IMPETUS

Turning climate commitments into action

Deliverable Report Metrics for climate change vulnerability, resilience and adaptation

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Disclaimer

Abbreviations

Abbreviation / Acronyms	Description
CAP	Climate Action Planning programme
DRR	Disaster Risk Reduction
EU	European Union
I & M	Indicators & Metrics
Ind.	Indicator
MRE	Monitoring, Reporting and Evaluation
SDG	Sustainable Development Goal
WHO	World Health Organization
WP	Working Package

Executive Summary

Climate change urges strategic decision-makers across sectors and geographies to both mitigate and adapt, while weighing different interests and dealing with uncertainties and unknowns. To support local stakeholders with such complex strategic and transdisciplinary decision-making, the aim of this deliverable has been to develop a flexible framework of indicators to undertake resilience assessments and evaluate climate vulnerability and climate adaptation measures and pathways. The proposed IMPETUS indicator framework consists of two complementary core frameworks related to climate vulnerability and climate adaptation. The core frameworks are considered most essential with respect to the demonstration sites and therefore account for Europe's diversity in bio-geographical regions that range from continental, coastal, Mediterranean, Atlantic, arctic, boreal and mountains. Both core frameworks have been complemented with a list of additional indicators that apply to a more limited number of demonstration sites or bio-geographical regions. Next, a resilience handbook has been provided that enables the use of the core indicators and additional indicators to support more in-depth resilience assessments in task 3.4 of the IMPETUS project. The extensive literature inventory and the review of existing frameworks of indicators that are being applied at different spatial scales has ensured that the resulting set of indicators have been well embedded in leading academic debates and policy approaches. To ensure that indicators can be used by practitioners – being within the IMPETUS demonstration sites and beyond – they are designed to be easy to understand, timely and relevant, and with the end-users in mind. In this regards, stakeholders' feedback has proved to be crucial in setting the IMPETUS indicator framework, allowing to incorporate experience from practitioners working at the local, regional and national scale.

In total, 69 core indicators (with 12 supporting indicators to calculate them) and 43 additional indicators have been proposed. The proposed IMPETUS indicator framework provides a structure for climate-sensitive strategic decision-making as well as a repository of indicators. On a case-by-case basis, different indicators might be selected from the categories and subcategories and potentially being supplemented by other place-based indicators. Hence, the proposed set of indicators are by no means exhaustive but can be regarded as a meaningful point of departure for a continuous learning-by-doing process. To further support this intended use, the proposed flexible IMPETUS indicator has been built on key lessons of overcoming commonly observed limitations identified from the main body literature on climate-related frameworks. Hence, the proposed IMPETUS indicator framework specifically accounts for ensuring conceptual coherence between different definitions, providing user-guidance in selecting relevant indicators, incorporating stakeholders' feedback, developing flexible indicators, avoid complexity in calculation methods, consider process indicators or proxies when appropriate, build on existing knowledge, and allow for iterative revisions.

Categories, sub-categories and indicators were derived by a wide literature inventory, different monitoring, reporting and evaluation initiatives in place at the global, European and national scale, and complemented by stakeholders feedback). Accordingly, climate vulnerability indicators are categorised into five categories:

1. Health & well-being, which considers climate-related health risks, vulnerability of health infrastructure and overall socio-economic well-being.
2. Security of food & shelter, since both basic needs can be threatened by climate extremes such as heatwaves, water scarcity, floods or lack of adaptation capacity.
3. Water, particularly delivery of water services and availability of water resources, which are key vulnerabilities for many regions in Europe.
4. Energy supply, including energy demand and energy provision, are critical to reduce vulnerabilities to climate extremes particularly for marginalised communities.
5. Innovation power, meaning economic, human and institutional capacity necessary to develop and apply innovations, which is considered essential in addressing climate vulnerabilities.

Similarly, climate change adaptation indicators are categorised into four categories:

1. Institutional strength, to include coordination, strategies, plans & policies as well as laws and regulations that strengthen climate adaptation.
2. Allocated resources, to consider the application of instruments to provide financial incentives, insurance and risk sharing.
3. Knowledge and education, with reference particularly to climate information and adaptation tools as well as awareness and capacity-building, as a key elements of successful climate adaptation.
4. Adaptation interventions, to assess the progress in actual implementation of green measures (using vegetation and ecosystem services), grey measures (using infrastructure solutions such as dikes or building design) and behavioural change.

Local, regional and national climate practitioners in both Attica (Greece) and Zeeland (the Netherlands) have provided their feedback on a preliminary version of the core indicators. Their suggestions to better account for socio-economic capacity of citizens in relation to water, energy and food vulnerabilities as well as the inclusion of a vulnerability indicator about human migration have been incorporated. Besides providing indicators of adaptation and vulnerability, this report also proposes a resilience handbook. This brief guidance shows how the indicators selected from the IMPETUS indicator framework can be translated into a resilience assessment performed in task 3.4. In doing so, the guide intends to inspire practitioners, stakeholders and decision-makers that are going to undertake an evaluation of resilience to climate change in different sectors or bio-geographical areas.

The whole set indicators proposed in this report is meant to form the basis for and be supported by the analysis of climate change hot-spots (tasks 3.1 and 3.3; deliverable 3.2), resilience assessments (task 3.4) the analysis of costs, benefits and risks related to specific interventions (task 3.5) and the strategic resilience and multi-hazard management tools that support dynamic adaptation pathways (task 3.6). In conclusion, the proposed IMPETUS indicator framework provides a structured state-of-the-art reflection of key climate vulnerabilities and adaptation aspects that accounts for key challenges across Europe's bio-geographic regions. It may therefore from a solid basis for the demonstration sites and other European areas.

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Readers guide

The aim of this report is to produce a flexible (superset of) indicators and metrics to undertake resilience assessments and evaluate climate vulnerability and climate adaptation measures and pathways.

In this line, this document is structured in two main parts. Part I consists of chapters 0, 2, and 3 that provide general information about the objectives of this task (chapter 1), the methods used to achieve them (chapter 2), and an overview of existing indicators frameworks within which the IMPETUS proposal is framed (chapter 0). Part II of this document contains chapters 4, 5, and 6. In this second part, readers will find the proposed IMPETUS indicator framework: how it is structured (4.1), the contribution from stakeholders' involvement (4.2), and the core indicators on vulnerability and adaptation (4.3 and 4.4). Since processes that determine vulnerability or climate adaptation are strongly dependent on different bio-geographic and socio-economic contexts, chapter 5 contains an additional set of indicators to better account for specific issues that are not covered by the core indicators. Chapter 6 includes the resilience handbook, a guidance to undertake a resilience assessment. A final chapter, with the main conclusion, is provided at the end of the document (chapter 70).

A detailed description of all the indicators proposed in this document is provided as Annex I (a, b, c) and as a separate Excel database: Impetus superset - Climate vulnerability, Impetus superset - Climate adaptation. Annex II includes the questionnaire used to collect feedback from stakeholders.

Part I

1 Introduction

1.1 Setting the scene

Climate change urges strategic decision-makers across sectors and geographies to both mitigate and adapt, while weighing different interests and dealing with uncertainties and unknowns. The Paris Climate Agreement has been a substantial break-through as it sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C by 2100. However, whether or not this goal will be achieved is uncertain. For instance, the United Nations (2021) report on the National Determined Contributions of Greenhouse Gas Reduction indicates that nations must redouble their climate efforts if they are to reach the Paris Agreement. Even with global commitment to cut net global emissions in the short term, it would take a long time for atmospheric CO_2 to return to “pre-industrial” levels and many decades for surface air and sea to begin to decrease. In this context, understanding climate vulnerabilities and undertaking climate change adaptation must play a central role. In 2021, as part of the Green Deal, the European Commission adopted a new Adaptation Strategy that aims to increase and accelerate the EU’s efforts to protect nature, people and livelihoods against the unavoidable impacts of climate change (European Commission, 2019). The Strategy works on four principles: to make adaptation smarter, swifter and more systemic, and to accelerate international action on adaptation.

While governments and international agencies work on ambitious climate targets, many areas globally have been facing the local realities of climate change impacts. In Europe, climate-induced changes are causing the redistribution of some infectious diseases, as well as shifts in the distribution of many plant and animal species. These changes can adversely affect human health as well as livelihoods. Specific bioregions across Europe are particularly vulnerable to climate change, included southern Europe, the mountainous areas, coastal zones, deltas and floodplains, as well as the Arctic (EEA, 2020). In fact, Europe’s average annual surface temperature has been increasing at a faster rate than that of the global average temperature (IPCC, 2021). Especially, summer temperatures in southern Europe are increasing, whereas precipitation is generally decreasing. Floods and heatwaves are projected to increase in intensity and frequency (EEA, 2020), as has been seen with two recent extreme events seen across Europe (2022),namely floods in 2021 and heatwave in 2022:

1. In July 2021, several European countries including Germany, Belgium and the Netherlands were affected by catastrophic floods killing over 200 people. A month’s rainfall fell within 48 hours (Thieken et al., 2022). Historically, rivers have been straightened leaving little room for the river to meander. The extreme rainfall combined with poor climate adaptation has led to unprecedented water levels. As a result, roads and railways were destroyed and thousands lost their homes, with tens of billions of euros in economic losses.
2. In July and August 2022 (i.e., at the time of writing), the European Commission’s Joint Research Centre reported that the prolonged drought in the European Union (EU) shows that a staggering portion of Europe land surface is currently exposed to warning (44%) and alert (9%) (Toreti et al., 2022). Although large parts of Northern and central Europe are affected, water stress is most severe in Italy, France and the Iberian Peninsula. Drought emergency has been declared in five Italian regions in the Po River basin. Particularly, up to 60% of the risotto rice production (making up 40% of Italy’s agricultural output) could be lost because of salinity and seawater intrusion. Multiple water-use restrictions across municipalities have been implemented. Similar water-use restrictions have been taken in France. Notably, more than 100 French municipalities have no access drinking water through the tap and are being supplied by truck (Toreti et al., 2022). Spain has received less than half of the expected rainfall. In Portugal, hydroelectric energy stored in water reservoirs is at half the average of the previous seven years. Moreover, just halfway the typical fire season, wildfires have burned the second-largest area on record in Europe. Finally, drought is exacerbating the current energy/gas crisis (due to the war in Ukraine and associated geo-political tensions). Low river runoff and increased water temperatures limited power plants as well as the boat transport of coal in much of mainland Europe. Moreover,

hydropower reservoir levels have dropped suspending hydroelectric power generation (Copernicus, 2022).

These two extreme events show the complexity of understanding climate vulnerabilities (socioecological systems, geopolitics, human livelihoods, etc.) and emphasize the need of prompt action to enhance climate resilience. However, climate adaptation actions are extremely diverse and depend on tailored solutions to local geographic, climatic and socio-economic contexts. Climate adaptation decision-making typically involves many different stakeholder interests, and therefore requires a transdisciplinary approach. In order to support local stakeholders with such complex strategic decision-making, IMPETUS has developed a set of indicators as a powerful decision-support mechanism. Indicators are able to point to, provide information about, and describe the state, with a meaning that often extends beyond what is directly associated with the parameter value (OECD, 2003). Hence, indicators are effective guide for climate change adaptation actions.

1.2 Aim & Scope

The objective of Work Package (WP) 3 is to support strategic planning for the effective application of climate adaptation packages by developing and validating methodologies and tools for the assessment of European Regions and communities and their system's exposure and vulnerabilities to climate change related risks. More specifically, the final product of this task is the identification of a flexible superset of indicators that will be adopted by IMPETUS to undertake assessments and evaluate adaptation measures and pathways. The flexible superset of indicators focusses on assessing climate vulnerability, resilience and climate adaptation and will be available (also through WP2) to local stakeholders within the project and beyond.

The aim of this deliverable is to develop a flexible framework – the IMPETUS indicator framework – that forms the basis to undertake resilience assessments and evaluate climate vulnerability and climate adaptation measures and pathways.

In doing so, climate change vulnerability, resilience assessment, and adaptive capacity will be considered as the three pillars for identifying the most relevant indicators & metrics (I & M; Figure 1). The resulting superset of I & M will be referred to as the IMPETUS indicator framework.

Three pillars of the IMPETUS indicator Framework

I. **Climate vulnerability**
The propensity or predisposition to be adversely affected. Climate vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (Annex II, IPCC 2021)

II. **Climate adaptation**
The process of adjustment to actual or expected climate and its effects in order to moderate harm or exploit opportunities (Annex II, IPCC, 2021)

III. **Resilience**
The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation (Annex II, IPCC 2021).

2 Activities & methods

2.1 Activities

In order to define a superset of I & M for climate IMPETUS, we took a science-practice oriented approach. Therefore, the following activities ensure both scientific rigour and potential for practical application of outputs through a knowledge co-creation process:

I. Literature inventory of relevant I & M for climate vulnerability, resilience assessment, and climate adaptation actions.
II. Involvement of stakeholders: expert feedback from key demo-site representatives was gathered through a written questionnaire about the frameworks' preliminary scope, and the first draft list of I & M. The demo-site experts (representing local, regional and national scales) were given the opportunity to suggest additional indicators or eliminate redundancy. Moreover, they were asked to indicate which indicators they consider as relevant and applicable for their case study.
III. Finalisation of the framework, by processing feedback and finalising indicators.

2.2 Methodology

Definition of indicators and metrics

To identify a flexible framework indicators related to climate change vulnerability, resilience assessment and climate adaptation, we applied the definitions for I & M provided by Arnott et al. (2016). They define indicators as "*a quality or trait that suggests effectiveness, progress, or success*". Hence, indicators typically are normative and goal oriented. Basically, a low score implies poor levels of success, whereas a high score implies high levels of success. Metrics on the other hand are defined by Arnott et al. (2016) as "*a variable that can be measured (if quantifiable) or tracked (if qualitative) that represents the indicator*". In this deliverable, we added supportive metrics that are required to calculate the indicators. Indicators usually consist of a single factor or variable, while indices are made up of multiple indicators and combine them into a single number. For instance, indicator-based approaches to assess coastal vulnerability consist of a set of independent elements (i.e., the indicators) that characterise key coastal issues (ETC-CCA, 2011). The design of indices is more complex and requires more detailed guidance for the exact computation (Leiter et al., 2022). For instance, the vulnerability to extremes of heat can be measured through an index (The Lancet Countdown, 2021) that combines data on the proportion of the population older than 65 years; the prevalence of chronic respiratory disease, cardiovascular disease, and diabetes in this population, and the proportion of the total population living in urban areas.

Index-based approaches have the advantage of integrating multiple information in a single value (the index), while they are not often immediately transparent in communicating results, and may not enable the understanding of assumptions and aggregations that led to their calculation (ETC-CCA, 2011).

Indicator terminology & selection criteria

Based on the above definitions and considering the specific different demonstration sites, the IMPETUS indicator framework includes two types of indicators:

I. **Core indicators**: Indicators shown in the key framework because they are supposed to be of particular relevance for most demonstration sites.
II. **Additional indicators**: Indicators that are more related to specific contexts or bio-geographical regions. These can be used in order to complement the core indicators on a case-by-case basis.

Moreover, a third group of indicators – supportive metrics – complete the overall IMPETUS indicator framework. Supportive metrics are meant to be used to complement the information provided with core indicators.

In order to select indicators that are timely, salient and convenient for the intended use and data availability, a few principles are adhered to:

1. Focus on publicly available data (at least at country level);
2. Selecting indicators with respect to the estimated relevance for the demo-sites;
3. Wherever possible select indicators that are already applied in practice;
4. Selection of additional, more tailored, methodologies that require case-by-case data collection;
5. Providing the demo-site stakeholders the opportunity to complement indicators or eliminate redundancies.

Literature inventory

Climate vulnerability – For identifying climate vulnerability indicators, the literature inventory was conducted through consulting English scientific literature using Scopus and Google scholar. In order to align with topical indicators, only papers were selected that are published between 2010 and 2022. Next, the resulting papers have been read and further evaluated for inclusion. Inclusion criteria for the full review were based on applicability in relation to the envisioned use, timeline, data population main purpose of the IMPETUS indicator framework of the project's demo-cases. Finally, by applying the 'snowball method', we used the reference list of articles to search for other relevant papers as well as relevant work through the earlier research and experiences of all co-authors- and inventory of grey literature such as non-academic websites, reports or evaluation schemes. Moreover, suggestions by the demo-site representatives were included too. The literature inventory is by no means comprehensive but intended to outline key I & M that are timely, salient and convenient for its intended use and data availability.

Climate adaptation – For identifying climate adaptation indicators a more practice-oriented approach was taken. Since many complex sets of place-specific indicators exist – each with slightly different methods of calculation and application – a focus on indicators that have been applied by practitioners was deemed as most valuable.

To avoid an excessively long list of specific indicators that could only be applied in a few sites, the adopted approach is to use flexible indicators, quite general in their statements, that can be hence adjusted to different sectors or geographical scales. Outcome indicators that refer to the long-term impact of adaptation interventions (i.e., measuring the overall change in the resilience) are not included in this framework because they are more difficult to calculate and are not commonly found and implemented in current frameworks. Moreover, adaptation interventions may require several years before their effects can be measurable and long-term changes in natural resources and ecosystems cannot be entirely attributed to the interventions but can be the final result of diverse changing factors.

The climate adaptation indicators were mainly derived from:

- Global frameworks (e.g., The Sendai Framework for Disaster Risk Reduction, the indicators for the Sustainable development goals)
- International frameworks that track adaptation progress at the subnational level (C40, Covenant of mayor, UN New Urban Agenda)
- National systems (Adaptation Plans and Strategies)
- Papers and publications

If similar indicators between different information sources were found, they were merged in a single (flexible) indicator, keeping the reference to all the original frameworks used for its final formulation. Finally, the indicators are divided over category and subcategories. The used approach is inspired by the categorisation of Key Type Measures proposed by the ETC/CCA Technical Report 2021 (Leitner et al. 2021) to support EU Member states in the reporting under the Regulation on the Governance of the Energy Union and Climate Action in 2021.

Resilience assessment – To identify the resilience assessment methods, the same approach was used as described for climate vulnerability. However, in order to describe the theoretical foundations of the resilience concept, papers from before 2010 were consulted.

A database is compiled for each indicator (see Table 1).

Table 1 List of features and explanations used to define the indicator of the IMPETUS indicator framework. Annex I A and B provide a detailed overview of the indicator features. Further details can be found in the. Excel database: Impetus superset - Climate vulnerability, Impetus superset - Climate adaptation.

Indicator feature	Explanation
Indicator typology	Core indicator, additional indicator or supportive metric
Indicator name	Indicator number followed by the name
Principal	The key meaning of what the indicator represents
Framework, main category	Specifies the main category to which the indicator is allocated
Framework, subcategory	Specifies the subcategory to which the indicator is allocated
Main climate change factor	Air Temperature; frost; precipitation and river flood; aridity and drought; fire weather; wind; snow, glaciers and ice sheets; relative sea level; coastal flood; ocean temperature or ocean chemistry (factors are the hazard types identified by the IPCC (2021))
Other climate change factor	If applicable, an additional climate factor is added
Main affected sector	Agriculture and food; biodiversity (including ecosystem-based approaches); buildings; coastal areas; civil protection and emergency management; energy; finance and insurance; forestry; health; marine and fisheries; transport; urban; water management; ICT (information and communications technology); land use planning; business; industry; tourism; rural development; nonspecific (EEA, 2021)
Other affected sectors	If applicable, an additional sector is added
Indicator type	Quantitative, semi-quantitative or qualitative
Corresponding metric(s) and unit(s)	List and description of metrics and their units that constitute the indicator
Spatial scale (lowest resolution)	Lowest resolution for which the indicator can be applied given the available data or capacity to populate this data. A distinction between local, regional, national and nonspecific was made
References	Scientific reference to document where the indicator is proposed and, if applicable, reference to database

Collecting stakeholders' feedback on the IMPETUS indicator framework

A careful selection and/or formulation of indicators is strongly reinforced by the collaboration of and input from relevant stakeholders and decision-makers, who, being directly involved in vulnerability management and adaptation actions, can give concrete input in co-developing the indicator framework.

As such, a stakeholder feedback process was initiated. A preliminary overview of the framework's core indicators was provided together with nine questions regarding the framework's usability and prompting stakeholders to provide suggestions in useability. In order to account for multiple levels of climate decision-making, the questionnaire was sent to specific professionals at the local, regional and national level in two of the demonstration sites, namely Attica in Greece and Zeeland in the Netherlands. The questions and preliminary framework shared with the stakeholders can be found in Annex II. The stakeholders were asked to provide their written answer and considerations. Support from WP2 in filling in the questions was provided if necessary. Moreover, the survey questions, indicator names and indicator descriptions were translated to both Greek and Dutch to avoid potential confusions due to language barriers. All target stakeholders replied to the queries. Five of them provided detailed feedback in writing. The Ministry of Infrastructure and Water Management in the Netherlands replied too but abstained from providing detailed feedback. Instead, they referred to two leading policies which are acknowledged in several indicators in the proposed framework. The stakeholders' feedback proved valuable and several improvements in the framework were made to fully account for this feedback.

3 Existing climate indicators – An overview

3.1 Introduction

Though monitoring and evaluation of climate vulnerability adaptation progress is key for climate risk management, it is still in an early stage in many countries (IPCC, 2021) and insufficiently used to assess the long-term effects of adaptation interventions.

The IPCC (2014) has identified three main uses of indicators for assessing adaptation:

I. Determining the need for adaptation,
II. measuring the process of implementing adaptation, and
III. measuring the effectiveness of adaptation.

For the first point, the need of adaptation directly refers to measuring vulnerability (the more vulnerable a region, the greater the need for adaptation). Secondly, measuring the progress in the adaptation process can refer to both the improvement of enabling conditions (defined by governance, funding, knowledge) and to the progress of implemented climate adaptation interventions. Thirdly, assessing effectiveness is the most complex task, since adaptation interventions can take a long time before measurable results can be identified.

Common approaches, as found in the literature (e.g., Stadelmann et al., 2015; OECD, 2017) structure adaptation indicators in input, output and outcome (or impact) categories. Input indicators refer to the potential climate adaptation. Output indicators reflect the immediate results of adaptation actions (e.g., impact of adaptation policies). Outcome indicators refer to the actual effect of adaptation in reducing the climate change impacts. By using this approach to measure the effectiveness of adaptation, the (residual) vulnerability after the intervention(s) are completed, is also measured.

To date, experiences in monitoring national adaptation progress have focused more on adaptation outputs than on adaptation outcomes and evaluations. This is due to the reason that in many cases adaptation policies and programmes lack measurable targets or clearly defined expected outcomes, which are necessary to assess their effectiveness using indicators (OECD, 2017). In addition, authors such a Leiter and Pringle (2018) and Leiter et al. (2019) distinguish between *ex-ante* and *ex-post* metrics. Ex-ante metrics reflect the situation prior to the implementation of adaptation action whereas ex-post metrics show the change after implementation. As such, ex-ante metrics support decisions about resources allocation and ex-post metrics track adaptation actions mainly to support effective implementation and assess the effectiveness of adaptation actions.

Concerning vulnerability, indicators commonly reflect the complexity of the concept itself and refer to three key elements:

1. **Exposure** – The presence of people, livelihoods, assets, species or ecosystems, environmental functions, services, and resources that could be adversely affected by climate change.
2. **Sensitivity** -The degree to which a system is affected, either adversely or beneficially, by climate related stimuli. It depends on biophysical factors, social factors or a combination of both.
3. **Adaptive capacity** – The ability of a system to adjust to climate change to moderate damages, to take advantage of opportunities, or to cope with its consequences.

Borders between the aforementioned different types of indicators, and even between impact indicators, vulnerability indicators and adaptation indicators are quite fluid, so that different interpretations and different ways of categorising indicators are commonly found in different monitoring frameworks.

Moreover, several existing frameworks and approaches, proposed in different contexts to monitor adaptation progress and vulnerability change, are very heterogeneous, making comparability across different spatial scales and different regions challenging. An increasing number of studies (academic and grey literature) explore the challenge of measuring the progress of collective adaptation, outlining both advantages and trade-offs of this effort. Results indicate that, despite many advantages, measuring the progress and effectiveness of adaptation through I & M poses more constraints than monitoring climate change mitigation due to its greater complexity and dependency on specific place-based characteristics.

As described in the following sections, existing indicator frameworks track adaptation progress and change of vulnerability over time working at the global level (as described in section 3.2), at the European level by collating information from member countries (section 3.3) or at subnational level, comparing for example adaptation progress and change in vulnerability in different cities of the world (section 3.4).

3.2 Global evaluation frameworks

This section outlines the four main indicator-based frameworks (Paris Agreement, Sendai Framework for disaster risk reduction, Agenda 2030 and the Lancet Countdown) that directly or indirectly address the goal of tracking global climate change adaptation and climate change vulnerability. Figure 1 provides a visualisation of these four leading global frameworks on climate adaptation and climate vulnerability.

The **Paris Agreement** defines a Global Goal on adaptation (Art. 7) that features three core components:

I. Enhancing adaptive capacity,
II. strengthening resilience and
III. reducing vulnerability to climate change, in the overall context of limiting global temperature rise as close as possible to 1.5 degrees Celsius above pre-industrial levels.

Under this agreement, all parties are requested to communicate their priorities, plans, actions, and support needs through dedicated adaptation communications. The Art. 14 of the agreement establishes a global stocktake for the implementation of the Paris Agreement. The first global stocktake is planned for 2022–2023 and will support the assessment of collective progress towards achieving the global goal on adaptation. Discussions on how to undertake the global stocktake have started and a technical paper that analyses potential approaches to assessing the global goal on adaptation has been prepared (Adaptation Committee, 2021). Country-specific approaches to adaptation monitoring and evaluation, as well as approaches used at the subnational level, are found to be potentially useful to track progress towards global adaptation goals.

The **Sendai Framework on Disaster Risk Reduction** (2015-2030) outlines seven targets and four priorities for action to prevent new disaster risks and reduce existing ones. Both man-made risks and risks from natural causes are included in this strategy. Clear linkages and synergies between climate change adaptation and disaster risk reduction exist and are encouraged by the 2021 EU Strategy on Adaptation to Climate Change. This is encouraged because increasing extreme weather events induced by climate change are enhancing the disaster risks related to floods, droughts and wildfires. The Sendai Framework (UNISDR, 2015) includes a system of 38 indicators. Examples of indicators that are relevant for climate change adaptation and climate vulnerability are the measurement of the direct economic loss attributed to disasters in relation to global GDP (indicator C-1); the damage to critical infrastructure attributed to disasters (indicator D-1); and the number of countries that have multi-hazard early warning systems (indicator G-1).

The **Agenda 2030 for the Sustainable Development** includes a global indicator framework composed of 17 goals and 231 indicators, some of them offer interesting synergies for climate change vulnerability and climate adaptation. Goal number 13 is the more relevant for climate change (i.e., take urgent action to combat climate change and its impacts). Potentially relevant Sustainable Development Goal (SDG) indicators under this SDG 13 include: the number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population (indicator 13.1.1); the number of countries that have communicated the establishment or operationalisation of an integrated policy, strategy, or plan which increases their ability to adapt to climate change and foster climate resilience and low emissions development (indicator 13.2.1).

Other synergies can be clearly found under SDG 2 (end hunger, achieve food security and improved nutrition and promote sustainable agriculture), SDG 6 (ensure availability and sustainable management of water and sanitation for all), SDG 11 (make cities and human settlements inclusive, safe, resilient and sustainable") and SDG 15 (protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and half and reverse land degradation and halt biodiversity loss).

Indeed, climate change is a crosscutting issue that naturally finds common elements with most SDGs. Moreover, adaptation actions should avoid contradiction with sustainable development, otherwise they could potentially turn into maladaptation actions, affecting for instance marginalised and vulnerable groups, enhancing inequalities or constraining vital ecosystem services.

The **Lancet Countdown**, an international collaboration that independently monitors the health consequences of climate change, publishes a global report that proposes new and improved indicators and updates existing ones every year. The set of indicators is based on a consensus of leading researchers from academic institutions and UN agencies. The 2021 report outlines a list of 44 indicators, out of them there are:

- 14 indicators of climate change impacts, exposures, and vulnerability and
- 8 indicators regarding climate change adaptation, planning and resilience for health.

The first group of indicators addresses the direct implications of rising temperatures for health, climate-sensitive extreme events, climate-sensitive infectious diseases, food security and undernutrition, migration, displacement and rising sea levels. The second group of indicators refers to planning and assessment, information systems, delivery and implementation as well as funding and spending.

Figure 1 summarises the four leading global frameworks on climate adaptation and climate vulnerability.

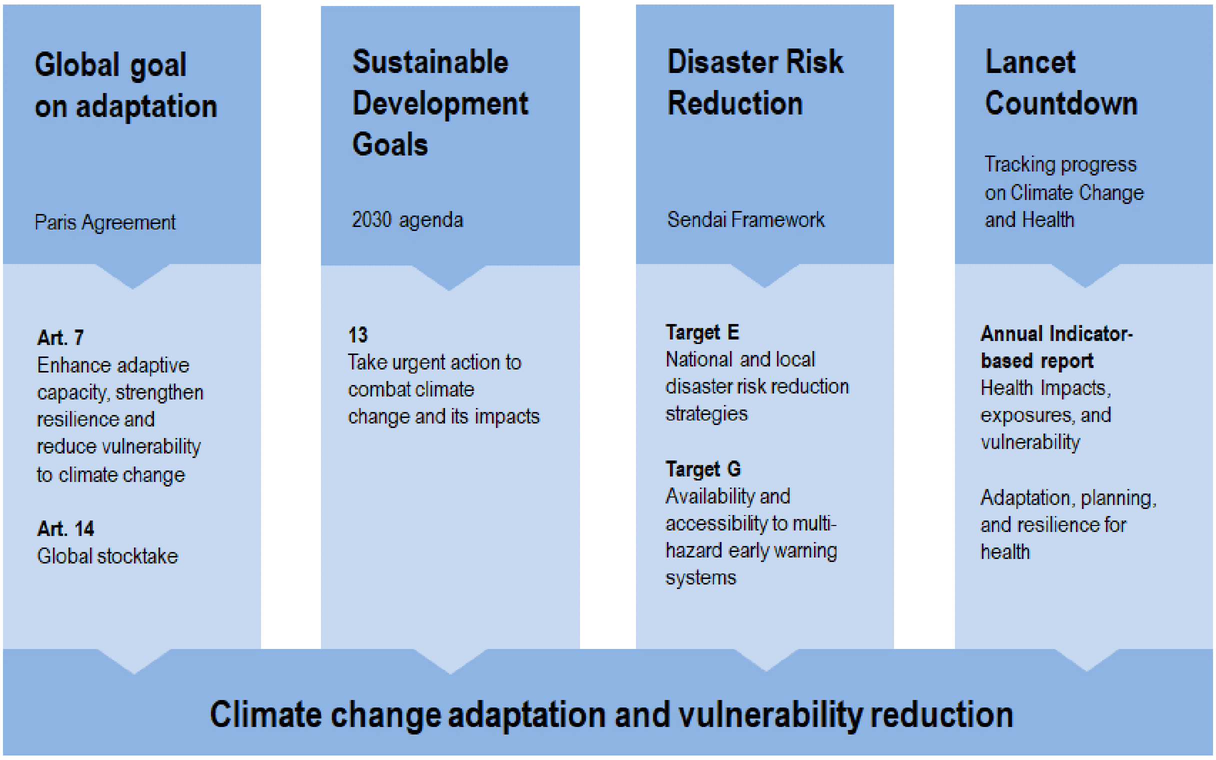

Figure 1 Main global frameworks for monitoring climate change adaptation and climate vulnerability reduction.

3.3 European evaluation frameworks

In order to assess the progress of EU Member States towards the adaptation goals set by the 2013 EU adaptation strategy, the European Commission issued the "**Adaptation preparedness scoreboard Country fiches** (SWD(2018)460)" in 2018. The approach was based on a scoreboard that allowed to assess Member States' progress in their adaptation policies, including the content of national adaptation plans and strategies.

The adaptation preparedness scoreboard methodology used by the European Commission identified 30 indicators with reference to the five steps of the adaptation cycle:

I. Preparing the ground for adaptation,
stakeholders' involvement in policy development;
II. assessing risks and vulnerabilities to climate change;
III. identifying adaptation options, and
IV. implementing adaptation actions.

Indicators are formulated as key questions (e.g., Is a central administration body officially in charge of adaptation policymaking? and, Are observation systems in place to monitor climate change, extreme climate events and their impacts?). Member states were asked to prepare short answers (i.e., yes, no or in progress) accompanied by a narrative.

The scoreboard results were elaborated and used by the European Commission to collect information from member states primarily for the evaluation of the 2013 EU Adaptation Strategy. Moreover, the system allowed to evaluate progress of adaptation over time at the national level and offered an opportunity for countries to learn from other countries' experiences and to explore the applicability and usefulness of indicators developed at national level.

Although most European countries have developed their national adaptation strategies and several countries have adopted a National Adaptation Plan, the experience in Monitoring, Reporting and Evaluation (MRE) is still limited. Relatively few existing systems for adaptation monitoring and evaluation are in place at the national level. The ETC-CCA (2018) technical paper provides an overview of the progress made in the development- and implementation of indicators used for monitoring and evaluating climate change adaptation at the national level. The paper reveals that only few European countries have an operational set of indicators in place. It should be noted that this is a paper evaluating the period before 2018 and of course more progress could have been made since then. In the paper the available sets of indicators at national level were analysed and compared ad this analysis revealed that:

- National adaptation indicators might require significant data resources to be developed,
- the involvement of a broad range of stakeholders in the process of defining indicators is key, and
- the process of developing indicators is iterative, requiring successive steps of development.

The **Regulation on the Governance of the Energy Union and Climate** (Reg. 1999/2018) currently establishes formal requirements for reporting on climate change adaptation by member states to the European Commission. The regulation aims to implement strategies and measures designed to meet the objectives and targets of the European Union consistent with the Paris Agreement and the 2030 targets for energy and climate. The regulation includes the obligation of member states to provide an integrated report on national adaptation actions (Article 19) on a biennial basis. Member states have to report "information on their national climate change adaptation planning and strategies, outlining their implemented and planned actions to facilitate adaptation to climate change".

Among various information provision requirements, member states are also requested to report about their MRE methodology related to reducing climate impacts, vulnerabilities, risks, and increasing adaptive capacity. Approaches, systems, transparency and indicators used by countries need to be explicitly specified in the national reports.

The latest web-based reporting (2021) includes information from 27 countries, showing a heterogeneous picture about systems used at the national level to track adaptation progress. Based on the information available in the Reportnet3 platform: https://reportnet.europa.eu/public/dataflow/110 (the infrastructure for supporting and improving data and information flows from member states), 13 countries reported about an established, or at least proposed, set of indicators (generally defined as part of the National Adaptation Plans). Five countries reported that a system of indicators is under study or is planned for the near future. Seven countries did not report about a system of indicators in place for their national adaptation policies and for the two remaining countries, there was no public information available.

3.4 Evaluation frameworks for climate action in cities

The success of Europe's adaptation efforts is strongly influenced by the action of cities and local authorities. Cities, as the centres of dense populations and infrastructure are particularly vulnerable to the effects of climate change. Indicator-based approaches have been proposed within the framework of international networks that promote cities cooperation to face climate change.

The **Mayors Adapt** initiative was launched by the European Commission in 2014. Mayors adapt is a sister initiative of the **Covenant of Mayors**, with the aim of addressing adaptation to climate change. Since 2016, the Covenant of Mayors, Mayors Adapt and the Compact of Mayors joined forces to create the Global Covenant of Mayors for Climate and Energy, becoming the largest movement of local governments committed to tackle three key issues:

I. Climate change mitigation,
II. climate change adaptation, and
III. universal access to secure, clean and affordable energy.

The reporting framework of the Covenant of Mayors initiative (https://www.eumayors.eu/support/adaptation-resources.html) includes a section with a list of adaptation indicators categorised as follows:

- Process-based indicators: track where the local authority is in the adaptation process (self-assessment questions).
- Vulnerability indicators: provide information about the level of the local authority's vulnerability to climate impacts (incl. exposure and sensitivity to risk).
- Impact indicators: give an indication of the impacts of climate change (e.g., affecting the environment, society and the economy) measured by the local authority in its territory.
- Outcome indicators: quantify progress in delivering adaptation actions and outcomes (e.g., vulnerabilities reduced / resilience strengthened) in the different sectors.

C40 cities is another large-scale cities focused initiative. It is a global network of nearly 100 world-leading cities taking urgent action to confront the climate crisis. C40 mayors and the cities they lead are taking ambitious, collaborative and urgent climate action that aligns with science-backed targets.

One of the crucial components of C40's Climate Action Planning programme (CAP) is the monitoring and evaluation of cities' climate change actions. The City CAP Monitoring, Evaluation and Reporting (MER) Indicator Matrix is the C40 tool that supports cities to put in place or strengthen their current MER system for climate action, cutting across mitigation, adaptation, and equity and inclusiveness. The C40 City Climate Action Planning MER Indicator Matrix is a database list of 106 climate priority actions and proposed results chain indicators (from action to impact) for monitoring and evaluation purposes (see: https://resourcecentre.c40.org/resources/monitoring-evaluating-and-reporting). It has been developed to support city climate action planning teams which are responsible for identifying, selecting and using MER indicators in a structured and effective way. The matrix includes a list of actions for climate change adaptation, proposing:

- Output indicators, to monitor the actions progress, e.g.: area of coastline protection created.
- Outcome indicators, to monitor the results of the adaptation, e.g.: percentage of storms leading to floods.
- Impact indicators, to monitor the effects of adaptation on people and assets at risk, e.g.: change in people/number of assets affected or damaged by floods.

Finally, the **UN New Urban Agenda** was adopted at the United Nations Conference on Housing and Sustainable Urban Development (Habitat III) in Quito, Ecuador. It was endorsed by the United Nations General Assembly at its sixty-eighth plenary meeting of the 21st session on 23 December 2016.The New Urban Agenda is an action-oriented document that mobilizes member states and other key stakeholders to drive sustainable urban development at the local level.

The implementation of the New Urban Agenda contributes to the 2030 Agenda for Sustainable Development and to the achievement of the SDGs and targets, with special reference to goal 11 of making cities and human settlements inclusive, safe, resilient and sustainable. The New Urban Agenda Monitoring Framework is composed of 77 indicators with some relevance also for climate change adaptation and vulnerability (see: https://www.urbanagendaplatform.org/data_analytics). Examples include indicators coming from the framework such as percentage of local governments that adopt and implement local disaster risk reduction strategies in line with national strategies. In addition, the New Urban Agenda Monitoring Framework includes indicators that refer to the presence of multi-hazard mapping, monitoring and forecasting systems.

3.5 Limitations and challenges

In the previous sections of this chapter, we have outlined the background of existing indicator frameworks addressing different topics that are also relevant for climate change vulnerability and adaptation.

Adaptation and vulnerability indicators are useful to policymakers and decision-makers in various ways. They are a tool to monitor progress towards the implementation of adaptation policies, strategies and actions, but they also offer a target, justify and monitor funding, and could be used as a tool for comparing adaptation achievements (across sectors, geographical areas and scales).

However, there are also limitations and challenges in developing and using indicators for climate change adaptation and vulnerability. Therefore, in this section 3.5 the main limitations and challenges, as described in several academic and technical papers (e.g., OECD, 2017; Stadelmann et al., 2015; UNEP-DTU partnership, 2018; Leiter et al., 2019; Bours et al., 2014; GIZ-IISD, 2014), are discussed.

In order to solve these limitations and challenges, this section also explores possible strategies and solutions that are used as guiding principles to build the IMPETUS indicator framework.

Limitations and challenges:

1. **Climate change is global, but adaptation is local**. The selection of the most suitable adaptation options is almost without exception site-specific. Accordingly, climate adaptation depends amongst others on the specific experienced vulnerabilities, the environmental context, the socio-economic context, and the sectors affected. The lack of universal metrics that can be used for adaptation and vulnerability (e.g., as tonnes of greenhouse gasses for mitigation) leads to a plethora of monitoring schemes that tend to be complex and diverse.
2. **Adaptation and vulnerability intertwine over multiple spatial scales.** Data that is useful for global policy and comparative research (e.g., number of countries that have adopted a disaster risk reduction strategy) might not be relevant to evaluate smaller-scale initiatives – and vice versa
3. **Adaptation typically lacks common measurable targets**. A key characteristic of climate adaptation is that it does not have a clear endpoint. On the contrary, adaptation can be understood as a process of continual adjustment to changing vulnerabilities that result from complex interactions in the social-ecological system. As such there often is hardly any measure or benchmark that signals that an adaptation programme is ‘successful’ or that its goals have been achieved. This makes adaptation monitoring more complex than for instance climate mitigation monitoring, which has a clear target to limit the global warming to an established temperature increase.
4. **Lack of a well-known, agreed and fixed baseline to assess change**. Simply comparing ‘before’ and ‘after’ the completion of an intervention may be insufficient to evaluate the impact of a programme since the overall context itself is dynamic.
5. **Measuring the success of adaptation is complex.** Monitoring adaptation results may require measuring the “avoided impacts”. Quantifying what would have happened in the absence of an intervention is more complex than measuring the direct positive effects of an intervention. Moreover, significant time lags can exist between adaptation interventions and measurable impacts and long-term changes might not be easily univocally attributed to adaptation interventions.
6. **A substantial number of subtle distinctions between different types of indicators exist**. Different definitions of input, process, output and outcome indicators create possible misunderstandings. Indicators for impact, vulnerability and adaptation are not always clearly presented in distinctive ways.
7. **Indicators may not sufficiently signal maladaptation**. Indicators that track adaptation progress can measure the extent of adaptation, but are not always able to assess the overall quality of adaptation, and the overall environmental and social sustainability in the long term. Moreover, it does not always track possible negative side-effects of the adaptation strategy.
8. **Indicators reflect only progress or change but rarely explain how, why and what could be done to improve**. Hence, the importance of explaining the overall process of adaptation (climate and vulnerability analysis, involvement of stakeholders, selection of adaptation options) and interpretation cannot by underemphasized.

9. **Monitoring adaptation can be resource-intensive, requiring proper data and technical capacity**. The lack of monitoring of some variables and the lack of a centralised system to coordinate and store data often form barriers for using indicators. Moreover, time series cannot be long enough or complete enough to detect changes. Finally, calculation details are not always specified, so that a single indicator, though developed and agreed in international frameworks, can be calculated in different ways, leading to contrasting results.

Strategies to address the listed challenges and limitations (which will guide the preparation of the IMPETUS indicator framework) are:

A. Clearly adopt the definitions of vulnerability, adaptation, and resilience; and clearly define the scope of indicators. *Challenge 6.*

B. Avoid indicator frameworks with too many indicators without giving guidance on the possibility of selecting most relevant and possibility for tailoring. Consider to start with a smaller number of indicators and build up the indicator set as experience grows. *Challenge 9.*

C. Engage a wide range of stakeholders in the indicators selection and in the monitoring and evaluation process*. Challenges 5, 7, 8 and 9.*

D. Define flexible indicators that can be adapted to different spatial scales (for example number of countries/regions/municipalities that have adopted a disaster risk strategy), and different sectors. Consider that indicators can be tailored to suit different contexts and stakeholder groups, in order to be widely applicable across numerous countries. *Challenges 1, 2, 3 and 4.*

E. Avoid too vague or too complex indicators. Adaptation indicators should be accompanied by details about their operationalization, including their rationale, guidance on interpretation, calculation, and data sources. The more difficult an indicator is to track, the less likely it is going to be applied. *Challenge 5 and 9.*

F. Consider the possibility of using process-indicators, whenever long-term effectiveness of adaptation interventions are hard to measure. *Challenge 5.*

G. Consider the inclusion of proxy indicators, as 'vulnerability' and 'resilience' are not easily measured. Also provide the possibility of illustrating efforts in a non-exhaustive way, including qualitative approaches and complementary narrative descriptions to better explain and frame results. *Challenges 3, 4, 7 and 8.*

H. Make use of- and maximise synergies with already existing or upcoming frameworks of indicators and monitoring and evaluation schemes. *Challenge 9.*

I. Consider the need of iterative revisions of indicator frameworks, based on a learning-by-doing processes. *Challenges 3, 4 and 5.*

The way solutions match limitations is illustrated in Figure 2. Stakeholder engagement to co-develop tailor-made indicators (C) can be regarded as quite common solution to several challenges, to develop indicators that are really relevant and actually quantifiable. The use of flexible indicators (D) (i.e., indicators that can be adapted and adjusted to each individual context) is another possible solution to overcome the lack of universal metrics and targets for adaptation. Periodical revision of the indicator framework through a learning-by-doing process (I) can be a strategy that allows to cope with uncertainties, lack of a well-known baseline or to improve indicators that reveal poor applicability. Qualitative approaches and narratives (G) can support and complement quantitative approaches especially when they fail to explain the complexity of adaptation interventions or vulnerability change.

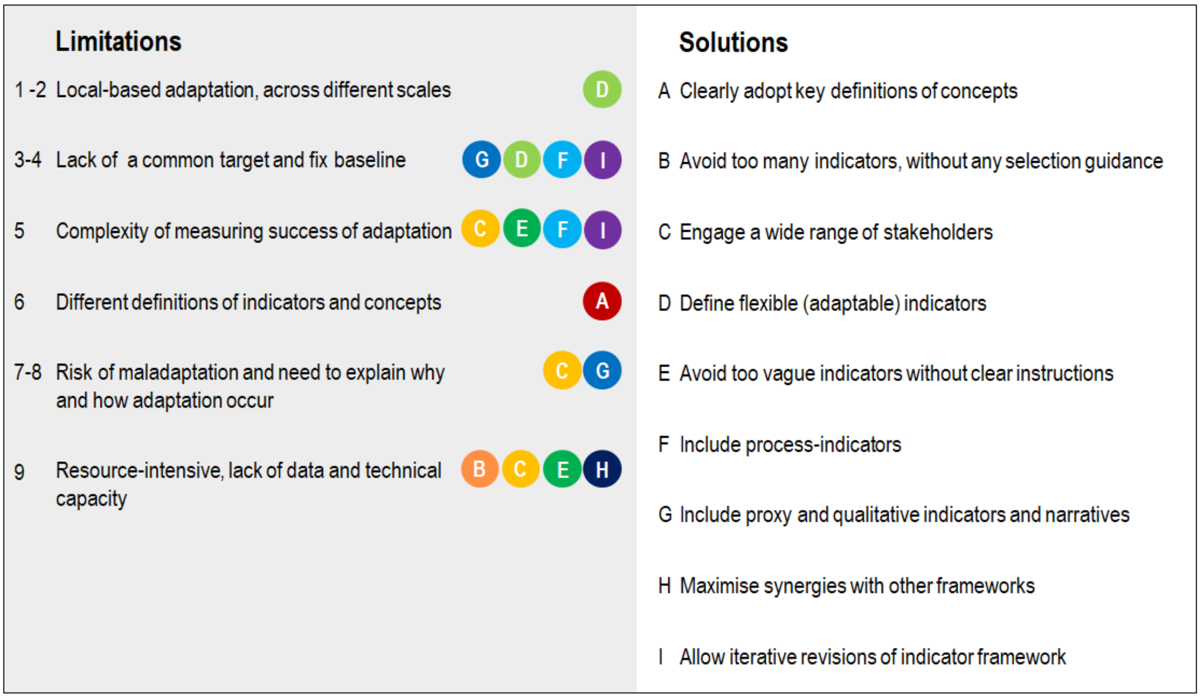

Figure 2 Main limitations of indicators frameworks for climate change adaptation and vulnerability and what solutions can be applied. For the full explanation of limitations and solutions, see the main text.

In the previous Part I of this deliverable, we have described the general objective of this task (chapter 1), the methods used to achieve them (chapter 2), and an overview of leading indicators frameworks within which the IMPETUS proposal is embedded (chapter 0). Hence, part I has been an introduction to- and theoretical basis for Part II, which presents the IMPETUS indicator framework.

The following chapters (4, 5 and 6), provide more in-depth information on the IMPETUS indicator framework. In Part II, readers will find an elaboration of the proposed IMPETUS indicator framework. More specifically: how it is structured (section 4.1), the contribution from stakeholders' involvement (section 4.2), the core indicators (sections 4.2 and 4.3) and additional indicators (chapter 5) on vulnerability and adaptation, and the resilience handbook, and a guidance to undertake a resilience assessment (4.5). A final chapter, with the main conclusions, is provided in chapter 0.

Part II

4 Constructing the IMPETUS indicator framework

4.1 Envisioned use & framework set-up

The idea of the IMPETUS indicator framework is to have a flexible, medium-sized collection of indicators that covers different aspects of social-ecological systems that are prone to climate change impacts, while at the same time, reflects the efforts and changes that we consider helpful in societies endeavouring to adapt to climate change. Furthermore, it needs to include solutions as formulated in Figure 2. Hence, the indicators that are included in this framework consider both climate vulnerability and climate adaptation. These indicators together provide an idea of our current status, challenges, and expectations, with regard to climate change.

The IMPETUS indicator framework is meant to be used within the IMPETUS project, especially by partners and stakeholders of demonstration sites, and beyond the project as a structured repository of indicators applicable to undertake resilience assessments and evaluate climate vulnerability and climate adaptation progress in Europe. In this sense, these indicators need to be clear enough to be understandable, unambiguous, and focused on something that can be measured in the most accurate and objective way. In addition, the IMPETUS indicator framework needs to put together the most relevant indicators of existing frameworks.

It is important to remark that these indicators will have different scales of application, some being reasonable to study at a local (city) scale, while some others are more suitable on a national scale, which is reflective of the demonstration sites and their climate change vulnerabilities. Hence, we have arranged these indicators in a table that is divided into categories and subcategories, and for each indicator we specify at which scale the indicator can be most beneficial in supporting climate-sensitive decision-making.

Stakeholders in general and partners within the IMPETUS project specifically, may select specific indicators for further use in strategic decision-making, analysis of climate resilience or hotspot analysis of vulnerabilities. The framework of core indicators is intended to be a cohesive and comprehensive set of indicators that stakeholders can use to determine their own key indicators relevant for the own contextual climate-related vulnerabilities and adaptation trajectories.

Figure 3 provides an overview of the different elements of the IMPETUS indicator framework. The framework consists of two core indicator streams, one for climate vulnerability and climate adaptation, having respectively five and four main categories. Both core frameworks have additional indicators that are more specific. Finally, the resilience assessment guide is included to provide an easy-to-understand introduction to the concept of resilience and how the proposed indicators link to task 3.4 on resilience assessments in the demonstration sites. More specifically, the three key components can be described as*:*

1. **Core Framework -** Two closely interlinked sets of indicators comprise the core framework. One for climate vulnerability and one on climate adaptation. Supportive metrics are developed to complement the core indicators.
2. **Additional indicators** – The core frameworks on climate vulnerability and climate adaptation each have a set of additional indicators that apply to more specific European contexts. The additional indicators are structured according to the same categories as the core frameworks.
3. **Resilience assessment guide** – The guide provides an easy-to-understand overview of how the complex concept of climate resilience can be considered and how resilience assessments enable climate-sensitive strategic decision-making. The guide also explains how the identified indicators can form the input for Task 3.4 on resilience assessments.

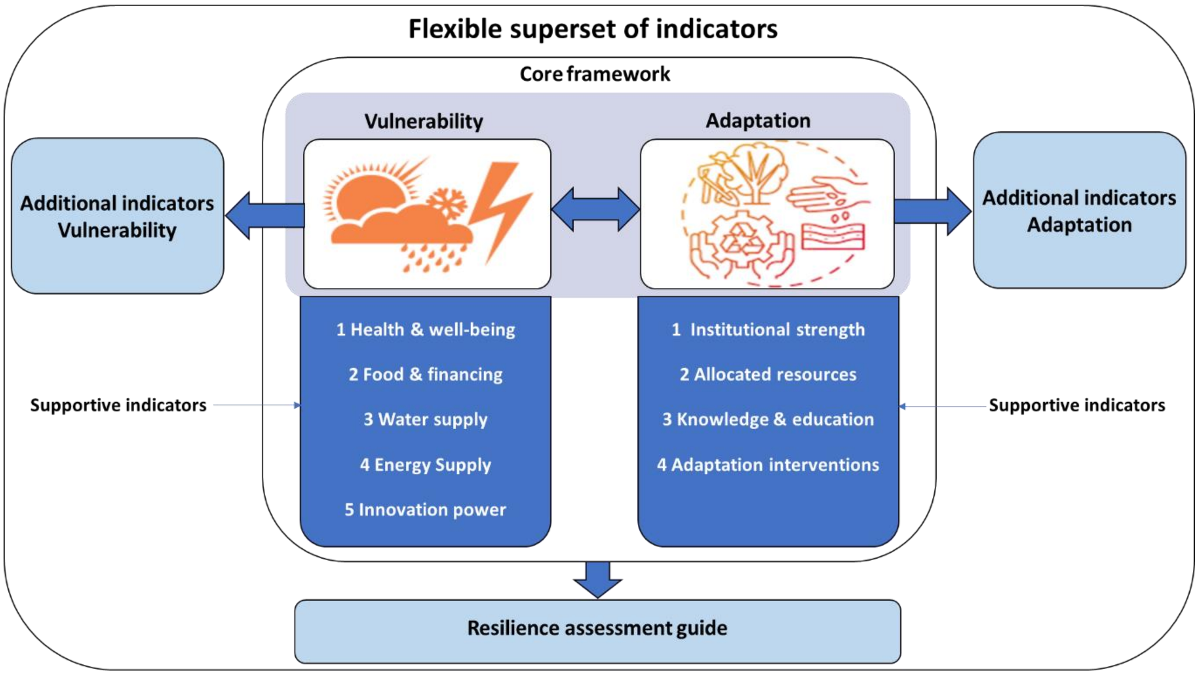

Figure 3 Set-up of IMPETUS indicator framework. The framework consists of two core indicator streams, one for climate vulnerability and climate adaptation. Both core frameworks have additional indicators that are more specific and supportive indicator or metrics needed to calculate the core indicators. The resilience assessment guide is included to provide an easy-to-understand introduction to the concept of resilience and how the proposed indicators link to task 3.4 on resilience assessments in the demonstration sites.

4.2 Stakeholders' feedback

Introductory questions

In order to account for multiple levels of climate decision-making, a questionnaire was sent to specific professionals at the local, regional and national level in two of the demonstration sites, namely Attica in Greece and Zeeland in the Netherlands. The questions and preliminary framework shared with the stakeholders can be found in Annex II.

The first part of the questionnaire focused on understanding the role of the stakeholder and the characteristics of the region represented by the stakeholder itself. Three introductory questions were included, two of which focused on understanding the main climate-related vulnerabilities over the past decade. The other question was about whether the country or region has a system of vulnerability and adaptation indicators.

Most of the respondents mentioned water as a key element of climate vulnerability. Energy and food security were added from the Zeeland region. They pointed out energy and more specifically the need to increase renewable energy sources as essential to understand climate vulnerability. Larger shares of renewable energy for instance lead to landscape impacts and higher infrastructure demands. Food security was mentioned as a vulnerability because of the possible decrease in food production as a result of saltwater intrusion polluting groundwater.

The Attica region, highlighted also health, ecosystems, and tourism as additional elements of climate vulnerability, as pointed out also in the Greek National Strategy for Adaptation to Climate Change. Degradation of ecosystems is mentioned as a vulnerable element due to extreme weather events (e.g., heatwaves and droughts) and forest fires, while tourism season is strongly linked to rising water demand

and damages to the water system as well as surges in energy provision and food production and demand.

Regarding the presence of formal documents on Climate Change indicators, the Attica region, as required by law 4414/2016, has elaborated its Regional Plan for Adaptation to Climate Change (RPACC; https://www.patt.gov.gr/en/), while Zeeland works with national websites and maps that collect know-how from various applied knowledge institutes and universities (https://klimaatkennisbanksd.nl/en/).

General questions about the IMPETUS indicator framework

The general questions included in the questionnaire were 6 (from question 4 to question). Some of them aimed to frame the experiences of stakeholders in the field of adaptation indicators and vulnerability indicators (e.g., question 4). In other cases, the questions were meant to stimulate suggestions and additions based on local knowledge and on the characteristics of the stakeholder's regions: Attica in Greece and Zeeland in The Netherlands (question 5 and 6). Finally, three questions were devoted to determine whether the proposed indicators were all equally understandable and useful (question 7 and 8) and whether the information base needed to measure indicators could be considered a weakness (question 9).

The following of this section provides an overview of all the questions and responses provided by stakeholders giving evidence when their suggestions, led to changes or additions to the indicator framework.

Question 4: *"Have you ever personally used any of the proposed indicators to keep track of vulnerability / adaptation progress in your region? Which one?"*
Answers: Respondents expressed that they do not have practical experience in using one or more of indicators proposed in the IMPETUS indicator framework to keep track of vulnerability/adaptation progress in their region. One stakeholder of Zeeland explained that they did not use indicators but general policy objectives to assess their climate adaptation efforts.

Question 5: *"Based on your first impression, to what extent does the set of core indicators represent the key aspects of vulnerability and adaptation to climate change in Europe?"*
Answers: Respondents expressed that the proposed core indicators fully represent key aspects of vulnerability and adaptation to climate change considerations in Europe. One respondent indicated that the selected indicators cover the main climate change impacts and vulnerabilities that need to be considered and monitored while being simple, precise and easy to follow and understand. A suggestion came from Attica representative who highlighted the need to reinforce the set with indicators representative of intersectoral impacts in order to better integrate socio-financial capacity of citizens in the main categories of health, food and energy. Another respondent noted that he/she thought the number of core indicators could pose a problem in the process of information collection and maintaining the knowledge up to date.

Discussion and integration into IMPETUS indicator framework:

The comment about the need for intersectoral impacts fully captures the complexity of climate change and the difficulty of finding appropriate indicators to represent phenomena that both affect multiple sectors and, at the same time, are highly specific of a single component affected by climate change impacts. For this reason, such cross-sectoral reinforcements are the main focus of resilience assessments in task 3.4 of IMPETUS project.

Regarding the observation on the large size of the database and the consequent difficulty of being able to get information and keep the indicators up to date, it is a critical feedback since many monitoring programmes are indeed hampered by the overdemand of data. Accordingly, the set of core indicators is intended to be a valuable starting point in selecting relevant indicators from the core indicator set, case by case. Different subsets of the whole indicator framework could therefore be identified to fit specific requirements of strategic climate-sensitive decision-making in individual demonstration sites.

Question 6:

"What would be key indicators that you would add to the framework in order to make it more useful for strategic decision-making in European regions or in your region specifically?"

Answers:

In response to this question, several valuable suggestions have been made. Emphasis has been put on the need for a vulnerability indicator related to climate-induced migration and to the socio-economic conditions (limited income and its consequences) as elements of vulnerability.

Discussion and integration into IMPETUS indicator framework:

The suggestion provided by the Attica representative (General Directorate of Sustainable Development and Climate Change for the region of Attica) stressed the importance of considering human migration as a climate change vulnerability. In this case, climate change is often not a direct driver but rather of intermediary influence in rising food prices, social unrest and geopolitical tensions that lead to migration. To account for this critical aspect of climate vulnerability, *climate change induced migration* (ind. **1.3.9**) is included in subcategory 1.3 socio-economic well-being in the IMPETUS additional indicator framework. The indicator is aimed at evaluating the number of people that will find in need of migrating to cope with climate extremes. The most common climatic drivers for migration and displacement are drought, tropical storms and hurricanes, heavy rains and floods, that affect food security, nutrition and livelihoods. According to the IPCC Sixth Assessment Report (Pörtner et al., 2022,), most climate-related displacement and migration occur within national boundaries, with international movements occurring primarily between countries with contiguous borders. Countries need to be prepared for these migrations, and anticipate the impact that these may have on local resources. The interpretation of this indicator in the IMPETUS indicator framework in the context of vulnerability is essential and context specific.

Beyond migration, the socio-economic conditions (limited income and its consequences) were emphasized. In this context, access to electricity (% of population) was opted by the same respondent to account for climate vulnerability, particularly under conditions of rising costs (partially) due to climate change. This suggestion led to the addition of two new indicators under the subcategory 4.1 Energy demand. The first one is ind. **4.1.3** energy-efficiency label. Although this is not a direct indication of affordability, the energy efficiency label (ind. **4.1.3**) does indicate to what extent homes are vulnerable to extreme heat and cold. Such monitoring information can enable the identification of households or neighbourhoods that have underlying affordability issues. Beyond affordability, the energy label does provide a direct representation of energy efficiency. The second indicator included in order to monitor this kind of vulnerability is the indicator **4.1.4** Low absolute energy expenditure (European Energy Poverty Observatory). It represents the share of households whose absolute energy expenditure is below half the national median, or in other words abnormally low. This could be due to high energy-efficiency standards, but may also be indicative of households dangerously under-consuming energy because they cannot afford these costs.

Finally, the representative of local administration from Zeeland emphasized that beyond indicators, the stories, tacit knowledge and feelings of citizens are critical. We therefore make the suggestion to perform additional citizen surveys in climate hotspots being identified in task 3.1 of IMPETUS project.

Question 7: *"Are the proposed indicators equally understandable?"*
Answers: Respondents expressed that the indicators are all equally understandable and no amendments are suggested. One comment was provided from the Attica representative who highlighted that for climate vulnerability the indicators on health risk may be difficult to calculate due to uncertainties.
Discussion and integration into IMPETUS indicator framework: Indicators related to subcategory 1.2 health infrastructure do indeed rely on local data to be provided by the health care sector. This might be challenging to acquire. However, because health infrastructure is a critical determinant for climate vulnerability, it was decided to keep the indicators.

Question 8: *" Are there indicators that you consider poorly useful/not applicable for your case"*
Answers Generally, the stakeholders consider the indicators to cover the main vulnerabilities arising from climate change that are common for many countries and regions. Suggestions to include population movements due to climate change and protection of shelters are proposed.
Discussion and integration into IMPETUS indicator framework: The indicator related to population movements has been included in the set of additional vulnerability indicators as already described in relation to question 6. The concept of the protection of shelters is included in two different adaptation indicators: the core indicator **4.2.3** Adapted/relocated assets at risk and the additional adaptation indicator **4.4.5** Retrofitted properties against heat. Both these indicators measure the extent to which risk management infrastructures and procedures are ready to efficiently manage climate-related impacts. In particular, indicator **4.2.3** refers to actions that are mainly implemented according to the disaster risk reduction strategies, while the indicator **4.4.5** is thought for the urban environment and buildings and refer to a mix of highly interconnected green and grey measures that measure the efforts mainly made by cities and local authorities to be more resilient to higher temperature (especially during heatwaves).

Question 9: *" For which of the proposed indicators do you expect that a lack of data may limit the use of the indicator in your region"*
Answers Most stakeholders did not provide feedback in this regard. Instead, the local representative from Zeeland pointed out several categories of indicators related to health, food production, institutional empowerment and water supply whose use may be limited by lack of data.
Discussion and integration into IMPETUS indicator framework: We recognise potential limitations and therefore emphasize that on a case-by-case basis different indicators might be selected. Data limitation can be a consideration to not incorporate it an indicator. On the other hand, it may encourage practitioners to expand their monitoring system because certain aspect could be essential for ensuring a climate-resilient regions.

4.3 Core indicators of climate vulnerability

This section provides an outline of the categories, subcategories and its corresponding indicators that were chosen for the IMPETUS indicator framework on the basis of the methods, theoretical background and stakeholder input as described in the previous sections.

Climate vulnerability is defined by the International Panel on Climate Change (IPCC) as the propensity or predisposition to be adversely affected by climate change. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Vulnerabilities to climate change are either directly or indirectly linked to many societal aspects that shape our societies. In this context, vulnerability of a system is not only a function of the magnitude of climate change, its exposition and sensitiveness. It also depends on how the society is shaped and to what extent it is ready to face the consequences of climate change. To account for and comprehend the multi-faceted dynamics, the proposed climate vulnerability indicators are organised into five categories, each of them split into several subcategories. The approach integrates and is inspired by the extensive literature on climate vulnerability databases and existing indicators that assess climate vulnerability (incl. Füssel (2010), Ludeña & Won Yoon (2015), or Byers et al. (2018)).

This section outlines the motivation behind each category and subcategories (see Table 2) and briefly explain the indicators that are included in each category.

Table 2 Climate vulnerability indicators: overview of categories and subcategories.

Category	Subcategory
1 Health & well-being	1.1 Health risk
	1.2 Health infrastructure
	1.3 Socio-economic well-being
2 Food & finance	2.1 Food production
	2.2 Food finance
3 Water	3.1 Service delivery
	3.2 Water resources
4 Energy	4.1 Energy demand
	4.2 Energy provision
5 Innovation power	5.1 Economic
	5.2 Human capacity
	5.3 Institutional empowerment

Category I: Health & well-being

Health and climate vulnerability are closely related. There is a strong consensus that climate change has, and will have, a strong impact on human health, with either direct or indirect consequences that can be severe. It has been estimated by the United Nations Office for Disaster Risk Reduction that the heatwave of the 2003 summer caused an excess of mortality in Europe of around 72.000 people, mostly in France and Italy (Human cost of disasters, an overview of the last 20 years, 2000-2019; CRED, UN Office for Disaster Risk Reduction). Excess of mortality is mainly related to exacerbating underlying health issues of mainly elderly and people with underlying health conditions. However, mortality due to direct exposure to extreme heat in workplaces, or during common daily tasks, is at risk of becoming more prevalent. It is therefore important to analyse what may cause these fatalities, as they represent a notable example of vulnerability. An understanding of health-related climate vulnerabilities is critical in addressing them adequately. Since there are several perspectives to look at this subject which all shape the health vulnerability related to climate change, this category is split into three subcategories. These are: health risk, health infrastructure, and socio-economic well-being (Table 3).

Table 3 Proposed subcategories and indicators for Health and well-being.

Subcategory	Indicators
1.1 Health risk	1.1.1 Heat vulnerability
	1.1.2 Burden of disease attributable to the environment
	1.1.3 Increased risk of death due to ozone air pollution
	1.1.4 Population living in risk regions under extreme events
	1.1.5 Vector-borne disease
1.2 Health infrastructure	1.2.1 Access to emergency services during extreme weather events
	1.2.2 Patient capacity
	1.2.3 Workforce capacity
	1.2.4 Equipment capacity
	1.2.5 Health services dependency on external resources
1.3 Socio-economic well-being	1.3.1 Lack of social cohesion
	1.3.2 Instability and violence

Health risk

Health risk (subcategory I) is primarily related to human health and contains five indicators (see Table 3). These indicators are aimed at studying the impact of extreme temperatures on human health, either directly or indirectly. The first indicator, **1.1.1** heat vulnerability, aims at measuring the population whose health is known to be more susceptible to long prolonged periods of extreme heat; in this group are included people over 65 years of age, and in particular the segment that has chronic medical conditions. Indicator **1.1.2** burden of disease attributable to the environment, studies the years of life lost due to premature mortality or years of healthy life lost due to disability, linked to an environmental problem. Indicator **1.1.3** increased risk of death due to ozone air pollution, is meant to monitor the potential effects of ozone, a colorless unstable toxic gas with a pungent odor and powerful oxidizing properties, formed by the action of the ultraviolet radiation of the sun upon nitrogen dioxide present in the air, on human health. Ozone effects, exacerbated by climate change, might pose populated cities at risk, leading to a worsening air quality and thus breathing conditions. Populations living in regions that are more prone to suffer extreme events, such as floods, drought, hailstorm, etc., are accounted for in Indicator **1.1.4** population living in risk regions under extreme events (Dilley, 2005). Indicator **1.1.5** vector-borne diseases has the goal of tracking the number of vector-borne diseases that may appear in regions where these were non-existent, but are now appearing due to a migration of the vectors that transmit them (Medlock & Leach, 2015).

Health infrastructure

The second subcategory is Health infrastructure, and it is built to group five indicators that aim at providing an overview of the resources required for health infrastructure counts in case of extreme events. Indicator **1.2.1** access to emergency services during extreme weather events, is motivated by the need of accessing emergency services under an unexpected event, such as a flood or a wildfire. Assessing how easy is to access to these services (firemen, ambulances, medical personnel, etc.) guarantees a better protection. The next three indicators are **1.2.2** patient capacity, **1.2.3** workforce capacity, and **1.2.4** Equipment capacity, are meant to quantify the capacity, in terms of beds, physicians, and medical equipment, per 100 000 people, to prevent saturation of the health system that could lead to an underperformance at the cost of human health. Indicator **1.2.5** health Services dependency on external resources is included to motivate an assessment of all the dependencies (in terms of personnel, vehicles, medicines, or infrastructure, among others) that a given heath service has on an another one to which is not directly related. Understanding these dependencies allows to find vulnerabilities that may hinder our capacity to react in times of need.

Socio-economic well-being

This category is complemented with a third subcategory, Socio-economic well-being, that contains two indicators to account for additional aspects of health. The first indicator of vulnerability in this category is lack of social cohesion (ind. **1.3.1**). Social cohesive societies[1] are shown to enjoy increased resilience against extreme weather events (Baussan, 2015). Strategies to increase social cohesion are especially effective in reducing the vulnerability of low-income areas, which are areas that are especially vulnerable to the effects of climate change (Baussan, 2015). Neighbourhood social cohesion, through for instance civic participation, moreover protects against psychological harm caused by climate change events, making these neighbourhoods less vulnerable (Greene, Paranjothy, & Palmer, 2015).

Indicator **1.3.2** deals with issues related to instability and violence, which can exacerbate climate vulnerabilities. Furthermore, instability can lead to many short-term emergencies and investment in recovery that can potentially be prioritized over climate-related endeavors that require long-term allocation of resources and commitment.

Category II: Food

The second aspect of vulnerability that is addressed in this the IMPETUS indicator framework is related to food. This category is aligned with the works by Füssel (2010), Byers et al. (2018), and other national and supranational frameworks. To better separate the indicators belonging to this category, two subcategories are considered: Food production and food financing (Table 4).

[1] *A cohesive society works towards the well-being of all its members, fights exclusion and marginalisation, creates a sense of belonging, promotes trust, and offers its members the opportunity of upward social mobility (*Baussan, 2015).

Table 4 Proposed subcategories and indicators for Food.

Subcategory	Indicators
2.1 Food production	2.1.1 Proliferation of pests and diseases in pastures, crops, and livestock
	2.1.2 Reduced availability of pasture
	2.1.3 Impact of food production requirements on environment health
2.2 Food financing	2.2.1 Increased farm-related production costs
	2.2.2 Food loss and economic cost of extreme events

Food production

It is recognized that food has a strong impact on people's health. A poor or imbalanced diet may lead to health-related issues such as obesity, diabetes, or nutrient deficiencies. In this regard, the first subcategory of indicators (2.1) aims at understanding the potential socioecological vulnerabilities of food production. Two indicators are proposed: Indicator **2.1.1** proliferation of pests and diseases in pastures, crops, and livestock, which focuses on understanding the potential risks that exogenous pests and diseases, brought on by climate change, may pose to crops, pastures, and livestock in regions where a proper response is lacking (Grünig et al., 2020; Skendžić et al., 2021, Spanish National Climate Change Adaptation Plan 2021-2030). Indicator **2.1.2** is related to the availability of pasture for livestock farming. Intensive animal farming, or Concentrated Animal Feeding Operations are known to exacerbate environmental degradation, with increased water and air pollution. Hence, more integrated and less resource intensive solutions to livestock farming are required. Aligned with this indicator, Indicator **2.1.3** aims at studying the impact of food industry and production on the environmental health. Both the use of pesticides, or the need to change a land type to use it for food production, may leave an impact on the local environment and ecosystem. If climate change brings exogenous pests to regions where it was not found, new pesticides may have impact on the local flora and fauna, In the same way, climate change may require changes in the land use to adapt food production to the new conditions (Vermeulen et al., 2012).

Food financing

The other subcategory (2.1) is related to the cost of maintaining food production, either in crops or in livestock. Indicator **2.1.3** relates to increased farm-related production costs. Additionally, it is of interest to monitor food loss and economic cost of extreme events (ind. **2.2.2**). This could include floods affecting farms, or hailstorms affecting fruit or cereal crops (Climate change adaptation in the agriculture sector in Europe, EEA Report No 4/2019; Púčik, et al., 2019).

Category III: Water

The next vulnerability category that the IMPETUS indicator framework looks at, along with health and food, is water. Water management poses one of the most ambitious challenges for the future, as it has been shown that climate change will have an impact on temperature and precipitation, leading to severe episodes of drought and flooding (Table 5).

Table 5 Proposed subcategories and indicators for Water.

Subcategory	Indicators
3.1 Service delivery	3.1.1 CSO detection and water loss assessment after heavy rainfall
	3.1.2 Wastewater treatment coverage (%)
3.2 Water use and resources	3.2.1 Water stress index
	3.2.2 Agricultural water exploitation index
	3.2.3 Non-renewable groundwater stress index

Service delivery

To address this challenge within the IMPETUS project, a set of five indicators are proposed, divided into two subcategories. The first of these subcategories is 3.1 Service delivery, and it contains two indicators. Indicator **3.1.1** aims at monitoring Combined Sewer Overflows. This occurs after heavy rainfalls when sewers cannot collect and efficiently transport domestic and industrial sewage, along with the excess of water coming from rain. In these cases, sewers overflow, and the excess of untreated water is discharged into a waterbody (rivers, canals, or the sea). This means that the risk of introducing domestic and industrial pollutants into water ecosystems increases. This is complemented by indicator **3.1.2** wastewater treatment coverage (%), which is intended to monitor the share of water that wastewater treatment systems can process from domestic or industrial sources. According to the United Nations – Water, currently only around a 30% of wastewater flows received at least some form of treatment.

Water use and resources

The second subcategory is water use and resources and contains three indicators. The first is **3.2.1** Water Stress Index, which represents the fraction of water that is demanded by human-economic activities (irrigation, industry, households) relative to available renewable surface water supply (Gleik, 1996; Raskin et al., 1997). Aligned with this, Indicator **3.2.2** agricultural water exploitation index tracks the agricultural water demand, related to its availability. Another source of water, groundwater, must be protected the period needed for replenishment is long in comparison to the normal timeframe of agricultural extraction. Indicator **3.2.3** Non-renewable ground water stress index allows the identification of vulnerable situations related to the over exploitation of this resource.

Category IV: Energy

Category five is related to the impact that climate change may pose on energy (Byers et al., 2018). As with previous categories, energy vulnerability comes from different angles. In this regard, two subcategories are proposed for the IMPETUS indicator framework. The first subcategory is Energy Demand, and it contains three indicators (Table 6).

Table 6 Proposed subcategories and indicators for Energy.

Subcategory	Indicators
4.1 Energy demand	4.1.1 Primary energy consumption per capita
	4.1.2 Energy demand due to extreme temperatures
	4.1.3 Energy-efficiency label
	4.1.4 Low absolute energy expenditure (M/2)
4.2 Energy provision	4.2.1 Diversity of renewable sources in primary energy production
	4.2.2 Number of energy supply interruptions per year

Energy demand

Indicator **4.1.1** is primary energy consumption per capita. Primary energy consumption per capita refers to the direct use at the source, or supply to users without transformation, of crude energy (see Ivanović, 2012). A country that is consuming more energy per capita can be more vulnerable if it cannot adapt to the potential lack of energy that climate change may pose. Indicator **4.1.2**, energy demand due to extreme temperatures, aims at monitoring the excess of energy that is required to ensure that indoor spaces are maintained at the desired temperature during extreme heat or cold events. Indicator **4.1.3** is related energy-efficiency labels. The EU energy labelling and eco-design legislation helps improve the energy efficiency of products on the EU market. It sets common EU-wide minimum standards to eliminate the least performing products from the market. In this regard, the energy labels, currently divided into 7 levels, provide a clear and simple indication of the energy efficiency. This makes it easier for consumers to save money on their household energy bills and contribute to reducing greenhouse gas emissions across the EU (European energy labels: rescaling and transition periods; retrieved from European Commission about the energy label and eco-design). The last indicator under this category is ind. 4.1.4 Low absolute energy expenditure, which is aligned with Energy Poverty Observatory, aims at the share of households whose absolute energy expenditure is below half the national median, or in other words abnormally low, being indicative of households dangerously under-consuming energy because they cannot afford it (Thema & Vondung, 2020).

Energy provision

In the second subcategory, Energy provision, two indicators are included. Indicator **4.2.1** Diversity of renewable sources in primary energy production is aimed at understanding how energy is produced when using renewable sources, to spot how vulnerable a population can be to an unexpected change in the source of energy that they rely on; diversifying sources of energy should make populations less vulnerable to these unexpected changes. The second indicator, **4.2.2** Number of energy supply interruptions per year should gather information on the lack of energy provision due to vulnerabilities in the network that were aggravated by a climatic extreme event (shortages on electricity due to a storm, or a flood). Monitoring these situations becomes important to prevent them from happening again, and to be ready to apply different solutions when these occur.

Category V: Innovation power

The fifth category is innovation power. Abdelzaher et al. (2020) conducted a longitudinal study from 1998 to 2013 with a sample of 73 countries examining the impact of innovation, openness to trade, and regulatory quality on a country's vulnerability to climate change. They found that these factors decrease the vulnerability of a country to climate change. The development and full-scale application of innovations ranging from technology that can enhance efficiency of water and energy use, resource recovery from waste or improved batteries for electricity security, are essential to mitigate climate vulnerabilities. The extent that regions can develop and apply innovations is therefore critical. Hence, this category outlines key conditions - related to economic enablers, human capacity and institutional empowerment - that jointly form a self-strengthening enabling environment for innovation (Table 7).

Table 7 Proposed subcategories and indicators for Innovation power.

Subcategory	Indicators
5.1 Economic	5.1.1 Income inequality
	5.1.2 Public debt
	5.1.3 Time to start a business
5.2 Human capacity	5.2.1 Learning poverty
	5.2.2 Human flight and brain-drain
	5.2.3 Lack of women's political power
5.3 Institutional empowerment	5.3.1 Fragmentation of state institutions
	5.3.2 Power distance
	5.3.3 Weakness of rule of law

Economic

Wealth inequalities, in the indicator defined as income inequality (**ind**. 5.1.1), lead to exacerbated climate impacts on poor and vulnerable people (due to persistent inequalities in access to assets, opportunities, political voice and participation). Furthermore, vulnerability is shaped when available resources are concentrated in fewer hands of the population, reducing communal allocation of resources and pooling of risk. Higher public debts (ind. **5.1.2**), lead to less room for investment in resources to cope with climate change or to respond to direct impacts, thereby enhancing climate vulnerability or limiting the necessary investments in innovation to tackle climate issues. Finally, the adverse effects of climate change requires innovation power to respond in a timely and adequate fashion to emerging challenges. In order to do so, start-ups and small-medium enterprises need to be enabled to seek and seize new opportunities to combat climate change. This level of flexibility is necessary to foster new innovation trajectories, experiment and mobilise creativity to mitigate climate change. The time to start a business (ind. **5.1.3**) is a proxy for the level of flexibility to innovate and thereby address climate vulnerabilities.

Human capacity

Endorsing observations of Muttarak & Lutz (2014) that *"Education can directly influence risk perception, skills and knowledge and indirectly reduce poverty, improve health and promote access to information and resources"*, learning poverty (ind. **5.2.1**) is critical element that enhances climate vulnerability. On the contrary, educated societies boost the human capacity to innovate and thereby address climate vulnerabilities. Another key aspect shaping this human capacity is related to the human flight and brain drain (ind. **5.2.2**). That is when people leave their region or country – often either directly or indirectly related to climate factors – they also take their knowledge and innovation power (to combat climate change) with them. In addition, human flight and brain drain leads to fewer tax incomes, thereby lowering the resources that could be spend on strategies to cope with climate change. Lastly, woman empowerment (ind. **5.2.3**) is increasingly considered as an important element of enhancing the human capacity to address climate change (Asongu, Messono, & Guttemberg, 2021). The inclusion of women in strategic decision-making frequently led to more holistic, long-term and risk-considered decision-making (e.g., Profeta, 2017). Many studies find that woman are better aware of and worry more about climate change (McCright, 2010). By increasing woman's participation in national parliaments, it is likely that more stringent climate change policies are adopted (Women, 2022).

Institutional empowerment

Fragmentation of state institutions (ind. **5.3.1**) is considered a key limiting factor of the institutional empowerment of climate adaptation actions. Institutional fragmentation is closely related to factionalised elites, which is the discordance of a society into different political groups that promote rhetoric and actions which are harmful to society (St. Edwards University, 2015). This fragmentation leads to more climate vulnerability, because polarisation and power struggles tend to consume much resources and attention that, as a consequence, will not be directed to more long-term issues such as climate change. Moreover, the effects of climate change tend to increase this fragmentation of state institutions (Werrell, Femia, & Sternberg, 2015), hence creating a negative feedback loop that further increases climate vulnerability. Next, power distance (ind. **5.3.2**) is considered a determinant factor for institutional empowerment. In countries or regions with higher power distance scores, people lower in the hierarchy are less likely to express concerns (about climate related problems) to their 'superiors'. However, it is at the 'lower level' (e.g., in the field) where the effects of climate change tend to be most evident. Therefore the 'superiors' lack this critical input, while they are in the position of decision-making, making them more vulnerable to climate change. As a result, regions with lower power distance levels are found to be less vulnerable to climate disaster (Dückers et al., 2015) and more frequently report on the Sustainable Development Goals (Rosati & Faria, 2019). Lastly, rule of law (ind. **5.3.3**) *captures perceptions of the extent to which agents have confidence in and abide by the rules of society. In particular, the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and* violence (Kaufmann and Kraay, 2022). This coherent and effective rule of law is often emphasized to play a decisive role in long-term solutions necessary to address climate change.

4.4 Core indicators of climate adaptation

Adaptation is a big umbrella concept which groups together many different adaptation actions in different economic sectors and natural systems. Moreover, adaptation is site specific and often locally implemented. Due to the overall complexity of adaptation and consequent heterogeneity of different possible indicators, the climate adaptation framework is organised in four main categories:

I. Institutional strength,
II. allocated resources,
III. knowledge and education and,
IV. adaptation interventions

Each category is split in subcategories (Table 8). The used approach is inspired by the approach used in the IPCC AR5 (WGII, Chapter 14 adaptation options and needs), AR6 (WGII, Chapter 17: Decision Making Options for Managing Risk) and by the categorisation in Key Type Measures proposed by the ETC/CCA Technical Report 2021 to support EU Member states in the reporting under the Regulation on the Governance of the Energy Union and Climate Action in 2021.

Table 8 Climate adaptation: overview of categories and subcategories.

Category	Subcategory
1 Institutional strength	1.1 Coordination, strategies, plans & policies
	1.2 Laws & regulations
2 Allocated resources	2.1 Financing & incentive instruments
	2.2 Insurance & risk sharing instruments
3 Knowledge & education	3.1 Climate services & information tools
	3.2 Awareness raising & capacity building
4 Adaptation interventions	4.1 Green measures
	4.2 Grey measures
	4.3 Behaviour change
	4.4 Non-specific

Category 1: Institutional strength

The extent that government, private stakeholders, and citizens can jointly implement climate adaptation actions and policies is strongly enabled through institutions that manage and regulate, implement and continuously improve actions through inclusive, flexible and integrated approaches (e.g., Levitsky et al., 2009; Amaru and Chhetri, 2013). In order to assess this institutional strength to implement climate adaptation actions, two subcategories and nine indicators are Identified (Table 9). The two identified subcategories (**1.1** coordination, strategies, plans & policies; **1.2** Laws and regulations) reflect the two main aspects of governance introduced by IPCC (AR6, IPCC, 2021) as enabling conditions for implementing adaptation. In particular:

- Climate change policies, strategies and plans guide national and subnational authorities enabling actions across multiple spheres and scales of government and non-government institutions and actors.
- Legal systems play an important governance role in facilitating responses to climate change across all levels of society. Extensive revision of legal acts to incorporate issues related to climate change has the potential to foster adaptation.

Table 9 Proposed subcategories and indicators reflecting the institutional strength to implement climate adaptation actions.

Subcategory	Indicators
1.1 Coordination, strategies, plans& policies	**1.1.1** Local disaster risk reduction strategies
	1.1.2 Area covered by local emergency plans or action groups
	1.1.3 Mainstreaming of climate change in disaster risk reduction plan
	1.1.4 Pre-emptive evacuation following early warning
	1.1.5 Sector/land-use management plans with significant climate change considerations
	1.1.6 Institutional frameworks for climate change adaptation
1.2 Laws, regulations & procedures	**1.2.1** Environmental impact assessment & strategic environmental assessment with climate change considerations
	1.2.2 Revised building codes and climate proofing of buildings
	1.2.3 Adapted standards for transport infrastructures

Coordination, strategies, plans & policies

The issue of disaster risk reduction is covered under the subcategory **1.1**. Disaster risk reduction and climate change are closely related, since many natural disasters occur as consequences of extreme weather events that are increasingly occurring due to climate change. The indicator here proposed is the proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies (ind. **1.1.1** in Table 9). This indicator is derived from the indicator framework of the Sustainable Development Goal and from the Sendai Framework for Disaster risk reduction. The existence of pre-emptive evacuation plan in place following early warning (ind.**1.1.4**) is another indicator derived from the Sendai Framework (target G) and can be applied also to climate-related risks. Accordingly, the area covered by climate emergency plans (or action groups) is endorsed as an indicator (ind. **1.1.2**) that shows the proportion of a city or region which is protected by emergency management or evacuation plans, in this case derived from the C40 initiative. Besides the number of plans and the area and population covered by these plans, another important information is the extent to which disaster risk strategies take into consideration quantitative projections of climate change factors (ind. **1.1.3**).

Beyond disaster risk reduction, the subcategory 1.1 includes indicators about the level of adaptation of different sector plans and strategies to account for climate change impacts. Land-use plans and management plans prepared for different policy objectives at European level (e.g., Floods Directive, Natura 2000 sites, Water Framework Directive) or at national level can be adapted to take into considerations changing risks posed by climate change. The degree of adaptation of sectoral plans and strategies represents a measure of climate change adaptation progress (ind. **1.1.5**).

Indicators 1.1.3 and 1.1.4 can be measured through the number of strategies and plans that include significant considerations about climate change. Qualitative information that explain how this integration has been achieved can be especially relevant to better frame the adaptation process.

Since climate change is a cross-cutting theme, institutional coordination (vertical, among national and subnational levels and horizontal, among different sectors) represents a recognised enabling environment for adaptation. The number and type of initiatives that encourage coordination in tackling climate change impacts (e.g. establishment of dedicated focal points) is included as indicator of adaptation (ind. **1.1.6**).

Laws, regulations & procedures

Finally, climate change adaptation may require the adjustment in laws and regulations (subcategory **1.2**). Permitting procedures (ind. **1.2.1**), building codes (ind. **1.2.2**) and transport infrastructure standards (ind. **1.2.3**) can be adjusted to include considerations of climate change. The extent to which such regulations are adjusted and the corresponding level of implementation are indicators that measure the progress in adaptation capacity.

Category 2: Allocated resources

The second category, allocated resources**,** includes financing instruments and incentives (subcategory **2.1**) and the issue of insurance and risk sharing schemes (2.2)

Finance has long been recognised as an important enabling and catalysing factor for adaptation, climate resilient development and climate risk management (IPCC, 2021).

The nine indicators proposed for this category are listed in Table 10.

Table 10 Proposed subcategories and indicators reflecting the allocation of resources to implement climate adaptation actions.

Subcategory	**Indicators**
2.1 Financing instruments and incentives	2.1.1 Expenditure in studies and research projects
	2.1.2 Number of funded studies and projects
	2.1.3 Funds for adaptation
	2.1.4 Revision of funding schemes for specific sectors to take into account climate change
	2.1.5 Expenditure in dissemination/information about climate change impacts adaptation
	2.1.6 Investments for planning and management of emergency
	2.1.7 Investments in specific climate adaptation interventions
	2.1.8 Economic incentives
2.2 Insurance and risk sharing instruments	2.2.1 Insurance against extreme events

Financing instruments and incentives

The issue of studies and research projects focussed on climate change impacts and adaptation is covered under the subcategory **2.1**. Research projects and studies have the potential of creating and improving the enabling conditions for adaptation. They create knowledge, support the selection of most suitable adaptation options, and create networks of knowhow exchange. Projects can be funded at local, subnational, national and international level. The two proposed indicators measure the total budget allocated for such studies (ind. **2.1.1**) and the number of studies and projects (ind. **2.1.2**). These indicators mainly derive from national sources (national adaptation plans) that considerer studies and projects at the national and international level. However, they can be easily applied also at the subnational level, considering the allocation of resources coming from subnational regions and municipalities.

Two other indicators included in the same subcategory are about funds. The first indicator refers to the availability of funds specifically dedicated to climate change adaptation (ind. **2.1.3**). It can be expresses as the percentage (or total number) of national, subnational/local government budgets specifically dedicated to climate change adaptation actions. The second indicator refers to the extent to which funds established for other policy objectives (e.g., biodiversity conservation, human health, and ecosystem restoration) integrate climate change considerations (ind. **2.1.4**).

Funds that support the designation of protected areas or the restoration of degraded habitats, even though do not specifically include climate change considerations, can also contribute to increasing the overall resilience of natural areas to climate change impacts and can be used as proxy indicator of climate change adaptation.

Dissemination and education in climate change issues is key to enable adaptation. Although this topic is specifically addressed under the category 3 (knowledge and education), the total allocated budget in various dissemination activities targeted to different users is here included as indicator of allocated resources (ind. **2.1.5**). Similarly, this subcategory includes an indicator that tracks the expenditure in planning and management of climate-related emergencies (ind. **2.1.6**), an issue that spans across other categories. The amount of investments and expenditure for different specific interventions of adaptation (ind. **2.1.7**) is finally considered. This indicator can measure the adaptation progress made at different spatial and governance levels, with different types of resources (private and public), different sectors and different climate impacts.

Finally, properly designed economic incentives are included in this category. They can significantly favour the achievement of policy objectives by encouraging, rather than imposing, behavioural changes that may lead to adaptation. Innovative incentives can for example boost energy efficiency investments in buildings, reduce water and energy demand in agriculture or enhance the sustainability of fishing practices. Hence, the number of economic incentives established (at subnational or national level) and/or the allocated budget is proposed as an indicator of adaptation (ind. **2.1.8**).

Insurance and risk sharing instruments

As a final point, insurances are financial mechanisms that are gaining more and more importance: they can create compensation for losses due to extreme weather events exacerbated by climate change: e.g. crop loss in agriculture, losses in houses from flooding, forest losses due to storm or forest fires. The proposed indicator (**2.2.1)** is quite general and can be adjusted (with different metrics) to be applied in different economic sectors (private business, animal farming and agriculture, buildings etc.).

Category 3: Knowledge and education

The third category, knowledge and education, is split into technological information tools (**3.1**, to include climate data provision services, meteorological-forecasting services, early warning systems and information tools) and awareness raising and capacity building initiatives (**3.2**, to include the initiatives of training, education, and information). Four indicators are included, as presented in Table 11.

Table 11 Proposed subcategories and indicators reflecting the progress in knowledge and education as enabling factor for climate change adaptation.

Subcategory	**Indicators**
3.1 Climate services and information tools	3.1.1 Development of forecasting, early warning, climate services and decision support systems
	3.1.2 Availability of information on different and multiple climate change impacts and adaptation
3.2 Awareness raising and capacity building	3.2.1 Events of dissemination/information
	3.2.2 Events of training/capacity building

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Climate services and information tools

The first subcategory includes a wide range of information tools that can support climate change adaptation. Climate services provides decision makers in climate-sensitive sectors (e.g., agriculture) with tailored information, enabling evidence-based adaptation. Early warning systems for climate risks, based on advanced forecasting systems, are key elements of climate change adaptation and disaster risk reduction. Tools can be specific for a single risk or address multiple hazards. They can be developed at different spatial scales, from local to national and international one. The indicator **3.1.1** (Development of forecasting, early warning, climate services and decision support systems) aims to quantify their level of development (number of systems developed, area and population covered by these systems, number of municipalities or regions with such systems in place). Accordingly, the presence of accessible, understandable, usable and relevant information (advices, information portals, knowledge exchange platforms, information on how to act in disaster situations - ind. **3.1.2**) can increase the level of knowledge and the capacity of response to adverse climate change impacts. The indicator in this case refers to the number of the available communication tools, but its meaning can also be enlarged to consider the level of actual usage by citizens and stakeholders affected by climate change.

Awareness raising and capacity building

As part of the subcategory **3.2**, dissemination, information and education campaigns targeted to the citizens (ind. **3.2.1**) as well as capacity building initiatives targeted to specific groups (decision-makers, stakeholders of different sectors) (ind. **3.2.2**) can help to increase awareness on climate change, and trigger behavioural changes and adaptation initiatives. The two proposed indicators of this subcategory refer to the number of initiatives developed but they can be also complemented by information about the level of participation (e.g., number of participants). Also in this case, qualitative information about the level of satisfaction by users (through questionnaires) can be especially useful to understand if the initiatives met the interest and needs of participants.

Category 4: Adaptation interventions

While the first three categories (Institutional Strength, Allocated resources and Knowledge and education) are about initiatives that create the enabling conditions (IPCC, 2021, chapter 17) for adaptation, this fourth category directly refers to indicators of implemented adaptation actions, by measuring the output of policies and plans. The identified subcategories include: green measures (**4.1** based on services provided by natural ecosystems), grey measures (**4.2** based on technological and engineering solutions) and behavioural change measures (**4.3** changes of practices and habits). Since complex adaptation interventions can include different typologies of measures (grey, green, behavioural), a non-specific category is included (**4.4**). Green measures (or Nature Based Solutions) are being increasingly bolstered by the European Commission to support major EU policy priorities, in particular the European Green Deal, the Biodiversity strategy, the Green Infrastructure Strategy, and the Climate Adaptation strategy. These measures working with nature rather than against it have the potential of achieving multiple social and environmental benefits (beyond adaptation), consistently with the Sustainable Development Goals.

Core indicators for this category (Table 12) refer to some key themes that are found across most of IMPETUS demonstration sites: coastal areas, water management, risk management, biodiversity conservation and agriculture. Beside the 12 core indicators presented in Table 12, this category also includes other indicators that were defined as “additional indicators” (chapter 5), since they might not meet the interest of all demo-cases, highly depending on the sector affected or the impacts experienced.

Table 12 Proposed subcategories and indicators about implemented adaptation actions.

Subcategory	Indicators
4.1 Green measures	4.1.1 Restoration of coastal wetlands and coastal areas
	4.1.2 Retrieval and restoration of degraded ecosystems - Area undertaking habitat creation/restoration
	4.1.3 Specific interventions for species and habitats at risk from climate change
	4.1.4 Climate-adapted crop varieties
4.2 Grey measures	4.2.1 Re-use of wastewater or use of harvested rainwater
	4.2.2 Implemented water efficiency technologies (water saving devices.)
	4.2.3 Adapted/relocated assets at risk (hardening, elevating)
	4.2.4 Irrigation systems
4.3 Behavioural change	4.3.1 Water rationing systems
	4.3.2 Uptake of soil conservation measures
4.4 Non-specific	4.4.1 Coastline protection
	4.4.2 Implementation of actions in flood risk management plans

Coastal areas. For this topic, indicators measure the progress towards the protection of vulnerable coastal areas in terms of total surface area or coastal length that underwent any protection interventions against the impacts caused by sea level rise and storm surges (flooding, erosion). Indicators include both green and grey measures that are often jointly implemented in the same location. In particular, for coastal areas, the indicator **4.1.1** - Restoration of coastal wetlands (green measures) tracks the adoption of interventions made to safeguard these systems that are extremely important to provide natural defence against sea level rise and storm surges. The indicator **4.4.1** - coastline protection, measures the progress made in any adaptation intervention implemented to keep safe the coastline. Since many different options can be implemented to this aim, the indicator embraces the overall result of both green (beach nourishment, dune restoration) and grey measures (wave breakers, seawalls etc). Indicators are expressed with numerical values, as the surface/linear length of coastal area that underwent restoration interventions. In order to ensure adaptation is undertaken in a sustainable way, without exacerbating the existing vulnerabilities of other sectors and areas, qualitative information and narrative text can be extremely important to complement any numerical value expressed by this indicator.

Water resource. Safeguarding water resource is key to face water scarcity, especially in areas that are affected by decrease of precipitation and suffer from extreme temperature. Water saving behaviours, regulations, devices and technologies as well systems that allow recycling wastewater can significantly support the preservation of precious water resources. The proposed indicators track the degree of adoption of some measures that allow saving water. The recycling of wastewater and the use of rainwater (to be used for non-potable uses, as for example agriculture, gardening, car washing, ind. **4.2.1**) can significantly support the preservation of precious water resources. This can be measured as percentage of wastewater being reused or as percentage of water demand for secondary uses (e.g., gardens and toilets) being met with alternative water resources. An additional amount of water can be gained through the installation of water efficient devices (including tap and pipe repairs, ind. **4.2.2**). Finally, water restrictions and rationing systems (ind. **4.3.1**) limit certain uses of water (non-essential uses), includes temporary suspension of water supply or a reduction of pressure. All these indicators can be measured as number of actions implemented or as the additional water capacity created.

Risk management actions. Indicators measure the extent to which risk management infrastructures and procedures are ready to efficiently manage a climate-related disaster. They refer to actions that are mainly implemented according to the disaster risk reduction strategies (e.g., hardening of infrastructures at risks, ind., **4.2.3**) and that are strictly interconnected to indicators proposed for the first category (Institutional strength) about the establishment of plans and policies to address disaster risk reduction. The implementation of actions envisioned by flood risk management plans is an indicator of this subcategory (ind. **4.4.2**) related in this case to the Floods Directive that requires Member States to take adequate and coordinated measures to reduce flood risk. The indicator can be formulated as percentage of planned actions actually implemented and its measurement can benefit from the current monitoring framework of the Directive.

Biodiversity conservation. The natural resilience of ecosystems to climate change can be impaired by anthropogenic pressures. Interventions that are aimed to restore the natural ecosystem functioning are able to increase resilience to the negative effects of climate change. The indicators for this topic measure the progress towards climate smart management of the most vulnerable areas, the restoration of degraded ecosystems (in terms of the total restored area, ind. **4.1.2**), and the preservation of biodiversity with interventions targeted to preserve species and habitats at risk from the effect of climate change (ind. **4.1.3**).

Agriculture. It is one of the most impacted sectors by climate change, especially considering extreme weather events and drought events. A high number of measures are available to make the agricultural sector more resilient to climate change. The adoption of new sustainable irrigation systems (ind. **4.2.4**) allows to save water and energy resources, while the use of resilient crop varieties minimise possible yield losses due to unfavourable climate conditions. Conservation agriculture includes a wide range of practices as minimal soil disturbance, permanent soil cover and crop rotations (ind. **4.3.2**). All these indicators can be expressed as total agricultural area (or percentage of total agricultural area) covered by the implementation of these measures.

5 Accounting for context: additional indicators

The previous chapter has described which and how the chosen core indicators can be used to assess most common aspects of vulnerability and progress in adaptation. However, the state of climate vulnerability itself is linked to a specific population (Adger & Kelly, 1999). In this regards, vulnerability to climate change differs substantially between bio-geographical regions across Europe. Beyond the geographical characteristics, differences in socioeconomic context matters too in the context of climate vulnerability. The important role of context is further emphasized since climate adaptation often take place at the lowest governance levels, where the impacts of climate change are experienced.

For this reason and to account for context, a substantial share of the proposed IMPETUS indicator framework consists of additional indicators, as proposed in sections 5.1 for climate vulnerability and 5.2 for climate adaptation. The relevance of additional indicators vary in relevance from one demonstration case to another depending on the main focus of each case, the bio-geographical region and the socio-economic context. The list of additional indicators is by no means exhaustive. However, together with the core indicators, – they provide a quite complete framework from which relevant indicators can be selected case by case. .

5.1 Additional indicators for Climate vulnerability

In the following, a list of Additional indicators for Climate vulnerability is presented. These indicators, as described above, complement the core ones. For consistency, they have been categorised in the same categories as presented in Table 2, despite not all the subcategories are present for these indicators.

Category I: Health & socio-economic well-being

Table 13 shows the proposed additional indicators for category I health & well-being.

Table 13 Additional indicators for Health & well-being.

Subcategory	Additional Indicator
1.1 Health risk	**1.1.7** Flood emergency evacuation time
	1.1.8 People living in urban heat island
1.3 Socio-economic well-being	**1.3.3** People with pre-existing (mental) health conditions
	1.3.4 Overarching awareness of climate change threats
	1.3.5 The existence of citizen led initiatives
	1.3.6 The under-housed and homeless
	1.3.7 Outdoor labourers
	1.3.8 Share of marginalised communities
	1.3.9 Climate-induced migrations

Health risk

In this category, a collection of eight additional indicators is added. Flood emergency evacuation time has the purpose of monitoring the capacity of rescue services to coordinate an evacuation after a flood as well as the time it takes for the population to move to a secure shelter (ind. **1.1.7**). This is related, not only to the organisation capacity of the rescue forces and services, but also to the state of the evacuation routes (roads, railways, etc.). People living in urban heat island (ind. **1.1.8**) should provide an estimation of the people that are living in urban areas that are more prone to accumulate heat inertia during daytime, becoming heat islands (regions with high solar exposure, lack of greenery, etc). People living in these areas are prone to suffer the effects of heat on health in a worst way, while having to spend more resources on conditioning the temperature inside home.

Socio-economic well-being

Mental health issues and psychosocial aspects related to climate change tend to be underestimated (Hayes & Poland, 2018). A more holistic understanding of mental health in the context of climate change is typically less tangible but perhaps one of the biggest vulnerabilities in addressing climate change. For instance, several studies have identified a link between extreme weather events (i.e., floods, hurricanes and wildfires) with increased levels of depression, anxiety, post-traumatic stress disorder, suicidal ideation, substance abuse, vicarious trauma and loss of identity (Hayes & Poland, 2018). Poor health tends to lead to inability to contribute to climate solutions and increased vulnerability for climate change impacts. On top of this, a sense of climate despondency can equally lead to inaction and thereby exacerbate climate vulnerabilities.

Because climate change effects like extreme heat have been shown to increase mood and behavioural disorders amongst people with pre-existing mental illness and elderly who have poor thermoregulation. People with pre-existing (mental) health conditions (ind. **1.3.3**) is an important determinant of climate vulnerabilities related to social well-being. The overarching awareness of climate change as a threat to well-being and livelihood or way of life (ind. **1.3.4**) forms in combination with affirmative mental health a strong enabler to reduce climate vulnerability because people take climate action. However, with poor affirmative mental health, it could also constitute feelings of distress, anxiety, and fear that inhibit climate action. Hence it depends on whether a region has ways to direct this distress, anxiety and fear into coping methods and ways to take action. In the absence of initiatives or perspective, it may lead to a fatalistic attitude. Hence, the opportunity for collective action (ind. **1.3.5**) is therefore proposed as a vulnerability indicator. Next, Hayes and Poland (2018) have listed population groups which are found to be most affected in their mental- and psychosocial health by specific hazard types. People with pre-existing health conditions (ind. **1.3.3**), people with low socio-economic status (defined as ind. **1.3.8**: share of marginalised communities), outdoor labourers (ind. **1.3.7**) and homeless people (ind. **1.3.6**) are most vulnerable to climate change hazards like extreme heat, extreme weather events and vector-borne diseases. Finally, under indicator **1.3.9**, we consider another potential and undesired consequence of Climate change: Climate change induced migrations, which account for the amount of people that will have to migrate to another region or country due to the effects of climate change. The most common climatic drivers for migration and displacement are drought, tropical storms and hurricanes, heavy rains and floods, that affect food security, nutrition and livelihoods. According to the IPCC Sixth Assessment Report (Pörtner et al., 2022), most climate-related displacement and migration occur within national boundaries, with international movements occurring primarily between countries with contiguous borders. These migration flows might have an impact on the available resources to cope with climate change.

Category II: Food

Table 14 Additional indicators for Food production

Subcategory	Additional Indicator
2.1 Food production	**2.1.3** Saltwater intrusion
	2.1.4 Soil salinisation
	2.1.5 Flash floods

The first two additional indicator of the Food category are ind. **2.1.3** saltwater intrusion, and ind. **2.1.4** soil Salinisation. Saltwater intrusion is the movement of saline water into freshwater aquifers, which can lead to groundwater quality degradation, including drinking water sources, and other consequences. This may affect the availability of drinking water in coastal regions, and pose a challenge to water-processing units, as well as a problem for agricultural regions that rely on this water (Bhattachan et al., 2018). In the same fashion, soil salinisation measures the degree to which agricultural soil can be affected by the same process, resulting into a potential and irreversible loss of land to produce food, while altering ecosystems (Corwin, 2021).

Category III: Water

Table 15 Additional indicators for Water.

Subcategory	Additional Indicator
3.1 Service delivery	**3.1.3** Industrial freshwater intensity
	3.1.4 Excess demand during tourist season
	3.1.5 Lack of protection to flash floods
3.2 Water resources	**3.2.4** Water infiltration capacity
	3.2.5 Water footprint of food consumption

Service delivery

Four extra indicators are identified that apply to one a few demonstration sties. These additional indicators are divided into the two subcategories that defined this category. First ind. **3.1.3** industrial freshwater intensity relates the volumes of water that is used in industry per unit of value added. Lower industrial freshwater intensity represents economic development being decoupled from freshwater demand, hence pointing at a low vulnerability (Water intensity of crop production in Europe, European Environment Agency (2019). Indicator **3.1.4** excess of demand during tourist season aims at measuring the challenges that tourism poses to already vulnerable regions, where water can be scarce during the touristic seasons. Tourist put pressure on water resources particularly during the dry summer season. Their water-use (**ind.** 5.1.10) (reduction) can be critical and measures such as amending hotel showers, hotel cloth washing schemes or awareness campaigns can make a difference.

This subcategory has one more indicator, **3.1.5** Lack of protection to flash floods. Flash floods are usually characterised by raging torrents after heavy rains that pour in a short period of time. Flash floods flow through river beds, urban streets, or mountain canyons, with a lot of strength, posing serious damage to anything on their way. These kinds of floods, as opposed to regular ones, are more likely to become predominant in the future (Brunner et al., 2021).

Water resources

In the water resources subcategory, we find three indicators. Indicator **3.2.4** water infiltration capacity measures the amount of water that can infiltrate into the soil after a rainfall, not becoming part of potential floods. Indicator **3.2.5** water footprint of food consumption, aims at studying the amount of water that is put into the production of different kinds of food (from vegetables to meat) (Vanham et al., 2016).

Category V: Innovation power

Table 16 Additional indicators for Innovation power.

Subcategory	**Additional indicator**
5.1 Economic	**5.1.4** Low monetary credibility
	5.1.5 Loss of international tourism revenue
	5.1.6 Loss of revenue from forest resources
5.2 Human capacity	**5.2.4** Material deprivation
	5.2.5 Engagement in health & climate change
5.3 Institutional empowerment	**5.3.4** Lack of management cohesion
	5.3.5 Low research & development expenditure
	5.3.6 Low government engagement in health & climate change
	5.3.7 Low industrial sector engagement in health & climate change

Economic

In countries with banks that have low established credibility (ind. **5.1.4**), sectorial price shocks (e.g., food prices) risk de-anchoring (short-term price shocks can change long-term expectations) inflation expectations, leading to a second-round effect increasing inflationary pressure in the medium term. Countries with banks with well-established credibility and well-anchored inflation expectations are less likely need to respond to sectorial price shocks and the effects of inflation are more likely to be short-lived (Batten et al., 2016). Therefore, countries with banks that have low established credibility are more vulnerable to climate change, since climate change effects (such as droughts, heat waves or floods) may lead to upward pressure on commodity and food prices, and hence on inflation (Batten et al., 2020).

The tourism sector (ind. **5.1.5**) can be vulnerable to climate change. When a large proportion of the GDP is received from tourism, climate change not only influences the environment but also the region's financial gains from tourism, limiting the financial resources to deal with the effects of climate change. The same counts for ind. **5.1.6**: as climate change will affect forests, and affect possibilities to create revenue from forests (e.g., pulp and paper industry or ecotourism), therefore nations that receive a substantial share of their GDP from forest revenue are more vulnerable to climate change (policies), increasing their vulnerability.

Human Capacity

Severe material deprivation (ind. **5.2.4**) means "*the proportion of the population that cannot afford at least four of the following items: to pay their rent, mortgage, utility bills or loan repayments, to keep their home adequately warm, to face unexpected financial expenses, to eat meat or protein regularly, to go on holiday for a week once a year, a television set, a washing machine, a car, a telephone*" (Breil et al., 2018). When people face such deprivation, they have less resources (i.e., time, energy and money) to prepare for climate change (e.g., Ong et al., 2019). Moreover, it is this group which often is hit hardest by, and hence most vulnerable to, the effects of climate change.

Individual engagement in health and climate change (ind. **5.2.5**) is assessed by tracking individual's information seeking behaviour on Wikipedia in relation to climate change and health. When people are more engaged in the topic, they are more prepared and willing to take action, making them less vulnerable.

Institutional Empowerment

Lack of management cohesion (ind. **5.3.4**) is about to the extent that climate-related policies align across sectors, government levels, and technical and financial possibilities (**Koop et al., 2017**). Fragmentation of policies across different governmental layers and inter-departmental rivalries signifies a lack of continuity, coherence and inability to turn global strategies into regional realities. For instance, demonstration site 1: Berlin-Brandenburg indicates that they face fragmentation of policy strategies on a sectorial and regional level and that they miss a common strategy (across sectors and regions) to address challenges in an integrated way.

Research and development (ind. **5.3.5**) improves local knowledge and innovation to address climate change, particularly for developing place-based solutions. This makes regions more vulnerable to climate change.

Accelerated and ambitious interventions to decrease a region's climate vulnerability requires the public recognition that human health and climate change issues are important areas of concern. If this engagement is however absent and government and grassroots see no reason for change and action, their regions will only become more vulnerable to climate change. Public engagement in health and climate change (**i**nd. **5.3.6**) is therefore a crucial element in regions vulnerable to climate change.

The industrial sector is responsible for a large share of the greenhouse gas emission and can play a key role in tackling climate vulnerabilities and taking adaptive measures. However, in order to do so, this sector must be willing to take action. We will use this indicator to measure how corporations or industry are involved in coping mechanisms for climate change, and therefore be able to determine level of climate vulnerability (ind. **5.3.7** low industrial sector engagement in health & climate change).

Category VI : Miscellaneous

Table 17 Non-specific additional indicators.

Subcategory	**Additional indicator**
6. Non-specific	**6.2** Urban density
	6.3 Scarcity of land
	6.4 Ageing society

Urban density (ind. **6.2**) and especially rapid urbanisation is making regions more vulnerable to the impacts of climate change. Many cities are due to their location particularly prone to floods. Sea level rise, extreme downpours and river flooding already form major concern for particularly urban areas and this vulnerability is likely to increase substantially due to climate change. Moreover, many cities lack sufficient coverage of vegetation and water which increases vulnerability to extreme heat and downpours. Massive water demand also lead to critical vulnerabilities leading to water resources being overexploited in the vicinity of many urban agglomerates (Koop and Van Leeuwen, 2017). Particularly marginalised urban communities may be exposed to these climate impacts (Breil et al., 2018). Scarcity of land (ind. **6.3**), or lack of available land, can form a strong climate vulnerability indicator. In particular in regions characterised by the coexistence of critical infrastructure; industries; tourism; high urban density; and agricultural production are all severely competing for the same available resources. Share of population 65+ years (ind. **6.4**) is more vulnerable to the effects of climate change, manifested in mental and physical health risks. Elderly care can amount to a significant share of the available resources. Particularly, if the ratio 65+/work force age (roughly 20-65 years) is high. For instance, Germany – Europe's largest economy – already spends 13.1% of its GDP and 18% of its workforce in hospital nursing. This number is likely to rise substantially as the population is aging. Similar pattern can be observed across Europe. The more human and financial capacity is (justly) spent on elderly care, the less is available for critical innovations necessary to address climate vulnerabilities.

5.2 Additional indicators for Climate adaptation

A wide range of adaptation options are available to cope with the effects of climate change and the selection of most suitable options depends on the unique context of each country, region, municipality, business or ecosystem and the experienced specific impacts of climate change. For this reason, additional indicators for climate change adaptation, as defined for the purposes of this report, are not less important than core indicators but their applicability cannot be extended to all demonstration sites. All additional indicators identified in the IMPETUS indicator framework belong to the fourth category described in chapter 4 (adaptation interventions), since the other three categories, that refer to the creation of an enabling environment for adaptation, are quite general and can be applied to most situations.

Category 4: Adaptation interventions

As for core indicators, this category includes three subcategories to embrace different typologies of measures: green measures (4.1 based on services provided by natural ecosystems), grey measures (4.2 based on technological and engineering solutions) and behavioural (4.3 referring to changes of practices and habits). Whenever indicators refer to actions that are a combination of more than one subcategory, these are regarded as subcategory 4.4 "nonspecific" (Table 18).

Table 18 Proposed subcategories and additional indicators for implemented climate adaptation actions.

Subcategory	Name
4.1 Green measures	**4.1.5** Reforestation/Afforestation
	4.1.6 Green infrastructure in urban areas
	4.1.7 Improved Sustainable Urban Drainage Systems
4.2 Grey measures	**4.2.5** Installing floodgates
4.3 Behavioural measures	**4.3.3** Sustainable and resilient tourism
4.4 Non specific	**4.4.3** Stabilised river banks
	4.4.4 Cooling centres
	4.4.5 Retrofitted properties against heat
	4.4.6 Stabilised slopes and sediment on hilled areas
	4.4.7 Management interventions in terrestrial and marine protected areas
	4.4.8 Protection of climate refugia
	4.4.9 Fire management and related infrastructures

Additional indicators included in this category refer to:

- topics that have been already covered by core indicators (biodiversity conservation, coastal areas): in this case, additional indicators can be used to track more specific actions of adaptation.
- topics that have not been covered by core indicators (since they are not directly addressed by all demo-cases), but equally important: forest and river ecosystems, urban areas & buildings, tourism.

For **forest ecosystems**, afforestation (i.e., converting long-time non-forested land into forest) and reforestation (replanting of trees on more recently deforested land) are recognised as green climate change adaptation options, offering important synergies with mitigation (forests as carbon sink). The indicator **4.1.5** afforestation/reforestation measures the increase in re-forested or afforested areas (in terms of surface area), especially referring to the use of climate-resilient species that can tolerate changing conditions. Actions of afforestation and reforestation have the potential of counteracting the degradation of forest habitats due to human pressures, also enhancing landscape connectivity and reducing fragmentation. Species migration under climate change conditions is thus facilitated. In this regards, afforestation and reforestation may also contribute preserving biodiversity, increasing the overall resilience of ecosystems to climate change and other pressures. To include consideration of fire risk in forestry areas, the indicator **4.4.9** State of development of infrastructures and management practices for fire management aims to track progress in a wide range of possible practices (e.g., controlled burns, vegetation removal, firebreaks) to prevent forest fires from spreading.

Afforestation and reforestation can also control soil degradation and erosion, reducing hydraulic and landslide risks: the extension of reinforced river banks (**4.4.3**) and slopes (**4.4.6**) are other additional indicators proposed in the IMPETUS indicator framework. These risks are often managed with a combination of green (vegetation, trees) and grey (use of stones, concrete) measures. Narratives are especially required for these indicators to help assess how the area has been stabilised and the long term sustainability and effectiveness.

For the **urban environment and buildings**, indicators refer to a mix of highly interconnected green and grey measures that measure the efforts mainly made by cities and local authorities to be more resilient to higher temperature (especially during heatwaves) and to the increasing risk of flooding. Indicators for example refer to actions that increase green areas in cities both to offer a more comfortable environment (ind. **4.1.6** Green infrastructure) and to specifically increase the water infiltration potential, to decrease runoff volumes and attenuating peak flow (ind. **4.1.7** Improved Sustainable Urban Drainage Systems). Indicators also refer to the retrofitting of buildings against excessive heat (ind. **4.4.5**) and to the establishment of cooling centres and routes in urban areas (ind. **4.4.4**) with special consideration to most vulnerable groups (children, elderly, women, low income people). Retrofitting of buildings can include different strategies related to building design (use of IT technologies to optimise thermal comfort) and building envelopes (roof, ceilings, external walls, doors, windows). The assessment of this aspect can be performed in combination with other related core indicators, as 4.2.2 (water efficiency devices and technologies) and 4.2.3 (adapting/relocating buildings at risk) to assess the overall progress towards the adaptation of properties to climate change.

For **biodiversity conservation** in a changing climate, indicators refer to the improved management of terrestrial and marine protected areas (ind **4.4.7**) as well as to the establishment and protection of climate refugia *(*ind*,* **4.4.8**), as areas to be preserved as they remain relatively buffered from climate change over time and enable persistence of valued physical, ecological, and socio-cultural resources. These indicators can be considered as complementary to other more general indicators included among “core indicators” for biodiversity that aim to monitor restoration interventions in highly vulnerable or highly degraded ecosystems.

For coastal areas, the indicator **4.2.5** Installing floodgates can be considered as highly specific for those areas that have actually planned to install this type of intervention especially to protect urban areas or valuable infrastructure located in high-risk areas. This indicator can be used in combination with other “core” indicators, that are more broadly applied in most coastal areas (see section 4.2).

Finally, one particular indicator refers to the adaptation of the tourism sector to the effects of climate change (ind. **4.3.3**). Adaptation can for instance include initiatives that relief natural areas from the anthropogenic pressures (e.g., alternative eco-tourism offers) or modifications in tourism destinations and tourism seasons to take into account increasing temperature or change in rainfall patterns. The number and typologies of such initiatives can measure the progress of adaptation for this sector and it is taken as indicator. In this case, narratives that explain what solutions have been implemented and their environmental and social sustainability of new developed tourist offers are extremely relevant.

6 Resilience handbook

The proposed core indicators and additional indicators of the IMPETUS indicator framework form the basis for the resilience assessment. More specifically, it is proposed that a few indicators are selected for further analysis. This does not necessarily be limited to the indicators proposed in this deliverable.

Resilience is at the core of the sustainable development goals. Moreover, ‘building resilience’ is a frequently mentioned objective in policy agendas and has also been introduced into the systems analysis discipline across a multitude of different domains e.g. engineering, infrastructure, socio-ecological, economic, safety management, business and organizational systems. However, what ‘resilience’ exactly implies, how it can be improved and/or assessed is understood differently across and within different communities of research and practice, whereas a universal consensus of its definition is not available (Francis and Bekera, 2014; Lade et al., 2019; Lama et al., 2017). Hence, the resilience handbook will first provide an overview of key concepts and thereafter move beyond the elusiveness of the concept and provide an applicable method that can be used to assess resilience in your region and/or sector as a way to support strategic climate-aware decisions. This handbook is an additional module supporting the IMPETUS indicator framework that focusses on indicators to assess climate vulnerability and climate adaptation.

Introduction to resilience thinking

The world around us is rapidly changing with unprecedented rate (Koop & Van Leeuwen, 2017), stressing our systems with a multitude of stresses such as climate change, urbanization, population increase, decrease of natural resources, wars, epidemics, global crises, etc. Furthermore, these stresses, and their complex dynamic interplay do not fall under the classical “risk” definition, which is assigned to measurable chance-controlled factors, i.e., characterised by a frequency distribution or probabilities or events, well-known and measurable. Rather, these stresses relate with “uncertainty”, i.e. no known, reasonably valid probability distribution of events exists (Haimes, 1977, 2009). Furthermore, as most of the strategic planning problems that contemporary decision makers face, are characterised by long term future uncertainties that cannot be reduced by gathering past information, scholars characterize such situations as affected by “deep uncertainty” (Walker, 2013). Thus, system thinking and analysis shifted from the past notion of “fail-safe” systems against all eventualities to systems that are “safe-to-fail” (Ahern, 2007; Butler et al., 2017; Ahern, 2011). Pivotal in this paradigm shift was the introduction of the term resilience, initially a desired trait for ecological systems against external pressures (Holling, 1973, 1996) that rapidly branched out to engineering systems as a concept. Many different definitions of resilience emerged throughout the literature; Lama et al. (2017) describe that definitions of resilience can be divided into three main categories, each emphasizing a particular behaviour of a system, regarding to its response to disturbances that can be both gradual and long-term (i.e., climate change, social-demographic changes) or short-term shock events (i.e., floods, earthquake or economic recession; Lama et al., 2017).

1. Firstly, resilience can be described as the capacity to return to a certain equilibrium in response to a disturbance.
2. Secondly resilience can be explained as the buffering capacity of a system to remain in equilibrium.
3. Thirdly resilience can be defined as the ability to adapt in reaction to a disturbance.

Francis and Bekera (2014) identify two branches of definitions, where interpretations refer to the capacity of a system to absorb, adapt to, or recover from disturbance and cope with stress:

1: The amount of disturbance that a system can withstand without changing self-organised processes and structures

2: The return time to a stable state following a disturbance

More generally, resilience thinking is often understood as the ability to learn from disturbances and respond in a different, more resilient way after each significant disturbance (Lama et al., 2017). The concept of resilience can also be considered as either an outcome or as a process. Both approaches have its strengths and weaknesses.

- The *outcome*-oriented approaches to resilience are grounded in the concept of maintaining a system functioning under different levels of disturbance. Particularly when resilience is as the capacity to return to an equilibrium state or as buffering capacity, outcome-oriented resilience profiling is most suitable as a resilience assessment approach. Although minimising vulnerability and reducing loss is emphasised in the outcome-oriented approach, critics consider an overly focus on maintaining a status quo as a fallacy, particularly as the status quo might not be desirable. Moreover, this approach is relatively technocratic and restrained to disaster events, thereby not sufficiently accounting for other aspirations such as health- or education system developments. Moreover, key aspects of resilience such as social learning, preparedness and capacity development tend to be overlooked (Lama et al., 2017).
- The approaches to resilience as a *process* on the other hand, focus more on the future resilience of communities. This approach therefore is also more interlinked with approaches to adaptation and adaptive capacity. The critique to this approach includes the notion that it ignores the anticipatory aspect of resilience by focusing too much on the "positive trajectory of functioning and adaptation after a disturbance" (Lama et al., 2017).

The selection of definition and approach to assessment, depends on the system at hand, its boundaries and external environment; for instance, an outcome-oriented approach with would be suitable as an anticipatory approach to optimise the design of a technological engineering system. On the other hand, a process-oriented approach might be more suitable when considering the resilience of a community living in a certain area. In both cases, a different definition of resilience would be utilised, as performance against disturbances would be measured with unrelated metrics. A conjunctive approach including both resilience outcome and process analyses is often most supportive in strategic decision-making. This handbook provides guidelines on how to initiate a resilience assessment for enhancing well-informed decisions about climate adaptation. Before selecting an approach and its indicators, it is important to define the scope of assessment.

Defining the scope

According to Lama et al. (2017) there are three central aspects that need to be considered when assessing resilience and describing the relationship between resilience and adaptation in the context of risk and sustainable development.

1. The first step is to identify the values, goals, and aspirations of the people in the area or system under study (Lama et al., 2017). In other words, to explore what the system intends to protect and understand the rationale for being resilient (Lundberg & Johansson, 2019). Lundberg and Johansson (2019) moreover argue that in times of crisis, values are often re-negotiated, therefore it is useful to define these core values in a core value ladder reflecting the prioritisation of the core values that require protection.
2. The second step is the spatial and scalar delineations of the system (as well as the linkages between scales) under consideration should be clarified (Lama et al., 2017).
3. The third step is determining the timeframe which is under consideration (Lama et al., 2017).

The importance of thinking through these three steps cannot be underemphasised. Particularly since what needs to be resilient can shift under stress (Lundberg & Johansson, 2019). For instance, consider the case of a forest fire. For a firefighting operation the initial core value of the fire brigade (step 1) is to stop the fire in their region. However, when the forest fire is spreading faster and/or more intense than expected due to for example a prolonged heatwave, this value of stopping the fire might shift to evacuating people. Beyond the change of core values also the spatial scale can shift because the evacuation may exceed the spatial/geographical boundaries (step 2) that was initially considered.

Accordingly, the timeframe may shift too (step 3). Hence, beyond anticipating (climate) stress, resilience is about adapting simultaneously to both inherent uncertainties (i.e., a prolonged heatwave in our example) and the shift in goals as a result of increasing stress (Lundberg & Johansson, 2019 p. 115). Finally, a system can have several different objectives that can be conflicting at times. To stick to the example of forest fires, the objectives to protect houses in fire-prone areas while controlling the rising costs that this requires. Therefore, it is likely that you make several resilience frameworks for the same ‘topic’ that cover multiple events and objectives in order to make well-informed decisions.

Resilience framework

Having considered different categories of resilience thinking, the strengths and limitation of both outcome- and process-oriented approaches and considering three steps for determining the scope of resilience assessments, we now move to introducing a methodology to perform resilience assessments. This methodology is particularly useful as it provides a rationale for different types of resilience thinking outlined in the previous sections. Nikolopoulos et al. (2022) developed a source to tap simulation and stress testing framework for complete Urban Water Systems (UWS) to assess the systems overall resilience under long-term uncertainty and non-linearity/variability/stochasticity of different future world views (scenarios) based on the works of Makropoulos et al. (2018) and Nikolopoulos (2019). This resilience assessment stress-testing framework can be adapted to other domains and systems, e.g., as presented in Nikolopoulos et. al (2021), where it was applied at assessing resilience of a Contamination Warning System against cyber-physical attacks. The IMPETUS resilience assessment methodology will be based on these works and will be analysed in depth within Task 3.4 and discussed in Deliverable 3.3. The indicators and metrics framework that is formulated within Task 3.2 will allow stakeholders from the diversified regions of WP4 identify the most useful I&Ms and use a set of them for the resilience assessment.

In the next section we provide a brief introduction to the assessment methodology and provide insights about how the Task 3.4 (Analyse and assess resilience of key systems) could interconnect with the findings of Task 3.2 (Adopt and adapt indicators and metrics for climate change vulnerability, resilience assessment and pathway adaptation capacity), and the IMPETUS project in general.

From Urban Water Systems’ resilience to a generalised methodology for climate-change resilience

In the work of Makropoulos et al. (2018, p. 312), an operationalised definition is formulated: "resilience is the degree to which an urban water system continues to perform under progressively increasing disturbance.” Although this definition applies specifically for water systems, it can be translated more generally and allows modification to suit other problem settings.

The term “urban water system” describes a set of technologies installed (infrastructure) and design philosophy. In Nikolopoulos et al (2022) where the same methodology is used, decision making also is a part of the system being assessed. Therefore, it is reasonable to suggest that any well-defined system definition (i.e., that can delineate into boundaries, environment, technologies, actors, drivers and design philosophy) can be the target of the resilience assessment. Indeed, in Nikolopoulos et al. (2021), the assessment is implemented at a cyber-physical entity, a contamination warning system. In the IMPETUS realm, a whole region with its built environment, the physical properties, the environmental drivers, the stakeholders’ actions and decisions and climate change adaptation pathways can constitute such a system.

The term performance in Makropoulos et al. (2018, p. 312) is quantified by the system’s reliability, defined as “the ability of the system to deliver on its objectives in a consistent matter, consider over a timespan”. Any quantifiable metric or indicator that describes performance to meet objectives can be utilised in a generalised manner (see Figure 4). For example, in Nikolopoulos et al. (2021), the performance metric is the detection rate of contamination events, a quantifiable measure that describes how fit is the system to deliver protection to consumers during events of cyber-physical attacks. In Nikolopoulos et al. (2022) the metric is constructed from two different objectives pertaining to fitness against two failure modes over a long operating horizon, one hydraulic and one hydrological. Within IMPETUS, the resilience assessment can be undertaken using a multitude of suitable metrics/indicators (to be formulated within Task 3.4) that can describe the fitness of the system against climate change vulnerability and for climate adaptation over a long-term period, utilising the rich indicator framework of Task 3.2.

Finally, disturbance is modelled though scenarios, which define the superset of external changes and pressures the system must endure over the assessments timespan. In Makropoulos et al. (2018), scenarios are static i.e., a specific set of different scenario types, with a single realization, ranging from mild to extreme pressure to the system (picture). In the enhanced framework of Nikolopoulos (2022), scenarios are stochastically generated, with an ensemble of realizations for each scenario type (picture), allowing the capturing of uncertainty in the resilience assessment. Undeniably, within IMPETUS the driver of disturbances of scenarios is climate change, with a multitude of stochastic, dynamic and intertwining variables in hydroclimatic and socioeconomic effects, that should be tackled in the assessment.

Figure 5 depicts the use of a resilience profile graph for two different urban water systems, comparing their resilience against an ideal system design, under deterministic scenario types. The scenarios reside on the x-axis on an ordinal scale from least to most stressful to the system and the y-axis represents the overall performance metric (specifically in this graph, reliability of water supply). The area under the performance curves (is defined as resilience, expressed as a ratio to the area of the ideal system, i.e., ranges from 0 to 1. The "ideal system" is a fully robust system, meaning it is completely reliable regardless of the increasing amount of stress that each consecutive scenario imposes. If the scenarios are stochastic in nature and many realizations are generated and simulated for each scenario type, a performance curve and a resulting resilience metric can be pertained to each confidence level interval, as shown in the example from Figure 6.

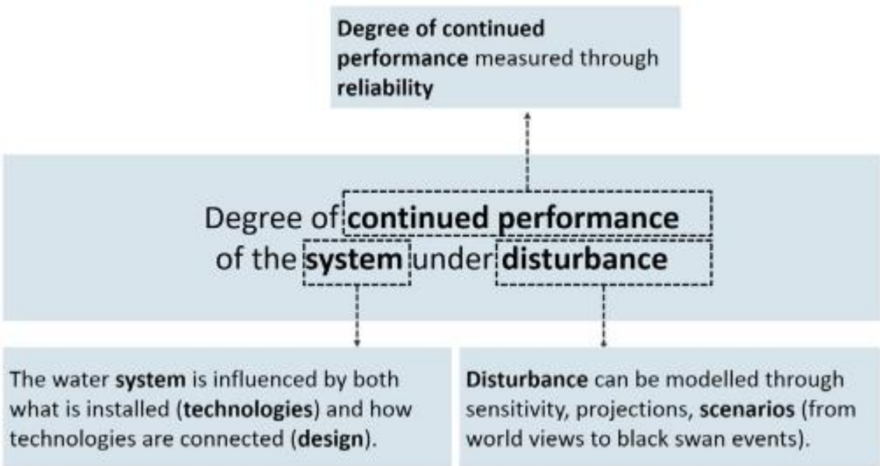

Figure 4 A visualisation of the resilience methodology by Makropoulos et al. (2018, p. 320).

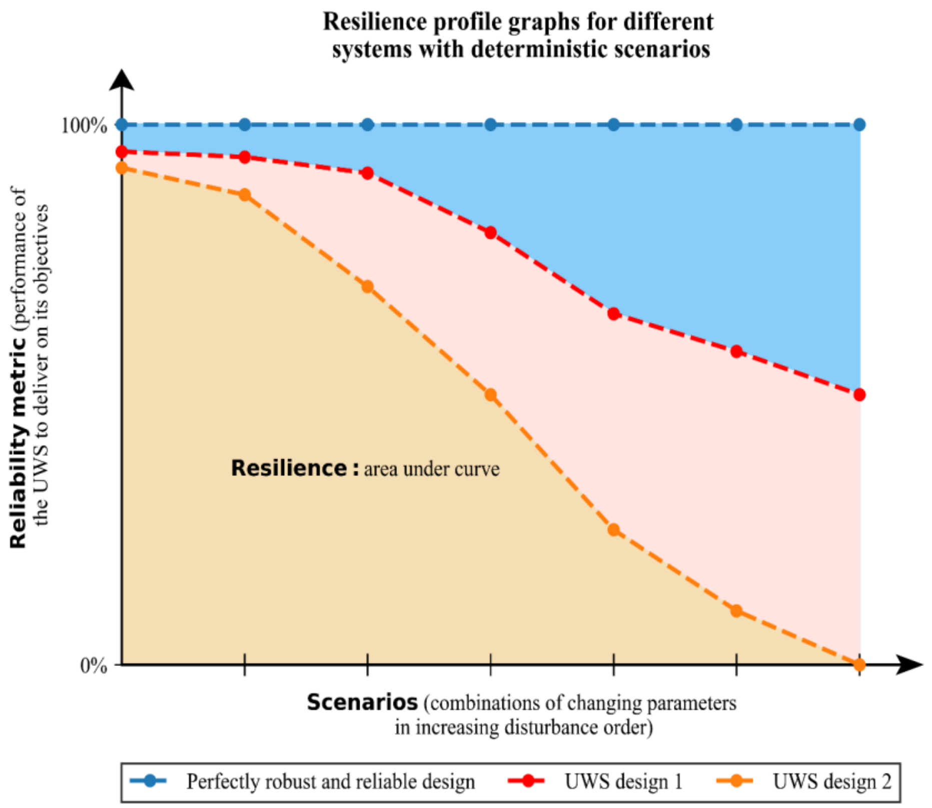

Figure 5 Resilience profile graph for different systems with deterministic scenarios, figure by Nikoloupos et al. (2022, p. 153).

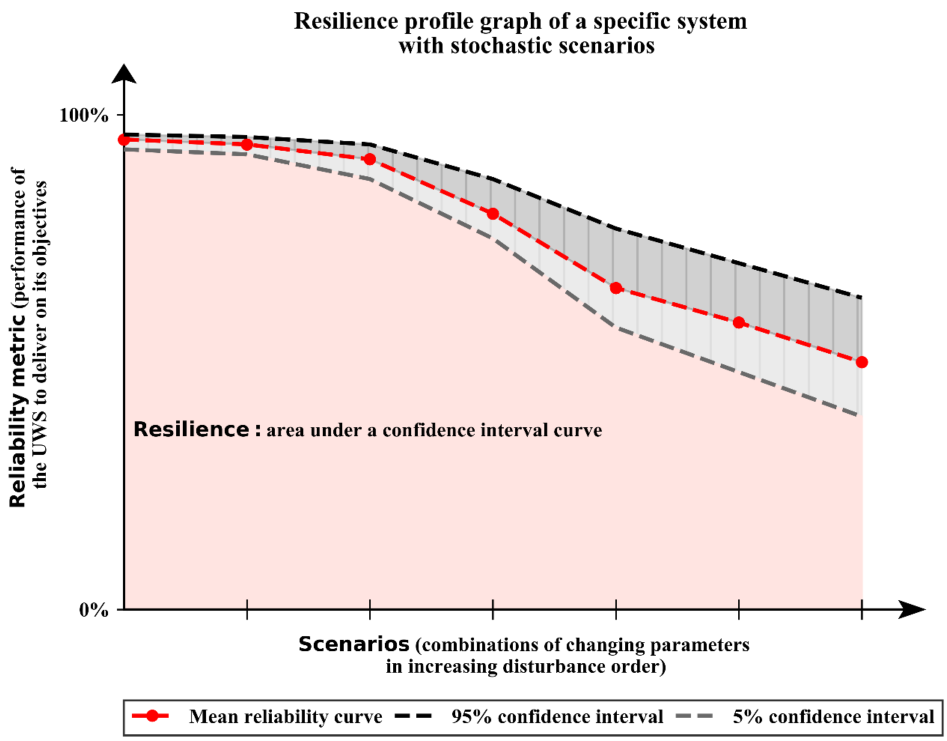

Figure 6 Resilience profile graph for different confidence intervals, generated from using stochastic scenarios, figure by Nikoloupos et al. (2022, p. 153).

Envisioned use of the IMPETUS indicator framework within resilience

The I&M framework can be used as an instrument to involve resilience in decision-making processes in two ways:

a) By giving context to the Regional Climate Resilience Footprint Tool (also developed within Task 3.4: Analyse and assess resilience of key systems) for stakeholders in WP1 (Governance & Stakeholder Co-creation for Transformative Adaptation) to perform a self-assessment of how resilient the current region under consideration is. For each region, a stakeholder-customizable set of I&Ms that are applicable to the particular use can be selected. These I&M can then be compared interactively with a visualization aid (e.g., spider graphs) with other regions or National/EU-wide averages, providing a useful conversation starter for resilience.

b) By providing the resilience assessment methodology (Task 3.4: Analyse and assess resilience of key systems) with the necessary performance metrics, distinct in every DS, to assess the resilience of any interventions (Task 3.5: Analyse and assess costs, benefits and risks related to interventions) to the region and system configurations. These will allow the evidence-based quantification of performance for the adaptation pathways in the Task 3.6 (Strategic Resilience and Multi-Hazard Management tool for identifying dynamic adaptation pathways)and provide insights about the resilience for the regional innovation packages developed in WP5 (IMPETUS Adaptation Pathways and Innovation Packages).

7 Discussion & Conclusions

Very recently, the importance of tracking changes in climate vulnerability and climate change adaptation has once again been emphasized by catastrophic events such as the flooding in Germany, Belgium and the Netherlands in 2021 and the unprecedented drought of summer 2022 across Europe. Increasingly, unexpected dynamics and vulnerabilities emerge and lead to adaptation efforts that are easily overtaken by the reality of an accelerating pace of climate change. These events urge for further climate adaptation action and consequently for monitoring of progress. As such, indicators and metrics offer a valuable tool to assess vulnerability and adaptation in a measurable way, enabling comparison among different areas, assessment of change over time and guiding strategic decisions.

Heterogeneous frameworks and approaches to monitoring, reporting and evaluation are being proposed in different international initiatives addressing topics that are strictly connected to climate change, such as disaster risk reduction (the Sendai Framework), sustainable development (the Agenda 2030 and its goals) and affordable energy (Global Covenant of Mayors for Climate and Energy).

Nonetheless, it is widely recognised by scientific and technical papers that measuring adaptation progress and vulnerability change through indicators and metrics is especially challenging and likely substantially more complex than monitoring climate change mitigation. Indeed, the impacts of climate change happen locally and affect local livelihoods, economic sectors and ecosystems in different ways, strongly depending on specific elements of vulnerability (related to different bio-geographic features and socioeconomic development) and on the adaptation capacity of each context. Consequently, adaptation often takes place at the lowest governance levels (subnational scale), where the reality of the impacts of climate change are experienced.

Recognising these complexities, the overall challenge for the preparation of the IMPETUS framework of indicators and metrics has been not only to cover the main crosscutting aspects of vulnerability and adaptation but also to account for context, considering indicators that might be specific for different ecosystems, geographic areas and economic sectors.

To address these issues, the IMPETUS framework is composed of core indicators (that are supposed to be of relevance for most demonstration sites) and additional indicators (to account for the peculiarity of different contexts). Supportive indicators are also proposed to complement some information provided by core indicators. Besides the previously mentioned lack of universal metrics for vulnerability and adaptation, several other challenges have been encountered in developing the IMPETUS indicator framework, as also reported in other frameworks and discussed in recent scientific and technical papers. Commonly reported challenges, include the lack of universal targets (adaptation is a process and not an end-point) and of fix and agreed baselines that can be used to assess changes and that continue to be a point of attention in applying the indicators in practice. One of the adopted solutions to overcome these barriers has been to develop indicators that can be used in a “flexible” way. Hence, the proposed indicators are relatively easy to adjust or tailor to site-specific characteristics and different spatial scales. In this regard, stakeholder engagement is considered a relevant opportunity for policy-makers, spatial planners and other practitioners to better define and tailor their framework of useful indicators to support climate-sensitive strategic decision-making and monitor progress. Furthermore, the use of qualitative metrics (when quantitative information is not available or easily derived) and of adding narratives that complement quantitative measures is widely recognised and also forms a guiding principle in applying the proposed IMPETUS indicator framework. In fact, indicators that lack of correct interpretation and continuous evaluation are by definition insufficient to identify maladaptation (which is an increasingly emerging and concerning issue) or explain the overall process that led to any change in vulnerability or to specific adaptation interventions. In this regard one of the stakeholders’ feedback was spot on in stating that “*One of the most useful ‘indicators’ are the stories, knowledge and feelings of the inhabitants*”.

In conclusion, the proposed IMPETUS indicator framework provides a structured state-of-the-art reflection of key climate vulnerabilities and adaptation aspects that accounts for key challenges across Europe’s bio-geographic regions. Accordingly, we argue that the indicators form a solid basis for the demonstration sites and other European areas because they are designed to be i) flexibly tailored to site-specific characteristics at different spatial scales, ii) easy to understand, and iii) timely and relevant. At the same time, the proposed set of indicators might not be exhaustive in tracking all possible types of adaptation interventions, detecting all aspects of vulnerability and solving all identified challenges. It rather can be regarded as a meaningful point of departure for a continuous learning-by-doing process. Further improvements might derive from incorporating emerging knowledge and from testing the proposed indicators in different bio-geographical areas.

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Annex I IMPETUS framework of indicators

References in annexes a and b are provided in full detail in the Excel database: Impetus superset - Climate vulnerability, Impetus superset - Climate adaptation.

a) Climate change vulnerability

I. Core indicators: Overview of proposed framework - Climate change vulnerability

Category	Subcategory	Core indicator
1 Health & well-being	1.1 Health Risk	1.1.1 Heat vulnerability
		1.1.2 Burden of disease attributable to the environment
		1.1.3 Increased risk of death due to ozone air pollution
		1.1.4 Health services dependency on external resources
		1.1.5 Population living in flood-prone regions
		1.1.6 Vector-borne disease
	1.2 Infrastructure	1.2.1 Access to emergency services during extreme weather events
		1.2.2 Patients capacity
		1.2.3 Workforce capacity
		1.2.4 Equipment capacity
	1.3 Socio-Economic Well-Being	1.3.1 Lack of social cohesion
		1.3.2 Instability and violence
2 Food and finance	2.1 Food Production	2.1.1 Proliferation of pests and diseases in pastures, crops, and cattle
		2.1.2 Reduced availability of pasture
		2.1.3 Impact of food production requirements on environment health
	2.2 Food Financing	2.2.1 Increased farm-related production costs
		2.2.2 Food loss and economic cost of extreme events
3 Water supply	3.1 Delivery	3.1.1 CSO detection and water loss assessment after heavy rainfalls
		3.1.2 Waste-water treatment coverage (%)
	3.2 Resources	3.2.1 Water Stress Index
		3.2.2 Agricultural water exploitation index
		3.2.3 Non-renewable groundwater stress index
4 Energy supply	4.1 Demand	4.1.1 Primary energy consumption per capita

		4.1.2 Energy demand due to extreme temperatures
		4.1.3 Energy efficiency label
		4.1.4 Low absolute energy expenditure (M/2)
	4.2 Provision	4.2.1 Diversity of renewable sources in primary energy production
		4.2.2 Number of energy supply interruptions per year
5 Innovation power	5.1 Economic	5.1.1 Income inequality
		5.1.2 Public debt
		5.1.3 Time to start a business
	5.2 Human Capacity	5.2.1 Learning poverty
		5.2.2 Human flight and brain drain
		5.2.3 Lack of women's political power
	5.3 Institutional Empowerment	5.3.1 Fragmentation of state institutions
		5.3.2 Power distance
		5.3.3 Weakness of rule of law

II. Core indicators: Detailed list of indicators for climate change vulnerability

Name	Brief description	Lowest Spatial scale	Sources
1.1.1 Heat vulnerability	This indicator aims at measuring the population whose health is known to be more susceptible to long prolonged periods of extreme heat; in this group are included people over 65 years of age, and in particular the segment that has chronic medical conditions (e.g diabetes and heart, lung and/or kidney disease). In a world that is increasingly warming due to climate change, this periods of extreme heat may become more frequent, and it becomes convenient to monitor the fraction of the population that is more exposed to these scenarios. When a country has a large share of the population that is vulnerable to heat (due to factors like age and health) (and the built environment is not prepared to cope with this heat) this makes a nation more vulnerable to the heat effects of climate change. The vulnerability to extremes of heat scores by Lancet Countdown (2021) can be used as input in the IMPETUS framework.	National	Lancet Countdown. (2021). 1.1 health and heat [Dataset]. In *1.1.1 vulnerability to extremes of heat.* https://www.lancetcountdown.org/data-platform/climate-change-impacts-exposures-and-vulnerability/1-1-health-and-heat/1-1-1-heat-vulnerability

Name	Brief description	Lowest Spatial scale	Sources
1.1.2 Burden of disease attributable to the environment	When a nation has more burden of disease attributable to the environment people are more susceptible to adverse climate impacts such as extreme heat, floods, food scarcity etc. The data by WHO (2022) on the burden of disease attributable to the environment expressed as the Disability-adjusted life years (DALYs) attributable to the environment can be used as input in the IMPETUS framework	National	WHO. (2022). Mortality and burden of disease attributable to the environment [Dataset]. In *Disability-adjusted life years (DALYs) attributable to the environment*. https://www.who.int/data/gho/data/indicators/indicator-details/GHO/disability-adjusted-life-years-(dalys)-attributable-to-the-environment
1.1.3 Increased risk of death due to ozone air pollution	Ozone levels at ground zone are increased due to the creation of ozone molecules by chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOC), all of them pollutants emitted by cars, industries, refineries, etc.. When these are in presence of solar radiation, ozone molecules are formed, increasing the concentration. When high levels of ozone are reached, previous medial conditions, such as asthma, may be aggravated	Local	Vicedo-Cabrera et al., 2020 https://www.epa.gov/ground-level-ozone-pollution/ground-level-ozone-basics
1.1.4 Health services dependency on external resources	Aligned with the previous indicator arises the need for a fast and efficient response that provides the required help to assist vulnerable population. It becomes important to be aware of the dependencies that our health service have with other countries and/or institutions, and to quantify to which extent a heath service can act independently in the case of a climate extreme event (heatwaves, heavy rains, hailstorms), or a consequence of it (wildfires or floods). Not having a thorough understanding of these dependencies makes us more vulnerable in the case of need. When countries rely more on external resources for their health services, they are less able to cope with the health effects of climate change because these external resources are less reliable or stable. ND-GAIN has an index in which they measure the proportion of total expenditures to health or related services that are provided by entities external to the country, which can be used as input for the IMPETUS framework.	National	ND-GAIN. (2015). University of Notre Dame Global Adaptation Index Country Index Technical Report [Dataset]. In SENSITIVITY INDICATOR 1: *Dependency on external resource for health services.* https://gain.nd.edu/our-work/country-index/download-data/

Name	Brief description	Lowest Spatial scale	Sources
1.1.5 Population living in risk regions under extreme events	To be able to provide an efficient response in the case of a natural disaster that can be consequence of a climate extreme (a flood after a heavy rain, a wildfire after a storm, or the isolation after a heavy snow), a census of the population that is living in regions that are prone to suffer these disasters is required. This provides a better planification in the case of need, and a better allocation of human and material resources when the disaster occurs.	Regional	Dilley, 2005
1.1.6 Vector-borne desease	World Health Organization defines Vectors are living organisms that can transmit infectious pathogens between humans, or from animals to humans. Following this line, vector-borne diseases are human illnesses caused by parasites, viruses and bacteria that are transmitted by vectors. Examples of these are malaria, dengue, schistosomiasis, or the yellow fever, among many others. In many cases, the living organisms that transmit these conditions live in regions with tropical climates. Under climate-change projections of global warming, these living organisms will find a place to adapt and proser where it was not possible before, bringing new diseases to places that may not be ready to react efficiently to these new viruses	Regional	Medlock, J. M., & Leach, S. A. 2015.
1.2.1 Access to emergency services during extreme weather events	Emergency services are the first link to react after a disaster occurs, and its role is essential for emergency care sensitive conditions and to ensure the security and wellbeing of the citizens. This makes it convenient to conduct a proper assessment of the access to emergency services (state of roads, distance to closest emergency service, telecommunications, etc.) that may be required after an extreme event.	Regional	https://www.researchgate.net/publication/343216902_Anywhere_Enhancing_Emergency_Management_and_Response_to_Extreme_Weather_and_Climate_Events

Name	Brief description	Lowest Spatial scale	Sources
1.2.2 Patients capacity	Under the expectations of an increase in the number and severity of heatwaves in the forthcoming summers, the risk for vulnerable population (older than 65 years old, or with previous medical conditions) increases, and it becomes crucial to anticipate the needs of healthcare infrastructure to cope with the consequences that extreme temperatures may represent. An indicator of the readiness to absorb the patients that may suffer health problems after a heatwave is the number of available beds per 100 000 habitants.	Regional	https://apps.who.int/iris/rest/bitstreams/1310975/retrieve
1.2.3 Workforce capacity	Health systems rely on an effective health workforce to achieve optimal results in the context of available resources and circumstances. Climate variability and change may increase local demand for services, thus potentially altering the number of health workers and staff required, the type of health workers, as well as their level of training. This helps providing a faster and more reliable response in the case of a sudden increase in the number of patients due to a climate extreme event.	Regional	https://www.who.int/teams/environment-climate-change-and-health/climate-change-and-health/country-support/building-climate-resilient-health-systems/health-workforce
1.2.4 Equipment capacity	Health system resilience to climate risks builds on provision of essential preventive and curative health products, from vaccines for climate-sensitive diseases to surgical equipment. It can be further enhanced through investment in specific technologies that can reduce climate vulnerabilities	Regional	https://www.who.int/teams/environment-climate-change-and-health/climate-change-and-health/country-support/building-climate-resilient-health-systems/climate-resilient-and-sustainable-technologies-and-infrastructure
1.3.1 Lack of social cohesion	Social cohesive societies are shown to enjoy increased resilience against extreme weather events (Baussan, 2015). Moreover does neighborhood social cohesion, protect against psychological harm caused by climate change events, such as flooding (Greene, Paranjothy, & Palmer, 2015). The Group Grievance indicator by Fund for Peace (2022b) can be used as input for the IMPETUS framework as a proxy for a lack of social cohesion. Group grievance index focuses on divisions and schisms between different groups in society – particularly divisions based on social or political characteristics – and their role in access to services or resources, and inclusion in the political process.	National	Fund for Peace. (2022b). Group grievance index [Dataset]. In *Fragile state index.* theGlobalEconomy.com. https://www.theglobaleconomy.com/rankings/group_grievance_index/

Name	Brief description	Lowest Spatial scale	Sources
1.3.2 Instability and violence	Political stability is an important criterion for the coping range of a population (Heltberg & Bonch-Osmolovskiy, 2011). Violence and instability (politically related) issues are often prioritized over climate related matters. Directing the allocation of resources and attention towards these (often more) short term problems instead of long term oriented solutions related to combatting climate change. The Political Stability and Absence of Violence/Terrorism indicator by the world bank (Kaufmann and Kraay, 2021) can after some alteration (for IMPETUS a higher score should mean less stability and absence of violence/terrorism) used as input for the IMPETUS framework,	National	Kaufmann, D., & Kraay, A. (2021). Political Stability and Absence of Violence/Terrorism [Dataset]. In *World Wide Governance Indicators.* World Bank. http://info.worldbank.org/governance/wgi/Home/Reports
2.1.1 Proliferation of pests and diseases in pastures, crops, and livestock	Despite being still an open subject, that needs a better understanding of all the complex relation that conform it, observations suggest that climate change will change the geographical distribution of crop insects and parasites, causing them to move towards regions where no natural predator for these plagues is present. This, if not properly controlled, may have an impact on crops upon which large populations may depend on, both as a source of food as well as economically. This indicator aims at monitoring changes in the proliferation of pests among time.	National	Grünig M. et al., 2020; Skendžić et al., 2021
2.1.2 Reduced availability of pasture	Availability of pasture for livestock farming. Intensive animal farming is known to be aggressive with the environment, usually polluting water and risking surrounding crops. Hence, a shift towards extensive animal faming is desired. To do so, the availability and preservation of pastures must be ensured	Regional	https://www.miteco.gob.es/es/cambio-climatico/temas/impactos-vulnerabilidad-y-adaptacion/impactos_vulnerabilidad_adaptacion_cambio_climatico_sector_agrario__tcm30-178448.pdf
2.1.3 Impact of food production requirements on environmental health	Both the use of pesticides, or the need to change a land type to use it for food production, may leave an impact on the local environment and ecosystem. If climate change brings exogenous pests to regions where it was not found, new pesticides may have impact on the local flora and fauna, In the same way, aridity and drought climate change may require changes in the land use to adapt food production to the new conditions (Vermeulen et al.,, S. J., Campbell, B. M., & Ingram, J. S.; 2012).	Regional	Vermeulen et al., 2012

Name	Brief description	Lowest Spatial scale	Sources
2.2.1 Increased farm-related production costs	Maintenance in adequate conditions of hydration, ventilation, and temperature to cattle in intensive farms	Regional	https://www.miteco.gob.es/es/cambio-climatico/temas/impactos-vulnerabilidad-y-adaptacion/impactos_vulnerabilidad_adaptacion_cambio_climatico_sector_agrario__tcm30-178448.pdf
2.2.2 Food loss and economic cost of extreme events	This climate extreme events might be floods affecting big farms of livestock, or hailstorms affecting fruit or cereal crops	National	Climate change adaptation in the agriculture sector in Europe, EEA Report No 4/2019 Púčik, et al., 2019
3.1.1 CSO detection and water loss assessment after heavy rainfalls	CSOs are Combined Sewer Overflows. These events occur after heavy rainfalls, when sewers cannot collect and efficiently transport domestic and industrial sewage, along with the excess of water coming from rain. In these cases, sewers overflow, and the excess of untreated water is discharged into a waterbody (rivers, canals, or the sea). This means that the risk of introducing domestic and industrial pollutants into water ecosystems increases	Local	Brunner et al, 2012
3.1.2 Wastewater treatment coverage (%)	control the amount of water that waste-water treatment systems can process from domestic or industrial sources. According to the United Nations – Water, currently around a 30% of wastewater flows received at least some treatment. With year 2030 in mind to increment this percentage, and under the menace of more frequent and severe droughts, it is important to monitor this process	Local	
3.2.1 Water Stress Index	Water stress index represents the fraction of water that is demanded by human-economic activities (irrigation, industry, households) relative to available renewable surface water supply. It is commonly considered that levels around 0.4 or larger represent high vulnerability. To understand how vulnerable we are under our current use of water, it becomes important to monitor this indicator.	Regional	Gleik, 1996 Raskin et al., 1997 Byers et al., 2018
3.2.2 Agricultural water exploitation index	Agricultural water exploitation index tracks the agricultural water demand, related to its availability. Another source of water, groundwater, must be protected the period needed for replenishment is long in comparison to the normal timeframe of agricultural extraction		

Name	Brief description	Lowest Spatial scale	Sources
3.2.3 Non-renewable groundwater stress index	Non-renewable groundwater stress index is calculated as the fraction of total annual groundwater abstraction that is non-renewable. This is, groundwater that is taken out of the aquifers that will likely not be replenished on human time scales. This water might be of importance in many places that have difficulty accessing to rivers, and opted to extract water from the underground. These water reserves may be consumed faster than they refill, posing a vulnerability to the people that depend on them.		Gleeson et al 2012
4.1.1 Primary energy consumption per capita	Average primary energy consumption measures the total energy demand of a country. Energy intensity is calculated as units of energy per unit of GDP	National	https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Energy_intensity
4.1.2 Energy demand due to extreme temperatures	Under the current scenario of an increasing global warming, heatwaves will become more frequent and severe, as well as periods of cold temperatures. These, if prolonged, put the health of vulnerable population under a lot of stress. To cope with both extremes, households and workplaces must use conditioning systems, often for long periods of time. These conditioning systems consume large amounts of energy, that may put into stress	Regional	https://www.ncei.noaa.gov/access/monitoring/redti/overview
4.1.3 Energy efficiency label	The EU energy labelling and ecodesign legislation helps improve the energy efficiency of products on the EU market. It sets common EU-wide minimum standards to eliminate the least performing products from the market. In this regard, the energy labels, currently divided into 7 levels, provide a clear and simple indication of the energy efficiency. This makes it easier for consumers to save money on their household energy bills and contribute to reducing greenhouse gas emissions across the EU. In particular, this legislation for energy labels and ecodesign has been estimated to bring energy savings of approximately 230 million tonnes of oil equivalent (Mtoe) by 2030. For consumers, this means an average saving of up to €285 per year on their household energy bills. Moreover, energy efficiency measures will create €66 billion in extra revenue for European companies	National	European energy labels: rescaling and transition periods (https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/about_en)

Name	Brief description	Lowest Spatial scale	Sources
4.2.1 Diversity of renewable sources in primary energy production	The use of renewable energy has many potential benefits, including a reduction in greenhouse gas emissions, the diversification of energy supplies and a reduced dependency on fossil fuel markets (in particular, oil and gas). The growth of renewable energy sources may also stimulate employment in the EU, through the creation of jobs in new 'green' technologies	National	https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics
4.2.2 Number of energy supply interruptions per year	Monitoring the number of times, and the respective duration, that energy supply was interrupted due to a Climate extreme event	Local	

Name	Brief description	Lowest Spatial scale	Sources
5.1.1 Income inequality	Income inequality (ind. 5.1.1) can form a strong barrier to climate innovations and exacerbate climate vulnerability. First of all, it hampers innovation and thereby limits society's ability to mitigate climate vulnerabilities. With large income inequalities, part of the population cannot afford access to basic needs such as education or proper health care, or cannot invest in personal professional skills and labor productivity. Consequently, a substantial part of society's innovation potential is lost. The know-how, creativity and skilled workers that are critical for developing and applying innovations decline under increased levels of income inequalities. Secondly, income inequality leads to a direct increase in vulnerability since a larger share of the population cannot afford measures to mitigate vulnerability such as flood insurance or insulating houses, and live in areas deprived of, for instance, sufficient flood protection measures or green areas that mitigate urban heating (note interlinkages with ind. 1.1.1 heat vulnerability, 1.1.4 population living in risk regions under extreme events, 4.1.2 energy demand due to extreme temperatures, 4.1.3 energy-efficiency label). Limited access to assets, opportunities and reduced political voice and participation further exacerbate climate vulnerability (United Nations, 2016). If the available resources are concentrated in fewer hands, communal allocation of resources and pooling of risk is more limited (Adger & Kelly, 1999). The social impact of inequality cannot be underemphasized as greater inequality fuels distrust, discontent and unstable politics (Burgoon, van Noort, Rooduijn, & Underhill, 2018) which tend to lead to less stable and therefore more vulnerable societies. The Gini index by the World Bank (2021) measures the extent to which the distribution of income (or, in some cases, consumption expenditure) among individuals or households within an economy deviates from a perfectly equal distribution and be used as input for the IMPETUS framework.	National available Local inventory possible	The World Bank. (2021). Gini Index [Dataset]. In *Poverty and Inequality Platform*. https://data.worldbank.org/indicator/SI.POV.GINI?view=chart

Name	Brief description	Lowest Spatial scale	Sources
5.1.2 Public debt	Higher public debts lead to less room for investment in resources to cope with climate change or to respond to direct impacts, thereby enhancing climate vulnerability or limiting the necessary investments in innovation to tackle climate issues The public debt scores by the Central Intelligence Agency (2017) can be used as input in the IMPETUS framework.	National	Central Intelligence Agency. (2017). Public debt [Dataset]. In *The World Fact Book*. https://www.cia.gov/the-world-factbook/field/public-debt/country-comparison
5.1.3 Time to start a business	Coping with the adverse effects of climate change requires innovation power to respond in a timely and adequate fashion to emerging challenges. In order to do so, start-ups and small-medium enterprises need to be enabled to seek and seize new opportunities to combat climate change. This level of flexibility is necessary to foster new innovation trajectories, experiment and mobilise creativity to mitigate climate change. The time to start a business is a proxy for the level of flexibility to innovate and thereby address climate vulnerabilities. The data by The World Bank (2021b) on time required to start a business can be used as input in the IMPETUS framework.	National	The World Bank. (2021b). Time required to start a business (days) [Dataset]. In *Doing Business*. https://data.worldbank.org/indicator/IC.REG.DURS?page=1
5.2.1 Learning poverty	Endorsing observations of Muttarak & Lutz (2014) that "Education can directly influence risk perception, skills and knowledge and indirectly reduce poverty, improve health and promote access to information and resources", learning poverty is a critical element that enhances climate vulnerability. On the contrary, educated societies boost the human capacity to innovate and thereby address climate vulnerabilities. The scores by the World Bank (2019) on learning poverty: share of children at the end-of-primary age below minimum reading proficiency can be used directly for the IMPETUS framework	National available Local inventory possible	The World Bank. (2019). Learning Poverty: Share of Children at the End-of-Primary age below minimum reading proficiency adjusted by Out-of-School Children (%) [Dataset]. In *Education Statistics*. https://databank.worldbank.org/indicator/SE.LPV.PRIM?id=c755d342&report_name=EdStats_Indicators_Report&populartype=series

Name	Brief description	Lowest Spatial scale	Sources
5.2.2 Human flight and brain-drain	Another key aspect shaping human capacity is related to the human flight and brain drain. That is when people leave their region or country – often either directly or indirectly related to climate factors – they also take their knowledge and innovation power (to combat climate change) with them. In addition, human flight and brain drain leads to fewer tax incomes, thereby lowering the resources that could be spend on strategies to cope with climate change. The scores of the human flight and brain drain indicator by Fund for Peace (2022) can be used as input for the IMPETUS framework.	National	Fund for Peace. (2022). Human flight and brain drain index [Dataset]. In *Fragile state index*. theGlobalEconomy.com. https://www.theglobaleconomy.com/rankings/human_flight_brain_drain_index/
5.2.3 Lack of women's political power	Woman empowerment is increasingly considered as an important element of enhancing the human capacity to address climate change (Asongu, Messono, & Guttemberg, 2021). The inclusion of women in strategic decision-making frequently led to more holistic, long-term and risk-considered decision-making (e.g., Profeta, 2017). Many studies find that woman are better aware of and worry more about climate change (McCright, 2010). By increasing woman's participation in national parliaments, it is likely that more stringent climate change policies are adopted (Women, 2022). The gender parity index by Vogelstein and Bro (2021) can, after some alteration (for IMPETUS a higher score should mean less women's empowerment) be used as input for the IMPETUS framework.	National	Vogelstein, R. B., & Bro, A. (2021, March 29). Women's Power Index [Dataset]. In Women and Foreign Policy Program. Council on Foreign Relations. https://www.cfr.org/article/womens-power-index

Name	Brief description	Lowest Spatial scale	Sources
5.3.1 Fragmentation of state institutions	Fragmentation of state institutions is considered a key limiting factor of the institutional empowerment of climate adaptation actions. Institutional fragmentation is closely related to factionalised elites, which is the discordance of a society into different political groups that promote rhetoric and actions which are harmful to society (St. Edwards University, 2015). This fragmentation leads to more climate vulnerability, because polarisation and power struggles tend to consume much resources and attention that, as a consequence, will not be directed to more long-term issues such as climate change. Moreover, the effects of climate change tend to increase this fragmentation of state institutions (Werrell, Femia, & Sternberg, 2015), hence creating a negative feedback loop that further increases climate vulnerability. The scores on the factionalized elites index by Fund for Peace (2022a) can be used as input in the IMPETUS framework.	National	Fund for Peace. (2022a). Factionalized elites index [Dataset]. In *Fragile state index.* theGlobalEconomy.com. https://www.theglobaleconomy.com/rankings/factionalized_elites_index/
5.3.2 Power distance	Power distance is considered a determinant factor for institutional empowerment. In countries or regions with higher power distance scores, people lower in the hierarchy are less likely to express concerns (about climate related problems) to their 'superiors'. However, it is at the 'lower level' (e.g., in the field) where the effects of climate change tend to be most evident. Therefore the 'superiors' lack this critical input, while they are in the position of decision-making, making them more vulnerable to climate change. As a result, regions with lower power distance levels are found to be less vulnerable to climate disaster (Dückers et al., 2015) and more frequently report on the Sustainable Development Goals (Rosati & Faria, 2019). The power distance scores by Hofstede Insights (n.d.) can be used as input for the IMPETUS framework.	National	Hofstede Insights. (n.d.). Power distance [Dataset]. In *6-D Model of National Culture*. https://www.hofstede-insights.com/fi/product/compare-countries/

Name	Brief description	Lowest Spatial scale	Sources
5.3.3 Weakness of rule of law	*Rule of law captures perceptions of the extent to which agents have confidence in and abide by the rules of society. In particular, the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence* (Kauffman and Kraay, 2022). Coherent and effective rule of law is often emphasized to play a decisive role in long-term solutions necessary to address climate change. Data on the rule of law by Kaufmann and Kraay (2022) can, after some alteration (a higher score should indicate weaker rule of law) , be used as input for the IMPETUS framework.	National	Kaufmann, D., & Kraay, A. (2022). Rule of Law [Dataset]. In *World Wide Governance Indicators*. World Bank. http://info.worldbank.org/governance/wgi/Home/Reports

III. Additional indicators: Overview of proposed framework - Climate change vulnerability

Category	Subcategory	Additional Indicator
1 Health & well-being	**1.1 Health risk**	**1.1.7** Flood emergency evacuation time
		1.1.8 People living in urban heat island
	1.3 Socio-economic well-being	**1.3.3** People with pre-existing (mental) health conditions
		1.3.4 Overarching awareness of climate change threats
		1.3.5 The existence of citizen led initiatives
		1.3.6 The under-housed and homeless
		1.3.7 Outdoor labourers
		1.3.8 Share of marginalised communities
		1.3.9 Climate change induced migration
2 Food and finance	**2.1 Food production**	**2.1.3** Saltwater intrusion
		2.1.4 Soil salinisation
		2.1.5 Flash floods
3 Water supply	**3.1 Service delivery**	**3.1.3** Industrial freshwater intensity
		3.1.4 Excess demand during tourist season
	3.2 Water resources	**3.2.4** Water infiltration capacity
		3.2.5 Water footprint of food consumption
		3.2.6 Cooling water exploitation index
5 Innovation power	**5.1 Economic**	**5.1.4** Low monetary credibility
		5.1.5 Loss of international tourism revenue
		5.1.6 Loss of revenue from forest resources
	5.2 Human capacity	**5.2.4** Material deprivation
		5.2.5 Engagement in health & climate change

	5.3 Institutional empowerment	**5.3.4** Lack of management cohesion
		5.3.5 Low research & development expenditure
		5.3.6 Low government engagement in health & climate change
		5.3.7 Low industrial sector engagement in health & climate change
6 Non-specific	**6. Non-specific**	**6.2** Urban density
		6.3 Scarcity of land
		6.4 Ageing society

IV. Additional indicators: Detailed list of indicators for climate change vulnerability

Name	**Brief description**	**Lowest spatial scale**	**Sources**
1.1.7 Flood emergency evacuation time	of monitoring the capacity of rescue services to coordinate an evacuation after a flood as well as the time it takes for the population to move to a secure shelter	Regional	
1.1.8 People living in urban heat island	Estimation of the people that are living in urban areas that are more prone to accumulate heat inertia during daytime, becoming heat islands (regions with high solar exposure, lack of greenery, etc). People living in these areas are prone to suffer the effects of heat on health in a worst way	Local	
1.3.3 People with pre-existing (mental) health conditions	Because climate change effects like extreme heat have been shown to increase mood and behavioural disorders amongst people with pre-existing mental illness and elderly who have poor thermoregulation. The percentage or amount of people with pre-existing (mental) health conditions is an important determinant of climate vulnerabilities related to social well-being.	Local	Local data sources on mental health, such as: Castelpietra G, Skrindo Knudsen AK, et al. The burden of mental disorders, substance use disorders and self-harm among young people in Europe, 1990–2019: Findings from the Global Burden of Disease Study 2019. The Lancet Regional Health. 1 April 2022. doi:10.1016/j.lanepe.2022.100341. GBD 2019 Mental Disorders Collaborators. Global, regional, and national burden of 12 mental disorders in 204 countries and territories, 1990–2019: a systematic analysis from the Global Burden of Disease Study 2019. The Lancet Psychiatry. 10 January 2022. doi: 10.1016/S2215-0366(21)00395-3.

1.3.4 Overarching awareness of climate change threats	The overarching awareness of climate change as a threat to well-being and livelihood or way of life forms in combination with affirmative mental health a strong enabler to reduce climate vulnerability because people take climate action. However, with poor affirmative mental health, it could also constitute feelings of distress, anxiety, and fear that inhibit climate action. Hence it depends on whether a region has ways to direct this distress, anxiety and fear into coping methods and ways to take action. In the absence of initiatives or perspective, it may lead to a fatalistic attitude. Hence, the opportunity for collective action (ind. 1.3.5) is therefore also proposed as a vulnerability indicator.	National data available Local inventory possible	The Peoples' Climate Vote | United Nations Development Programme. (n.d.). *UNDP*. Retrieved September 29, 2022, from https://www.undp.org/publications/peoples-climate-vote
1.3.5 The existence of citizen led initiatives	The overarching awareness of climate change as a threat to well-being and livelihood or way of life (ind. 1.3.4) forms in combination with affirmative mental health a strong enabler to reduce climate vulnerability because people take climate action. However, with poor affirmative mental health, it could also constitute feelings of distress, anxiety, and fear that inhibit climate action. Hence it depends on whether a region has ways to direct this distress, anxiety and fear into coping methods and ways to take action. In the absence of initiatives or perspective, it may lead to a fatalistic attitude. Hence, the opportunity for collective action (ind. 1.3.5) is therefore proposed as a vulnerability indicator.	Local	*How citizen-led initiatives can revitalize small city centers* | *European Week of Regions and Cities.* (n.d.). Retrieved September 29, 2022, from https://europa.eu/regions-and-cities/how-citizen-led-initiatives-can-revitalize-small-city-centers
1.3.6 The under-housed and homeless	homeless people are among the most vulnerable to climate change hazards like extreme heat, extreme weather events and vector-borne diseases (Hayes and Poland, 2018)	National data available Local inventory possible	Esteban Ortiz-Ospina and Max Roser (2017) - "Homelessness". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/homelessness' [Online Resource]
1.3.7 Outdoor labourers	Outdoor labourers are among the most vulnerable to climate change hazards like extreme heat, extreme weather events and vector-borne diseases (Hayes and Poland, 2018)	Local	Hayes, K., Poland, B. (2018). Addressing mental health in a changing climate: Incorporating mental health indicators into climate change and health vulnerability and adaptation assessments. International journal of environmental research and public health, 15, 1806.

1.3.8 Share of marginalised communities	Marginalized communities are those *excluded from mainstream social, economic, educational, and/or cultural life. Examples of marginalized populations include, but are not limited to, groups excluded due to race, gender identity, sexual orientation, age, physical ability, language, and/or immigration status*. (Sevelius et al., 2020, p.2010) Marginalization occurs due to unequal power relationships between social groups marginalized communities are among the most vulnerable to climate change hazards like extreme heat, extreme weather events and vector-borne diseases (Hayes and Poland, 2018)	Local	Hayes, K., Poland, B. (2018). Addressing mental health in a changing climate: Incorporating mental health indicators into climate change and health vulnerability and adaptation assessments. International journal of environmental research and public health, 15, 1806.
1.3.9 Climate change induced migration	amount of people that will have to migrate to another region or country due to the effects of climate change	National	Pörtner et al., 2022
2.1.3 Saltwater intrusion	Movement of saline water into freshwater aquifers, which can lead to groundwater quality degradation, including drinking water sources, and other consequences. This may affect the availability of drinking water in coastal regions, and pose a challenge to water-processing units, as well as a problem for agricultural regions that rely on this	Regional	Bhattachan et al., 2018
2.1.4 Soil salinisation	Soil salinisation measures the degree to which agricultural soil can be affected by the same process, resulting into a potential and irreversible loss of land to produce food, while altering ecosystems.	Regional	Corwin, 2021
2.1.5 Lack of protection to flash floods	Flash floods are usually characterized by raging torrents after heavy rains that pour in a short period of time. Flash floods flow through river beds, urban streets, or mountain canyons, with a lot of strength, posing serious damage to anything on their way	Regional	Brunner et al., 2021
3.1.3 Industrial freshwater intensity	Relates the volumes of water that is used in industry per unit of value added. Lower industrial freshwater intensity represents economic development being decoupled from freshwater demand, hence pointing at a low vulnerability	National	Water intensity of crop production in Europe, European Environment Agency, 2019

3.1.4 Excess demand during tourist season	Measuring the challenges that tourism poses to already vulnerable regions, where water can be scarce during the touristic seasons. Tourist put pressure on water resources particularly during the dry summer season	Regional	
3.2.4 Water infiltration capacity	The amount of water that can infiltrate into the soil after a rainfall, not becoming part of potential floods		
3.2.5 Water footprint of food consumption	The amount of water that is put into the production of different kinds of food (from vegetables to meat		Vanham et al., 2016
5.1.4 Low monetary credibility	In countries with banks that have low established credibility, sectorial price shocks (e.g., food prices) risk de-anchoring (short-term price shocks can change long-term expectations) inflation expectations, leading to a second-round effect increasing inflationary pressure in the medium term. Countries with banks with well-established credibility and well-anchored inflation expectations are less likely need to respond to sectorial price shocks and the effects of inflation are more likely to be short-lived (Batten et al., 2016). Therefore, countries with banks that have low established credibility are more vulnerable to climate change, since climate change effects (such as droughts, heat waves or floods) may lead to upward pressure on commodity and food prices, and hence on inflation (Batten et al., 2020).	National	Batten, S., Sowerbutts, R., & Tanaka, M. (2016). Let's talk about the weather: the impact of climate change on central banks. Batten, S., Sowerbutts, R., & Tanaka, M. (2020). Climate change: Macroeconomic impact and implications for monetary policy. Ecological, societal, and technological risks and the financial sector, 13-38.
5.1.5 Loss of international tourism revenue	The tourism sector can be vulnerable to climate change. When a large proportion of the GDP is received from tourism, climate change not only influences the environment but also the region's financial gains from tourism, limiting the financial resources to deal with the effects of climate change. The data on tourism by OECD (2022) can be used as input for the IMPETUS framework.	National available Local inventory possible	OECD (2022), Tourism GDP (indicator). doi: 10.1787/b472589a-en (Accessed on 30 September 2022)

5.1.6 Loss of revenue from forest resources	As climate change will affect forests, and affect possibilities to create revenue from forests (e.g., pulp and paper industry or ecotourism), therefore nations that receive a substantial share of their GDP from forest revenue are more vulnerable to climate change (policies), increasing their vulnerability. Data on forest resources revenue by the CIA (2022) can be used as input for the IMPETUS framework.	National available Local inventory possible	Central Intelligence Agency. (2022). Revenue from forest resources [Dataset]. In *The World Fact Book.* https://www.cia.gov/the-world-factbook/field/revenue-from-forest-resources/
5.2.4 Material deprivation	The proportion of the population that cannot afford at least four of the following items: to pay their rent, mortgage, utility bills or loan repayments, to keep their home adequately warm, to face unexpected financial expenses, to eat meat or protein regularly, to go on holiday for a week once a year, a television set, a washing machine, a car, a telephone When people face such deprivation, they have less resources (i.e., time, energy and money) to prepare for climate change (e.g., Ong et al., 2019). Moreover, it is this group which often is hit hardest by, and hence most vulnerable to, the effects of climate change.	National available Local inventory possible	Eurostat. (2022). Severe material deprivation rate [Dataset]. In *Social protection performance monitor - indicators*. eurostat. https://ec.europa.eu/eurostat/databrowser/product/view/ILC_MDDD11
5.2.5 Engagement in health & climate change	Individual engagement in health and climate change is assessed by tracking individual's information seeking behaviour on Wikipedia in relation to climate change and health. When people are more engaged in the topic, they are more prepared and willing to take action, making them less vulnerable. Data by lancet countdown (2020a) can be used as input in the IMPETUS framework.	National data available local inventory possible	Lancet Countdown. (2020). Individual engagement in health and climate change [Dataset]. In *Public and political engagement*. https://www.lancetcountdown.org/data-platform/public-and-political-engagement/5-2-individual-engagement-in-health-and-climate-change
5.3.4 Lack of management cohesion	Lack of management cohesion is about to the extent that climate-related policies align across sectors, government levels, and technical and financial possibilities. Fragmentation of policies across different governmental layers and inter-departmental rivalries signifies a lack of continuity, coherence and inability to turn global strategies into regional realities. For instance, demonstration site 1: Berlin-Brandenburg indicates that they face fragmentation of policy strategies on a sectorial and regional level and that they miss a common strategy (across sectors and regions) to address challenges in an integrated way.	Local	Koop, S. H. A., Koetsier, L., Doornhof, A., Reinstra, O., Van Leeuwen, C. J., Brouwer, S., ... & Driessen, P. P. J. (2017). Assessing the governance capacity of cities to address challenges of water, waste, and climate change. Water resources management, 31(11), 3427-3443.

5.3.5 Low research & development expenditure	Research and development improves local knowledge and innovation to address climate change, particularly for developing place-based solutions. This makes regions more vulnerable to climate change	National data available local inventory possible	OECD. (2022). Research and Development Statistics (RDS) [Dataset]. In *Science, technology and innovation policy.* https://www.oecd.org/sti/inno/researchanddevelopmentstatisticsrds.htm
5.3.6 Low government engagement in health & climate change	Accelerated and ambitious interventions to decrease a region's climate vulnerability requires the public recognition that human health and climate change issues are important areas of concern. If this engagement is however absent and government and grassroots see no reason for change and action, their regions will only become more vulnerable to climate change. Data by lancet countdown (2020a) can be used as input in the IMPETUS framework	National	Lancet Countdown. (2020a). Government engagement in climate change [Dataset]. In *Public and political engagement*. https://www.lancetcountdown.org/data-platform/public-and-political-engagement/5-4-government-engagement-in-health-and-climate-change
5.3.7 Low industrial sector engagement in health & climate change	Accelerated and ambitious interventions to decrease a region's climate vulnerability requires the public recognition that human health and climate change issues are important areas of concern. If this engagement is however absent and government and grassroots see no reason for change and action, their regions will only become more vulnerable to climate change. Data by lancet countdown (2020b) can be used as input in the IMPETUS framework	National data available local inventory possible	Lancet Countdown. (2020b). Corporate sector engagement in health and climate change [Dataset]. In *Public and political engagement*. https://www.lancetcountdown.org/data-platform/public-and-political-engagement/5-5-awaiting-data-corporate-sector-engagement-in-health-and-climate-change
6.2 Urban density	Urban density and especially rapid urbanisation is making regions more vulnerable to the impacts of climate change. Many cities are due to their location particularly prone to floods . Sea level rise, extreme downpours and river flooding already form major concern for particularly urban areas and this vulnerability is likely to increase substantially due to climate change. Moreover, many cities lack sufficient coverage of vegetation and water which increases vulnerability to extreme heat and downpours. Massive water demand also lead to critical vulnerabilities leading to water resources being overexploited in the vicinity of many urban agglomerates. Particularly marginalised urban communities may be exposed to these climate impacts. Data by Ritchie and Roser (2018) can be used as input for the IMPETUS framework	National data available local inventory possible	Hannah Ritchie and Max Roser (2018) - "Urbanization". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/urbanization' [Online Resource]

6.3 Scarcity of land	Scarcity of land (ind. 6.3), or lack of available land, can form a strong climate vulnerability indicator. In particular in regions characterised by the coexistence of critical infrastructure; industries; tourism; high urban density; and agricultural production are all severely competing for the same available resources.	Local	
6.4 Ageing society	Share of population 65+ years (ind. 6.4) is more vulnerable to the effects of climate change, manifested in mental and physical health risks. Elderly care can amount to a significant share of the available resources. Particularly, if the ratio 65+/work force age (roughly 20-65 years) is high. For instance, Germany – Europe's largest economy – already spends 13.1% of its GDP and 18% of its workforce in hospital nursing. This number is likely to rise substantially as the population is aging. Similar pattern can be observed across Europe. The more human and financial capacity is (justly) spent on elderly care, the less is available for critical innovations necessary to address climate vulnerabilities .	National data available local inventory possible	United Nations. (n.d.). Ageing. Retrieved September 30, 2022, from https://www.un.org/en/global-issues/ageing#:%7E:text=Globally%2C%20the%20population%20aged%2065%20and%20over%20is,Northern%20America%20could%20be%20aged%2065%20or%20over.

b) Climate change adaptation

I. Core indicators: Overview of proposed framework - Climate change adaptation

Category	Subcategory	Core indicator
1 Institutional strength	**1.1** Coordination, strategies, plans & policies	**1.1.1** Local disaster risk reduction strategies
		1.1.2 Area covered by local emergency management plans or action groups
		1.1.3 Mainstreaming of Climate change adaptation in Disaster Risk Reduction legislation
		1.1.4 Pre-emptive evacuation following early warning
		1.1.5 Sector/land use management plans with significant climate change considerations
		1.1.6 Institutional frameworks for climate change adaptation
	1.2 Laws & regulations	**1.2.1** Environmental Impact Assessment and Strategic Environmental Assessment with climate change considerations
		1.2.2 Revised building codes and climate proofing of buildings
		1.2.3 Adapted standards for transport infrastructures
2 Allocated resources	**2.1** Financing & incentive instruments	**2.1.1** Expenditure in studies and research projects
		2.1.2 Number of studies and projects

		2.1.3 Funds for adaptation
		2.1.4 Mainstreaming of Climate change adaptation into funding schemes for specific sectors
		2.1.5 Expenditure in dissemination/information about climate change impacts adaptation
		2.1.6 Investments for planning and management of emergency
		2.1.7 Investment in specific climate adaptation interventions
		2.1.8 Economic incentives
	2.2 Insurance and risk sharing instruments	**2.2.1** Insurance against extreme events
3 Knowledge and education	**3.1** Climate Services and information tools	**3.1.1** Development of forecasting, early warning, climate services and decision support systems
		3.1.2 Availability of information on different and multiple climate change impacts and adaptation
	3.2 Awareness raising and capacity building	**3.2.1** Events of dissemination/information
		3.2.2 Events of training/capacity building
4 Adaptation interventions	**4.1** Green measures	**4.1.1** Restoration of coastal wetlands and coastal areas
		4.1.2 Retrieval and restoration of degraded ecosystems - Area undertaking habitat creation/restoration
		4.1.3 3 Specific interventions for species and habitats at risk from climate change
		4.1.4 Climate-adapted crop varieties
	4.2 Grey measures	**4.2.1** Reclaimed wastewater (converting wastewater to use for other purposes) or harvested rainwater
		4.2.2 Implemented water efficiency technologies (water saving devices.)
		4.2.3 Adapted/relocated assets at risk (hardening, elevating)
		4.2.4 Irrigation systems
	4.3 Behavioural change	**4.3.1** Water rationing systems
		4.3.2 Uptake of soil conservation measures
	4.4 Non-specific	**4.4.1** Coastline protection
		4.4.2 Implementation of actions in flood risk management plans

II. Core indicators: Detailed list of indicators for climate change adaptation

Name	Brief description	Lowest Spatial scale	Sources
1.1.1 Local disaster risk reduction strategies	Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies. Climate change adaptation and disaster risk reduction are highly correlated: the number of strategies for disaster risk reduction are also indicators of preparedness to climate change risks	Local	Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development; Sendai Framework for DRR, target E
1.1.2 Area covered by local emergency management plans or action groups	Proportion of city/region covered by any emergency plan or with emergency active groups (e.g. local Red Cross groups, voluntary firefighting associations, etc.). Climate change adaptation and disaster risk reduction are highly correlated: this indicator tracks the area covered by a local plan or by a local group active in the management of emergencies	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix OECD (2018). Indicators for resilient cities
1.1.3 Mainstreaming of Climate change adaptation in Disaster Risk Reduction legislation	Extent to which DRR legislation and Civil Protection planning consider adaptation a relevant aspect, for example including quantitative projections of climate change parameters or evaluating increasing risks posed by climate change,	National	ETC/CCA technical paper Annex TP-3-2018 Austria
1.1.4 Pre-emptive evacuation following early warning	Population exposed to or at risk from disasters protected through pre-emptive evacuation following early warning. Disaster risk reduction and climate change are strictly related, since many natural disasters occur as consequences of extreme weather events. This indicator assesses the establishment of pre-emptive evacuation plans in high-risk areas	Local	Sendai Framework for DRR, target G
1.1.5 Sector/land use management plans with significant climate change considerations	Extent to which policy and management plans for specific sectors (e.g. management of protected areas, Natura 2000 sites, drought, urban mobility, river basin, hydrogeological risk, fire, coastal areas; landscape planning) consider local climate-related hazards and climate change adaptation.	Regional	Pearce-Higgins et al., 2022. A framework for climate change adaptation indicators for the natural environment; National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted); ETC/CCA technical paper Annex TP-3-2018 Austria; ETC/CCA technical paper Annex TP-3-2018 Germany GIZ (2014). Repository of Adaptation Indicators OECD, 2018. Indicators for resilient cities

Name	Brief description	Lowest Spatial scale	Sources
1.1.6 Institutional frameworks for climate change adaptation	Number and type of coordination mechanisms explicitly addressing climate change and resilience (e.g. focal points established). Climate change is a cross-cutting theme: institutional coordination (vertical among national and subnational level and horizontal among different sectors represents a recognised enabling environment for adaptation.		GIZ (2014). Repository of Adaptation Indicators
1.2.1 Environmental Impact Assessment and Strategic Environmental Assessment with climate change consideration	State of implementation of EIA and SEA that consider climate change. Environmental and Strategic Assessment can contribute to the integration of climate change in an early stage of project/plan development, with the potential of reducing vulnerability and increase the resilience of natural and human systems.	Regional	National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)
1.2.2 Revised building codes and climate proofing of buildings	State of implementation of building codes to protect and prevent multi-hazard effects, (e.g. heat insulation, flood resistant materials etc.). Climate proof and advanced building codes has the potential to contribute to energy saving and to the quality of urban spaces.	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)
1.2.3 Adapted standards for transport infrastructures	Presence of adapted standards for transport infrastructures, to take into account the impacts of climate change. The update of standards governing the safety and performance of infrastructure in a changing climate helps ensure infrastructure resilience to harmful climate change impacts, like flooding, strong wind or extremely high temperatures. Revised technical standards should be able to respond to current and future potential impacts of climate change.	National	GIZ (2014). Repository of Adaptation Indicators GIZ (2021). Sustainable Transport: A Sourcebook for Policy-Makers in Developing Cities. Module 5f National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)
2.1.1 Expenditure in studies and research projects	Total expenditure (all funds) for studies and research projects on climate change impacts and adaptation. Research projects and studies have the potential of creating and improving the enabling conditions for adaptation. They create knowledge, support the selection of most suitable adaptation options, and create networks of knowhow exchange. Projects can be funded at local, subnational, national and international level	Local	ETC/CCA technical paper Annex TP-3-2018 Germany National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) Mayor Adapt reporting template

Name	Brief description	Lowest Spatial scale	Sources
2.1.2 Number of studies and projects	Number of funded studies and projects on climate change impacts and adaptation (local, subnational, national and international). Research projects and studies have the potential of creating and improving the enabling conditions for adaptation. They create knowledge, support the selection of most suitable adaptation options, and create networks of knowhow exchange. Projects can be funded at local, subnational, national and international level	Local	National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)
2.1.3 Funds for adaptation	Percentage (or total amount) of national, subnational/local government budgets specifically dedicated to climate change adaptation actions. The availability of funds that directly address climate change can trigger adaptation actions	Local	UN-Habitat (2020). New Urban Agenda Monitoring Framework and related indicators National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)
2.1.4 Mainstreaming of Climate change adaptation into funding schemes for specific sectors	Extent to which existing funds for specific sectors consider adaptation relevant aspects. Interventions that are relevant for adaptation might be carried out also within other policy objectives (e.g. biodiversity conservation, human health, ecosystem restoration).	National	ETC/CCA technical paper Annex TP-3-2018 Austria GIZ (2014). Repository of Adaptation Indicators
2.1.5 Expenditure in dissemination/information about climate change impacts adaptation	Amount of money spent in the organisation of events of public dissemination and information on climate change impacts and adaptation. This indicator is strictly related to indicators 3.2.1 and 3.2.2. Investments in education and training initiatives create conditions that favour adaptation in the long period.	Local	National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)
2.1.6 Investments for planning and management of emergency	Total amount (or percentage) of investments/number of active workers for planning and managing climate-related emergencies. This indicator is strictly related to indicators 1.1.1 and 1.1.2 about local emergency plans and strategies. The management of climate-related emergency can be measured through the investments made in this sector or through the number of involved workers	Local	ETC/CCA technical paper Annex TP-3-2018 Germany National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) OECD (2018). Indicators for resilient cities

Name	Brief description	Lowest Spatial scale	Sources
2.1.7 Investment in specific climate adaptation interventions	Investments in specific climate adaptation measures, such as: investments in coastal protection; in the development in climate services; in road and railways infrastructures against possible climate related impacts; in livestock protection etc.	Local	GIZ (2014). Repository of Adaptation Indicators ETC/CCA technical paper Annex TP-3-2018 Germany; National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) Mayor Adapt reporting template
2.1.8 Economic incentives	Presence of financial mechanisms (as economic incentives) that support initiatives of adaptation. Economic incentives can significantly favour the achievement of policy objectives by encouraging, rather than imposing, behavioural changes that may lead to adaptation. Examples of innovative financing mechanisms can for example boost energy efficiency investments in buildings, reduce water and energy use in agriculture, and enhance the sustainability of fishing practices.	Local	National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) GIZ (2014). Repository of Adaptation Indicators
2.2.1 Insurance against extreme events	Level of adoption of insurance schemes against extreme events. Insurance can strengthen socio-economic resilience under a changing climate, by spreading the costs associated with the negative impacts of climate change. Insurance schemes can be used in different economic sectors (private business, animal farming and agriculture, buildings etc.)	Non-specific	National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted); ETC/CCA technical paper Annex TP-3-2018 Austria; ETC/CCA technical paper Annex TP-3-2018 Germany; C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix GIZ (2014). Repository of Adaptation Indicators OECD (2018). Indicators for Resilient cities

Name	Brief description	Lowest Spatial scale	Sources
3.1.1 Development of forecasting, early warning, climate services and decision support systems	Presence of developed (and tested) systems for forecasting, data provisioning, early warning and decision support systems for different or multiple climate risks (e.g. floods, heatwaves). These knowledge systems can guide the adoption of sound decisions and the implementation of interventions based on updated and reliable climate data	Local	Sendai Framework for DRR, target G C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) GIZ (2014). Repository of Adaptation Indicators UN-Habitat (2020). New Urban Agenda Monitoring Framework and related indicators
3.1.2 Availability of information on different and multiple climate change impacts and adaptation	Presence of accessible, understandable, usable and relevant information/communication tools for different and multiple climate change impacts and adaptation including disaster risk reduction (e.g. advices, information portals, knowledge exchange)	Local	Sendai Framework for DRR, target G ETC/CCA technical paper Annex TP-3-2018 Germany National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) GIZ (2014). Repository of Adaptation Indicators OECD (2018). Indicators for resilient cities. The Lancet countdown: tracking progress on health and climate change
3.2.1 Events of dissemination/information	Organisation of public events (workshops, dissemination, awareness raising campaigns) with focus on different aspects of climate change adaptation (e.g. energy/water/waste in household, water saving campaign, heatwave awareness etc.). Increasing knowledge and awareness on climate change issues creates a favourable environment for adaptation	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix Mayor Adapt reporting template National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)

Name	Brief description	Lowest Spatial scale	Sources
3.2.2 Events of training/capacity building	Number and level of participation in training /capacity building events for stakeholders and officers of public authorities (evacuation procedures, communication of risks, adaptation options etc.). Increasing skills and capacity building on climate change issues creates a favourable environment for adaptation	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix ETC/CCA technical paper Annex TP-3-2018 Germany National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) ETC/CCA technical paper Annex TP-3-2018 Austria GIZ (2014). Repository of Adaptation Indicators
4.1.1 Restoration of coastal wetlands and coastal areas	Extent of restored coastal wetlands. Coastal wetlands provide natural defence against coastal flooding and storm surges by wave energy dissipation and erosion reduction and by helping to stabilise shore sediments. The restoration of coastal wetlands is increasingly considered as measure for adaptation.	Regional	National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)
4.1.2 Retrieval and restoration of degraded ecosystems - Area undertaking habitat creation/restoration	Area covered by grant approval or undertaking habitat creation/restoration. Safeguarding biodiversity and promoting ecological connectivity, even though not directly targeted to climate change, allows to enable dynamic adaptation processes in ecosystems. Healthy and connected ecosystems provide numerous goods and services that are vital to human society.	Non-specific	Pearce-Higgins et al., 2022. A framework for climate change adaptation indicators for the natural environment
4.1.3 Specific interventions for species and habitats at risk from climate change	Species/populations/habitats with specific climate change adaptation interventions in place. Climate change can impair biodiversity, with a number of species and habitats at risk. Prioritising nature conservation and embracing strategies to promote climate change adaptation can enhance species survival. This indicator can be combined with indicator 4.4.7 about terrestrial and marine protected areas and 4.4.8 about the establishment of climate refugia (additional indicators)	Non-specific	Pearce-Higgins et al., 2022. A framework for climate change adaptation indicators for the natural environment Mayor Adapt reporting template
4.1.4 Climate-adapted crop varieties	Agricultural area where climate-adapted crop varieties are cultivated. Drought and flood resistant crops can help farmers adapt to a changing climate. Selecting specific crop varieties that are better adapted to higher temperatures can avoid economic losses, keeping adequate yields	Regional	GIZ (2014). Repository of Adaptation Indicators

Name	Brief description	Lowest Spatial scale	Sources
Re-use of wastewater or use of harvested rainwater	Additional capacity of water (unpotable purposes) created from reuse of wastewater or from harvesting of rainwater. Recycling waste-water and use of rain-water can significantly support the preservation of precious water resources, especially in areas affected by decrease of precipitation and enhanced water use due to higher temperature. This indicator, together with indicators 4.2.2 and 4.3.1 capture the effects of different types of water efficiency measures	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix
4.2.2 Implemented water efficiency technologies (water saving devices.)	Additional capacity of water created from of the installation of water efficient devices (including tap and pipe repairs). Water saving, devices and technologies support the preservation of precious water resources in areas affected by water scarcity due to climate change. This indicator, together with indicators 4.2.1 and 4.3.1 capture the effects of different types of water efficiency measures	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix GIZ (2014). Repository of Adaptation Indicators
4.2.3 Adapted/relocated assets in high risk areas	Number of assets located in high risk zones made safe through retrofitting (hardening, elevating) or planned re-location. This indicator measures how much properties have been secured from extreme events due to climate change risks (floods, avalanches, landslides) The additional indicator (4.4.5 about retrofitting properties against excessive heat) complement this indicator is assessing progress in making properties more adapted to climate change	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix GIZ (2014). Repository of Adaptation Indicators
4.2.4 Irrigation systems	Surface area where irrigation systems has been converted as a response of climate change. Improved irrigation systems are more water efficient and more precise, allowing more sustainable water use and energy consumption.	Regional	GIZ (2014). Repository of Adaptation Indicators National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)

Name	Brief description	Lowest Spatial scale	Sources
4.3.1 Water rationing systems	Number of water companies applying limiting and rationing systems. Calling on citizens to limit water use to the bare minimum cannot be enough to significantly reduce water use in critical period of water scarcity. Water restrictions limit certain uses of water (non-essential uses) while water rationing includes temporary suspension of water supply or a reduction of pressure. This indicator, together with indicators 4.2.1 and 4.2.2 capture the effects of different types of water efficiency measures	Local	GIZ (2014). Repository of Adaptation Indicators
4.3.2 Uptake of soil conservation measures	Extent to which soil conservation measures are adopted to make the agriculture sector more resilient to climate change. Preserving good ecosystem services, including productive soil, is essential to promoting sustainable Agriculture in a changing climate. Conservation agriculture include a wide range of practices that include minimal soil disturbance, permanent soil cover and crop rotations.	Regional	GIZ (2014). Repository of Adaptation Indicators
4.4.1 Coastline protection	Surface area covered by coastal defence interventions (including green and grey measures). Coastal areas are increasingly exposed to sea level rise, erosion and flooding risk. This indicator measures the progress towards the protection of vulnerable coastal areas in terms of total surface area or coastal length that underwent any protection interventions.	Regional	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)
4.4.2 Implementation of actions in flood risk management plans	Degree of implementation of flood risk management plans. The EU floods directive now requires Member States to assess if all water courses and coast lines are at risk from flooding, and to take adequate and coordinated measures to reduce this flood risk. Flood risk management plans are required from the Directive with measures to be progressively implemented	Regional	ETC/CCA technical paper Annex TP-3-2018 Finland

III. Additional indicators: Overview of proposed framework - Climate change adaptation

Category	Subcategory	Additional indicator
4 Adaptation interventions	**4.1** Green measures	**4.1.5** Reforestation/Afforestation
		4.1.6 Green infrastructure in urban areas
		4.1.7 Improved Sustainable Urban Drainage Systems
	4.2 Grey measures	**4.2.5** Installing floodgates
	4.3 Behavioural measures	**4.3.3** Sustainable and resilient tourism
	4.4 Non specific	**4.4.3** Stabilised river banks
		4.4.4 Cooling centres
		4.4.5 Retrofitted properties against heat
		4.4.6 Stabilised slopes and sediment on hilled areas (
		4.4.7 Management interventions in terrestrial and marine protected areas
		4.4.8 Protection of climate refugia
		4.4.9 Fire management and related infrastructures

IV. Additional indicators: Detailed list of indicators for Climate change adaptation

Name	Brief description	Lowest spatial scale	Sources
4.1.5 Reforestation/Afforestation	Forested area (ha) that underwent reforestation or afforestation interventions, especially with climate-resilient species. Afforestation (i.e. converting long-time non-forested land into forest) and reforestation (replanting of trees on more recently deforested land) are recognised as climate change adaptation options, offering important synergies with mitigation (forests as carbon sink). This Indicator refers to the area that underwent reforestation/afforestation practices and especially focus on planting tree species more adapted to a changing climate.	Regional	GIZ (2014). Repository on Adaptation Indicators National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) Mayor Adapt reporting template
4.1.6 Green infrastructure in urban areas	Extension of new green infrastructure through new urban planning. Green infrastructure includes any vegetated area as green roofs, trees, canopy cover in urban area. They offer shaded areas mitigating heatwaves effects in cities. They also help absorb, delay, and treat stormwater, mitigating flooding and	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix Mayor Adapt reporting template Lancet countdown: tracking progress on health and

	pollution downstream. This indicator can be combined with indicator 4.1.6 (Improved Sustainable Urban Drainage Systems).		climate change National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)
4.1.7 Improved Sustainable Urban Drainage Systems	Level of implementation of improved drainage systems in cities. Sustainable Urban Drainage Systems is an approach to make use of measures designed to restore or mimic natural infiltration patterns by decreasing runoff volumes and attenuating peak flows. This indicator can be assessed together with indicator 4.1.5 (green infrastructure).	Local	National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix
4.2.5 Installing floodgates	Installation of floodgates to control water flow. They can close the sea mouth of a river, the sea mouth of a waterway or a tidal inlet. These barriers generally are major infrastructure systems, built to protect urban areas or infrastructure at high risk. Due to their complexity and high construction cost, they are relatively rare. Their implementation can be complemented with other grey and green flood protection measures	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix
4.2.6 Fire management and related infrastructures	State of development of infrastructures and management practices for fire management (e.g. controlled burns, vegetation removal, firebreaks)	Local	GIZ (2014). Repository of Adaptation Indicators National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted)
4.3.4 Sustainable and resilient tourism	Development of sustainable tourism initiatives to increase the resilience of the sector. Diversification of tourism and tourist products are often presented as a possible options for adapting to the effects of climate change. They can include initiatives that relief natural areas from the anthropogenic pressures (e.g. alternative eco-tourism offers) or modifications in tourism destinations and tourism seasons to take into account increasing temperature or change in rainfall patterns.	Local	ETC/CCA technical paper Annex TP-3-2018 Austria National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) Mayor Adapt reporting template
4.4.3 Stabilised river banks	Extension of stabilised/restored river banks including green (vegetated areas, buffer strips, trees) and grey measures (reinforced banks with concrete) River bank degradation leads to property damage or loss, erosion, water quality deterioration, and flooding risk. Wetter and more extreme weather patterns are causing serious damage to most vulnerable riverbanks.	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix National Adaptation Plan on Climate Change Adaptation for Italy (draft, not still adopted) GIZ (2014). Repository on Adaptation Indicators
4.4.4 Cooling centres	Establishment of centres and routes created for cooling purposes in urban areas. Cooling routes and centres during heatwaves are particularly relevant for	Local	C40 City Climate Action Planning Monitoring, Evaluation and

	most vulnerable people (low income, elderly, and children). Cooling centres also include water features built across cities (fountains/water sprinklers) for drinking or cooling purposes.		Reporting (MER) Indicator Matrix
4.4.5 Retrofitted properties against heat	Retrofitting of properties (public/residential/tertiary buildings) against excessive heat. Retrofitting can include different strategies relate to building design (use of IT technologies to optimise thermal comfort) and building envelopes (roof, ceilings, external walls, doors, windows). This indicator can be assessed together with indicators 4.2.2 (water efficiency devices and technologies) and 4.2.3 (adapting/relocating buildings at risk) to assess the overall progress towards the adaptation of properties to climate change	Local	GIZ (2014). Repository of Adaptation Indicators Mayor Adapt reporting template
4.4.6 Stabilised slopes and sediment on hilled areas (	Area of slopes stabilised. Measures can include the use of vegetation (seeded, transplanted and matted) or other materials (reinforced with concrete). The stability of slopes can be affected by many factors including climate change (increasing extreme weather events, change in rainfall patterns and in groundwater level and pressure, longer periods of droughts etc)	Local	C40 City Climate Action Planning Monitoring, Evaluation and Reporting (MER) Indicator Matrix
4.4.7 Management interventions in terrestrial and marine protected areas	Implementation of actions to increase climate change resilience in protected areas. Protected areas provide areas with reduced stress for organisms increasing their health and ability to escape climate change impacts. Specific interventions can be implement to ensure the survival of more vulnerable species and habitats in terrestrial and marine protected areas. This indicator can be combined with indicator 4.1.3 about interventions to protect species and habitats at risk from climate change and 4.4.8 about the establishment of climate refuges.	Non specific	Pearce-Higgins et al., 2022. A framework for climate change adaptation indicators for the natural environment
4.4.8 Climate refugees	Climate refuges are areas that remain relatively buffered from climate change over time and enable persistence of valued physical, ecological, and socio-cultural resources. This indicator track adaptation progress through the identification and conservation of climate change refuges. This indicator can be combined with indicator 4.1.3 about interventions to protect species and habitats at risk from climate change and 4.4.7 about management of terrestrial and marine protected areas.	Non specific	Pearce-Higgins et al., 2022. A framework for climate change adaptation indicators for the natural environment

Annex II Questionnaire for stakeholders

Dear Madam / Sir,

Thank you for taking the time to provide advice to our preliminary climate IMPETUS Indicators Framework. Your input will be greatly appreciated and used for the benefit of supporting climate-sensitive decision-making across Europe.

Please consider the following questions about the framework. The questions mostly offer multiple choices with additional free room to share your expert input, provide suggestions and overall impressions. In total, grasping the framework and answering our questions, will take you approximately **30 minutes**.

Introductory questions

1. Could you indicate how you have been professionally associated with climate change challenges?

2. In the last 10 years, which climate vulnerabilities have played a key role in affecting the sustainable development in your region? Multiple answers are possible.
   A. Water
   B. Energy
   C. Food
   D. Ecosystems
   E. Health
   F. Economic
   G. Social
   H. Other, namely

Please briefly explain **how** this has been an impact: Please **rank** the vulnerabilities from most vulnerable to least vulnerable.

3. Do you have a system of vulnerability and adaptation indicators in place in your country/region?
   A. Yes

If yes, please indicate where we could find this. In this way, we can ensure full alignment with the indicators that you already work. For instance, provide the link here.

   B. No
   C. I don't know

General questions about the Climate IMPETUS Framework

4. Have you personally ever used any of the proposed indicators to keep track of vulnerability/adaptation progress in you region? Which one?

   A. Yes

If A: I have used the following indicators (or very similar indicators) reported in the framework (please provide the indicator number and name):

   B. No, I have used different indicators

If B: I have used the following indicators:

   C. No, I have not used indicators for climate vulnerability or climate adaptation before

5. Based on your first impression, to what extent does the set of core indicators represent the key aspects of vulnerability and adaptation to climate change in Europe?
    A. Indicators **fully** represent the key aspects of vulnerability and adaptation to climate change in Europe
    B. Indicators **partially** represent the key aspects of vulnerability and adaptation to climate change considerations in Europe
    C. Indicators **poorly** represent the key aspects of vulnerability and adaptation to climate change in Europe

Please, briefly motivate your answer:

6. What would be key indicators that you would add to the framework in order to make it more useful for strategic decision-making in European regions or in your region specifically?

Please provide suggestions by specifying a name, (very) brief description or reference to the indicator. For instance by providing a web link. Also specify if the indicator specifically refers to your region or, in your opinion, can be relevant also at the European level Indicator suggestions for **Europe**: Indicator suggestions **for your region specifically**:

7. Are the proposed indicators equally understandable?
   A. Yes, no suggested amendments
   B. Most indicators are understandable. However some indicators are not sufficiently clear

If B: Please provide the name and number of the indicators that in your opinion are not easily understandable. Feel free to provide motivation and possible suggestions

8. Are there indicators that you consider poorly useful/not applicable for your case?

Please provide the name and number indicators that you consider poorly useful and/or how they can be made more applicable for your region. For each indicator, please specify which of the following options applies: A. The indicator does not represent the climate change impacts experienced in my region B. The indicator is poorly linked to climate change C. The indicator does not actually represent the adaptation progress/vulnerability change D. Other (please specify)

9. For which of the proposed indicators do you expect that a lack of data may limit the use of the indicator in your region?

   A. Data for all indicators could be made available
   B. For some indicators, data availability could become an issue

Please provide the number and name of the indicators that may face limitations in terms of data availability according to your experience:

   C. I don't know