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# Projecting future vulnerability and exposure to climate-related health risks in Europe: a hybrid approach using Shared Socioeconomic Pathways

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# Contents

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## Summary

Climate change will reshape not only Europe's environment but also the social conditions that determine health and wellbeing. The physical impacts of heat, floods, droughts, and pollution are increasingly well characterised, yet their consequences depend on the social systems in which they occur. This report provides guidelines to project such non-climatic impact (NCID) drivers - exposure and vulnerability - under alternative socioeconomic futures, combining quantitative data and qualitative narratives through a hybrid scenario approach based on the Shared Socioeconomic Pathways (SSPs). We build from the first European Climate Risk Assessment (EUCRA) presentation of NCIDs to more explicitly incorporate the SSP projections, mindfully of already existing data sources and policy agendas.

The report builds on the story-and-simulation (SAS) tradition, integrating model-based projections and participatory or expert-based reasoning. It recognises that no single dataset or modelling technique can represent the diversity of European health vulnerabilities; instead, it offers a transparent way to connect different evidence sources. The approach is designed to be replicable, data-agnostic, and scenario-consistent, supporting analysts who wish to expand climate-risk assessments beyond purely climatic drivers.

At the core of the framework is a typology of four indicator classes, each describing a distinct facet of vulnerability and exposure:

- Structural indicators capture the slow-moving demographic and infrastructural stocks that shape baseline sensitivity (for example, the proportion of elderly living alone, housing age, or population density).
- Systemic indicators describe the strength of service systems and institutional capacity, such as access to healthcare, care infrastructure, or governance quality.
- Behavioural indicators reflect social norms and practices that modify how people perceive and respond to hazards - civic trust, social cohesion, digital exclusion, or risk awareness.
- Exposure indicators quantify where people or assets are physically co-located with climate hazards (for example, urban heat-island intensity or green-space access).

The hybrid pipeline operationalises this typology in four main steps:

1. Classification – each indicator is first assigned to one typology according to its projection logic (top-down/bottom-up, quantitative/qualitative).

2. Scenario translation – indicators are linked to the logic of the five SSPs through qualitative storylines and, where possible, corresponding quantitative trajectories (e.g. IIASA or Eurostat data).

3. Integration and computation – qualitative assumptions and numerical trends are normalised, scaled to NUTS-2 regions, and combined into scenario-consistent spatial indicators. A divergence score is defined to identify where local or national developments diverge from SSP expectations, allowing transparent weighting between top-down and bottom-up sources.

4. Output and validation – the resulting hybrid indicators are visualised and compared across scenarios, preserving both local realism and global consistency.

A practical example is provided for the Eurostat indicator "Persons at risk of poverty or social exclusion (AROPE)", extrapolated to approximately the 2050s (mid-term) using observed regional trends and SSP-specific multipliers. This demonstration shows how a single vulnerability indicator can be transformed into, and interpreted through, five scenario projections while retaining traceable logic.

The same procedure can be applied to any health-relevant variable, such as elderly living alone, access to healthcare, or urban form, using either quantitative data or expert-elicited judgements, depending on which typology the indicator belongs to.

The results illustrate that European vulnerability patterns diverge sharply between scenarios. SSP1 (Sustainability) reduces social and spatial inequalities through inclusive governance; SSP2 (Middle of the Road) maintains present disparities; SSP3 (Regional Rivalry) amplifies them through institutional erosion; SSP4 (Inequality) polarises regions and groups; and SSP5 (Fossil-fuelled Development) reduces poverty through economic growth but widens technological divides.

By integrating measurable data with scenario-based reasoning, the hybrid approach offers a replicable foundation for Europe's next generation of climate-health risk assessments. Its transparent typology supports the comparability of regional analyses while preserving the contextual depth of local evidence. This framework directly contributes to improving coherence between European and national adaptation monitoring systems - including the forthcoming 2027 Governance Regulation reporting cycle - by enabling consistent treatment of non-climatic impact drivers across hazards, sectors, and governance levels. Looking ahead, these methods can inform the design of future EUCRA phases and related European Environment Agency workstreams, ensuring that scenario-based foresight and risk tracking evolve as an integrated process rather than separate exercises. The hybrid approach thus provides not only a methodological advance but also a practical instrument for aligning scientific foresight with policy implementation under the EU Climate Adaptation Strategy and the European Climate and Health Observatory.

# 1 Introduction

Climate change will not only transform the physical environment across Europe. It will also intensify the social and health inequalities that determine who suffer, how, and where. Rising temperatures altered precipitation patterns, and more frequent heatwaves, floods, and droughts are well-documented climatic impact drivers (CIDs). But their impact depends far more on the underlying socioeconomic landscape: age, income, housing conditions, access to care, and the hidden architecture of social isolation. In this report, we exemplify how such socioeconomic landscape can be understood for current and future health impacts in Europe.

The European Climate and Health Observatory[1] provides a comprehensive overview of data (through 450 resources of maps, charts, indicators etc) of physical and mental health risks, and impacts associated with CIDs such as aero-allergens and pollutants, droughts and flood, climate-sensitive diseases, heat and wildfires. Health impacts on people from these range from respiratory illnesses, and infectious diseases, to fatalities and injuries and mental illnesses.

The future projection of such impacts is generally performed with CIDs projections with estimates of exposed populations. For example, exposed populations to heat mortality include "vulnerable" people such as elderly (and estimates of proportion of people over 65)[2]. Analyses of health impacts consistently highlight the interconnectedness and spatial inequity between geographic and economic regions and population groups and the need to understand the exposure, sensitivity and adaptative capacities, which we refer to as non-climatic impact drivers (NCIDs) to truly appreciate the full spectrum of risk (van Daalen et al., 2024). *Because CIDs tend to be projected for the future more systematically than NCIDs*, particularly when it comes to other indicators than exposure (Pedde et al., 2024a), we provide these practical guidelines, applied for adaptation to health impacts, for users interested in adding the NCIDs component in their analyses of future risk and impacts. Additionally, even with the ever-growing literature on scenarios (see Table 3 for an overview) and associated NCID projections, these guidelines will support informed choices for users unfamiliar with specific projections, such as the Shared Socioeconomic Pathways (SSPs), or those preferring alternative datasets and baselines.

This report introduces a four-indicator typology designed to operationalise the IPCC AR6 vulnerability dimensions (IPCC, 2023) in a scenario-consistent manner. While grounded in established theory, the typology provides an applied structure tailored to European data and policy processes, filling a methodological gap between conceptual frameworks and operational risk assessments.

The broad qualitative and quantitative SSPs offer a structured foundation to explore these futures for both experienced and new users. This is possible because there is no one-size-fits-all methodology or dataset - indicators vary in scale, availability, and cultural relevance. So, the real question becomes: "How can we systematise this process without flattening its complexity?**"**

This report concretises the broad steps to implement non-climatic factors in climate risk assessment in Pedde et al. (2024b), with a step-wise hybrid approach that could support Europe's preparedness[3] to extreme events. with the need to inform more comprehensive perspectives of risk, which may be broadly underestimated due to less visible consideration of exposure and vulnerability as drivers of risk, rather than impacts. This is even more relevant, given the growing importance of monitoring,

[1] https://climate-adapt.eea.europa.eu/en/observatory (assessed 20 November 2025)
[2] https://climate-adapt.eea.europa.eu/en/metadata/indicators/exposure-of-vulnerable-populations-to-heatwaves (assessed 20 November 2025)
[3] https://discomap.eea.europa.eu/ClimatePreparedness2025 (assessed 20 November 2025)

evaluation and learning (MEL) to track adaptation progress in Europe (Leitner et al., 2024). A positive feedback and outcome of this report could be a more streamlined approach that maintains (rather than prescribing) complexity derived by the multiple scales, actors and perspectives involved in climate adaptation, connecting users and data sources such as Eurostat, Copernicus Land Monitoring Service datasets (such as Urban Atlas), JRC tools to national and local sources like the Netherlands' *toekomstverkenning* on public health the Buurtatlas and Klimaateffectatlas and local adaptation planning such as in the Helsinki metropolitan area (see section 3.5.1 in Pedde et al. (2024b)).

Understanding vulnerability in Europe requires acknowledging that it is not a uniform concept (Section 2), beyond methodological considerations. It is shaped by demographic, social, economic, and infrastructural realities across regions that need hybrid approach to facilitate this diversity (Section 3). The hybrid approach and pipeline that allows multiple sources of data and interpretation is exemplified in Section 3.6. The visualisation of these results is in Section 4. The method and data are contextualised and discussed in Section 5 and discussed in realistic cases, such as the most common situation where each participatory process leads to different results (Section 5.3). The final section (Section 6) summarises all these points and includes the hybrid pipeline link to the hazard dimension of risk.

## 2. Framework and definitions: examples of vulnerabilities relevant for health

While vulnerability indicators typically capture structural forms of exclusion (such as aging or living alone), certain emotional or perceptual dimensions, such as loneliness, may resist straightforward quantification. While the relative importance of drivers across these dimensions varies across contexts, they interact with exposure in ways that magnify underlying vulnerabilities and risks (Ayalon, 2025; Stepanova et al., 2025). The challenge is not just identifying *who is vulnerable* but anticipating *where* these dynamics will intensify in the future**,** for example under different SSP scenarios. This is because the relative importance of these factors varies across geographical and social contexts, complicating comparability or relevance. For example, what is (self-) reported and measurable as loneliness as a public health indicator in on Member State, may be absent or politically sensitive in other Member States (OECD, 2025).

Despite these challenges, we need a shared conceptual basket of vulnerability indicators to guide pan-European action. One that is:

- Flexible enough to allow national and subnational interpretation;
- Anchored in empirical evidence and salient;
- Compatible with global frameworks (e.g. WHO Alliance for Transformative Action on Climate and Health[4], UNFCCC Global Goal on Adaptation[5]);
- And operationalisable under alternative futures, such as SSP-based futures.

This basket does not need to start from scratch. Our work builds on existing national practices (e.g. RIVM's health outlooks in the Netherlands), European platforms (e.g. OECD Data Explorer, EUROSTAT, DRMKC Risk Knowledge Centre, European Climate and Health Observatory to cite a few), and scenario literature (see Table 4 for an overview) and European projects (such as the HealthRisk project). Such literature often develops methods and frameworks to reflect socio-demographic vulnerability and

[4] WHO Atach https://www.who.int/initiatives/alliance-for-transformative-action-on-climate-and-health (assessed 24 November 2025)
[5] The Global Goal on Adaptation was established in the 2015 Paris Agreement, Article 7. For an overview, see https://unfccc.int/topics/adaptation-and-resilience/workstreams/gga (assessed 20 November 2025)

adaptive capacity (Sibilia et al., 2024). Eurostat, for example, covers an ever-growing number of indicators for current and past. These data are usable for mapping, communication, and policy prioritisation at NUTS2 level and beyond, supporting a coherent baseline for projections, to be developed in scenario sets. Our position is pragmatic and acknowledges the wealth of data sources emerging in Europe. Rather than prescribing one dataset and source and aiming for perfect comparability at the cost of salience, we seek functional coherence for the user to connect the datasets they are most familiar with while developing coherent explorations of the future. Taking social isolation as an example, we show how a hybrid approach can be applied to address this complexity. Hybrid means providing a usable way forward for practitioners and decision makers to either or both downscale (when projections exist) and/or upscale (when context matters and/or projections do not exist) or cannot be quantified. We do not combine the single indicators into indices. We believe that indices should have specific and limited uses within the scope of their production and should not be opaquely applied elsewhere or generalised. They also can be relatively easily built by users, by combining generally in multiplicative form, single indicators and therefore do not require guidelines.

Before explaining the steps of hybrid approach in Section 3, we provide an overview of vulnerability dimensions. A recent systematic review identifies identified 113 factors in 15 categories associated with social vulnerability (Li et al., 2023) and similarly a recent overview by WHO Atach of 22 countries identified a total 1684 indicators for health, of which about half consist of vulnerability and enabling factors such as leadership and governance and the other half of hazards, exposure, health outcomes and projections (WHO, 2025). These examples show the importance of understanding vulnerability for health but they are also the breadth the full spectrum. Rather than repeating such comprehensive lists of indicators, we synthesise this knowledge through five broad themes that characterise vulnerability to health in Europe that considered additional literature. The goal is to understand the *systemic dimension* of vulnerability, which we believe is both the essential and hard to quantify part. The five themes, recurring in such reviews and lists, and their rationales are the following:

1. Chronic diseases in ageing Populations: Older populations, especially those living alone or with limited capacities due to chronic illnesses, are disproportionately affected by climate extremes, particularly heatwaves (Cissé et al., 2022; van Daalen et al., 2024). These groups are also more likely to be located in rural areas (Fastl et al., 2024) or live with poor cooling infrastructure or overstretched care services. Additionally, older populations at risk may underestimate the severity of risk, particularly in populations urban contexts adding to their effective exposure and delaying behavioural response during heat events (Wrotek et al., 2025).

2. Low-Income Households and Energy Poverty: Economic constraints limit the capacity to reduce exposure (e.g., through lack of cooling, limited relocation possibilities and limiting housing improvements). Across 32 European countries, households in energy poverty report significantly worse general health and emotional well-being than non-energy-poor households, even after socio-demographic controls. Notably, the largest within-country gaps occur in Sweden and Slovenia, underscoring that relative deprivation can amplify health impacts even in more equal societies (Thomson et al., 2017). Vulnerable groups often live in low-quality dwellings in urban heat islands and/or in polluted areas (synergy with air pollution), amplifying both exposure and sensitivity.

3. Access to Healthcare and Care Networks: Disparities in healthcare access, especially between urban and rural areas, significantly affect communities' ability to respond to climate-induced health challenges. Elderly individuals in rural or remote regions frequently have reduced

access to healthcare services higher risk of social exclusion. This in turn can increase their vulnerability during extreme weather events, for instance, limited mobility or service capacity can delay treatment during heatwaves or floods (European Environment Agency, 2024; Rohat et al., 2019). Healthcare access disparities influence both preventative resilience and response capacity during climate-induced health emergencies. Spatial disparities (urban-rural, east-west, north-south) interact with age and poverty to shape vulnerability across Europe (Urbaniak et al., 2021)

4. Social Isolation and Loneliness: Psychosocial factors such as social isolation (social level) and loneliness (individual level), emotional support, and neighbourhood cohesion significantly influence adaptive capacity - especially under heat stress or disaster conditions (Hajek and König, 2022; Li et al., 2023). Such metrics remain underutilised in many national frameworks.
5. Urban Form and Green Space Access: Exposure to CIDs is spatially structured. Urban morphology - such as density, impermeable surfaces, and green cover - affects microclimates, air pollutants and heat exposure. Vulnerable groups often reside in areas with limited green infrastructure (D'Ambrosio et al., 2023) and poor ventilation (Lundgren Kownacki et al., 2019), compounding both physical and mental health risks.

# 3 Methods

## 3.1 Hybrid approach

The hybrid approach is preferred to integrate different sources and methods because the appropriate way to project indicators is neither purely top-down nor bottom-up, and neither fully quantitative nor qualitative (Figure 1).

We base our forward-looking guidelines primarily on the Shared Socioeconomic Pathways (SSPs), which represent "top-down" projections. To identify methodological or dataset advances beyond those used by Rohat et al. (2019) and Rohat (2018), we reviewed studies published after 2021 (complementing the literature screened in Pedde et al. (2025) up to 2023) and included publications up to mid-2025. However, we found no pan-European, consistently projected, scenario-ready datasets covering the full range of health-relevant vulnerability indicators required here. The most comprehensive work remains Rohat et al. (2019) and Rohat (2018), who systematically linked SSP-based future socio-demographics with climatic projections. This forms the scientific basis for the hybrid approach. While the underlying rationale is similar, this report expands that work to a wider set of indicators and a more systematic inclusion of mixed quantitative–qualitative methods, as summarised in Table 1 and detailed in Table 4 (Section 3.4). These references remain key methodological inputs, particularly where granular, scenario-consistent datasets for future vulnerability are still unavailable.

**Table 1. Overview of main differences between Rohat et al. (2019) and Rohat (2018) with the hybrid approach**

| Aspect | Rohat (2018, 2019) | Hybrid approach (this report) |
|---|---|---|
| **Scale** | Primarily national or NUTS-0, with occasional NUTS-2 downscaling | NUTS-2 or finer, ensuring alignment with EUCRA regional narratives and pan-European coverage (Pedde et al., 2024, 2025) |
| **Indicator scope** | Demographic and exposure indicators (population age, density, education, income) | Structural, systemic, and behavioural indicators of vulnerability and adaptive capacity, including social isolation, access to care, and digital exclusion |
| **Approach type** | Quantitative extrapolation; qualitative when data absent ("top-down with expert elicitation") | Explicit hybrid: linear trend extrapolation where data exist + ordinal scenario scoring where trends are non-projectable → integrated via normalisation and weighting |
| **SSP usage** | Downscaling of global SSP demographic trajectories; consistency prioritised with population models | Two-way consistency: aligns with SSP narratives while respecting regional institutional logic and observed trends; priority given to coherence with socio-institutional context |
| **Examples** | Elderly population, population density, education level, obesity (as proxy for vulnerability) | Elderly living alone, civic trust, access to care, digital exclusion, green space access – mix of quantitative and qualitative indicators |
| **Outcome metric** | Vulnerability as exposure × sensitivity; limited adaptive-capacity treatment | Vulnerability as multi-system property (structural + systemic + behavioural + exposure); tangible metrics to assess spatial heterogeneity. Divergence diagnostics |

In our usage of SSPs, top-down does not necessarily equate quantitative. Qualitative narratives may be top-down products, such as narrative based on expert judgement or causal loop diagrams explaining the trends and the system. Bottom-up may include local datasets or local narratives, either in qualitative or quantitative form (Figure 1). Given our pan-European scope, local refers to Europe-specific or regional data that have not been used to calibrate global datasets.

Because SSP assumptions in the literature are substantially top-down, that is developed from Integrated Assessment Models (IAM) simulations and aimed at developing IAM-based emission scenarios and not Europe-specific and not harmonised across indicators. The hybrid pipeline integrates this source of data (top-left corner in Figure 1) with the other three type of sources by explicitly combining quantitative extension of structural/systemic indicators where data support it, and scenario-consistent, ordinal scoring for indicators that are not robustly projectable (behavioural, contested, or poorly measured).

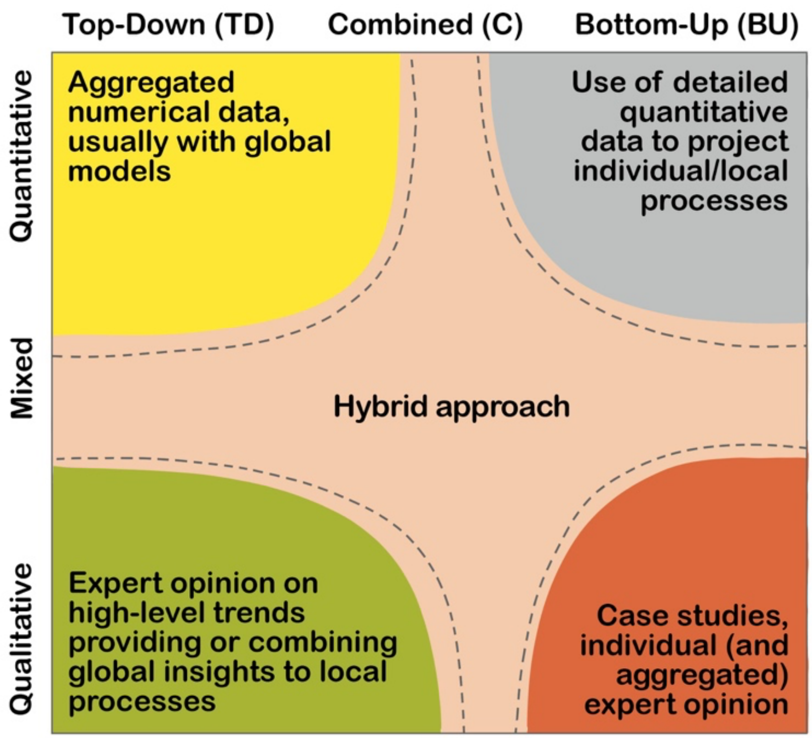


**Figure 1. Conceptual typology quadrant situating the method within the spectra of top-down to bottom-up and quantitative to qualitative approaches. The hybrid approach reflects the iteration between qualitative and quantitative elements, typical of the story-and-simulation approach (Alcamo et al. 2008), with combined top-down and bottom-up knowledge sources (adapted from Pedde et al. (2025)).**

The hybrid approach logic is based on story-and-simulation (SAS) (Alcamo, 2008), consisting of iterations between narratives and numbers until a consistent, credible and salient scenario set is developed. SAS is an approach developed since the early climate change scenarios in the 1990s (for instance the IPCC scenarios), popularised in the 2008s with the development of the integrated scenario approach (see short history in Moss et al. (2010)) and still mainstream in the scenario literature (Trutnevyte et al., 2019). Particularly for European SSPs that were developed both my modelling teams and stakeholders, the SAS iterative approach is now more explicitly incorporating participatory and, more broadly, bottom-up knowledge (regional data/plans) to its top-down core, to enhance its credibility and policy relevance, also for diverse users and needs (e.g. Kok et al. 2019, and Rohat et al. 2019).

The hybrid approach pipeline (Figure 2) is described in four parts and dedicated sections (3.2-3.5) and summarised as follows:

1. Typology as the entry point: the indicators are classified as explained in Section 3.2. According to the classification, they are quantified or qualitative according to the typology.
2. The SSP translation, based on SAS-type approach, results in the “bifurcation” of Figure 2 between qualitative and quantitative elements to develop coherent future assumptions about the future, using the same umbrella (SSP-)framework. Where feasible, quantitative extrapolated model-based trends are developed for structural, systemic, and exposure indicators (Section 3.3). The qualitative and quantitative paths run in parallel; sequencing depends on data readiness and typology. Section 3.4 explains both qualitative and quantitative paths, which include both top-down and bottom-up data and processes.

3. The integration node consists of computation of different data sources into hybrid spatialised indicators. To compute this, we use different techniques that bridge different outputs through normalising, weighting and averaging (Section 3.5). We provide an example of the right-hand side of the pipeline in Section 3.6 because it is the most difficult to implement (translation from qualitative and inclusion of bottom-up participatory sources) and present this along the more straightforward quantitative case (e.g. quantified projections directly available at the desired scale for all scenarios). We also define a “divergence score” to map where the biggest difference is between top-down and bottom-up approaches that could be used for better accuracy, although it is not applied here (it is a novel but untested approach).
4. The outputs are the final maps accompanied by priorities.

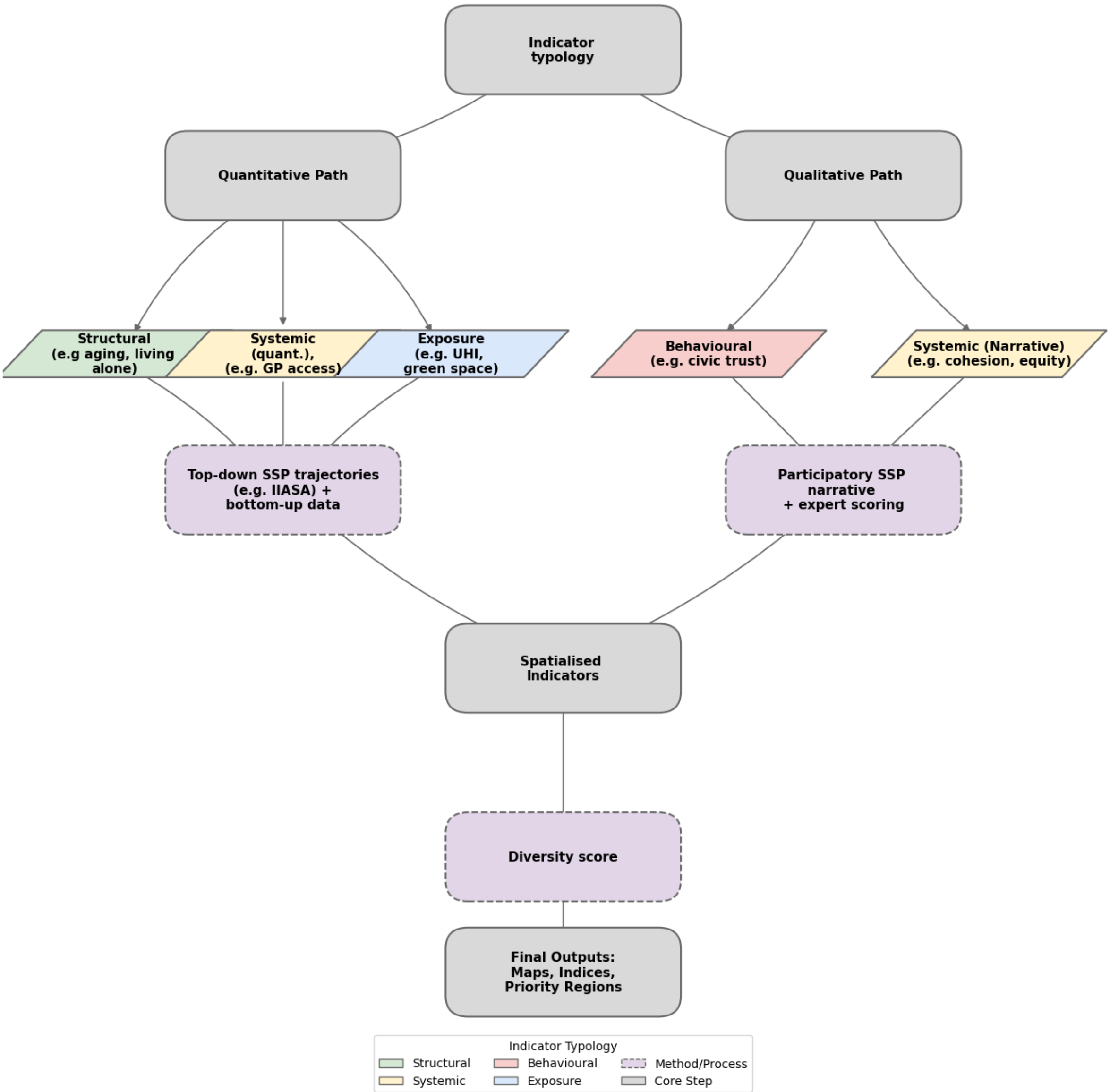


**Figure 2. Hybrid approach pipeline for projecting vulnerability and exposure. Operational pipeline linking indicator typology to outputs. Grey boxes represent methodological stages; coloured boxes denote indicator categories (structural, systemic, behavioural, exposure); and purple dashed boxes**

**indicate final output metrics.**

In Section 3.6, we describe the practical example to implement the hybrid pipeline for the indicator "Persons at risk of poverty or social exclusion" (Eurostat (2024) for definition and metadata).

## 3.2 Indicator typology and treatment

We use the IPCC AR6 definition of exposure as "the presence of people, livelihoods, species, ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, and cultural assets in locations and settings where they could be adversely affected by a climate hazard" (IPCC, 2023). Operationally, we treat exposure as presence × hazard and distinguish it from vulnerability (susceptibility and capacity).

$$Exposure = P(x,t) \times H(x,t),$$

Where $H(x,t)$ denotes the intensity or probability of a hazard at a given location and time, and $P(x,t)$ represents the presence of people, assets, or activities occupying that same space. Exposure therefore emerges at the interface of two independent subsystems - the climatic hazard subsystem and the social or infrastructural presence subsystem. It is *not* equivalent to presence itself but an *interaction term* that matters only where these two distributions overlap. In this sense, exposure is an emergent property of spatial and temporal coincidence, not a definitional identity. Exposure therefore increases when either the hazard intensifies or when more people or infrastructure are situated within its range. Practical combinations of these indicators with specific climate hazards are illustrated in Section 6 (Table 6), which provides guidance on spatial and temporal scaling for applied assessments.

Presence and, more comprehensively, exposure, refer to *who* or *what* is there, *where*, and *for how long*. Vulnerability - comprising susceptibility and adaptive capacity - captures how severely they are affected. Adaptive capacity corresponds to the implementation or potential of adaptation measures that mitigate or offset impacts.

Exposure includes:

a) people: population density, occupant- or passenger-hours;
b) assets: dwellings, roads, platforms, hospitals, energy systems; and
c) activities-the time spent outdoors, travelling, or working in exposed settings.

When exposure is defined solely by this co-location without accounting for protection, design, or behaviour, we refer to it as "pure exposure". In practice, pure exposure is rare: most real-world indicators blend aspects of exposure and vulnerability or adaptative capacity, which imply already the presence of (or lack thereof) adaptation measures in place to reduce impacts. For example, the urban heat-island effect arises from impervious surfaces (presence) but is moderated by vegetation and materials (adaptation measures).

Another example is transport infrastructure which has a dual form of presence: its physical network (roads, tracks, stops, stations) and its human use (passenger-hours, waiting times). Both represent exposure when they coincide with heat or flood-prone zones. Yet once adaptation measures such as shading, air-conditioning, vegetation cover, or cooling rooms are introduced, the physical network or its human use no longer represents pure exposure but incorporates vulnerability or capacity. In the same way, green spaces, although "present" within hazard zones, mitigate rather than amplify the hazard; they therefore act as exposure-reducing buffers rather than components of pure exposure.

Likewise, housing insulation and access to cooling infrastructure straddle exposure and vulnerability depending on whether they are counted as existing assets in hazard zones (presence) or as factors that reduce harm (capacity).

Such indicators are thus classified as exposure or adaptive capacity or vulnerability, depending on further specification e.g.:

- Urban heat island amplification → pure exposure (imperviousness where people live)
- Green space accessibility → exposure-reducing buffer
- Housing insulation & resilience → physical building envelope in exposed zones (exposure-capacity)
- Transport infrastructure → mobility-related presence; pure exposure if unshaded, buffered if shaded or cooled.
- Cooling inequality (AC, shelters) → modified exposure; presence of cooling assets introduces capacity dimension.

Because of such definitions and overlaps between exposure and vulnerability, the first methodological step of our pipeline is to typologise indicators according to how they evolve over time and how they can be projected, rather than by exposure or vulnerability. This ensures that each indicator's dual nature - whether leaning towards exposure or vulnerability and, methodologically, quantitative or qualitative definition - is made explicit before translating them into scenario-consistent assumptions (Section 3.3). The typology provides a shared conceptual foundation for hybrid analysis and integration.

This typology is therefore compatible with the IPCC risk framework. Exposure and vulnerability jointly determine potential impacts. Exposure defines who or what is co-located with a hazard, whereas vulnerability describes how severely they are affected, depending on their sensitivity and capacity to respond. In practice, these dimensions are not disjoint subsystems but overlapping layers of the same socio-ecological structure. Indicators can therefore represent different positions along the exposure-vulnerability-capacity continuum, depending on their function and projection logic.

Such typology synthesises these components: the IPCC concepts of exposure, vulnerability (susceptibility and adaptive capacity), and hazard; health indicators syntheses as introduced in Section 2., European SSP-based logic (which separates between structural and systemic variables stemming from e.g. socioeconomic, technological, economic, environmental and policy (STEEP) categories (see Kok et al. (2019)) expanded with governance dimensions emerging in SSP regional and adaptation literature (such as behavioural variables) as documented in Pedde et al. (2025) and Andrievijc et al. (2023)

This typology consist of structural, behavioural, systemic and exposure types of indicators. We refer to Section 3.4 for the data sources of each typology

- **Structural** typology is the bridge between exposure and vulnerability. Structural indicators represent the demographic or infrastructural stocks that determine who is exposed and how sensitive they are (e.g. % elderly living alone, household composition, building age) independentely of service and behaviour. Their evolution is largely governed by slow-moving population and built-environment processes.
- **Behavioural** typology includes primarily vulnerability and capacity. This typology captures social norms and social practices that shape how individuals and groups perceive, respond to, and recover from climate hazards (e.g. civic trust, risk awareness, digital exclusion). These indicators represent fast variables that modify exposure outcomes through decision-making,

cooperation, or avoidance behaviour. They influence effective vulnerability rather than exposure itself.

- **Systemic** indicators measure how well service systems and governance arrangements work (e.g. access to care, social services). They determine both sensitivity and adaptive capacity by mediating access to protection, information, or assistance. Systemic indicators therefore anchor the *capacity* dimension of vulnerability, quantifying the institutional buffers that reduce realised risk.
- **Exposure indicators** are the spatial and physical co-location. The intersection of presence and hazard (P x H) These indicators quantify potential impact space, that is where and when people or assets are physically situated within hazard zones. They often provide the quantitative baseline for the other three types, which modulate how that potential becomes realised loss or adaptation.

## 3.3 SSP storyline translation to qualitative trends

The next step converts the typology into SSP-consistent qualitative trends. This translation links each indicator to the logic of the five SSPs, interpreting how demographic, institutional, behavioural, and exposure dynamics evolve under each storyline.

The process to translate SSPs qualitatively[6] tends to be either participatory or expert-driven, depending on the degree at which the quantitative component is well understood, straightforward and shared by all users. The qualitative step was exemplified in Pedde et al. (2024b). The translation involves different sources from the global SSP literature, European regional (downscaled) extensions and local knowledge and datasets where available and/or expert judgement. For behavioural indicators, lacking robust projections and being perceived as “less direct” or more subjective, narrative translation generally precedes expert-drive quantification. Using co-production techniques, indicators can be assigned a directional change (increase, decrease, stable) consistently with the narrative developed. More directional can be added (e.g. very low/strong/ increase/decrease) although doing so may increase complexity in stakeholder engagement if not well designed. A confidence score (see example of such scoring in Section 3.5), reflecting interpretive uncertainty, could also be applied when uncertainty is large either on the direction of change or the baseline of the indicator. Explicit time steps can be added (decadal, 30-year etc) etc. depending on resources and needs. In this report we show trends for the mid-term, which best capture the essence of each scenario logic.

Tables 2 and 3 summarise these assumptions in the form of qualitative trends, divided in two parts for ease of interpretation. Table 2 describes exposure-related indicators (urban form, green space, housing, mobility, cooling infrastructure). Table 3 lists vulnerability-related indicators (social isolation, trust, access to services, digital inclusion). The separation is not definitive or net, as explained in Section 2. Instead, together these tables constitute the backbone of the SSP storylines and the qualitative track of the hybrid pipeline. The qualitative pipeline is useful to “glue” the single quantitative projections, through SAS iterations. For instance, by cross-checking the quantitative trend in relation to its consistency to the whole narrative.

Tables 2 and 3 demonstrate the type of output expected in this stage. The sources for trends are author judgement and synthesis on Kok et al. (2019), Papadimitriou et al. (2019), Rohat et al. (2019),

[6] Tabular forms are not the sole way to present translated SSPs. Qualitative products can be presented in tabular form, causal loop diagrams, words or images and videos, depending on the specific needs, and associated co-coproduction technique for the project. For an entry-level learning module see https://climatescenarios.org/co-production and an overview of 77 co-production techniques to translate knowledge https://climatescenarios.org/finder/techniques

Terama et al. (2019) and Mitter et al. (2020). In the Results, Section 4.1., we describe the SSP qualitative trends (O'Neill et al., 2017) for 20 indicators derived from EUCRA Chapter 2 consistent with the SSP qualitative translation in Tables 2 and 3. These trends are described in Figure 3, also consistent with the European SSP narratives in Kok et al. (2019) and derivative sectoral extensions. The trends of the Tables´ indicators will be read through the SSP futures in Section 4.1.

The main difference between Table 2 and Table 3 is that the latter includes more explicitly vulnerability and capacity and is not-hazard dependent. It refers more directly to the vulnerability of elderly living alone, a category fitting structural type of indicator. Table 2 includes the examples of exposure indicators mentioned on page 15, ranging from pure exposure to more mixed exposure with vulnerability adaptive capacity. Table 3 shows the trends direction for systemic, structural and behavioural indicators under different SSPs that affect the vulnerability, including the qualitative trend of the structural indicator **"**People at risk of poverty or social exclusion" that is used in Section 3.6.

**Table 2. SSP-based exposure indices for Europe and their qualitative trends until approximately the 2050s (as a proxy for mid-term) for the fives SSPs: urban heat exposure and infrastructure that mitigates heat stress. Arrows indicate the direction of change – ↓↓: strong decrease, ↓: moderate decrease, →: no change, ↑: moderate increase, ↑↑: strong increase.**

| **Indicator** | **SSP1 Sustainability** | **SSP2 Middle of the Road** | **SSP3 Regional Rivalry** | **SSP4 Inequality** | **SSP5 Fossil-fuelled development** |
|---|---|---|---|---|---|
| **Urban Heat Island (UHI) amplification** | ↓↓ Mitigated via green infrastructure, zoning, and densification strategies. | → Gradual expansion of UHI in fast-growing cities. | ↑↑ Intensifies due to unregulated sprawl and degraded planning. | ↑ Localised extremes in poor urban zones. | ↑↑ Driven by high-density, impervious development. |
| **Access to green space** | ↑↑ Urban greening prioritised; equity-driven design. | → Stable but uneven; legacy inequalities persist. | ↓↓ Disinvestment in public space; elite enclaves preserved. | ↓ Fragmented: gated luxury vs. green deserts. | → Quantity may increase, but access inequitable. |
| **Housing insulation and heat resilience** | ↑↑ Strong standards, retrofits, equitable upgrades. | → Patchy progress; dependent on local policies. | ↓↓ Decay of existing stock; minimal regulation. | ↓ Upgrades only in wealthy areas. | ↑ Smart tech + air conditioning prevail in wealthy homes. |
| **Active transport (walkable, shaded, accessible) and mobility infrastructure enabling this, in contrast to passive/car-based or cooling-intensive transport** | ↑↑ City design reduces exposure (cooler, walkable, shaded). | → Inconsistent; car-dependence remains in many areas. | ↓↓ Public transport degraded, private cars dominate. | ↓ Access to resilient transport tied to income. | ↑↑ Infrastructure expands, but emphasises cars/AC mobility. |
| **Cooling inequality (access to cooling, air-conditioning** | ↓ Minimized via shared cooling and | → Mixed: rising AC use, | ↑↑ Vast disparity: elite AC use, | ↑ Highly stratified—AC | ↑ Tech-heavy cooling widens |

| | | | | | |
|---|---|---|---|---|---|
| **AND public adaptation infrastructure)** | public adaptation services. | limited public provision. | vulnerable left exposed. | as private privilege. | energy and access divides. |

**Table 3. SSP-based vulnerability indices for Europe and their qualitative trends until approximately the 2050s for the fives SSPs: social isolation and related factors. Arrows indicate the direction of change – ↓↓: strong decrease, ↓: moderate decrease, →: no change, ↑: moderate increase, ↑↑: strong increase.**

| Indicator | SSP1 Sustainability | SSP2 Middle of the Road | SSP3 Regional Rivalry | SSP4 Inequality | SSP5 Fossil-fuelled development |
|---|---|---|---|---|---|
| **Elderly living alone** | ↓ Reduced due to community programmes and integrated ageing policies. | → Status quo trends continue, ageing grows but modest mitigation. | ↑↑ Sharp increase, due to austerity, poor care infrastructure, rural depopulation. | ↑ Highly segmented, rich well-served, poor isolated. | → Tech-assisted independence grows, but isolation risk remains. |
| **People at risk of poverty or social exclusion** | ↓ Reduced due to community programmes and low hierarchy. | → Status quo trends continue. | ↑↑ Sharp increase, due to austerity, poor care infrastructure, rural depopulation. | ↑ Highly segmented, rich well-served, poor isolated. | ↓↓ Very high human and social capital with economic growth benefits. |
| **Emotional loneliness / subjective isolation** | ↓ Strong cultural shifts towards inclusion and wellbeing. | → Mixed; modest investments in mental health/social infrastructure. | ↑↑ High due to fragmentation, distrust, and weak public services. | ↑↑ Deep disparities; elite enclaves vs. social neglect. | ↑ Worsening mental health despite connectivity and affluence. |
| **Access to community services** | ↑↑ Robust investment in place-based care and services. | → Uneven across countries or regions | ↓↓ Severely underfunded, shrinking local services. | ↓ For lower-income groups; elite access only. | ↑ Infrastructure improves, but access shaped by digital divides. |
| **Digital exclusion / tech-based isolation** | ↓ Tech used inclusively (e.g., for ageing in place, telemedicine). | → Some groups benefit, others excluded. | ↑↑ Many elderly fall through gaps. | ↑ Widening divides in access and skills. | ↑ High reliance on tech, but not always socially supportive. |
| **Neighbourhood cohesion / civic trust** | ↑↑ Revitalised public spaces, co-housing, participatory planning. | → Mixed levels; trust declines in cities, rises in small towns. | ↓↓ Erosion of cohesion, rising fear, polarisation. | ↓ Very fragmented; trust declines sharply. | ↓ High urbanisation but limited cohesion. |

## 3.4 Data sources by indicator typology

The hybrid approach draws on two complementary evidence streams: quantitative (top-down and bottom-up) and qualitative (narrative-based) which together populate the four-indicator typology: structural, systemic, behavioural, and exposure. Data sources differ in spatial resolution, update frequency, conceptual meaning, and methodological robustness and alignment with qualitative trends; these differences determine how each dataset is used in the hybrid workflow (see Box 1).

Structural indicators such as population by age, household composition, income distribution, education attainment, dwelling characteristics rely almost entirely on quantitative data rooted in administrative or census-like sources and not perceptions. They are slow-moving demographic and socio-economic stocks. The primary sources include EU-SILC[7], Eurostat Regional Database (a subset of variables at NUTS2/3 of the full Eurostat database for the variables mentioned here), OECD Local Data Portal, National census data (e.g. DESTATIS, INE, Statistics Sweden etc).

Systemic indicators including datasets involving geocoded provider locations (e.g. number of hospitals, number of general practitioners (GPs)), network-based travel time or distance, and population demand surfaces are combined via established accessibility methods (e.g. gravity-based or two-step floating catchment area variants). Databases include GISCO, National registers of health facility registries, GP lists, hospital locations (e.g. NHS Digital; German InEK; Sweden's Socialstyrelsen; Dutch CDS, Italian ISTAT etc). Results are then aggregated at NUTS-2 (or kept at finer resolution if needed) and used as vulnerability modifiers rather than exposure. As a minimal, fully transparent proxy, median network travel time to the nearest GP per 1,000 residents and classify quantiles into accessibility tiers; this serves as a systemic vulnerability modifier for heat-health risk. An example of such application of such data exists UK SSP-based projections (Merkle et al., 2023). Historical datasets such as Eurostat HLTH_RS_PHYSREG (physicians per region) are now obsolete and inadequate for forward-looking SSP applications; instead, accessibility-based indicators derived from open spatial data provide a more robust measure of systemic capacity relevant for heat-health or ageing vulnerability assessments.

**Box 1: Wellbeing indicators – which source and which definition?**

Similarly to indicators of other sectors and themes, wellbeing has an ambiguous definition and can fit all types of indicators within the typology, therefore requiring different sources of data according to its specifications. That is, on the one hand, wellbeing can be subjectively defined as "the ways that people experience and think about their lives"[8] which complements objective definitions based on indicators of quality-of-life, such as income and health. An analysis building on the preference of this report for single indicators rather than indices, would define wellbeing as a subjective behavioural indicator and therefore build from sources such as Eurobarometer, OECD or ESS data[9].

Similarly, indicators such as social cohesion, quality of governance, and equity can also occupy different positions within the typology depending on how they are measured. When wellbeing indicators are derived from self-reported perceptions (e.g. trust, sense of belonging, perceived safety), they represent behavioural dimensions of vulnerability. In contrast, when these concepts are

[7] EU-SILC is the EU statistics on income and living conditions for data on income, poverty, social exclusion, and living conditions (cross-sectional and longitudinal data), including also data on "*Persons at risk of poverty or social exclusion"* used in this report

[8] https://www.oecd.org/en/publications/oecd-guidelines-on-measuring-subjective-well-being-2025-update_9203632a-en.html Accessed 28 November 2025

[9] European Social Survey is a biennial survey with cross-sectional data organised by a coordinating team and associated countries. Unlike Eurobarometer and EU-SILC, it is not a EU instrument

| |
|---|
| quantified through distributional or institutional measures, such as inequality of access to care, digital divide, or spatial segregation, they capture systemic properties of society and governance. This duality reflects the interpretation in IPCC AR6 vulnerability frameworks, where cohesion and equity influence adaptive capacity both as structural features of systems and as behavioural expressions of individual or collective agency. |

Behavioural indicators such as trust, subjective well-being, satisfaction, and perceived loneliness rely on self-reported survey data such as Eurobarometer[10], and ESS data. Even in high-quality surveys with strong methodological controls, these indicators reflect individual perceptions and culturally embedded response patterns rather than observed conditions. They therefore behave differently from exposure indicators derived from counts or spatial observations.

Exposure indicators are computed from EEA and Copernicus Land Monitoring Service datasets (including, for example, the Urban Atlas for UHI intensity, green infrastructure, land-cover imperviousness, mobility patterns), re-projected to ETRS89 / LAEA Europe (EPSG 3035) for consistent spatial aggregation. CORDA[11] provides geospatial reference layers required to support Copernicus hazard and land-monitoring products. Because CORDA includes only in-situ and reference datasets (e.g. topography, hydrography, administrative boundaries, transport networks, cadastral layers), it supports the exposure domain by enabling spatial co-location of people and assets with hazards and contributes indirectly to structural components through built-environment basemaps. CORDA does not contain systemic indicators (service provision, institutional capacity) nor behavioural indicators. For hazard intensity indicators, sources include Copernicus Climate Change Service (C3S).

Future trajectories for exposure are inferred from SSP-aligned projections of urban expansion and land-use change (Fujimori et al., 2018) and population grids (Wang et al., 2022). For systemic, behavioural and (partly) structural indicators, when extended to the future, these are linked to SSP-consistent demographic and economic trajectories from IIASA (SSP v3) and its European extensions, as in the approach developed by Rohat et al. (2019). Table 4 provides an overview of spatial datasets of SSP projections for socio-economic variables. Given the fast pace of scenario work, there may be updated datasets replacing the current list.

**Table 4. Datasets of socio-economic indicators using the SSPs**

| Dataset | Variables | Spatial coverage & resolution | Temporal coverage & resolution | Reference |
|---|---|---|---|---|
| **SSP data portals** | | | | |
| IIASA SSP database v2.0[12] | Population (by age, gender and education level), GDP, urbanization | Global at country-level | | (Crespo Cuaresma, 2017; Dellink et al., 2017; Jiang and O'Neill, 2017; KC and Lutz, 2017; Leimbach et al., 2017) |
| IIASA SSP database v3.1[13] | Population (by age, gender and education level) | Global at country-level | | (KC et al., 2024) |

[10] Eurobarometer is the EU polling instrument to monitor public opinion in Europe
[11] Copernicus Reference Access Data
[12] Data available at https://tntcat.iiasa.ac.at/SspDb/ (assessed 18 November 2025)
[13] https://data.ece.iiasa.ac.at/ssp/ (assessed 14 November 2025)

| | | | | |
|---|---|---|---|---|
| IIASA SSP extensions explorer[14] | Various, e.g. sectoral employment, governance index, human development index, gender inequality index | Global at country-level | | |
| **Global SSP datasets** | | | | |
| Jones & O'Neill global gridded population[15] | Population (rural and urban) | Global, 1/8-degree and 1 km | 2010-2100, 10-year intervals | (Gao, 2017; Jones and O'Neill, 2016) |
| Wang et al. global gridded population[16] | Population by age and sex | Global, 1 km x 1 km | 2020–2100 at 5-year intervals | (Wang et al., 2022) |
| Gridded GDP[17] | Downscaled national-level GDP with nighttime light and gridded population data | Global, 30 arc-seconds and 0.25 arc-degrees | 2005 and for 2030–2100 at 10-year intervals | (Wang and Sun, 2022) |
| Gridded land use[18] | 7 land use classes | Global, 0.5° x 0.5° | | (Fujimori et al., 2018) |
| **European SSP datasets** | | | | |
| European downscaled population[19] | Population by age | Europe, NUTS-2 level | 2010-2100 at 10-year intervals | (Terama et al., 2019) |
| Disposable income[20] | Disposable income based on economic growth, income distribution, population dynamics and urbanisation | Europe, 1 km x 1 km | decadal | (Mikou et al., 2025) |

## 3.5 Computation

The hybrid approach pipeline in Figure 1 shows a computation workflow from observed data and SSP-narrative assumptions through parallel (and iterative, where applicable) quantitative and qualitative paths, converging into a unified set of spatialised indicators. Each indicator $i$ in region $r$ and year $t$ is normalised, compared, and combined as follows:

1. Normalisation:

All indicators are harmonised to NUTS-2 and scaled to [0,1], with higher values representing greater exposure or vulnerability. Where needed, values are aggregated using simple or expert-defined weights to produce scenario-consistent vulnerability and exposure scores. Qualitative SSP trends

[14] https://ssp-extensions.apps.ece.iiasa.ac.at/ (assessed 14 November 2025)
[15] https://www.cgd.ucar.edu/sections/iam/modeling/spatial-population and https://data.isimip.org (assessed 19 November 2025)
[16] https://doi.org/10.6084/m9.figshare.19608594.v3 (assessed 19 November 2025)
[17] https://doi.org/10.5281/zenodo.5880037 (assessed 19 November 2025)
[18] https://www.nies.go.jp/doi/10.18959/20180403.001-e.html (assessed 18 November 2025)
[19] https://doi.org/10.6084/m9.figshare.3806478.v4 (assessed 18 November 2025)
[20] https://entrepot.recherche.data.gouv.fr/dataverse/JUICCE (assessed 18 November 2025)

(Tables 2 and 3) are translated into quantitative multipliers controlling the direction and strength of extrapolation, where $s_{r,i}^{SSP}$(t), $s_{r,i}^{local}$(t) denote the normalised SSP-based and observed values consistent with SSP trends. The detailed computation procedure is reported through the example in Section 3.6 and Appendix A.1.

2. Divergence analysis:

In mixed-method (qualitative and quantitative) scenario environments such as this one, it is good practice to quantify the difference between global (top-down) and local (bottom-up) trajectories. We adapt the principles of the Scenario Distance Analysis[21] (Carlsen et al., 2024), which measures the distance between scenarios as the sum of state-wise differences across variables. In our case, the same principles is applied at the level of a single indicator to quantify the distance between its top-down (SSP-derived) and bottom-up (locally observed) trajectories:

$$D_{r,i} = | s_{r,i}^{SSP}(\mathrm{t}) - s_{r,i}^{local}(\mathrm{t})) |$$

where $s$ represents the normalised indicator values at time t. When $D_{r,i} = 0$ it means full agreement and $D_{r,i} = 1$ maximum divergence.

$D_{r,i} = 0$ measures the phase-space distance between global and local attractors for a given indicator. High divergence (e.g. D > 0.5) highlights "hotspots" where global narratives and local developments conflict, often because of active policy intervention or unmodelled feedback.

For example, under SSP5, high national-level growth may coincide locally with rising loneliness or unequal access to cooling; under SSP3, austerity may contrast with regional expansion of the care sector. In such cases, the divergence score guides the weighting between global and local sources in the hybrid projection.

In these cases, for additional thoroughness, weights can be assigned according to evidence confidence: high-quality, verified local information receives greater influence, while missing or uncertain local evidence increases reliance on SSP logic. When D>0.5 both trajectories can be reported separately and annotated in metadata rather than forced into a single value.

$$s_{r,i}^{hyb}(\mathrm{t}) = (1 - w_{r,i})\, s_{r,i}^{SSP}(\mathrm{t}) + w_{r,i}\, s_{r,i}^{local}(\mathrm{t}))$$

Where $0 \leq w \quad \leq 1$ is the confidence in local evidence. For transparency, both trajectories can be reported separately when D > 0.5 rather than forcing a single composite value.

3. Projections consistent with scenario-mapping**:**

Baseline values (in this case, 2022) are extrapolated to 2040 using slope-multiplier combinations derived from observed linear trends and scenario-specific directionality. Extrapolations are bounded by regional empirical minima and maxima to prevent implausible values.

4. Aggregation and uncertainty:

Indicators are tagged by confidence level. Divergence between observed and SSP-implied trends highlights potential governance or policy mismatches linked to spatial-context variability. For this demonstration, divergence is assumed $D_{r,i} = 0$ (full consistency). The hybrid approach allows empirical trends to remain anchored in data while capturing the directional logic of the SSP narratives.

[21] "Diversity in SDA is to define a metric for the distance between any two scenarios such that the distance d between two scenarios xi and xj is large when the sum of the distances between the states for each variable"

In this report, qualitative and quantitative results are presented separately: Section 4.1 visualises narrative-based qualitative changes in indicators across SSPs, while Section 4.2 demonstrates a quantitative example of one structural vulnerability indicator ("persons at risk of poverty or social exclusion") projected to 2040. No full aggregation across indicator dimensions is performed in this pilot phase.

In this report, no divergence calculation or weighting has been conducted for the practical example in Section 3.6, as this is a novel approach that needs testing. The projection only follows the qualitative scenario multiplier logic.

### 3.6 Practical example on how to produce SSP-based projections using the hybrid approach

The illustrative computation operationalises normalisation, truncation and scenario extrapolation for one structural vulnerability indicator, Persons at risk of poverty or social exclusion (AROPE) (Eurostat, 2025), using bounded linear extrapolation combined with qualitative SSP directionality. The resulting 2040 NUTS-2 maps (Section 4.2) demonstrate the hybrid approach and complement the qualitative synthesis in Section 4.1. This indicator has been selected for its relevance for defining the population's vulnerability to heat stress (cf. Section 1.2.2) and because it is available as a time-series for a relatively large number of regions across Europe. The longest time-series in this dataset cover the period 2014-2024. The calculations for estimating scenario values for all NUTS2 regions for a single time in the future, 2040, were carried out in the following steps:

1. Observed linear trends were calculated for all NUTS2 regions with at least eight years of data.
2. Ranges of linear trends were defined for all NUTS2 regions within each of the four European sub-regions defined in EUCRA (European Environment Agency, 2024).
3. Scenario values for 2040 were estimated by interpreting qualitative scenario trends (Table 3) and applying these with different versions of linear trend extrapolations as follows:
    a. SSP5 (↓↓): The minimum trend across all NUTS2 regions within each EUCRA region has been used for the strong decrease of SSP5 by extrapolating it for all NUTS2 regions within a EUCRA region.
    b. SSP1 (↓): The minimum plus 1/3 of the difference between maximum and minimum was used for the moderate decrease of SSP1.
    c. SSP2 (0): The average between the minimum and maximum trends has been used for the little to no change of SSP2.
    d. SSP4 (↑): The minimum plus 2/3 of the difference between maximum and minimum for used for the moderate increase of SSP4.
    e. SSP3 (↑↑): The maximum trend for each EUCRA region has been used for the strong increase of SSP3.
4. SSP-based projections were truncated by bounding values defined by the range of observed indicator values for each EUCRA region.

This approach extends the preliminary analysis presented by Pedde et al. (2024b) and addresses some of their shortcomings. First, the data coverage that was used in this new analysis is slightly improved by using the latest version of the published Eurostat indicator in which some gaps were filled, and the time-series is one year longer by including data for 2024 (step 1 above). Second, ranges of observed trends were now defined for the each of the four EUCRA regions instead of defining ranges for each country (step 2); this ensures that the number of NUTS2 regions that are considered to define a range of trends is more balanced across the four EUCRA regions compared to the previous country-level aggregation that included some countries with a very small number of NUTS2 regions with sufficient data for calculating trends. This greatly increased the spatial coverage of SSP-based future projections in step 3 to all NUTS2 region for which a baseline value for the year 2022 was available. This resulted in nearly full European coverage, whereas in the preliminary analysis from Pedde et al. (2024b) results could only be constructed for a limited number of countries (see Figure 10 in Pedde et al. 2024b). Third, we redefined the preliminary definitions of qualitative trends in the indicator based on literature – see Table 3 which includes different interpretations for SSP1, SSP4 and SSP5 compared to the preliminary demonstration. Fourth, we introduced a truncation for extrapolated trends to avoid reaching implausible values that fall outside the range of observations that in some cases even reached negative values as was discussed in for the preliminary analysis. The mathematical translation for scenario analysis is attached in Appendix A.1. Results of this analysis are presented in section 4.2.

# 4 Results

Section 4 presents the results of the hybrid pipeline. Section 4.1 synthesises the qualitative SSP translation across indicators (Tables 2 and 3) in Section 3.3 into aggregated patterns of change, visualised through the spider diagrams. Section 4.2 illustrates the quantitative extension for two selected indicators, one is the AROPE indicator developed with the hybrid approach that quantifies qualitative scenario trends by inferring past trends and another example that is directly calculated from existing SSP dataset, and Section 4.3 outlines divergence results linking top-down SSP and bottom-up data streams. The other indicator is a scenario projection for old-age-dependency ratio estimated as the ratio of the population aged 65 and older to the working-age population 15–64. The quantification is developed top-down and already available for application. This is an example of how to use an existing dataset of projected data, at the same scale (NUTS2) as the indicator developed through the hybrid pipeline, to show how both datasets can be compared in the same analysis and scenario.

## 4.1 Qualitative trends

In this interpretation, vulnerability overall decreases in SSP1 because of its assumptions on a sustainable future with cooperation (e.g. tendency for stronger increase for indicators 17-20) and less intensive lifestyles (e.g. strong decrease in trends for indicators 10, 12-13). Likewise, SSP1 exhibits an overall increase of adaptive capacities. SSP2, being the middle of the road scenario, is a world towards convergence, which is illustrated by overall moderate changes compared to present with no or only slight increases in all indicators.

In SSP3, a future in which countries struggle to maintain living standards in a high-carbon intensive Europe, the trends are exemplified with strong increase in vulnerabilities reflected in an overall negative trend for almost all indicators (being the opposite of SSP1, both in global and European assumptions). Increased vulnerability is reflected in the increase of proportion of aging (because of low fertility and strong limitation to migration assumptions) and increase in resource depletion and social isolation.

SSP4: a world in which power becomes concentrated in a small elite and where Europe becomes an important player translates in the assumption of a slight (net) increase for technological and overall market indicators (albeit much lower than SSP1) and lower quality of governance indicators (17-19) and lower overall population density and migration.

The exponential economic growth of fossil-fueled based SSP5 is a world where a lack of environmental concern. The assumption is that such growth translates in an increase of trends of all indicators compared to presents, the sharpest of all SSPs. That is valid for vulnerability such as the strongest increase in obesity connected to assumption of highly individualistic lifestyles.

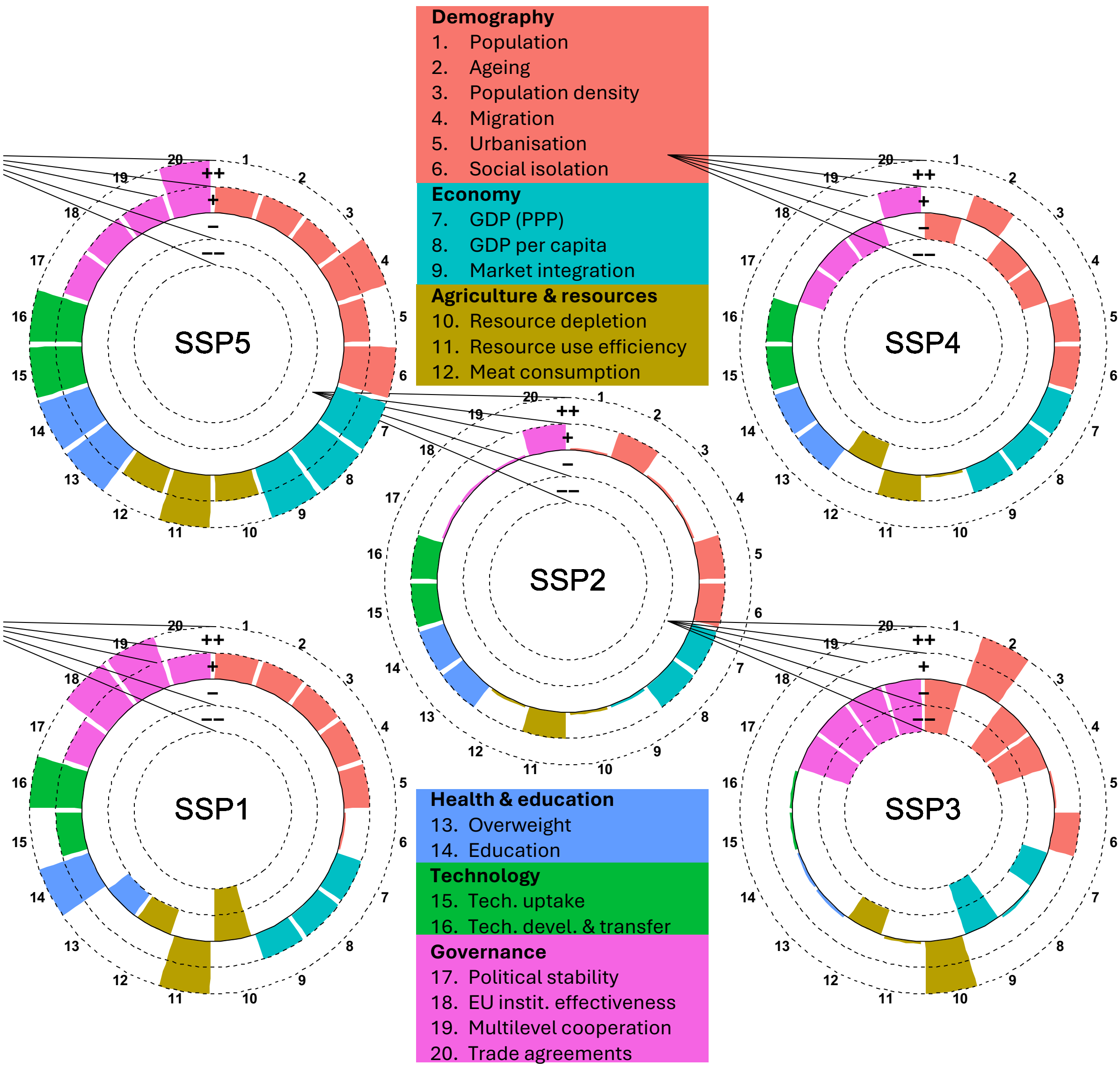


**Figure 3. Qualitative changes in 20 indicators of vulnerability and exposure for Europe derived from Chapter 2 of the first European Climate Risk Assessment. Five levels of change are shown between strong increase (outer dashed circle labelled ++) and strong decrease (inner dashed circle labelled ––), coloured boxes along the solid circle indicate little or no change. Source of qualitative trends: Pedde et al. 2024**

## 4.2 Quantitative trends

The qualitative narratives form the backbone to interpret the scenario individual indicator, providing the "future context" and glue to understand the scenario consistency of the single indicators. The Eurostat indicator "Persons at risk of poverty or social exclusions" is described through a wide range of values across NUTS2 regions in Europe. For the year 2022, for which the indicator has the largest spatial coverage, values range between 9% and 47% of the total population (Table 5). The largest values are found in regions in Central-eastern Europe (CEEU) and Southern Europe (SEU), whereas NUTS2 regions in Northern and Western Europe (NEU and WEU) have values below 30% (Figure 4). Linear trends observed over the past 11 years (2014-2024) show a range of positive and negative changes, with the majority of NUTS2 regions in Europe experiencing a decline in the indicator. This was particularly evident in CEEU where several NUTS2 regions experienced declines of more than -2%/year. In contrast, the strongest declines in the other three EURCRA regions were more modest at -1.3 %/year (SEU), -0.9%/year (NEU) and -0.5%/year (WEU), respectively. Increases in the indicator were also observed for NUTS2 regions across Europe of up to 0.6%/year, with the exception of SEU where one region experienced an increase of 1.7%/year (Figure 4).

**Table 5. Persons at risk of poverty or social exclusion, range of values for 2022 and range of linear trends (2014-2024) for NUTS2 regions within the four European subregions. See Table A2.2 in EEA (2024) for a definition of the regions.**

| EUCRA region | Value, 2022 (%) | | Linear trend 2014-2024 (%/year) | |
|---|---|---|---|---|
| | Minimum | Maximum | Minimum | Maximum |
| Western Europe (WEU) | 12.6 | 27.9 | -0.4 | 0.5 |
| Northern Europe (NEU) | 13.7 | 26.8 | -1.0 | 0.6 |
| Southern Europe (SEU) | 8.6 | 46.3 | -1.3 | 1.7 |
| Central-eastern Europe (CEEU) | 8.7 | 46.9 | -2.6 | 0.6 |

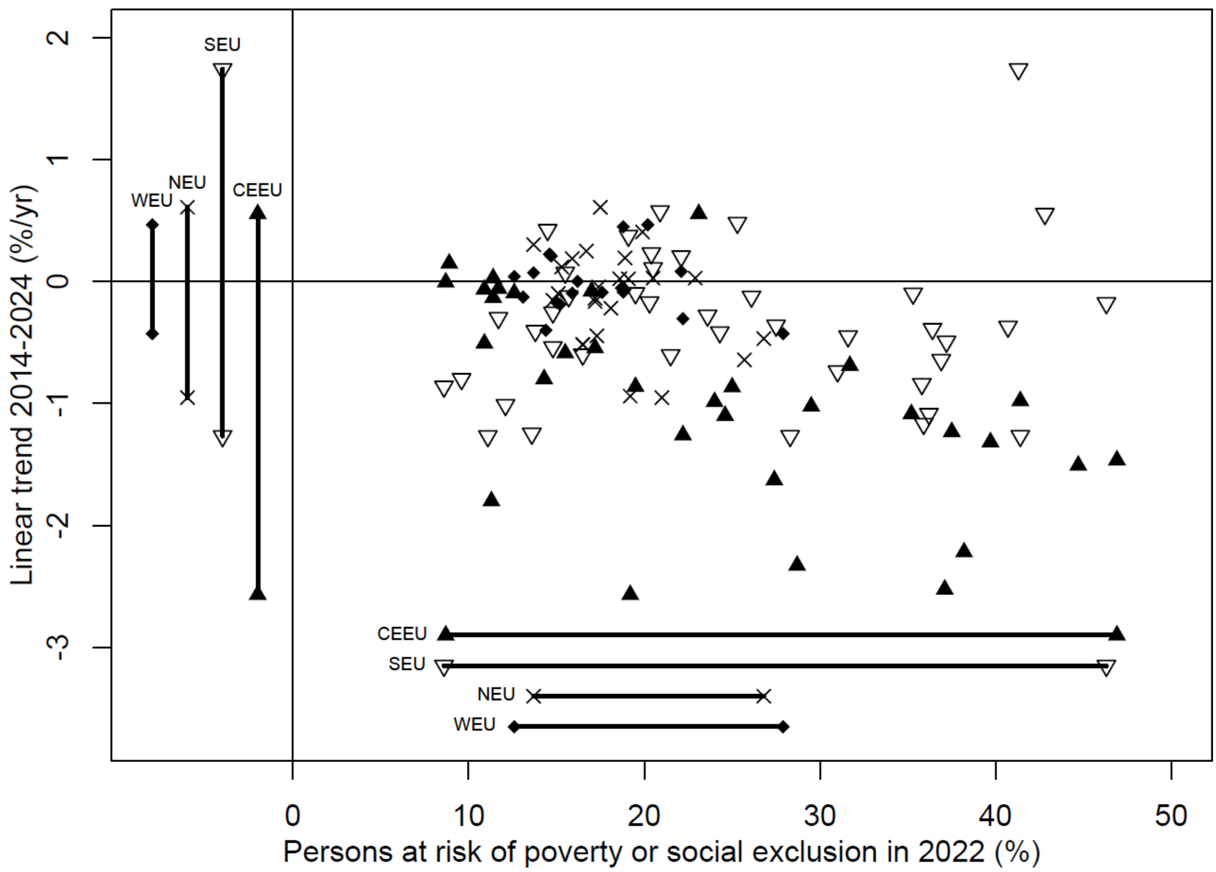


**Figure 4. Persons at risk of poverty or social exclusions in 2022 for individual NUTS2 regions in Europe and their linear trend for 2014-2024 (point symbols) and the ranges of values in 2022 (horizontal lines) and trends (vertical lines) of NUTS2 regions within four European sub-regions (WEU – Western Europe, NEU – Northern Europe, SEU – Southern Europe, CEEU – Central-eastern Europe). See Table A2.2 in EEA (2024) for a definition of the regions. Note that data were available only for a sub-set of NUTS2 regions in Europe.**

The range of observed trends for each of the four EUCRA regions were used to inform SSP-specific trend extrapolations. Examples of these are shown for two NUTS2 regions in Romania and Sweden

(Figure 5) which show future projections from the baseline value 2022 up until 2040 for the five SSPs (to remain within the scope of the qualitative trends to mid-century). The Nord-Est region in Romania starts with a larger baseline value and SSP trends cover a wider range of changes from a strong decline in SSP5 to an increase in SSP3, compared to the Norra Mellansverige region in Sweden. For both regions, the SSP3 and SSP5 projections were also truncated by the bounding values defined by range of observed baseline values. For two of the scenarios, SSP5 and SSP1, the stronger decline in Nord-Est results in lower values than in Norra Mellansverige before 2040, hence changing the order between these two regions. The overall scenario logic is thus overall consistent for both regions to the qualitative trends in Table 3 for each scenario.

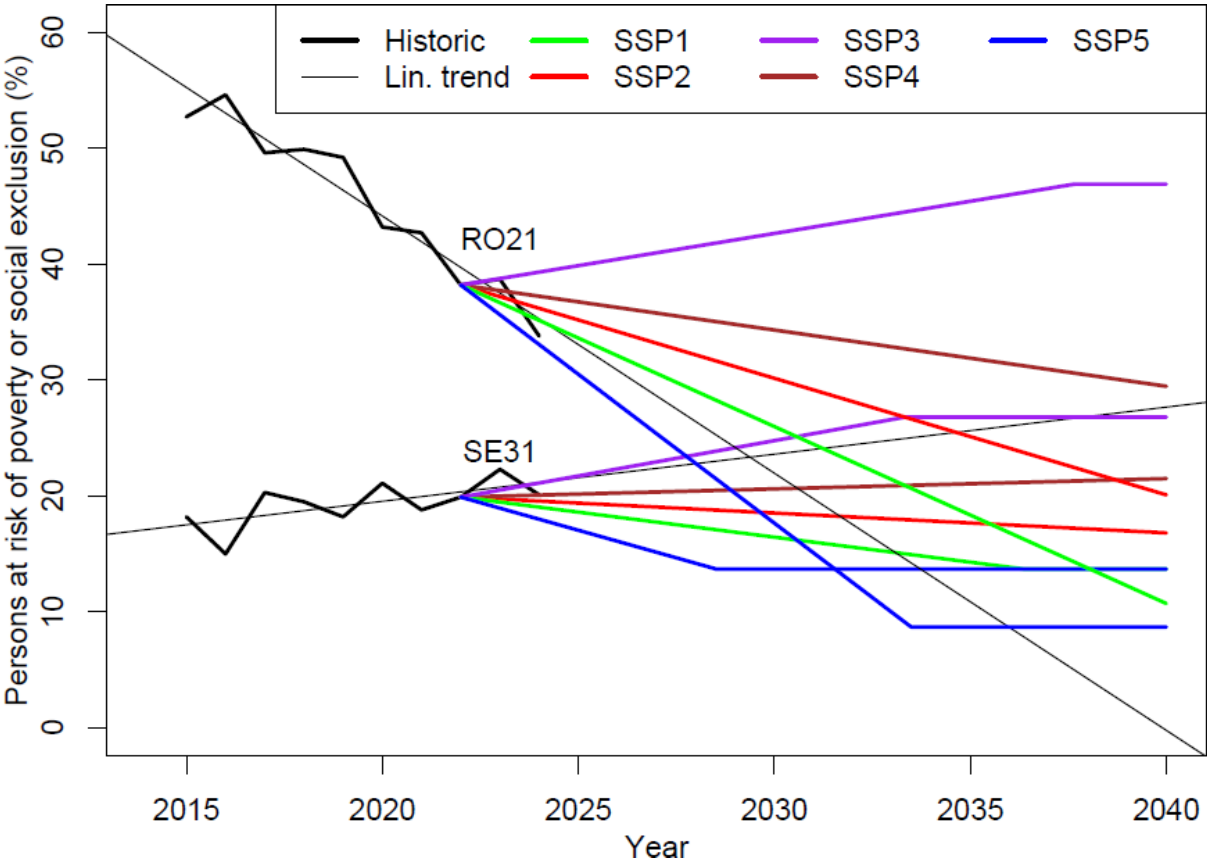


**Figure 5. Proportion of people at risk of poverty or social exclusion in two NUTS2 regions in Europe, Nord-Est (RO21) in Romania and Norra Mellansverige (SE21) in Sweden, in the observed time-series 2015-2024, its linear trendline and for projections for the period 2023 to 2040 for five SSP-based scenarios.**

The SSP-based projection of *persons at risk of poverty or social exclusion* (Eurostat, 2025) to 2040 reveals distinct regional patterns consistent with the scenario logic (Figure 6).

Under SSP3 (Regional Rivalry), vulnerability intensifies across most of Eastern and Southern Europe, where structural stagnation, limited welfare capacity, and regional inequality reinforce social exclusion (see qualitative rationale for this trend overall “Sharp increase, due to austerity, poor care infrastructure, rural depopulation” explained in Table 3). Pockets of high risk persist in rural and peripheral areas of Spain, Italy, Greece, and the Balkans. In contrast, SSP1 (Sustainability) and, particularly, SSP5 (Fossil-fuelled Development) show marked reductions in poverty exposure across Western and Northern Europe, though for different reasons, explained in Table 3: SSP1 through inclusive governance, community programmes and redistribution, SSP5 through economic expansion and technological gains that offset inequality. SSP4 (Inequality) produces a polarised landscape, with affluent metropolitan regions improving while marginalised regions - especially in Southern and Eastern Europe - experience relative decline. SSP2 (Middle of the Road) largely maintains current disparities, with gradual convergence in Western Europe but persistent gaps elsewhere.

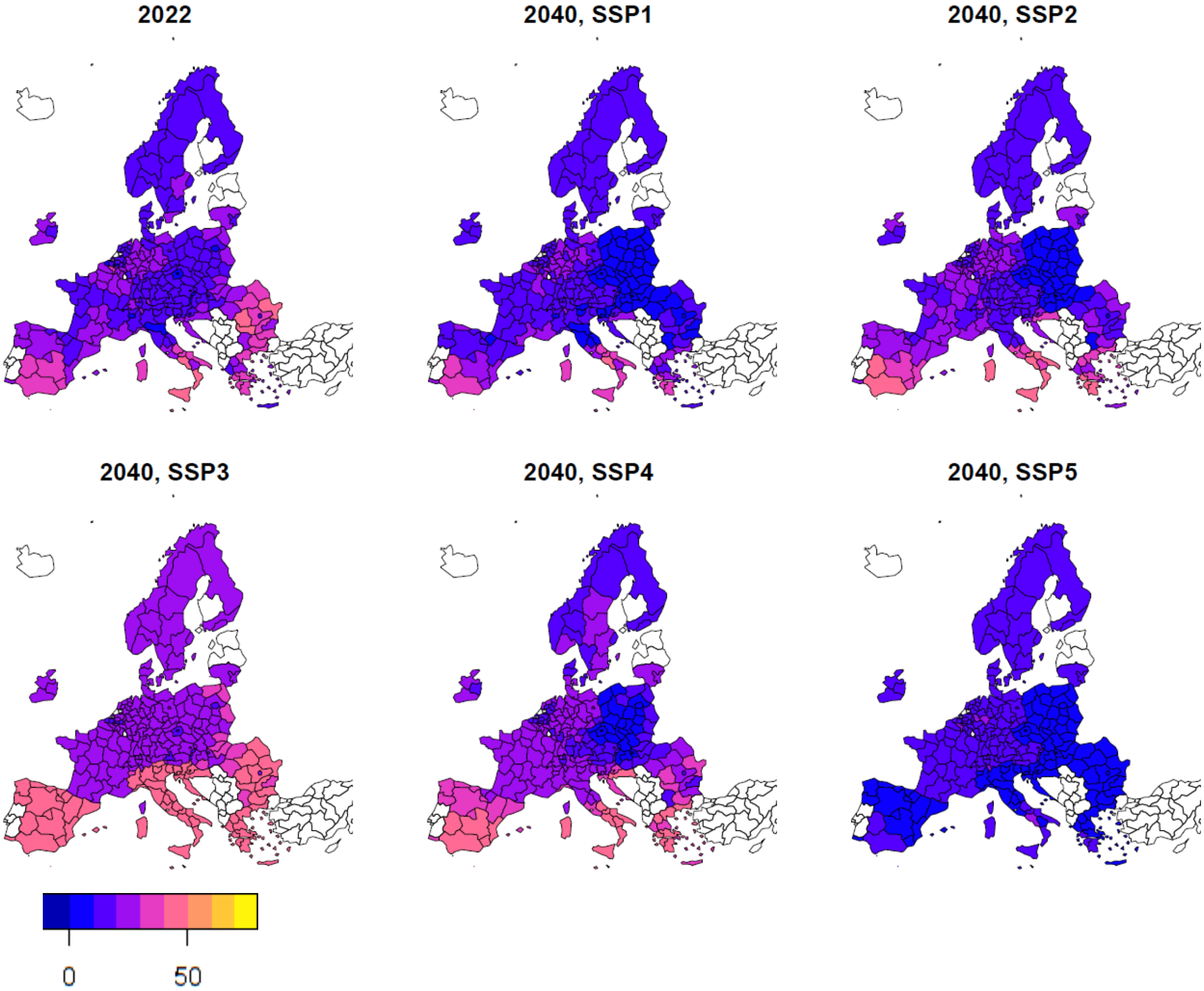


**Figure 6. Proportion of people at risk of poverty or social exclusion (%) at NUTS2 level across Europe in 2022 (Eurostat statistics) and projections for 2040 under five SSPs. White indicates regions with missing data.**

The quantitative trends developed in Figure 5, show an overall scenario-logic consistency. This is defined as an overall trend alignment between the qualitative interpretations of Table 2 and 3, with the quantitative top-down outcomes in Figure 6.

The second example for an indicator quantified at the regional NUTS2 level is the old-age dependency ratio that can be calculated directly from an existing SSP population dataset. This shows the general aging until 2050 across Europe under all five SSPs (Figure 7). The old-age-dependency ratio is largest in SSP5, with some NUTS2 regions for example in northern Spain and Italy reaching values above 150%. Generally, the difference between scenarios and the 2010 baseline values is larger compared to the differences between scenarios in 2050.

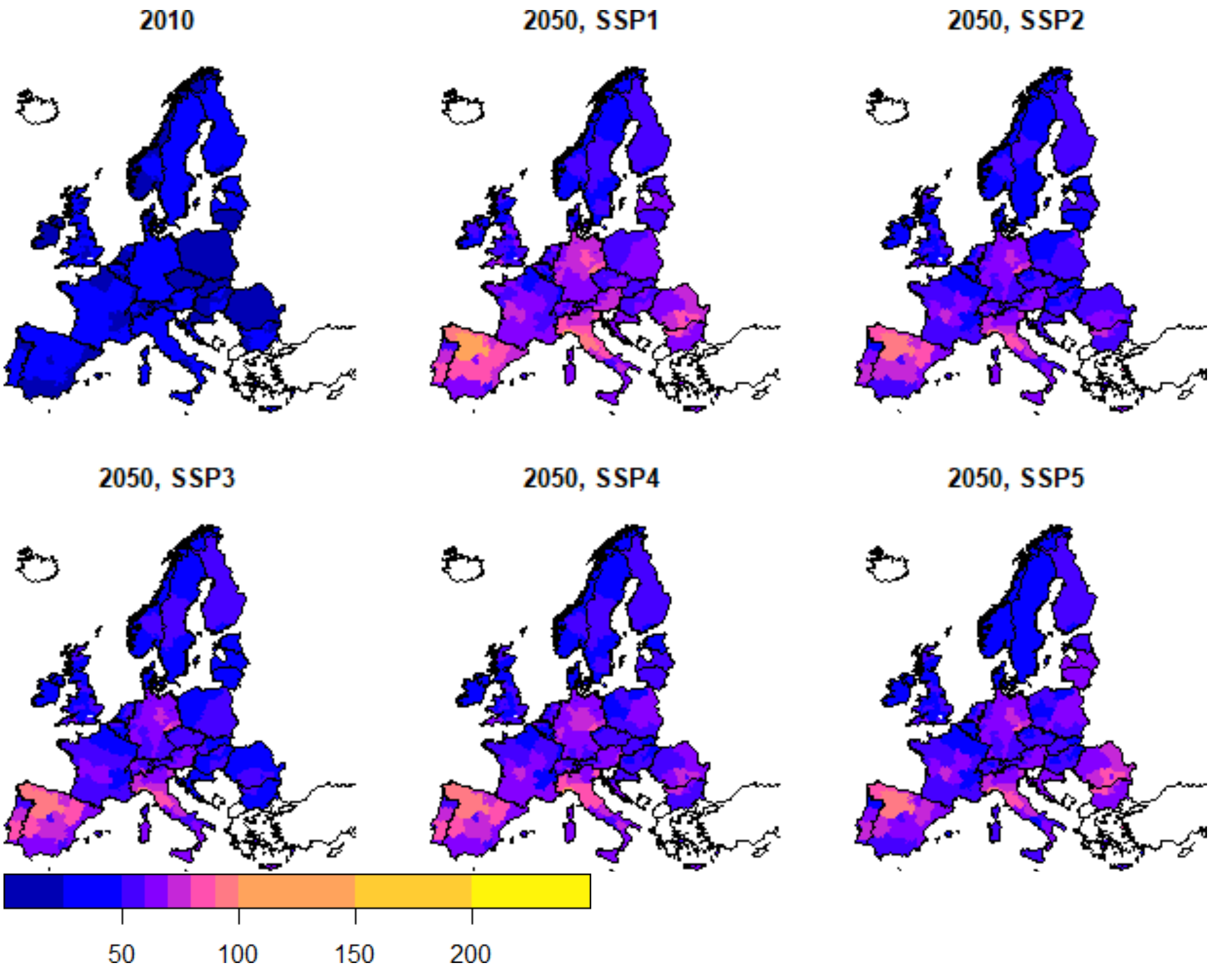


**Figure 7. Old-age-dependency ratio estimated as the ratio of the population aged 65 and older to the working-age population 15–64 at NUTS2 level across Europe in 2010 and projections for 2050 under five SSPs (%). Source: calculated with data from Terama et al. (2019).**

The quantitative results for AROPE in Figure 6 and old-age dependency in Figure 7 mirror the qualitative assumptions summarised in Tables 2 and 3. Under SSP3 (Regional Rivalry), structural vulnerability intensifies where Table 3 anticipates sharp increases in elderly isolation, reduced access to services and care, and wider poverty gaps, leading to the positive AROPE trends in Figure 6. Conversely, SSP1 (Sustainability) and SSP5 (Fossil-fuelled Development) both show reductions in poverty exposure, consistent with the expected decreases in structural and systemic vulnerability, though driven by different mechanisms: inclusive governance and welfare expansion in SSP1, and income growth through economic expansion in SSP5.

The spatial contrast visible in Eastern Europe in Figure 7, especially in Lithuania, Latvia, Romania, Bulgaria and Croatia, reflects the fertility and migration assumptions underpinning the SSP population projections (Terama et al., 2019). Under SSP3 and SSP4, sustained low fertility and net out-migration accelerate demographic ageing, while under SSP1 and SSP5, moderate fertility recovery and in-migration partially offset it. The high old-age dependency ratios projected for SSP5 are therefore coherent with Table 3, which anticipates continued ageing combined with technologically assisted independence rather than stronger community care. By contrast, the lower ratios under SSP3 arise from demographic contraction rather than healthier age balance, and these apparent gains are offset by weakened institutions and social fragmentation (Table 3 and Figure 3).

Together, these patterns confirm that the qualitative typology provides a consistent interpretive backbone for quantitative extrapolations and risk factors: exposure-related indicators (Table 2) define the physical context, while vulnerability-related indicators (Table 3) shape how demographic and social change translate into risk. Their combined reading explains why poverty and isolation evolve differently across SSPs, defining different types of risks, even when overall population ageing continues under all scenarios.

# 5 Discussion

## 5.1 Participatory processes: pros and cons and their relation to SSP datasets

Table 4 shows an overview of variables and their data sources. It also highlights that baseline or model updates may result in continuous updates datasets, suggesting that a flexible mechanism to access individual projections, rather than fully centralised and interconnected could be more resilient to this reality. By using a participatory process, the key advantage is that informed choices can be made on fundamental uncertainties that would otherwise remain hidden. This is very important to maintain transparency for socio-economic systems that operate locally and are subject to choices ("subjective") rather than physical processes ("objective"). For example, there are multiple ways to aggregate data that depend on the use Such choices can be made based on model constraints. In this analysis we demonstrate a plausible choice to aggregate data to prioritise harmonization across regions, defining a "credible" range through geographical boundaries, that is by aggregating regions that are geographically closer. An alternative could have been to aggregate regions by income, population density etc. These are all legitimate and can be used as alternative aggregating methods, where appropriate. The drawback is, being less formal, it is perceived as less credible particularly when paralleled with the formality of climatic impact drivers' analysis. This important aspect, on hard-to-communicate uncertainties has been addressed for both climatic and non-climatic impact drivers in the EUCRA Chapter 2 box on uncertainties.

Estimating (future) exposure and vulnerability involves addressing multiple types of uncertainties as summarised in EUCRA uncertainty box. Besides fundamental epistemic uncertainty, at the heart of natural and social sciences debates of what is *physically known and knowable,* an important uncertainty, in science-policy interfaces involves politically sensitive assumptions where framing values and communication play the leading role in informing decisions appropriately. Indicators such as institutional trust, vulnerability of marginalised groups, or the quality of public services can touch on contested narratives about governance, inequality, and social policy which are context dependent. Projections derived from global SSPs may diverge from local visions or provoke disagreement with national stakeholders.

We therefore emphasise:

- Transparency of assumptions behind each indicator trend (i.e. the logic of how SSP into narrative assumptions were translated to numbers at NUTS2 level (e.g. SSP4 = urban polarisation + shrinking social services)
- Clear labelling of indicators derived from narrative logic rather than trend data;
- The use of divergence analysis, where local developments contradict SSP-derived expectations, to highlight areas of policy complexity or foresight value;
- The option for bottom-up mapping, where local or national scenario processes are aligned with - or contrasted against- SSP logic.

"Granularity of data" is not the silver bullet for policy analyses, as granular data provides a complementary perspective but not the answer to all policy-relevant questions. In Wang et al. (2022), for example, the methodology can be identified as top-down because it starts with national-level SSP totals and downscales them to a 1 km-grid (high granularity) using a model that distributes the population spatially while adhering to the fixed national totals. Our example in 3.6, can be described as predominantly bottom-up, with a minor hybrid element, as it begins by calculating observed linear trends for individual NUTS2 regions and then extrapolates these region-specific trends, using higher-level European sub-regions only to define ranges and truncate implausible values. In such case, the safeguard of the divergence analysis could quantify the tension between global scenario logic (e.g. SSP3 assumes institutional erosion) and local empirical trajectories (e.g. a locally improving welfare system within a globally eroded social fabric scenario). This allows identifying when the SSP structure is *misaligned* with on-the-ground developments. High divergence values could indicate missing feedback or unmodelled policy dynamics.

In system dynamics terms, it flags where feedback loops are either suppressed or newly emergent compared to the baseline SSP model. Mapping divergence hotspots (even qualitatively) identifies where adaptation narratives diverge from governance practice, which is precisely what EEA and EUCRA are trying to capture. In such a hybrid approach, overall coherence of the scenario internal narrative and overall trend is prioritised above accuracy of downscaling technique.

## 5.2 Consistency within each SSP narrative (internal consistency)

Here we took the "expert judgement" fast track in Section 3.3 to simulate the expert judgement process typical of participatory processes. The main difference is legitimacy – while both qualitative and judgement-based, the participatory process has more legitimacy when co-developed by the stakeholders. While potentially less credible due to the lack of formal quantification, this allows to provide a coherent example within the limited resources of this task. In fully designed participatory processes it is possible to increase internal consistency – even in the presence of solely expert-judgement based approaches – using a mathematical matrix-based approach stemming from Cross Impact Balance approach (Schweizer and O'Neill).

## 5.3 Consistency between different participatory processes for the same variable

A key methodological insight emerging from this work is the necessity to use participatory processes to reveal and address epistemic uncertainties that could pass unnoticed when solely desktop and top-down analyses are applied. We demonstrate this through the apparent contradiction between our indicator trend and earlier SSP-based studies (e.g. Rohat et al., 2019) not reflect inconsistency but rather to exemplify how a shift in system boundaries affects the outcome of the analysis. The indicator "elderly living alone" illustrates this clearly (Table 6). Demographic projections such as those in Rohat (2018, 2019) treat living arrangements as outcomes of structural population flows - fertility, mortality, migration, and age composition - governed by static household-formation rules. These are structural dynamics within the demographic subsystem, as also formalised in the population projections by Terama et al. (2019).

By contrast, our hybrid approach introduces an additional feedback layer connecting those demographic stocks to institutional and behavioural subsystems - social policy, welfare capacity, and cultural norms - that can either amplify or dampen demographic effects. Under this framing, SSP1's inclusive governance and community programmes act as negative feedback on isolation despite continued ageing, whereas SSP3's fragmentation, austerity, and social atomisation act as positive feedbacks, reinforcing isolation and care deficits.

To illustrate the difference empirically, Rohat et al. (2019) reported the following mean values for the proportion of elderly living alone in Europe (baseline = 27.8 %): SSP1 = 32.1 % (+13 %), SSP3 = 23.5 % (–19 %), SSP4 = 26.4 % (–5 %), SSP5 = 35.8 % (+22 %; 50–60 % in Scandinavia). These estimates originate from Rohat (Rohat, 2018), where the same indicator was quantified through an expert-elicitation procedure using fuzzy-set aggregation of 29 expert responses based on qualitative EU-SSP narratives. Each expert provided directional judgements and quantitative ranges for 2050, which were aggregated into adjustment factors (e.g. +38 % for SSP5 Southern Europe, –19 % for SSP3 Central Europe) and applied to 2015 NUTS-3 data.

**Table 6. Comparison of plausible but diverging interpretations emerging from participatory processes for social isolation indicator through the proxy "% of people over 65 years old living alone" (Europe 2050)**

| SSP | Rohat et al. (2019): Mean (%) vs Baseline 27.8 % | Direction (Rohat) | Rationale (Rohat 2018): socio-demographic perspective | Direction (this report) | Rationale (this report): socio-institutional perspective |
|---|---|---|---|---|---|
| **SSP1 (Sustainability)** | 32.1 (+13 %) | ↑ Increase | Healthy, wealthier and more individualistic societies → more independent living among elderly | ↓ Decrease | Inclusive governance and co-housing programmes reduce isolation despite ageing |
| **SSP3 (Regional Rivalry)** | 23.5 (–19 %) | ↓ Decrease | Poorer health and strong familistic norms → multigenerational households | ↑↑ Strong increase | Austerity and fragmentation erode care systems → isolation rises |
| **SSP4 (Inequality)** | 26.4 (–5 %) | ↓ Decrease | Lower-income groups in familistic settings offset wealthy elites living alone | ↑ Increase (segregated) | Polarised society → elite independence vs neglected poor |
| **SSP5 (Fossil-fuelled Development)** | 35.8 (+22 %) (50–60 % in Scandinavia) | ↑↑ Strong increase | High income and technological comfort → more independent households | → Neutral / slight increase | Tech-assisted independence offset by expanded care infrastructure |

Rohat (2018) and Rohat et al. (2019) acknowledged behavioural and systemic determinants such as individualism, health, and family norms, but incorporated them only as directional assumptions within expert-derived adjustment factors. Both their analysis and ours use *"elderly living alone"* as a practical proxy for social isolation, acknowledging that solitary living does not necessarily imply social detachment but signals heightened potential for it when compounded by weak care systems or limited community support. Their approach linked these drivers to demographic outcomes through fixed, monotonic relationships. The hybrid approach presented here embeds the same determinants as dynamic feedback between demographic structure, welfare capacity, and social behaviour, allowing outcomes to shift direction when institutional or cultural conditions change. For instance, ageing combined with stronger welfare systems leads to declining isolation under SSP1, whereas austerity and fragmentation amplify it under SSP3. SSP4 produces polarised outcomes (elite independence versus deprivation), while SSP5 stabilises isolation through technology-mediated autonomy.

This divergence highlights a deeper epistemic responsibility in scenario work: projections should be treated as conditional choices, not future facts. Each projected trend encodes assumptions about social organisation, governance priorities, and human agency. Treating model outputs as deterministic truths risks freezing these assumptions into policy expectations, thereby legitimising one normative vision of the future over others.

Participatory and deliberative scenario methods are therefore not decorative inclusions but systemic safeguards. They reintroduce reflexivity into the modelling process, allowing stakeholders to identify, understand and challenge hidden assumptions, expose path dependencies, and reveal alternative feedback that quantitative models cannot capture. Through this reflexive co-production, projections evolve from prescriptive artefacts into decision-support heuristics - tools that illuminate policy choices rather than silently prescribe.

Further extensions could include compound heat-risk metrics combining exposure and social support, analogous to global 'cooling-gap' studies (Andrijevic et al., 2021) adapted for European datasets.

# 6 Recommendations for combining hazard and exposure indicators

Selecting suitable hazards and linking them to the right exposure and vulnerability indicators is the step where analytical design meets policy application. The examples presented here are deliberately focused on the hazard × exposure dimension of risk – where climatic drivers and human presence overlap – because this intersection is the most common operational entry point for European risk assessments. By first clarifying this interface, users can then extend the analysis to include the structural, systemic, and behavioural layers described earlier.

In most applied contexts, hazards are already quantified through physical models or monitoring systems (e.g. Copernicus, C3S). What remains uncertain is how to combine them with indicators that describe who or what is exposed and how that exposure is modified by vulnerability and adaptive capacity. Table 7 therefore maps examples from the literature of logical pairings between hazard type, exposure indicator, and vulnerability typology.

They show that: every hazard first requires a measure of presence (population, assets, activities) before vulnerability can be properly attached; the same indicator may behave differently across types. For example, access to green space mitigates heat exposure but functions as a systemic capacity when considered at neighbourhood scale; most datasets used in the examples quantify exposure rather than vulnerability, highlighting the current imbalance in available data and reinforcing the need for the hybrid approach propagated in this report as a way forward in quantifying indicators that are not readily available.

By keeping the table explicit, the guidelines make visible where vulnerability information is thin and where the hybrid method can fill the gap through qualitative translation or local knowledge. Users can apply the same structure to other sectors (e.g. labour productivity, infectious diseases) by identifying the relevant hazard, then systematically attaching the matching exposure and vulnerability dimensions.

**Table 7. Examples of hazard–indicator pairings illustrating spatial and temporal scale dependencies and data sources indicators (extended from Pedde et al. 2024)**

| Hazard | Exposure or vulnerability | Rationale | Scale | Reference |
|---|---|---|---|---|
| Heat indicators: Cooling Degree Days, number of Hot Days, 95th percentile of acute extreme heat exposure | Elderly population | Age structure determines populations' vulnerability to high temperatures | Global, high-resolution grid | (Falchetta et al., 2024) |
| Heat waves, droughts, climate-induced crop failure and river floods | Cumulative exposure of population to climate risks dependent on time of birth | Younger generations are facing a significantly increased likelihood of encountering extreme climate events within their lifetimes compared to older generations. | Global, high-resolution grid | (Thiery et al., 2021) |
| Compound climate extreme events | Population, agricultural and forest land exposed | | Global, high-resolution grid | (Schillerberg and Tian, 2024) |
| Drought and heat | Cropland | Drought and heat stress severely impact crops | Global | (Wang et al., 2023) |
| Heat | Population (number of people exposed per European subregion) | | Europe | (Naumann et al., 2020) |
| Coastal flooding | UNECSO world heritage sites | World Heritage sites located in coastal areas are increasingly at risk from coastal hazards due to sea-level rise | Site scale across the Mediterranean region | (Reimann et al., 2018) |
| Pluvial floods | City infrastructure | Cities are increasingly exposed to the occurrence and impacts of pluvial flooding due to climate change and urbanisation | City-scale | (Skougaard Kaspersen et al., 2017) |

Together, these examples serve not merely as an inventory of variables but as a design template: begin at the hazard × exposure interface, then layer on systemic, structural, and behavioural modifiers until the picture of risk is both spatially and socially coherent. This progression from hazard to exposure to vulnerability is the backbone of the hybrid pipeline and the reason these guidelines emphasise the hazard × exposure step as the practical anchor for integrated health-risk assessments in Europe.

## 7 Conclusion

This report demonstrated that projecting climate-related health risks in Europe requires more than climatic projections alone and vulnerability as outcomes of hazards and exposure. The decisive factors shaping future health outcomes lie in the social, demographic, and institutional architectures within which climate hazards occur. While this is well acknowledged, its implementation still lags behind. By operationalising a hybrid approach grounded in the Shared Socioeconomic Pathways (SSPs), we showed how these non-climatic impact drivers - vulnerability and exposure- can be integrated into risk assessments that are at once conceptually coherent, empirically anchored, and relevant for European policy processes.

The hybrid approach functions as a coherence framework rather than a new model. It aligns four complementary dimensions of socio-economic reality: structural, systemic, behavioural, and exposure indicators, within a story-and-simulation logic that iterates between narratives and data. This enables researchers and decision-makers to build consistent, scenario-based projections without prescribing a single dataset or disciplinary approach. This overcomes possible paralysis from lack of all data or uncertainty and lack of consensus on the *right* data, methods or sources.

By translating IPCC vulnerability dimensions into a scenario-ready, indicator-based structure aligned with European data infrastructures and policy processes, the four-indicator typology offers a methodological advancement that has not previously been formalised in the European adaptation and risk literature. In doing so, it bridges conceptual vulnerability frameworks with the concrete data and reporting logic of the European adaptation policy cycle.

A central insight of the typology is that a single indicator may serve multiple analytical roles depending on context and data source. The example of “Persons at risk of poverty or social exclusion” (AROPE) illustrates this versatility.

- As a **structural** variable, AROPE represents the demographic and economic stocks that define baseline sensitivity.
- In a **systemic** reading, it signals weaknesses or strengths in welfare and care systems.
- Under a **behavioural** lens, it reflects participation, trust, and help-seeking behaviours that influence adaptive capacity.
- In an **exposure** context, its spatial distribution identifies where vulnerable groups coincide with physical hazards such as heat or flooding.

Each layer tends to draw on distinct data sources - Eurostat and IIASA projections for structural trends; healthcare accessibility and administrative datasets for systemic aspects; European Social Survey and Eurobarometer for behavioural dimensions; and Copernicus or national hazard layers for exposure. The hybrid pipeline provides the operational bridge among these sources, ensuring that they can be combined while preserving their conceptual meaning.

The pilot analysis confirmed that this approach can be implemented using existing European data infrastructures, without having to wait for the perfect projections to exist. Linear extrapolations of AROPE, adjusted by SSP-specific multipliers and bounded by observed ranges, generated plausible 2040 projections for all NUTS-2 regions. The same workflow can be extended to other health-relevant indicators such as ageing, access to care, or green-space availability.

Besides the typology, an innovation is the divergence score part of the hybrid approach. Used systematically, this metric can support European-level harmonisation, via European Environment Agency (EEA) and the EIONET, by identifying data inconsistencies and regional hotspots that warrant closer assessment, even where future projections are not involved. This type of scoring could detect more easily and support the analysis of trends and hotspots, for example directly or indirectly inform the tools and indicator logic applied in forthcoming European reporting processes, including the 2027 Governance Regulation cycle**.**

This work contributes to the evolving European adaptation knowledge ecosystem. Learning from EUCR, it provides a methodological link between climatic impact drivers and the socioeconomic factors captured in this hybrid pipeline. It also complements state-of-art portals such as Destination Earth, which will generate high-resolution digital twins of the Earth system: the hybrid approach offers the corresponding *societal twin* needed to interpret those simulations through human vulnerability and institutional capacity. Through EIONET's coordinated indicator development and the emerging Monitoring, Evaluation and Learning (MEL) frameworks, these methods can progressively feed into national and European adaptation tracking.

Ultimately, this report supports a new generation of climate risk assessments (CRAs) that integrate physical, social, and institutional dimensions of climate risk. By treating scenarios as transparent heuristics rather than deterministic forecasts, the hybrid approach connects scientific analysis with decision-making, helping Europe anticipate where vulnerability will persist, where adaptation is succeeding, and where the social foundations of resilience still need to be built.

## List of abbreviations

| Abbreviation | Name | Reference |
| --- | --- | --- |
| EEA | European Environment Agency | www.eea.europa.eu |
| CID | climatic impact driver | |
| C3S | Copernicus Climate Change Service | https://climate.copernicus.eu |
| ECDE | European Climate Data Explorer | https://climate-adapt.eea.europa.eu/en/knowledge/european-climate-data-explorer |
| EUCRA | European Climate Risk Assessment | https://www.eea.europa.eu/publications/european-climate-risk-assessment |
| IPCC | Intergovernmental Panel on Climate Change | https://www.ipcc.ch |
| JRC | Joint Research Centre | https://joint-research-centre.ec.europa.eu |
| NCID | non-climatic impact driver | |
| SSP | Shared Socioeconomic Pathway | https://iiasa.ac.at/models-tools-data/ssp |

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# Appendix

## A.1 Technical translation of the hybrid approach quantification for scenario analysts

1. Trend estimation (empirical subsystem):

For each NUTS-2 region with ≥ 8 annual observations, an ordinary least-squares (OLS) linear regression was fitted:

$$y_{r,t} = \alpha_r + \beta_r t + \varepsilon_{r,t}$$

where $y$ is the percentage of people at risk of poverty or social exclusion and $\beta_r$(slope) gives the annual change in percentage points.

2. Regional aggregation (structural context layer):

To stabilise variance and avoid country-level imbalance, the distribution of slopes was summarised by the four EUCRA macro-regions (Northern, Western-Central, Eastern, Southern Europe). Within each macro-region, minimum (β_min) and maximum (β_max) values define the plausible range of social-trend trajectories.)

3. SSP interpretation (qualitative–quantitative coupling) based on Pedde et al. (2019):

The narrative tendencies from Table 2 (vulnerability matrix) were converted to directional multipliers, reflecting a bottom-up participatory approach utilised for European SSP projections (also, for European SSP health variables in Rohat (2018)), along that empirical slope range:

- SSP5 (--): strongest *decrease* → β = β_min
- SSP1 (-): moderate decrease → β = β_min + ⅓(β_max – β_min)
- SSP2 (0): baseline → β = (β_max + β_min)/2
- SSP4 (+): moderate increase → β = β_min + ⅔(β_max – β_min)
- SSP3 (++): strongest *increase* → β = β_max

4. Projection (simulation step):

$$y_{r,2040}^{SSP} = y_{r,2022} + \beta_{SSP,region} \times (2040 - 2022)$$

applied to each NUTS-2 region $r$within its macro-region.

5. Truncation (system boundary enforcement):

Values outside the observed empirical range (regional min–max of 2014–2024) were truncated to prevent non-physical or negative percentages.

6. Output:

A complete NUTS-2 map of projected poverty/exclusion share in 2040 for each SSP. This serves as the quantitative example in Section 4.2, complementing the qualitative spider diagrams of 4.1.