Transport Infrastructures from Multi-hazards in 2071-2100
8.5.1 CI_ts1_M.TOTAL	8.5.1 Annual Damages in Euros to Total Critical Infrastructures from Multi-hazards in 1981-2010
8.5.2 CI_ts2_M.TOTAL	8.5.2 Annual Damages in Euros to Total Critical Infrastructures from Multi-hazards in 2011-2040

8.5.3 CI_ts3_M.TOTAL	8.5.3 Annual Damages in Euros to Total Critical Infrastructures from Multi-hazards in 2041-2070
8.5.4 CI_ts4_M.TOTAL	8.5.4 Annual Damages in Euros to Total Critical Infrastructures from Multi-hazards in 2071-2100



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Stimulating innovation  
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