JASPERS practical sectoral guidance on climate resilience proofing

Energy – Municipal Solid Waste – Transport

Version 1.0 - November 2024

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Acronyms

AAP	Adaptation Action Plan
AD	Anaerobic Digestion
AR6-WGI	6th Assessment Report of Working Group I
ATC	Automatic Train Control
BESS	Battery Energy Storage Systems
BRT	Bus Rapid Transit
C3S	Copernicus Climate Change Service
CAPEX	Capital Expenditures
CBA	Cost-Benefit Analysis
CCKP	Climate Change Knowledge Portal
CCTV	Closed Circuit Television
CDS	Copernicus Climate Data Store
CER	Critical Entities Resilience Directive
CHP	Combined Heat and Power Generation
CLO	Compost Like Output
CO2	Carbon Dioxide
CPS	Cable Protection System
CRA	Climate Resilience Assessment
CTC	Centralised Traffic Control
DH	District Heating
DWL	Design Working Life
EC	European Commission
EEA	European Economic Area
EIA	Environmental Impact Assessment
ETCS	European Train Control System
EU	European Union
E&M	Electrical & Mechanical
GCM	Global Climate Model
GHG	Greenhouse Gas Emissions
GIS	Geographic Information System
H2	Hydrogen
HVAC	Heating, Ventilation, and Air Conditioning
ICT	Information and Communication Technology
IPCC	Intergovernmental Panel on Climate Change
IT	Information Technology
ITS	Intelligent Transportation Systems
LIDAR	Light Detection and Ranging
MCA	Multi-Criteria Analysis
NA	Not Applicable
NAP	National Adaptation Plan
NAS	National Adaptation Strategy
PPE	Personal Protective Equipment
PV	Photovoltaic
RA	Risk Area

RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RDF	Refuse-Derived Fuel
RMC	Rail Mounted Cranes
RRF	Recovery and Recycling Facility
SEA	Strategic Environmental Assessment
SMS	Short Message/Messaging Service
SODAR	Sound Detection and Ranging
SSP	Shared Socioeconomic Pathway
STS	Shore to Sea
SWEAT	Severe Weather Threat Index
UPS	Uninterruptible Power Supply
UV	Ultraviolet
VMS	Variable Message Signs
WGI	Working Group I
WRI	World Resources Institute

Introduction

This JASPERS' practical guidance document on climate change resilience proofing is meant to provide further technical support and concrete advice for the implementation of the European Commission Notice — Technical guidance on the climate proofing of infrastructure in the period 2021-2027 (hereafter EC Technical Guidance), with a specific focus on the sectors of Energy, Municipal Solid Waste Management, and Transport.

The document serves as a comprehensive resource for stakeholders involved in the development of infrastructure projects that are to be co-financed by the Cohesion Fund and the European Regional Development Fund (ERDF) in the EU Member States and therefore need to be climate proofed according to the requirements of Article 73(2)(j) of the EU Common Provisions Regulation (hereafter CPR)[1]. The CPR mandates managing authorities to ensure the climate-proofing of infrastructure investments having an expected lifespan of at least five years.

As defined by the CPR, climate proofing is a process to prevent infrastructure from being vulnerable to potential long-term climate impacts whilst ensuring that the 'energy efficiency first' principle is respected and that the level of GHG emissions arising from the project is consistent with the climate neutrality objective in 2050. It has two pillars of analysis that integrate (1) climate **mitigation** and (2) climate **resilience/adaptation** considerations into the development of infrastructure projects. This document addresses the second pillar of climate resilience. Overall, the guidance also aims to serve as a general reference on good practices for **climate change resilience proofing**.

The climate proofing assessment can also be used to support the **DNSH assessment** for projects that are to be co-financed by Cohesion Fund, ERDF and other EU funding sources but also support the **implementation of the EU Taxonomy** for other actors, most notably private companies.

This practical guidance document aims to facilitate the integration of climate resilience considerations into the full project cycle, from the initial conceptualisation and feasibility assessment to the final monitoring and evaluation phases. It offers practical insights and steps to enhance the climate resilience of infrastructure investments within those three sectors, fostering an effective climate change adaptation. The guidance is intended for a diverse range of stakeholders engaged in infrastructure development within the specified sectors, including project managers, engineers, environmental experts, policymakers, and financiers. JASPERS underlines that the guidance aims to provide practical and sector specific recommendations that might be considered as relevant to inform projects' assessments.

By adhering to the principles and recommendations outlined in this document, stakeholders can contribute to the creation of resilient and sustainable infrastructure that mitigates physical climate risks and enhances overall project performance. While this guidance provides overarching principles and methodologies for the sectors covered, it is essential to acknowledge that additional national and sectoral considerations may be necessary for comprehensive project planning and development. Stakeholders are encouraged to complement the use of this guidance with relevant national regulations, national climate proofing guidance and data sources, sector-specific standards, and other best practices to ensure contextual relevance and effectiveness.

The need for resilient infrastructure is widely recognised[2] and this guidance document can also support systemic analysis at both **plan and network levels**. Analysing climate impacts at the network level requires increased attention. Infrastructure systems are vital to our society, and **timely maintenance and renewal must be prioritised** due to the growing threat landscape, including more frequent and intense weather events from climate change and other hazards.

JASPERS is a joint initiative between the European Investment Bank (EIB) and the European Commission that provides advisory, appraisal and capacity building support for the preparation and

[1] Regulation (EU) 2021/1060 of the European Parliament and of the Council of 24 June 2021 laying down common provisions

[2] Recent reports, such as Enrico Letta's on the EU Internal Market and Mario Draghi's on European Competitiveness, highlight the urgency. For instance, approximately 40% of Europe's distribution grids are over 40 years old and need modernization. Additionally, revisions to the TEN-T Regulation and the recast of the Critical Infrastructure Directive underscore this necessity. Prioritising interventions and resource allocation should be informed by criticality and redundancy analyses at the network level. For example, under the JASPERS mandate, the EIB has advised Infraestruturas de Portugal on their climate change resilience plan for rail and road networks. Similar efforts have been undertaken for the Polish and Spanish road and rail networks, with more to follow.

implementation of programmes and projects financed by EU Cohesion policy, including Just Transition Fund and the Connecting Europe Facility. For more information please visit: https://jaspers.eib.org/.

JASPERS assistance is provided in good faith and with reasonable care and due diligence (diligentia quam in suis), drawing on the experience and business practices of its partners; however, the beneficiaries acknowledge that EIB in its role as JASPERS will not be responsible for any loss or damage resulting from any advice provided by JASPERS.

This guidance document was prepared by JASPERS with the support of GRID Engineers.

1. Overview of the EC Technical Guidance on Climate Resilience Proofing

Figure 1.1 illustrates the climate resilience pillar of the EC Technical Guidance document, along with the main steps included in the assessment. The process comprises two distinct phases, i.e. Phase 1 (Screening) and Phase 2 (Detailed Analysis). The outcome of Phase 1 (Screening) determines whether Phase 2 (Detailed Analysis) should be carried out. In the ensuing, the steps (modules) pertaining to each phase are briefly explained to assist the users' comprehension. For further details and full description of the approach principles, readers are referred to Chapter 3.3 of the EC Technical Guidance.

NOTE:

There's an overlap between the climate resilience proofing process detailed here and the EU's revised Environmental Impact Assessment (EIA) Directive (2011/92/EU, as modified by Directive 2014/52/EU). For projects required to undergo an EIA procedure, these two processes could be harmonised. For more details on the integration of the climate-proofing process into the EIA procedure, readers are referred to Chapter 5 and Annex D of the EC Technical Guidance.

Climate change aspects should be integrated in the Strategic Environmental Assessment (SEA) procedure carried out at the level of the plan/program, in the context of which the project should be implemented. For more details on the integration of climate change considerations into the SEA procedure, readers are referred to Annex E of the EC Technical Guidance.

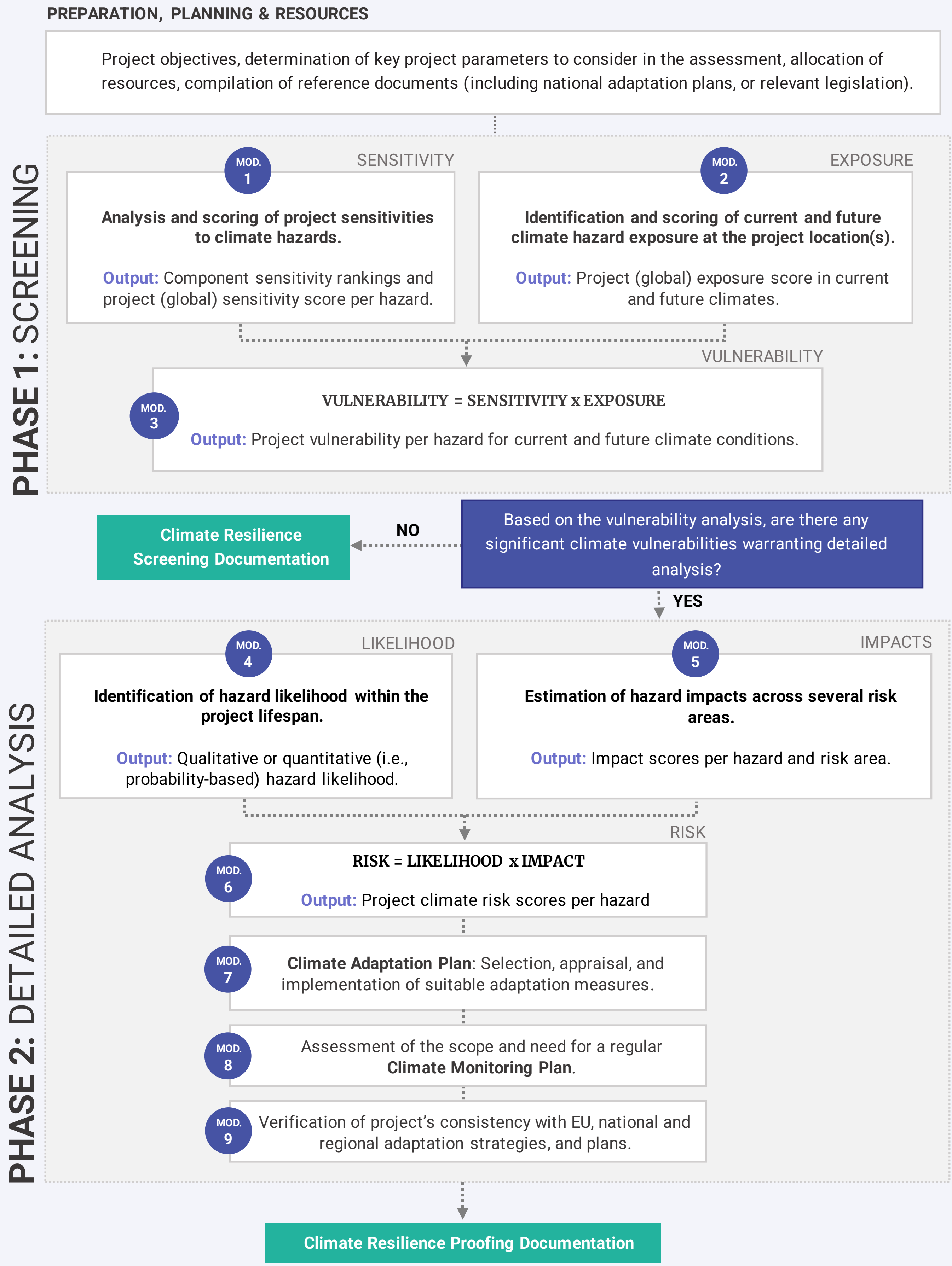

FIGURE 1.1 • Summary of the phases of climate resilience proofing as presented in the EC Technical Guidance on the climate proofing of infrastructure in the period 2021-2027.

Preparation, Planning & Resources

Prior to initiating the assessment, the project team will need to identify the project's objectives, determine the key project's parameters and components to include in the assessment, and allocate resources. The sector-specific chapters provide lists of indicative component categories[3] per sub-sector, including infrastructure assets, operational procedures, inputs, outputs, and links with the broader interdependent system along with an indication of their typical lifespan.

Phase 1 • Screening

The analysis in Phase 1 comprises three modules (Modules 1-3): (1) Sensitivity analysis of the project's components (assets and operations) to /relevant climate hazards; (2) Analysis of the current and future exposure to those hazards in the project location(s); and (3) Combination of the results above for the assessment of the project's vulnerability to climate hazards.

Module 1 • Sensitivity Analysis

Irrespective of the planned project location, the aim of this step is to assess the degree to which a type of infrastructure might be affected by a given climate hazard. This step refers to the type of infrastructure only without considering the specificities of the project location. A comprehensive list of climate-hazards to be considered in this process is provided in **Table 1.1** and follows the terminology and categorisation of the EU Taxonomy Climate Delegated Act[4].

[3] The terminology used for the component categories is general and follows EC Technical Guidance. It might be adapted as relevant to the sector/project specifics.
[4] European Commission (2021). Delegated Act 2021/2139, Annex 1, Appendix A – Section II or Annex 2, Appendix A -> Tables with classification of climate-related hazards. The list of climate-related hazards in those table is non-exhaustive, and constitutes only an indicative list of most widespread hazards that are to be taken into account **as a minimum** in the climate risk and vulnerability assessment to be compliant with the EU Taxonomy technical screening criteria.

TABLE 1.1 • List of climate-related hazards. Each hazard is linked to a fundamental climate variable (Temperature, Wind, Water, Solid-mass) and hazard indices are presented indicatively for each hazard[5].

HAZARDS	Temperature-related	Wind-related	Water-related	Solid mass-related
CHRONIC	**Changing temperature (air, freshwater, marine water)** -Annual/seasonal/ monthly/daily average temperatures -Annual number of days with temperature >25^{0}C (or other relevant threshold) -Heating and cooling degree days **Temperature variability** -Maximum and minimum temperature anomaly **Permafrost thawing** -Average/extreme yearly temperature variations -Sub-surface temperature	**Changing wind patterns** -Maximum annual/seasonal/ monthly/daily wind speed -Maximum wind gust speeds per month/year -Number of consecutive days with extreme wind (i.e., speed > 70 mph) per month/year, etc.	**Changing precipitation patterns and types (rain, hail, snow/ice)** -Annual accumulated precipitation -Frequency/duration of rainfall events (e.g., No of days of more than a certain precipitation threshold) **Precipitation or hydrological variability** -Mean precipitation -Annual consecutive dry days **Saline intrusion** -Salinity level -Electrical conductivity -Chloride concentration -Groundwater level **Sea level rise** -Relative sea level rise -Extreme sea level -Proximity to shoreline -Duration of tidal sea-level rise	**Coastal erosion** -Proximity to shoreline -Soil type -Wave height **Soil erosion** -Soil type -Soil inclination -Existence of vegetation
ACUTE	**Heat wave** -Frequency and duration of heat waves -Extreme temperature -Heat index **Cold wave/frost** -Extreme temperature -Freeze index -Duration of cold waves **Wildfire** -Total number of fires per month/year (frequency) -Total land area burned (magnitude) -Age of forest and plantation -Humidity of the area	**Storm (including blizzards, dust and sand- storms)** -Annual and decadal count of windstorms -Number of thunderstorm days/year -Maximum wind speeds -Maximum wind gust speeds -Turbulence intensity -Air quality, dust particle concentrations -Severe Weather Threat Index (SWEAT)6 -Hail size -Duration, hit area **Tornado** -Frequency of tornadoes per month/year -Wind speed **Cyclone, hurricane, typhoon** -Accumulated cyclone energy -Maximum wind speeds	**Drought** -Standardised Precipitation Index -Soil moisture -Groundwater storage -Length of dry period yearly **Heavy precipitation (rain, hail, snow/ice)** -Number of consecutive days with extreme rain -Total precipitation -Snow indicators -Size of hailstone size, mass -Frequency of events per unit of time **Flood (coastal, fluvial, pluvial, ground water)** -Flood depth -Peak water velocity -Maximum 24-h flood volume, -River discharge -Proximity to shoreline -Frequency/duration of flood events	**Avalanche** -Snow depth -Snow density -Temperature -Slope **Landslide** -Soil type -Groundwater level -Precipitation -Soil saturation level - Existence of slip surfaces -Inclination of ground level **Subsidence** -Soil type -Ground surface elevation -Soil plasticity index -Organic matter content

[5] In addition to the hazards listed in the table, other climate-related hazards include glacial lake outburst, heat stress, water stress, ocean acidification, soil degradation, solifluction, increased UV radiation, increasing CO2 concentration (marine waters), decreasing water quality (marine waters, surface water, groundwater), fog or freeze-thaw. Depending on the project's location and infrastructural type the user should extend the hazard list and include all (current and future) hazards that may threaten the project or its interdependent systems.

[6] https://www.weather.gov/lmk/indices

The sensitivity analysis should adopt a comprehensive approach, four themes (i.e., component categories) are considered in line with the EC Technical guidance and as relevant to the specific project.: *on-site assets, operations, inputs/outputs, and interdependent infrastructure***.**

The assignment of sensitivity scores may be conducted in qualitative terms (e.g., no, low, medium, high sensitivity or combined with a numerical score of 0,1,2,3), and it would be best to be undertaken by team members with a technical background on the project assets and processes. The team shall determine the susceptibility of a type of infrastructure (or a component) to experience physical damage or operational disruption when subjected to a climate hazard. Disruptions can either be associated with reduced functionality of the infrastructure itself (i.e., because damaged assets are operating at a sub-standard level), or loss of essential input/outputs and unavailability of interconnected infrastructure that are important for the operation of the infrastructure and the delivery of service. The analysis should be performed for all hazards that may potentially impact the infrastructure. The final result is a **global project sensitivity score** per hazard, considering the highest sensitivity value across the evaluated component categories. **Table 1.2** presents example definitions of sensitivity levels for projects in the energy, transportation, and waste management sectors. The sectoral guides further elaborate on the sensitivity definitions providing indicative sensitivity scoring for all key hazards affecting the examined sectors and sub-sectors.

TABLE 1.2 • Example sensitivity levels for projects in the examined sectors.

Sensitivity Level	Sector		
	Energy	**Transportation**	**Waste Management**
No Sensitivity	The project (or the project component) is not sensitive to the hazard (no damage or operational disruptions are expected).		
Low Sensitivity	**On-site assets** may experience minor damage.	**Assets:** Minor damage may occur to vehicles, and vessels, certain transport infrastructure or supporting infrastructure such as for roads parking facilities or rest stops.	**Assets:** Minor damage may occur to waste collection vehicles, waste equipment or facility.
	Operations: Non-critical assets/operations may temporarily lose functionality, but their repercussions are considered minimal (e.g., loss of a pipeline link that can be easily bypassed).	**Operations:** Non-critical transportation services may experience temporary disruptions with minimal overall impact (e.g. small delays).	**Operations:** Non-critical waste management services may experience temporary disruptions with minimal overall impact.
	Input/Output: Not important effect on the energy production/transmission/ distribution/storage capacity.	**Input/Output:** No significant effect on the overall capacity (vehicles/passengers/traffic flow) and transportation services.	**Input/Output:** No significant effect on the overall waste collection, treatment, or disposal services.
	Interconnections: Insignificant service disruptions of the supporting infrastructure are expected (e.g., water supply network).	**Interconnections:** Insignificant disruptions in supporting systems are expected (e.g., interdependent transport and electricity network or other supply chains).	**Interconnections:** Insignificant disruptions in supporting systems, such as the waste collection or the energy grid supporting the waste facility.
Medium Sensitivity	**Onsite assets** may experience moderate damage.	**Assets**: Moderate damage possible, requiring repairs or maintenance.	**Assets**: Moderate damages are expected, necessitating repairs or maintenance actions.

Sensitivity Level	Sector		
	Energy	**Transportation**	**Waste Management**
	Operations: Reduced functionality (or temporarily shutdown) of some utilities/ processes until inspections are performed.	**Operations:** Some transportation routes or modes may experience reduced functionality or temporary shutdowns for inspections or repairs.	**Operations**: Some waste collection routes, or treatment processes may experience reduced functionality or temporary shutdowns for inspections or repairs.
	Input/Output: Energy production/transmission/ distribution/storage capacity may temporarily decrease.	**Input/Output:** Temporary decreases in transportation capacity may be observed.	**Input/Output:** Temporary decreases in waste collection, treatment, or disposal services may be observed.
	Interconnections: Loss of service of the supporting infrastructure shall be expected affecting non-critical operations of the energy facility.	**Interconnections:** Loss of service in supporting systems, impacting non-critical transportation operations.	**Interconnections:** Loss of service in supporting systems and infrastructure, impacting non-critical waste management services..
High Sensitivity	**On-site** assets including expensive assets/equipment (e.g., turbine generators) may experience major damage or failure.	**Assets**: Major damage or failure of critical transportation assets, such as engine failure or structural damage to key infrastructure.	**Assets**: Major damage or failure of critical waste management assets, such as breakdowns in waste treatment plants or significant damage to waste collection and transport equipment.
High Sensitivity	**Operations:** Major equipment/ utilities cannot operate and several process cannot be performed. The facility may need to completely shutdown until replacements/repairs are performed.	**Operations:** Key transportation services cannot operate, leading to significant disruptions or complete shutdown until repairs or replacements are made.	**Operations**: Key waste management services cannot operate, leading to significant disruptions or complete shutdown until repairs or replacements are made.
High Sensitivity	**Input/Output;** A major decrease in energy production/transmission/ distribution/storage may occur.	**Input/Output:** Major decreases in overall transportation capacity, impacting the ability to transport goods or people.	**Input/Output:** Major decreases in overall waste collection, treatment, or disposal services, impacting the overall waste management service.
High Sensitivity	**Interconnections:** Service disruptions of the supporting infrastructure are impacting energy production (e.g., limited supply of water reduces the energy production capacity of a facility).	**Interconnections:** Severe disruptions in supporting systems severely affecting transportation services (e.g., limited availability of fuel leading to reduced operations of a fleet).	**Interconnections:** Severe disruptions in supporting infrastructure and systems severely affecting waste management services (e.g., closure of roads serving as major waste collection routes).

Module 2 • Exposure Analysis

The aim of the exposure analysis is to examine whether the project's location(s) lies within the threat zone of relevant climate hazards. The following steps describe the process for performing a high-level screening of climate hazards that have the potential to harm the project (or the project's components) in the present time or in future (as climate conditions change). When a type of infrastructure is not sensitive to a climate hazard then that hazard should not be considered in the exposure analysis.

STEP 1

Selection of the exposure analysis temporal and spatial scale.

Climate change can give rise to climate hazards that may not be evident now but become increasingly apparent in the future, thereby it is crucial to consider in the exposure analysis the intended lifespan of the project, which, in the case of infrastructure projects is considerably longer than the economic life. It is recommended to use for the lifespan the definition of the "design working life (DWL)", which is defined in the Eurocodes as the period for which the structure will be used with anticipated maintenance but without major repair. As an example, according to the above definition, the lifespan of buildings is defined as 50 years and of bridges as 100 years.

Based on the above, the temporal scale to be selected for the exposure analysis will need to encompass the whole lifespan of the project, i.e., **the longest lifespan of its infrastructure components**. The outcome of the exposure analysis will need in any case to include the current exposure scenario and one or more future exposure scenarios. For simplification, project components with short lifespans (e.g., < 10 years) do not have to be included in the assessment of future climate conditions. Project components with a service life longer than ten (10) years yet shorter than the infrastructure lifespan should be included in future climate scenarios accordingly.

When selecting the boundaries of the project area to be studied, attention should be paid to infrastructure projects that have assets in multiple locations: the analysis will need to cover both the project's direct location[7] and any other location where interdependent systems may exist, since many climate-related hazards present significant spatial variability. A documented justification on the selection of the spatial boundaries should be included in the climate proofing documentation.

STEP 2

Selection of climate-change scenario(s).

Depending on the **temporal scale**, the team can evaluate future climatic projections through a scenario-based approach. **Scenario-based climate projections**[8] (**Figure 1.2**), are appropriate for medium to longer-term projects (for example, up to 2060 or mid-century, and until the end of the century) to incorporate the higher uncertainty involved in this timeframe. It is the project's team responsibility to decide on the year horizon or on the need to have one or more future time horizons (e.g. to be able to distinguish between short-term and long-term adaptation needs). The following general guidance for the selection of climate scenarios may be followed:

- **Current exposure:** Present-day conditions, historical records, and recent (e.g., last 20 years) trends may be used.
- **Future exposure:** According to the EC Climate Guidance Note, for initial screening-type analyses, it is recommended to use climate projections based on RCP 6.0 (not available in all countries) or RCP 8.5. RCP 4.5 may be more relevant for projects where it is a practical option to increase the level of climate resilience during its lifetime as and when needed (for instance, it may be feasible to increase gradually the height of some flood defence systems). Once SSPs are available at country level then they should be used instead of the RCPs.

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[7] Note that for projects such as T&D networks or offshore wind farms (with assets both off and onshore), the project boundaries might extend significantly beyond those of typical energy generation plants that are cantered around a single location.

[8] Climate projections are commonly based on the Representative Concentration Pathways (RCPs) or the Shared Socioeconomic Pathways (SSPs). The RCPs (adopted in IPCC AR5) represent different levels of radiative forcing by the end of the century (namely, RCP2.6, RCP4.5, RCP6.0, RCP8.5). The SSPs (adopted in IPCC AR6), refined the RCP framework by considering five alternative scenarios (namely, SSP1, SSP2, SSP3, SSP4, SSP5) with different emissions and land-use changes for the 21st century. RCPs are the ones that should be used in the analysis if SSPs are not currently available at country level.

> **NOTE:**
>
> Selecting climate projections is the responsibility of the project promoter together with the climate-proofing manager and technical specialists. It should be seen as an integrated part of project risk management. National guidance and rules must also be followed.

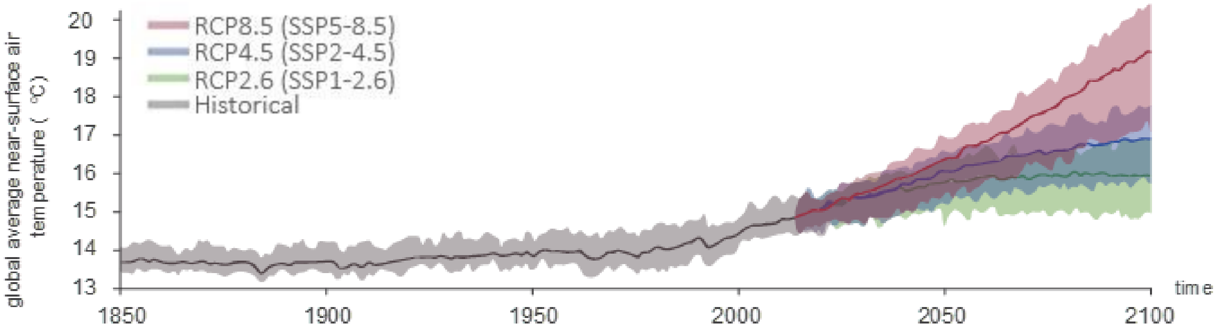

FIGURE 1.2 • Coupled Model Intercomparison Project (CMIP6) annual global average temperature (1850 – 2100) [Source: Copernicus]

STEP 3

Compilation of climate data/information per hazard.

For the hazards with low, medium or high sensitivity identified in the sensitivity analysis, the project team shall determine the exposure of the project location to that hazard at the present and in the future. Historic reviews of climate data, desk studies on past events, climate incidents at the broader project area, local knowledge and experience, and targeted consultations with climate experts and engineers may facilitate the overall materiality screening of the climate hazards and inform the current climate exposure scenario. For the future trends and future variability of the hazards, the team should use climate projections that are suitable for the temporal and spatial scale of the project (as concluded in Step 2). Data source include:

(1) National Climate Atlases (available in 17 of the 32 EEA member countries) that contain geospatial country-specific projections of several climate variables and Regional Climate Models (RCMs)[9].

(2) Climate Databases (such as the Copernicus Climate Change Portal, the IPCC WGI Interactive Atlas) that describe broader climate trends deduced at continent or sub-continent level using Global Climate Models (GCMs)[10] - which provide lower resolution information with respect to the RCMs (**Figure 1.3**) and should be used only in the case that National Climate data is not available.

(3) ClimateAdapt[11] or the Climate Change World Bank Portal that both contain country-level projections of essential climate variables computed for different RCPs.

(4) Recent national/regional/local adaptation plans/strategies.

(5) Project-specific analyses e.g., climate analyses performed for other projects at the broader area or region of the location of interest.

(6) Broader European or National official studies and European projects focused on climate change[12].

A comprehensive list of existing sources and the type of information each one contains may be found in **Box 1.1**.

[9] Typical resolution of 10-50km.
[10] Typical resolution of 100-500 km.
[11] https://climate-adapt.eea.europa.eu/
[12] Many Member States have already undertaken national or regional climate impacts and vulnerability analyses (EEA Report No 1/2018) • The 2018 study on 'Climate change adaptation of major infrastructure projects - A stock-taking of available resources to assist the development of climate resilient infrastructure' undertaken for European Commission DG REGIO, includes credible national sources of climate change information, data and projections for Member States • The EU Horizon projects on climate resilience may also include useful regional climate information, e.g., CLAIRCITY, ICARUS, NATURE4CITIES, GROWGREEN, CLARITY, CLIMATE-FITCITY, etc. • The 2013 JRC scientific and policy report 'Overview of Disaster Risks that the EU faces' published by the European Commission Joint Research Centre presents information from existing JRC projects and databases covering the main natural hazards that affect the Member States.

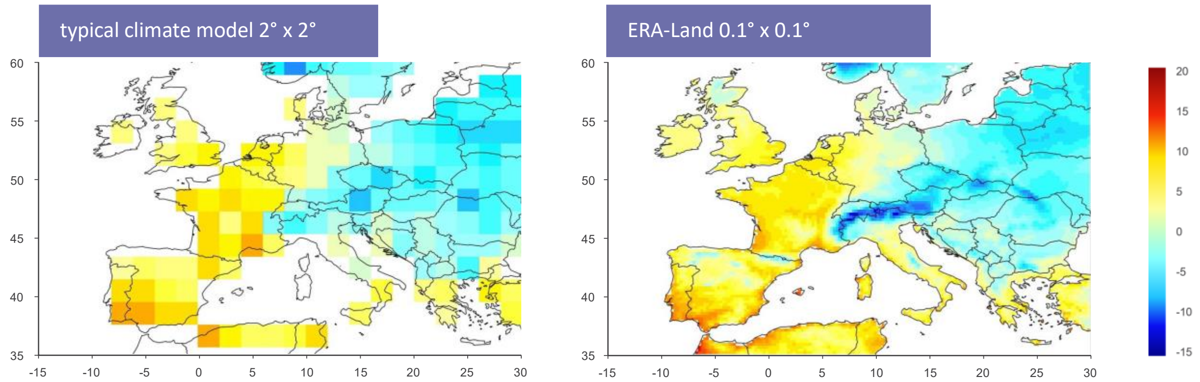

FIGURE 1.3 • Resolution enhancement between GCM and RCM for daily surface temperature [Source: Copernicus].

STEP 4 **Classification of exposure at the project location vis-a-vis current and future hazards.** The step commences with a systematic documentation of the climate data resources (output of Step 3) for each examined hazard, followed by a clear definition of exposure thresholds using qualitative descriptors. The analysis shall consider both acute and chronic relevant hazards. Example exposure thresholds are provided in **Table 1.3**, but it is the responsibility of the project team to set-up an exposure scoring system as they seem fit.

The next task is to characterise the **current hazard exposure** at the project site (Low, Medium, High). The exposure collectively describes the potential of a hazard to be experienced in the project location. For example, the exposure to flooding from a heavy rainfall will be higher for a project located in a low-lying region and lower for a project located uphill. Similarly, the exposure of a project to avalanche will be higher in a mountainous region. For projects with multiple assets in different locations, the most exposed component should determine the global project exposure score.

For the estimation of **future exposure** (in any of the selected climate scenarios) the team will need to obtain climate projections of relevant/available variables and indicators from available datasets – refer to **Table 1.1** for guidance on selecting the appropriate indicator. The climate projections will be used to determine whether the hazard future trajectory is stable, increasing, decreasing (and what is the rate of anticipated change), and based on that, to appropriately adjust the current exposure level to best describe the future trends. For example, a foreseeable increase in the mean precipitation could be translated as increased exposure to flooding (with respect to current conditions), or a significant increase in mean annual temperatures may indicate increased exposure to drought.

The analysis output is a global project exposure score which is the maximum from current and future exposure.

TABLE 1.3 • **Example of** qualitative general exposure levels.

Exposure Level	Acute Hazards	Chronic Hazards
No Exposure	The project is located in an area where hazard is (current) or will (future) not be expected to occur.	No significant change (with respect to present) is expected.
Low Exposure	The project is located in an area where hazard has occurred (current exposure) or expected to occur (future exposure) once in 25 years.	The rate of change is low. The change may be observable within a time horizon of 100 years (which exceeds the timeframe of the assessment and hence will not affect the project).

Medium Exposure	The project is located in an area where hazard has occurred (current exposure) or expected to occur (future exposure) twice in 10 years.	The rate of change is moderate. Observing a notable change within a time horizon of 50-years is considered probable.
High Exposure	The project is located in an area where hazard has occurred (current exposure) or expected to occur (future exposure) a number of times in five years.	The rate of change is rapid. A significant change is expected within a time horizon of 50-years or shorter.

Module 3 • Vulnerability Analysis

The vulnerability assessment forms the basis for the decision to continue to the risk assessment of Phase 2. The sensitivity and exposure analysis outputs are combined in this stage according to the equation:

VULNERABILITY = SENSITIVITY x EXPOSURE

The analysis employs the **global project sensitivity & exposure scores** per hazard and assigns the multiplication result in relevant matrices, denoting low, medium, or high vulnerability in accordance with the indicative scale provided in **Table 1.4**. Example calculations: Low x Low = **Low** | Low x Medium = **Medium** | Low x High = **Medium** | Medium x High = **High**.

Hazards for which the project has zero global sensitivity or zero global exposure are not included in the assessment. **It is recommended that climate hazards with 'medium' or 'high' vulnerability scores are forwarded to Phase 2** for a detailed assessment. The decision should be based on the informed judgement of the project promoter and the climate assessment team, considering also the 'acceptable' level of risk for the project of interest. In case the assessment concludes that all project vulnerabilities are low or zero, Phase 2 may be omitted.

TABLE 1.4 • Example vulnerability table with indicative vulnerability score scale.

Indicative vulnerability table		**Global exposure (current and future climate)**		
		Low	**Medium**	**High**
Sensitivity (global project sensitivity across the four themes)	**Low**			
	Medium			
	High			

Vulnerability Score	Low	Medium	High
Description	**Acute hazards:** The project may experience no or minor damages that can be quickly restored; The incurred cost and loss of functionality may be rather insignificant with respect to budgeted values/financial model. **For chronic hazards:** The climate-related O&M cost is not likely to increase, or the revenues are not likely to decline– with respect to projected values/assumptions made in the project's financial model. **Phase 2** (Detailed analysis) would probably not be required[13].	**Acute hazards:** Damage shall be expected to the project and the project components. Restoration to full functionality may last a few days. The incurred cost and loss of functionality may be moderate with respect to budgeted values/financial model. **For chronic hazards**: The climate-related O&M cost is likely to increase moderately or the revenues are likely to decline moderately – with respect to projected values/assumptions made in the project's financial model. **Phase 2** is recommended.	**Acute hazards**: The project may experience excessive damage or complete failure. The operations of the facility will be severely impacted or cancelled for an indeterminate amount of time. The recovery process is expected to be slow and costly. The incurred cost and loss of functionality may be significant with respect to budgeted values/assumptions made in the project's financial model. **For chronic hazards:** A significant increase in the climate-related O&M cost or decline of revenues is deemed likely (associated with rapid deterioration of structural materials, increased cost or unavailability of supplies (e.g., cost of energy) - with respect to projected values/assumptions made in the project's financial model. **Phase 2** is recommended.

Climate Resilience Screening Output

If the assessment is not entering Phase 2, the project team should compile the screening analysis results into a **Climate Resilience Screening Documentation**, which will ultimately serve as a reference document for the climate proofing of the project. This will would present the process and assessments performed for the project, as per above Phase 1. For specific instructions on the expected contents of such documentation, readers are referred to Annex B of the EC Technical Guidance and any relevant National climate proofing guidance. The readers should check their National climate proofing guidance (if available) for any specific requirements.

[13] depending on the project team preferences for minimum acceptable residual risk.

BOX 1.1

Climate Hazard Data Sources

Source	Description
EEA provides an overview of the national and transnational climate atlases in Europe.	National atlases contain spatially explicit information on past and projected climate change (including for different climate variables and/or hazards). Those national climate change forecasts sources might represent a first relevant reference before considering other more elaborate resources.
Websites of the national meteorological institutes and meteorological national platforms. EUMETNET provides an overview of the National Meteorological Services in Europe.	The websites and platforms of the national meteorological institutes usually provide a wide range of climate data, including real-time, past and forecast data, in situ and radar observations, numerical weather models, climate forecasts, etc. The type and resolution of the available data depend on each country.
• Copernicus Climate Change Service • Copernicus Climate Data Store, • Copernicus Atmosphere Monitoring Service, Copernicus Marine Environment Monitoring Service, • Copernicus Land Monitoring Service, • Copernicus Security Service, • Copernicus Emergency Management Service	The Copernicus Climate Change Service (C3S) provides information on historical, current, and projected climate conditions both in Europe and globally through its Copernicus Climate Data Store (CDS). The Copernicus monitoring services may provide useful data complementing C3S.
DRMKC - Risk Data Hub developed by the European Commission	A GIS web platform of European wide risk data and methodologies for disaster risk assessment at national and European level (including natural hazard information).
WCRP CORDEX EURO-CORDEX developed by the World Climate Research Program	The Coordinated Regional Climate Downscaling Experiment is a framework aimed at addressing climate information needs at the regional level. EURO-CORDEX is the European branch of the CORDEX initiative and will produce ensemble climate simulations based on multiple dynamical and empirical-statistical downscaling models forced by multiple global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5).
Flood Risk Area Viewer (europa.eu)	The Flood Risk Area Viewer, created by the European Commission in collaboration with the European Environment Agency, offers a tool to increase awareness about flood risks. Users can observe regions of potentially significant flood risk, as identified by individual Member States under the Floods Directive. The viewer showcases the varying approaches of countries, such as including or excluding existing flood protection measures, emphasising the unique contexts of each Member State.
The European Draught Risk Atlas	The European Drought Risk Atlas offers a detailed exploration of drought hazards across Europe, shedding light on their impacts on agriculture, public water supply, energy, and ecosystems. Through conceptual models and advanced machine learning techniques, it illustrates the complex interactions between drought hazard factors. This atlas provides crucial insights into sub-national level risks
Urban Adaptation Map Viewer (arcgis.com)	The Urban Adaptation Map Viewer by the European Environment Agency, focuses on illustrating current and future climate hazards confronting European cities, emphasising their vulnerability and adaptive capacity. It compiles data from diverse sources to display the spatial distribution and intensity of high temperatures, flooding, water scarcity, wildfires, and vector-borne diseases. This tool also highlights the adaptation planning and actions undertaken by European cities in response.
Climate Change Knowledge Portal (CCKP) developed by the World Bank Group	The CCKP offers global data encompassing historical and projected climate information through country profiles and watershed views.

Source	Description
KNMI Climate Explorer KNMI Climate Change Atlas developed by KNMI	The KNMI Climate Explorer is a web application that offers statistical climate data. It includes multiple tools such as the Climate Change Atlas that gives the possibility to plot climate model output for a variety or regions, seasons and variables.
WorldClim	WorldClim is a database of high spatial resolution global weather and climate data. It includes climate data for historical and future conditions for four different SSP scenarios.
IPCC WGI Interactive Atlas developed by the Intergovernmental Panel on Climate Change Working Group I	The Interactive Atlas provides regional climatic information based on the 6th Assessment Report of Working Group I (AR6-WGI). It includes trends and changes in important atmospheric and oceanic variables, extreme indexes, and climate impact drivers, e.g., temperature, sea level rise, sea ice, etc.
Aqueduct developed by WRI	Aqueduct's tools use open-source, peer reviewed data to map water risks such as floods and droughts.
Global Solar Atlas developed by the World Bank Group	The Global Solar Atlas offers global, regional, and country-level access to solar resource and photovoltaic power potential data. It provides long-term yearly averages of PV Electricity Output, Global Horizontal Irradiation, Diffuse Horizontal Irradiation, Direct Normal Irradiation, and Air Temperature at a height of two meters.
Global Wind Atlas developed by the World Bank Group	The Global Wind Atlas enables online access to downloadable datasets and high-resolution maps of wind resource potential. It offers data on wind speed, wind power density, topography, orography, land use roughness length, and bathymetry.
Think Hazard	The ThinkHazard tool, developed by the World Bank Group. offers an overview of natural hazards to consider in project planning for enhanced disaster and climate resilience. It assesses the likelihood of various hazards impacting project sites—ranging from very low to high—and offers guidance on mitigation strategies and additional information sources.
Climate Analytics Tools	Climate Analytics offers user-friendly tools focusing on climate hazards and impacts. Some useful examples include: the Climate Impact Explorer tool that shows how climate change effects will worsen over time across continents, countries, and provinces with different levels of warming, the Local Sea Level Rise tool that visualises projected sea level rises worldwide (based on local projections), helping users understand and prepare for the hazardous impacts of climate change, and the Climate risk dashboard that explores future impacts from climate change for countries, cities, and more.

Phase 2 • Detailed Analysis

Phase 2 provides a systematic approach for a more in-depth analysis of climate hazards that may pose significant vulnerabilities to the project of interest, as these are identified during the initial screening process. The hazard likelihood and potential severity of impacts on the project and its wider environment are evaluated, culminating in the assessment of risk significance for the project's success. Phase 2 concludes with guidance on the selection and evaluation of climate adaptation measures to mitigate the identified risks, suggestions for climate change monitoring in case of residual risk and information on data sources that may assist the verification of the project's consistency with EU, national, or regional adaptation plans and strategies. The phase encompasses six modules, namely: Module 4: Likelihood analysis; Module 5: Impact analysis; Module 6: Climate risk analysis; Module 7: Selection and appraisal of adaptation options; Module 8: Monitoring plans; and Module 9: Verification of consistency with EU, national, or regional adaptation plans and strategies.

Module 4 • Likelihood Analysis

The likelihood analysis examines how often, or if, an identified climate hazard is expected to happen at the project location within a specified timeframe, i.e., the lifespan of the project. For chronic hazards the likelihood analysis examines the probability of experiencing a projected change of a given range within the same timeframe. The output of the likelihood analysis may be summarised in a qualitative (i.e., with descriptive terms) or quantitative manner (i.e., based on probabilities). For qualitative assessment, it is sufficient to consider the likelihood of experiencing the maximum possible hazard in the region of interest (without differentiating between hazards of different intensity levels). For quantitative assessments (typically performed within a probabilistic framework), hazard events of different intensity shall be specified and associated with a probability of occurrence. In any case it is advisable to perform the likelihood analysis while considering a realistically wide range of future scenarios to avoid overlooking events that may seem unlikely under current climatic conditions but may become more probable in the future (as the climate conditions change).

For the case of acute hazards, Table 1.5 provides an example of a simplified likelihood scale, describing the likelihood of an event as its probability of occurrence (for example: an extreme snowfall in a Mediterranean region would probably be characterised as highly unlikely, but it could be possible in northern Europe). The project team is encouraged to define or adopt an alternative likelihood scale that better aligns with the specificities of the project.

TABLE 1.5 • Example general likelihood levels for acute hazards.

Level	Score	Qualitative	Probability of occurrence
Rare	1	Highly unlikely	0-10 %
Unlikely	2	Unlikely	11-30 %
Moderate	3	Possible	31-60 %
Likely	4	Likely	61-90 %
Almost certain	5	Very likely	91-100 %

For the case of chronic hazards, likelihood is not related to the probability of occurrence of single events (of specific intensity) but rather to the probability of observing changes in the mean values of climate stressors in the longer term. Hence, their likelihood may be correlated with the variation of the available climate projection scenarios (RPCs or SSPs) and/or the level of confidence of the employed data. For example, assume that an analysis is conducted for a period of n years, at the end of which, a 0.1m sea-level rise at the project location is forecasted in all examined RCP scenarios. Same studies demonstrate a 0.5m increase in sea-level in the RCP 8.5 which is not confirmed in the case of RCP6.0 and RCP4.5. Following the likelihood definition for chronic hazards provided above, the 0.1m sea level rise prediction would receive a high likelihood score, while that of a 0.5m sea-level would score lower in the likelihood scale.

BOX 1.2

Assigning likelihoods to future climate trends

Climate change will strongly affect not only the intensity of the hazards but also the frequency of extreme incidents. For instance, an extreme event that may be characterised as rare under the current climate conditions may become more likely in the future if harsh climate projections prevail. As of today, there is no consensus on the scientific approach to be adopted for associating a climate change projection with a specific probability of occurrence[14]. It is therefore recommended to resort to expert judgement to assist the assessment of likelihoods. Simplified guidance for assessing likelihoods is provided in IPCC[15] which correlates the confidence level of a finding (e.g., low confidence level) with a quantitative expression of likelihood (e.g., x% probability of the finding occurring).

For smaller projects, the team can follow a qualitative assessment similar to that described below.

STEP 1 Obtain climate projections of relevant/available variables and indicators from climate datasets – refer to **Table 1.1** for guidance on selecting the appropriate indicator.

STEP 2 For the representative indicator determine the level of anticipated change and the trajectory of change (stable, increasing, decreasing), and based on this define a climate change multiplier. Multipliers are proposed below as an example on how this can be "operationalised" when undertaking the assessments*. Nevertheless, those are not the ones that anyone needs to use neither of relevance for every project*.

Hazard indicator	Decreasing trend		Increasing trend	
	Low change	High change	Low change	High change
Climate Change Multiplier[16]	0.95	0.8	1.5	2.5

STEP 3 Combine the climate change multiplier with the current likelihood score (defined in **Table 1.5**) to estimate the future likelihood score for the specific hazard (see demonstration example of **Table 1.11**).

It is unavoidable that the estimation of likelihood involves **inherent uncertainty**, especially when considering an assessment timeframe that extends into the distant future, where the impacts of climate change have yet to fully unfold. As uncertainty increases substantially, it may become useful to employ advanced methods (e.g., ensemble regional climate modelling, downscaling climate data, scenario-based planning[17]) and involve the expertise of climate professionals, to assess and score the hazards' likelihood. If the resources at this stage are not sufficient to reduce the uncertainty and increase the confidence[18] of the available climate data, a conservative approach should be adopted when scoring the hazard's likelihood and documented accordingly[19]. More resources, tools, and guidance on how to communicate and how to factor uncertainty involved in climate change adaptation is provided in the

[14] due to the short time interval of available time-series and the lack of statistical data for making robust statistical correlations.
[15] IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, Chapter 1, p. 75, https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/05_SROCC_Ch01_FINAL.pdf.
[16] The definition of the climate change multipliers lies in the discretion and the responsibility of the project team. The proposed range is indicative and should not be adopted without examining the specific climate conditions at the project location.
[17] This information may be already available at national/regional climate platforms and data sources.
[18] Based on IPCC, confidence grows with more robust evidence and higher scientific consensus. Robust evidence relies on multiple, consistent, and independent high-quality research sources while greater consensus stems from well-established scientific evidence rather than competing or speculative findings.
[19] Such documentation may become very useful when determining the appropriate adaptation approach, as the degree of uncertainty may be an important criterion on the decision-making. For instance, in scenarios with very high uncertainty, it may be prudent to opt for a flexible adaptation plan. This approach involves implementing a structured monitoring system (Module 8) that continually updates the adaptation strategy and triggers specific adaptation measures as needed, rather than committing to costly resilience solutions from the project's outset that may prove unnecessary in the future.

Climate-ADAPT Uncertainty Guidance[20] or on national platforms when these are available (e.g. National Climate Atlases).

Module 5 • Impact Analysis

The impact assessment deals with the consequences of a hazard across several risk areas (RA) related to: the **direct & indirect impacts** stemming from damage to physical assets and/or operational disruptions (RA1) which can be directly linked with financial losses for the project (RA5), and (b) **cascading hazard impacts** concerning health & safety issues, socioeconomic, environmental, and cultural considerations, and reputational risks (RA2-RA4 and RA5 to RA7). Impacts per examined hazard and risk area could be ranked on a magnitude scale of 1-5, based on either qualitative or quantitative scoring criteria, similar to those presented in **Table 1.6**. If required, the project team may identify a group of stakeholders with expert knowledge to assist with the process.

The quantification of financial impacts (RA5) could incorporate two major cost categories: (a) the *direct costs* for repair and re-instatement of assets following a shock (including material costs, inspections, labour costs, project procurement, cost of installation/removal of temporary measures); (b) the increase in *O&M costs* due to augmented needs for preventive and reactive actions related to chronic climate stressors (e.g. due to faster corrosion, higher salinity, etc.) , and (c) the *indirect costs* stemming from reduced operations and/or downtime as a function of the disruption duration (i.e., the number of days the facility is out of service or underperforming). The quantitative assessment of cascading impacts is not straightforward, due to the high complexity and scale of the systems involved. To this end, it is recommended that the project team follows a qualitative scoring system as the example shown in **Table 1.6**. Although there is no strict requirement to conduct an impact assessment for all risk areas, it is advisable that the project team undertakes at least a high-level evaluation to ensure that no potential risk is overlooked during the early stages of the project.

The analysis should involve assessments for both current and future climate scenarios, for the relevant risk areas (RA). The outcome should be expressed in terms of **global impact score per hazard and selected climate scenario(s)**, assuming the highest score amongst the RAs examined (see the example in **Table 1.7**).

TABLE 1.6 • Example scoring principles for the impact of climate hazards across various risk areas (RA1 – RA7)[21]- largely adopted from the EC Technical Guidance.

Risk Areas (RA)	Impact Magnitude				
	1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
RA1: Asset damage/ Engineering/ Operational	**Qualitative:** The impact can be absorbed through normal activity, with potential slight damages to components and no consequences to the project's operations. **Quantitative:** -Asset damage <5% of total	**Qualitative:** An adverse event that can be absorbed by taking business continuity actions (e.g., by ensuring the availability of redundancies) and has minor consequences to the project's operations. **Quantitative:**	**Qualitative:** A serious event that requires additional emergency business continuity actions and has moderate consequences to the project's operations. **Quantitative:** -Asset damage 10-25% of total	**Qualitative:** A critical event that requires extraordinary business continuity actions and has significant consequences to the project's operations. **Quantitative:** -Asset damage 25-50% of total reconstruction cost	**Qualitative:** Disaster with the potential to lead to shut down, collapse or loss of the asset/network. **Quantitative:** -Asset damage >50% of total reconstruction cost -Recovery time is indefinite.

[20] https://climate-adapt.eea.europa.eu/knowledge/tools/uncertainty-guidance

[21] The ratings and values are illustrative and are largely adopted from EC's 'Technical guidance on the climate proofing of infrastructure in the period 2021 - 2027 (2021). The project promoter and project team may choose to modify them according to the specificities of the project under assessment.

Risk Areas (RA)	Impact Magnitude				
	1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
	reconstruction cost -Immediate Recovery is possible	-Asset damage 5-10% of total reconstruction cost -Recovery is possible within a few (e.g. 1-2) days	reconstruction cost -Recovery is possible within several (e.g. 5-10) days	-Recovery process is slow (e.g. 20-100 days)	
RA2: Safety & Health	First aid case.	Minor injury, medical treatment.	Serious injury or lost work.	Major/multiple injuries, permanent injury, or disability.	Single or multiple fatalities.
RA3: Environment	No impact on baseline environment. Localised in the source area. No recovery required.	Localised within site boundaries. Recovery measurable within one month of impact.	Moderate harm with possible wider effect. Recovery in one year.	Significant harm with local effect. Recovery longer than one year. Failure to comply with environmental regulations.	Significant harm with widespread effect. Recovery longer than one year.
RA4: Social	No negative social impact.	Localised temporary social impacts.	Localised, long-term social impacts.	Failure to protect poor vulnerable groups. National, long-term social impacts.	Loss of social licence to operate. Community protests.
RA5: Financial impacts	Direct and indirect costs are < 2% of the annual turnover.	Direct and indirect costs are < 2-10% of the annual turnover.	Direct and indirect costs are < 10-25% of the annual turnover.	Direct and indirect costs are < 25-50% of the annual turnover of the facility.	Direct and indirect costs are > 50% of the annual turnover.
RA6: Reputation	Localised, temporary impact on public opinion.	Localised, short-term impact on public opinion.	Local, long-term impact on public opinion with adverse local media coverage.	National, short-term impact on public opinion, negative national media coverage.	National, long-term impact with potential to affect the stability of the government.
RA7: Cultural heritage and cultural premises	Insignificant impact.	Short term impact. Possible recovery or repair.	Serious damage with wider impact to tourism industry.	Significant damage with national and international impact.	Permanent loss with resulting impact on society.

TABLE 1.7 • Example qualitative impact analysis for flood hazard considering different climate scenarios in a fictitious project location[22].

Flood			
Climate Scenario	**Current Climate**	**Future Projection (RCP 4.5)**	**Future Projection (RCP 8.5)**
RA1: Asset damage/ Engineering/ Operational	2	4	5
RA2: Safety and Health	1	2	3
RA3: Environment	2	2	3
RA4: Social	2	3	4
RA5: Cascading financial impacts	1	3	5
RA6: Reputation	1	2	4
RA7: Cultural heritage and cultural premises	1	1	2
Global impact score (without criticality)	**2** (Low)	**4** (Major)	**5** (Catastrophic)

Incorporation of project criticality in the impacts assessment

Although not compulsory, it is recommended that the impact analysis factors in the criticality of the project, i.e., a hazard-agnostic property describing how fundamental the infrastructure is to the wider 'ecosystem'[23]. In case this is not already available from infrastructure managers, such assessment may be informed by a number of parameters, indicatively including the number of affected populations in case of failures, existence of redundancies, cascading effects to interconnected infrastructure components, importance in the supply chain, etc. Examples of *sector-specific criteria for the energy, transport and waste management sectors are provided in sectoral chapters*.

The assignment of criticality scores may be conducted in accordance with the levels provided in **Table 1.8**, spanning from very low (1) to very high (5). Once defined, the criticality score can be used as a weighting factor to calculate **global impact score** per hazard. The attained criticality-weighted global impact score would hence receive values in a scale from 1 – 25 (**Table 1.9**).

TABLE 1.8 • Suggested criticality levels (refer to sector-specific guidance for the description of each level).

Criticality Level	**Very low**	**Low**	**Moderate**	**High**	**Very high**
Score	**1**	**2**	**3**	**4**	**5**
	The project does not constitute an important component for the community and surrounding ecosystem.	A failure of the project would create manageable disruption to the community.	Failure of the project creates disruption which would propagate to the surrounding ecosystem.	Failure of the project could hinder the operation of the surrounding ecosystem for a considerable time.	The project is fundamental for the surrounding ecosystem and its failure would result in catastrophic consequences.

[22] This example shows impact analysis for two climate scenarios (RCP 4.5 and 8.5) but it should be noted that in many cases (particularly for small projects with short lifespan) only one future scenario might be selected and assessed.
[23] The term 'ecosystem' refers to the integration and interdependencies of socio-economic, environmental and infrastructure systems in a region.

TABLE 1.9 • Suggested criticality-weighted impact magnitude scale.

Impact Level	Insignificant	Minor	Moderate	Major	Catastrophic
Score	1-4	5-9	10-14	15-19	20-25

Module 6 • Climate Risk Analysis

Having assessed the likelihood and impacts of each hazard, the significance level of each potential risk can be estimated by combining the two factors as follows:

RISK = LIKELIHOOD x IMPACT

Based on the risk classes suggested in **Table 1.10**, a risk matrix per climate scenario may be used for the representation (**Table 1.11**). **The estimated risk level will be the maximum value stemming from the 'Likelihood x Impact' combination.** The results of the analysis will aid users in identifying the most significant risks where adaptation measures may need to be implemented. The project team may choose to amend the definition of risk classes provided in **Table 1.10**, providing sufficient justification. In any case, the implications of each risk class should be clearly described (e.g., extreme risks must be prioritised for mitigation measures, moderate risk must be monitored etc.), to reflect the comfortable level of risk for the project.

For critical projects, risks marked as 'high' or 'extreme' may in some cases require a more elaborate risk assessment. An additional detailed risk assessment will be typically undertaken by specialists (e.g., engineers), will incorporate technical project details, and involve in-depth quantitative analyses that make use of climate impact and/or numerical models (e.g., hydrological, flood risk models, etc.) that describe the response of specific project elements. Depending on the risk level considered acceptable by the project promoter (e.g., in cases where a low-risk acceptance criterion has been defined during the planning stage) 'medium' risks could also qualify for additional detailed assessment.

TABLE 1.10 • Suggested risk classes.

Risk Class	Insignificant	Low	Medium	High	Extreme
Description	No adaptation measures will be required.	Risk should be monitored throughout the project lifespan.	Adaptation measures may be required, but risk monitoring could also be sufficient.	Adaptation measures must be implemented.	Significant adaptation measures must be implemented and are in priority.
Score	1-2	3-6	7-10	11-16	17-25
Criticality-weighted Score	1-10	11-30	31-50	51-80	81-125

TABLE 1.11 • Example risk calculations and risk matrix for flood hazard (per climate scenario).

Hypothetical Hazard: Flood[24]			
Climate Scenario	**Current Climate**	**Future Projection (RCP 4.5)**	**Future Projection (RCP 8.5)**
Likelihood score	2	3 = (2 x 1.5)	5 = (2 x 2.5)
Global criticality-weighted impact score	18	18	18
Risk score	36 (Medium)	54 (High)	90 (Extreme)
Overall risk	**Extreme** (90)		

FLOOD RISK MATRIX		**GLOBAL IMPACT MAGNITUDE**				
		Insignificant 1-5	**Minor 6-10**	**Moderate 11-15**	**Major 16-20**	**Catastrophic 21-25**
HAZARD LIKELIHOOD	**1- Rare**					
	2 -Unlikely				Current climate	
	3 -Moderate				RCP 4.5	
	4- Likely					
	5- Almost certain				RCP 8.5	

Module 7 • Selection & Appraisal of Adaptation Options

If Module 6 concludes that there are significant climate risks for the project, these should be reduced to an acceptable level by employing targeted adaptation measures (including identification of existing in-built project resilience and/or existing operational measures).

STEP 1

Selection of adaptation measures.

The selected solutions should be in line with the available technical and financial resources for the project, and may comprise hard-engineering (e.g., in-built resilience and/or structural measures), soft-engineering (e.g., monitoring and early warning systems), and operational measures (e.g., closing/limiting the service under certain conditions). For some hazard categories, adaptation measures may also include Nature-based Solutions (NbS) which employ natural processes/materials to mitigate risks, while delivering several socio-environmental benefits. Indicative examples of NbS for flood protection include the restoration of wetlands for flood protection or mangrove planting for mitigating the impacts of storm surge in coastal areas. Despite their huge potential and the growing interest, the concept is still new, and not yet streamlined in the current design.

Based on the nature of the selected adaptation options, these may have the following results in terms of risk management: (a) **Risk reduction** (i.e., reduction of the potential consequences), (b) **Risk sharing** (e.g., via insurance mechanisms), or (c) **Risk aversion** (e.g., change of project location).

The sector-specific chapters of the present document provide long-lists of indicative adaptation options for the energy, transportation, and waste management sectors, with specific guidance regarding the timing of their implementation. It is recommended to come up with an initial list of potential adaptation measures to be further evaluated in the ensuing.

The following (general) guidance applies to all hazards and sectors:

[24] A hypothetical precipitation intensity of 500mm has been chosen for the example. Note that this intensity event is assumed to be unlikely under current climate conditions; however, due to climate change (considering RCP 4.5 and 8.5) the frequency of such an event is increasing, hence the increased likelihood. Hypothetical climate change multipliers, 1.5 for the RCP4.5 and 2.5 for the RCP8.5 scenario have been assumed.

- For **'low risk' scenarios**, the project team may choose to accept the risk without any adaptation action and monitor the evolution of climate variables to decide whether adaptation actions may be needed at a later project stage (refer to Module 8 for further details on monitoring plans).
- If the **external risks** stemming from damages in interdependent systems are significant, the project team should mobilise a *'Risk Sharing Mechanism'* to transfer the loss, e.g., an insurance scheme. The procedure typically takes places in the O&M stage, after construction has been completed and the insurance premium can be calculated based on the existing climate residual risk.
- For **projects with long lifespans**, the project team should carefully select measures that will perform well under conditions of high hazard uncertainty to avoid maladaptation (**Box 1.3**). More specifically, the project team can initially opt for a robust approach up to the time that future climate projections align across the various climate change scenarios and show minimal variations. However, when the climate projections under different scenarios begin to diverge significantly, the project team should consider two distinct strategies:
    - They can adopt a flexible and adaptive approach, contingent upon a carefully crafted monitoring plan. This approach allows for the implementation of adaptation measures based on ongoing monitoring and assessment of the changing climate conditions. A precondition for this strategy is that that the project's design and planning possess have been outlined with inherent flexibility, i.e., the project is able to increase its resilience during its lifespan and adapt to possible future climate shifts (for example, the availability of reserve adaptation funds has been ensured, or contracts have been put in place to allow expansion of the project area for the development of additional defences).
    - Alternatively, when a flexible approach is not feasible, the project team may choose to proceed with the immediate implementation of adaptation measures that can mitigate the climate-related risks in the event of a worst-case projection. In this case the resilience level of the project is increased in advance, ensuring that the project remains resilient and responsive to the emerging challenges without additional adjustments.

BOX 1.3

Adaptation options under conditions of uncertainty

- **'No regret'/'Low regret' solutions**: Measures that are cost-effective now and provide relatively large benefits under a range of future climate scenarios. For example: project relocation, monitoring options, or development of contingency plans.
- **'Win-win' solutions**: Measures that contribute to the mitigation of hazard risks, but also create significant co-benefits (e.g., socioeconomic, or environmental), such as NbS.
- **Structural Upgrading**: Measures that typically come with significant CAPEX yet allow a project to perform satisfactorily and remain resilient under both current and future climate conditions.
- **Flexible/adaptive solutions**: Measures that facilitate easy future upgrades or modifications as conditions demand. For example, rather than locking into a single worst-case climate change scenario and investing in large-scale flood defences for a coastal project, it would be preferable to design a modular defence structure that can be easily raised/widened when the sea level rises above a pre-determined threshold.

STEP 2

Appraisal of adaptation alternatives.
The most appropriate adaptation solutions may be selected on the basis of their cost-effectiveness (in case it is relevant/needed to compare different measures for the specific project). In very critical projects, it may be necessary to compare a number of plausible alternatives using a robust appraisal methodology that will assess their economic soundness in conjunction with their capacity to reduce risks to the maximum acceptable level. Indicatively:

Cost-Benefit Analysis (CBA)[25] is particularly pertinent when potential losses from the hazard in question can be quantified. Throughout this process, the project team should monetise and integrate all pertinent costs and benefits into the analysis, including: (a) the CAPEX of the adaptation solution; (b) O&M costs; (c) direct adaptation benefits, which entail the mitigation of physical and operational damage resulting from solution implementation in both current and future climates; and (d) potential co-benefits (e.g. in transport, time savings for users which would be suffering traffic disruptions in case of hazards occurrence and related operational costs savings).

In situations where it is challenging to monetise benefits linked to an adaptation solution (e.g., social benefits), **Multi-Criteria Analysis (MCA)** can offer a comprehensive assessment approach. MCA captures the wide-ranging advantages of different adaptation strategies using qualitative criteria such as: (a) the level of risk reduction (under both current and future climates); (b) the relative cost; (c) the adaptive capacity of the intervention (can the option be modified to incorporate a range of plausible climate change futures); (d) the risk of maladaptation in the face of uncertainty; (e) the compatibility with existing planning initiatives and stakeholders objectives; (f) the solution's implementation timeframe; or (g) other co-benefits, such as the contribution to the increase of system competitiveness or the mitigation of GHG emissions.

STEP 3

Implementation of the adaptation plan.

The reasoning behind the selection of adaptation measures and the extent of risk reduction over the project's lifespan should be documented in the project's adaptation plan. When applicable, particularly in situations of high climate uncertainty, the plan ought to specify the timeline for subsequent climate risk assessments and outline a monitoring plan to support and validate decisions concerning future adaptation measures (see Module 8 for details on such plans). It should be noted that it is essential to ensure that the identified adaptation measures are integrated into further project development stages.

Adaptation strategies that will be implemented at the onset of the project should be advanced for detailed design, engaging engineering experts to consider both current and projected climate scenarios during the Design Phase. For adaptive/flexible strategies, the necessary actions for a seamless, phased adaptation in the future must be clearly documented, specifying the parties responsible and the timeline for their implementation.

Module 8 • Monitoring Plans

The project team should establish a plan to consistently monitor pertinent climate variables and the assets' condition and create alerts once critical thresholds are met. This is particularly relevant to projects that significant residual climate risks persist after implementation of the adaptation plan, or in cases where adaptive planning of risk mitigation measures is in place. However, it should be noted that some components of a monitoring plan (e.g. monitoring specific indicators and a registry of climate incidents) are relevant for all projects and they actually represent good practice for climate adaptation.

Such monitoring plans commensurate to the risk, typically comprise three (3) components as briefly described below:

Data collection

This component could indicatively encompass the following attributes (or some of them as most relevant), although it is up to the designer and project operator to set up the most pertinent infrastructure.

- *A set of indicators for relevant climate stressors* (e.g. sea level, temperature, max. precipitation, etc.) that would be systematically monitored to indicate any change in patterns or, in case of adaptive planning, to trigger the implementation of additional adaptation measures (as defined in the relevant plan)
- *Intensity thresholds for climate-related events* (storms, floods, heat, and cold waves – whichever relevant), above which an alarm status might be expected for the network signalling the need for

[25] For further information on the implementation of CBA for the appraisal of climate adaptation solutions, readers are referred to Section 2.3.6. of the European Commission's '[Guidelines for project managers: Making vulnerable investments climate resilient](#) (2013)'.

an operation intervention. Note that the values of such thresholds depend on parameters such as the project design and criticality (e.g. it may be acceptable for a secondary road to remain closed to traffic for 4-5 days following a flooding incident but in case of a primary road this would only be acceptable in case of a very extreme event).

- *Thresholds for the relative change of chronic climate variables* (i.e., permafrost thawing, droughts, or sea level rise), following consultation with experts. Such thresholds could indicatively be linked to the need to update the O&M procedures of the project (to respond to the changing weather patterns) or to proceed with additional adaptation measures in case of an adaptive plan.
- *A registry of climate incidents*, recording the frequency, intensity, and impacts on network's assets. As the events' registry is populated with more data, the latter will eventually provide an empirical basis for potentially modifying the initially set threshold values. The registry should provide as much as relevant data as possible (characteristics of climate hazard, location and time, details on impacts and costs…) and integrated, if possible, on any existing asset management system
- *An asset management platform* for storing, organising, managing and reviewing the collected data (i.e., assets and costs, performance logs, climate time-series etc.) incorporating those from the registry described above. Note that this could be a module of the project's asset management system (if available). The platform should be able to accommodate different types of datasets and file formats. Depending on the level of sophistication, the platform may deploy several technologies including Geographic Information Systems, multi-source information access methods, data fusion and integration, and condition assessment models.

Forecasting and early warning

This component of the monitoring system is meant to be used for predictive purposes in a dual manner:

- **Preventive Maintenance:** Using time series of climate stressors' data and correlating them to the performance of critical components of the asset/project it is possible to derive scenarios (i.e. predict) for the future performance of such components and support the decision-making process regarding the need for upgrading/retrofitting at an early stage, thereby avoiding damage in the future and allowing more efficient planning of resources and prioritization of inspections and/or maintenance actions.
- **Early Warnings:** When fed with real-time hazard data (e.g., storm events), the predictive infrastructure described above could be able to provide rapid condition assessments and potential damage diagnosis of the monitored critical infrastructure in near real-time and issue subsequent alerts (if necessary). Such alerts could indicatively be related to the evacuation of the facility, reduction of production capacity or temporary shutdown of operations in order to protect the equipment, etc.

The benefits of such a system can be summarised as follows:

- Rapid assessment of foundation condition, following a high-impact event
- Optimal response to emergency.
- Reduced reaction time - from days to a matter of hours after an extreme event.
- More efficient organisation of retrofits/rehabilitation.
- Increased reliability of life-long condition estimates, due to model updating.

Performance Assessment and Auditing

The third component is meant to assist the assessment of the effectiveness of the climate proofing strategy/plan and allow the regular auditing of its implementation throughout the project's lifecycle. It is hence most efficiently materialised using climate-adaptation KPIs which measure either the physical (i.e., % of damaged assets, grid failures) and/or operational performance of an infrastructure (i.e., downtime, time to recover functionality, etc.) related to specific climate hazards (and informed by the data gathered as per above). Such KPIs, as appropriate, may:

- correlate the performance of the infrastructure with specific intensity thresholds of the climate event
- include appropriate intensity thresholds for normal and extreme climate-related events
- may be used to assess the handling by infrastructure operators of emergencies
- may be used to incentivise resilience in the operation of the infrastructure or to penalise insufficient implementation of adaptation plans

Table 1.12 provides an indicative and non-exhaustive list of KPIs that can assist project promoters to assess the performance of the climate-proofing actions, differentiating between physical and operational indicators. Note that the quantification of the relevant thresholds should be performed by the project promoters in collaboration with relevant experts to reflect -among others- the project's acceptable risk level, the type of relevant hazards, and the criticality of the project.

Some cutting-edge technologies and informatics systems that may assist the implementation of the monitoring plan are presented in **Box 1.4**.

TABLE 1.12 • Examples of climate related KPIs.

KPI Category	Example Indicators
Impacts & Losses	▪ Climate-related losses (e.g. energy-yield losses, soiling[26] losses, temperature-induced losses) ▪ % of project inundated, % of project covered by snow, % of project affected by debris. ▪ Financial impacts of climate events (including any liabilities of the operator) ▪ Number of climate-related incidents causing disruptions or requiring significant capital mobilization ▪ Number of beneficiaries affected by climate-related disruptions ▪ Number and importance of interconnected infrastructure indirectly affected by the project's downtime due to climate-events ▪ Accidents attributable to climate hazards ▪ Complaints received as a consequence of climate-related disruptions
Disruption & time to recovery	▪ Time to repair physical damage as a function of the damage level ▪ Dispatch and time for spare parts for damaged equipment ▪ Reinstatement time i.e., the time required for the infrastructure to recover a specific level of functionality ▪ Time required for first responders to reach an area affected by an acute event ▪ Frequency of climate-related incidents impacting the operability of infrastructure ▪ Frequency of climate-related incidents causing significant (e.g. more than 12 hours) downtime of the infrastructure or requiring significant capital mobilisation
Preparedness	▪ Frequency of emergency drills ▪ Existence of updated procedures for post-event assessments ▪ Frequency of periodic condition assessments ▪ Frequency of preventive maintenance actions (e.g., anti-icing, anti-snow, anti-erosion) ▪ Density of emergency supply points (e.g. water supply points for firefighting, pumping stations, de-icing equipment, etc.) ▪ Number of emergency vehicles ▪ Number of installed sensors and frequency of calibration

[26] The soiling ratio is defined in the IEC 61724-1 as the "ratio of the actual power output of the PV array under given soiling conditions to the power that would be expected if the PV array were clean and free of soiling" and may be measured with the help of a reference PV module which is kept constantly clean by very frequent cleaning (e.g., daily) or other protective measures.

BOX 1.4

Intelligent informatics systems: Empowering efficiency while supporting resilience

The overarching objective for operators and asset owners is to strike a balance between minimizing operational costs and optimizing performance, while also safeguarding the socioeconomic environment and ecosystem associated with the project. To achieve this goal the implementation of **integrated informatics systems commensurate to risk** is highly recommended. Such systems enable seamless coordination and communication between various stakeholders, streamlining data management, analysis, and decision-making processes.

The **asset monitoring system** is used to detect instances of low performance, identify potential issues and failures, and provide valuable insights for maintenance planning. Asset condition data are obtained from different instruments, such as accelerometers, temperature sensors, or inclinometers.

A robust **data management system** is integral to handling the diverse and extensive datasets generated by asset monitoring and weather monitoring systems. It enables efficient storage, organization, and retrieval of asset condition data, climate variables, and other relevant information. The data management system ensures data integrity, accuracy, and accessibility, allowing for effective analysis, trend identification, and decision-making based on reliable and up-to-date information.

An **early warning system** acts as a proactive mechanism to mitigate risks and prevent potential disruptions in energy projects. By integrating the monitoring of assets' condition and weather data and by employing advanced predictive algorithms, the system can foresee potential damages and disruptions and issue warnings for extreme weather events, or other hazardous conditions. Timely alerts and notifications from the early warning system empower operators and stakeholders to take swift action, implement preventive measures, and ensure the safety, reliability, and continuity of energy generation.

The **weather monitoring system** measures, stores, and exports vast amounts of climate data. Climate variables may be measured on-site through instruments like anemometers (for wind speed and direction), wave radars (for wave heights), barometers (for air pressure), ice sensors (for ice formation), etc. or through remote sensing technologies like LIDAR (for surface mapping), SODAR (for atmospheric conditions), wave radars (for wave characteristics), etc.

Forecasting modelling plays a crucial role in anticipating future conditions and optimizing operational strategies for projects. By utilizing historical data, weather forecasts, and advanced modelling techniques, forecasting models can provide valuable insights into demand patterns, weather-related risks, and system performance. These models enable operators and asset owners to make informed decisions, optimize resource allocation, and maximise the efficiency and reliability of their project.

A **unified control and management system** encompassing business intelligence* consolidates the previously mentioned components into a seamless and cohesive framework. Such systems can be designed to be adaptable and customizable based on the specific equipment configuration, location, and size of the project. By incorporating decision support systems that combine the monitoring of project-specific key performance indicators with a user-friendly interface, the integrated informatics system promotes transparency and facilitates efficient decision-making processes.

*The term **business intelligence** refers to the deployment of innovative technologies such as the Internet of Things (IoT), machine learning, digital twins, smart metering, and virtual reality. These advancements have significantly enhanced the capabilities of informatics systems by assisting in diagnosing present failures, supporting personnel, predicting future failures, and providing accurate estimations of the remaining useful life of assets.

Module 9 • Verification of Project's Consistency with EU, National, or Regional Adaptation Strategies and Plans

The final module checks the alignment of the project with the broader policy landscape on climate adaptation. The module is structured in two steps. The first step summarises the current state of relevant policy for climate change adaptation initiated by the EU and its member countries. The second step verifies the alignment of the project with the overarching goals of the EU climate adaptation agenda and the relevant country-specific pledges.

STEP 1

Identify relevant strategies and plans.

EU STRATEGY ON ADAPTATION TO CLIMATE CHANGE

On 24 February 2021, the European Commission adopted its **new EU Strategy on Adaptation to Climate Change**[27]. The new Strategy outlines the European Union's path toward adapting to the inevitable consequences of climate change and achieving climate resilience by 2050. The Strategy centres around four primary objectives: making adaptation smarter, faster, more systemic, and stepping up international action for climate resilience. These four objectives form the basis to enhance, update and develop further the guidelines in the national adaptation strategies and plans (described in the following) of the Member States.

NATIONAL, REGIONAL OR LOCAL ADAPTATION STRATEGIES AND PLANS

National Adaptation Strategies & Plans (NAS/NAP), Adaptation Action Plans (AAPs) comprise frameworks that aim to integrate climate change adaptation into national planning to reduce vulnerability to the impacts of climate change by building adaptive capacity and resilience and facilitate the integration of climate change adaptation (in particular, development strategies, plans, and budgets) into new and existing national, sub-national, and sectoral policies, programs, and activities[28]. Users are referred to the ClimateADAPT[29] country profiles which provide information about National and sub-national adaptation strategies and plans. At regional and local level, regions and cities could have adaptation strategies and action plans. For example, those cities that are signatories to the Covenant of Mayors[30]:

STEP 2

Assessment of consistency.

The main question that needs to be answered in this step is if the project is compatible with the country's resilient development pathway as this is described in its National and, as relevant, regional or local adaptation strategies and plans.

The project promoters need to check the National Adaptation Plan/Strategy and verify whether the project is in line with its goals and the country's resilient development pathway. They should also check whether the NAS/NAP include any specific provisions for the sector that the project belongs to. These could include strategies to reduce exposure and mitigate risks through climate adaptation and resilience actions as the ones thoroughly described in the present guidance document.

Climate Resilience Proofing Output

The project team should compile the analysis results (Phase 1 & Phase 2) into a **Climate Resilience Proofing Documentation**. For specific instructions on the expected document contents, readers are referred to Annex B of the EC Technical Guidance and any relevant National climate proofing guidance. The climate resilience documentation could be either integrated in existing project documents (e.g. EIA study or feasibility study) or be a separate document. The readers should check their National climate proofing guidance (if available) for any specific requirements.

[27] Full Document: EUR-Lex - 52021DC0082 - EN - EUR-Lex (europa.eu)
[28] https://www.unep.org/explore-topics/climate-action/what-we-do/climate-adaptation/national-adaptation-plans
[29] Country Profiles — English (europa.eu)
[30] Covenant of Mayors - Europe | Covenant of Mayors - Europe (europa.eu)

2. Energy Sector Guidance

Introduction

Climate change presents a dual challenge for the energy sector, associated not only with the need to mitigate greenhouse gas (GHG) emissions, but also with the imperative to be resilient to the physical impacts of climate-induced hazards. Such impacts caused (among others) by rising temperatures, escalating water constraints, and/or increasingly frequent extreme weather events, threaten energy security worldwide and have potential implications for all major components of the energy value chain: input, generation, transmission, and supply.

For the operators or owners of energy infrastructure (including generation plants, transmission and distribution networks, and storage systems), climate change may result in considerable direct losses due to asset damage. More significantly, however, it may translate to large-scale operational losses due to substantial reductions in energy production. Additional impacts may include environmental effects (e.g., flooded substation equipment can leak insulating fluids, oils, or other pollutants into the soil and water), social disputes (e.g., conflicts in water requirements of a hydrogen electrolyser plant and the neighbouring communities during periods of drought) and ripple financial impacts related to the disruption of regional supply chains due to power outages and the rising costs for customers.

In light of this, the present chapter expands on the EC Technical Guidance for climate proofing of infrastructure (outlined in the **Introductory Chapter**), delving into the specific considerations required for climate resilience assessments within the Energy Sector. The chapter covers projects in six energy sub-sectors:

- Electricity Transmission & Distribution (T&D) networks
- Wind farms (onshore/offshore)
- Solar parks (PV)
- District Heating (DH) - networks and biomass-based heat generation
- Green hydrogen (H2) electrolysers
- Battery Energy Storage Systems (BESS)

The relevant climate hazards (chronic or acute) potentially affecting each sub-sector are listed in **Table 2.1**. The color-coded marks (No sensitivity-Low-Medium-High)[31] indicate the general sensitivity level of each subsector when considering typical infrastructure. These marks are only supposed to work as a general indication and do not necessarily reflect the relevance of the hazards to the project's specificities. It is important to note that the project promoter should extend the hazard list if necessary and consider any – potentially affecting – site- or project-specific hazards that may not mentioned in **Table 2.1** but still relevant for the project. The scoring levels to be applied in each Module should be adjusted by the project promoter depending on the project characteristics and the site's specificities.

Note that the timescale for the climate vulnerability and risk assessment should correspond to the intended lifespan of the investment being financed under the project. The lifespan is often (considerably) longer than the reference period used in the cost-benefit analysis.

[31] Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of the general sensitivity scores.

TABLE 2.1 • Relevant climate hazards affecting the examined energy sub-sectors[32].

Hazards (in accordance with the EU Taxonomy, refer to Table 1.1 of the Introductory Chapter)	Sub-sector					
	Electricity T&D	**Wind farms (onshore/ offshore)**	**Solar parks (PV)**	**Biomass-based DH systems**	**Green H_2 electrolysers**	**BESS**
CHRONIC						
Changing temperatures/ Temperature variability						
Permafrost thawing						
Changing wind patterns						
Changing precipitation patterns/ Precipitation or hydrological variability[33]			34			
Sea level rise Saline intrusion		(offshore)				
Coastal erosion/ Soil erosion						
ACUTE						
Heat wave						
Cold wave/frost						
Wildfire		(onshore)				
Extreme wind (including storm, hurricane, tornado)						
Drought					35	
Flood/Storm surge/ Heavy precipitation						
Landslide/Avalanche/ Subsidence						

Preparation, Planning & Resources

Project Characteristics

Tables 2.2-2.7 provide lists of indicative components that could be included in the climate assessment analysis for the energy projects examined herein[36]. The final component list for each project needs to

[32] The proposed No sensitivity-Low-Medium-High scoring levels are intended for a typical energy project; however, it is advisable for the project team to verify and/or review their relevance to the project and its specific context and adjust them accordingly.
[33] These hazards refer to the chronic changes in the average precipitation, the frequency of rainfall events, the duration and onset of rainy season. Extreme precipitation is covered in the acute hazard of heavy precipitation.
[34] Increased cloudiness, which is particularly relevant for solar parks, is reflected here through the increase (change) in precipitation.
[35] Water stress, which is particularly relevant for green H_2 electrolysers, is reflected here through the hazard of drought.
[36] The terminology used for the component categories is indicative and may vary from sub-sector to sub-sector as appropriate.

be defined by the project team based on project specificities. The typical lifespan[37] of tangible infrastructure assets is also listed on the tables[38]. As observed, infrastructure components may have varying lifespans. In the ensuing, the selected temporal scale of the exposure analysis should aim to encompass the whole physical life of the project (i.e., the longest lifespan of its main infrastructure components)[39]. It is noted that electricity T&D networks and their associated components are treated as separate projects; however, when transmission units constitute an integral part of the project (e.g., underwater transmission cables in the case of offshore wind farms), these are also mentioned under the relevant project category.

TABLE 2.2 • Indicative key **T&D network** components to be included in the climate resilience assessment.

Component category	Assets/Operations (non-exhaustive list)	Typical lifespan (years)[38]
On-site assets	▪ Transformers & substations	30-50
	▪ Transmission towers	40-60
	▪ Overhead lines	50-70
	▪ Underground cables	40-60
	▪ Equipment: conductors, insulators, circuit breakers, switchgear, metering systems etc.	10-25
On-site processes	▪ Voltage transformation ▪ Maintenance & repair ▪ Network monitoring, management & control (e.g., monitoring the flow of electricity throughout the network to meet demand, manage load, regulate frequency, and prevent failures, fault detection and management to minimise outages) ▪ Metering & billing	-
Inputs	▪ Electricity (Power generation facilities)	-
Outputs	▪ Electricity	-
Interconnected systems (outside the direct control of the project)	▪ Access roads ▪ Storage (BEES) ▪ Electricity power consumption/demand	-

[37] It is proposed to define the lifespan as the design working life (DWL), i.e., as the period for which the structure/equipment will be used with anticipated maintenance but without major repair.
[38] Values are indicative and may differ depending on project characteristics as appropriate. The actual lifetime of assets depends on material, regional context, economic conditions, procurement processes, etc. As such, a quite wide range is observed in the tables. It is noted that lifespan is of particular relevance for defining adaptation measures as result of risk analysis.
[39] Not all components of an infrastructure project need to be assessed for the same (long) lifespan. For example, electrical equipment (such as switchgears) will be replaced as part of regular maintenance more often than the transmission towers in a T&D network.

TABLE 2.3 • Indicative key **wind farm** components to be included in the climate resilience assessment.

Component category	Assets/Operations (non-exhaustive list)	Typical lifespan (years)[38]
On-site assets	▪ Turbine tower	20-30
	▪ Rotor-nacelle assembly (rotor blades, hub, and nacelle)	20-25
	▪ Nacelle mechanical & electrical equipment (gearbox, generator, controller, etc.	20-25
	▪ Support structure/foundation	25-30
	▪ Mechanical equipment of monitoring & control systems (e.g., for the adjustment of blades or for shutting down turbines in case wind speeds exceed safe operational thresholds)	15-20
	▪ Transmission lines that carry electricity from the wind farm to the grid (underwater cables in the case of offshore wind farms)	25-40
	▪ Offshore substation (collects the electricity generated by offshore wind turbines and steps-up voltage prior to transmission to the onshore grid connection point)	25-30
	▪ Onshore facilities to assist offshore wind farm operations (onshore substation, O&M facilities, facilities for the manufacturing or assembly of components)	30-40
On-site processes	▪ Energy generation ▪ Monitoring & control ▪ Maintenance & repair ▪ Environmental monitoring activities to assess and mitigate the impact on ecosystems ▪ Land management activities (onshore wind farms), e.g., managing vegetation around turbines	-
Inputs	▪ Wind	-
Output	▪ Electricity	-
Interconnected systems (outside the direct control of the project)	▪ Access roads for land-based wind farms ▪ T&D grid ▪ Energy consumption/demand	-

TABLE 2.4 • Indicative key **solar park** components to be included in the climate resilience assessment.

Component category	Assets/Operations (non-exhaustive list)	Typical lifespan (years)[38]
On-site assets	▪ PV panels	20-30
	▪ Mounting racks	20-30
	▪ Inverters	10-25
	▪ Batteries [if relevant]	10-15
	▪ Mechanical control systems & electrical equipment (e.g., to connect the individual panels to each other and to the inverters)	20-25
	▪ Transformers	25-30
	▪ Assisting buildings: Control rooms, maintenance/storage facilities	15-50
On-site processes	▪ Energy generation ▪ Maintenance & repair ▪ Energy storage management [if relevant] ▪ Monitoring & control ▪ Land management activities (e.g., vegetation control)	-
Inputs	▪ Sunlight, Water	-
Output	▪ Electricity	-
Interconnected systems (outside the direct control of the project)	▪ Access roads ▪ T&D grid ▪ Energy consumption/demand	-

TABLE 2.5 • Indicative key components of **biomass-based district heating systems** to be included in the climate resilience assessment.

Component category	Assets/Operations (non-exhaustive list)	Typical lifespan (years)[38]
On-site assets	▪ Boilers, condensers, and heat exchanger	15-30
	▪ Flue gas cleaning systems	15-25
	▪ Ash handling systems	20-30
	▪ Biomass storage facilities	20-30
	▪ Heat storage tanks	20-40
	▪ Heat distribution network (typically underground pipes)	30-50
	▪ Control systems (boiler control systems, fire control systems, etc.)	10-20
On-site processes	▪ Thermal energy generation ▪ Maintenance & repair ▪ Monitoring ▪ Fuel storage & management (managing biomass volume, prevent damage to the storage, etc.)	-
Inputs	▪ Biomass (wood chips, pellets, etc.) ▪ Water	-
Output	▪ Heat	-
Interconnected systems (outside the direct control of the project)	▪ Biomass fuel supply chain (including access roads/railways & transport vehicles) ▪ Energy consumption/demand	-

TABLE 2.6 • Indicative key components of **green H2 Electrolysers** to be included in the climate resilience assessment.

Component category	Assets/Operations (non-exhaustive list)	Typical lifespan (years)[38]
On-site assets	▪ Electrolyser units	10-20
	▪ Hydrogen storage facilities	20-40
	▪ Water purification systems	10-20
	▪ Cooling systems	15-25
	▪ Power electronics (converters, inverters, etc.)	15-25
	▪ Control systems (for managing operation conditions, start/stop procedures, etc.)	10-20
On-site processes	▪ Hydrogen production ▪ Maintenance & repair ▪ Monitoring & control ▪ Water purification	-
Inputs	▪ Electricity (from renewable sources) ▪ Water	-
Output	▪ Green hydrogen ▪ Oxygen (a by-product that can be vented or used) ▪ Heat	-
Interconnected systems (outside the direct control of the project)	▪ Power grid ▪ Water supply ▪ Hydrogen transport infrastructure (pipelines, trucks, etc.) ▪ Energy consumption/demand	-

TABLE 2.7 • Indicative key **BESS** components to be included in the climate resilience assessment.

Component category	Assets/Operations (non-exhaustive list)	Typical lifespan (years)[38]
On-site assets	▪ Battery modules (including multiple battery cells)	5-15
	▪ Racking and mounting	15-25
	▪ Cabling and electrical components (wiring, circuit breakers, fuses, disconnect switches)	15-25
	▪ Inverter/Converter	10-20
	▪ Monitoring and control system (including thermal management, fire suppression system and other safety systems)	10-20
On-site processes	▪ Maintenance & repair ▪ Monitoring & control	-
Inputs	▪ Electricity	-
Output	▪ Electricity	-
Interconnected systems (outside the direct control of the project)	▪ Power grid ▪ Energy consumption/demand	-

Project Criticality

In the energy sector, a project's criticality may be assessed based on its **role in regional energy supply/ distribution/storage and the existence of sufficient redundancies** (see also the Critical Entities Resilience Directive[40]). Indicative criticality levels (in qualitative terms) are suggested in **Table 2.8**.

TABLE 2.8 • Indicative criticality levels for projects in the energy sector.

Criticality Level	Description
Very low criticality	Very low` contribution in regional energy production/supply/distribution/storage
Low criticality	Low contribution in regional energy production/supply/distribution/storage. Redundancies/back-up systems exist allowing continuation of operations.
Moderate criticality	Considerable contribution in regional energy production/supply/distribution/storage. Above 50% operability can be achieved if the system operates with available redundancies/back-up systems/ inputs.
High criticality	Significant contribution in regional energy production/supply/distribution/storage. Reduced operability can be achieved when the (limited) available redundancies/back-up systems/inputs are used. The risk of a generalised system shutdown cannot be excluded.
Very high criticality	Major contribution in regional energy production/supply/distribution/storage. No redundancies exist or the system cannot operate using the available redundancies/back -up systems/inputs.

2.1 Electricity T&D Networks

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of T&D networks to climate hazards are provided in **Table 2.9** along with indicative scores per component category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.1** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical T&D infrastructure under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities[41]. Potential sensitivities of connecting power facilities (which may eventually impact a project's input) are dependent on the type of generation facility, and therefore, cannot receive a standard score in the table below. For example, low water availability combined with high water temperatures may limit the electricity generation provided by hydropower plants but will not affect a solar park. The project team should score this component category based on project specifics.

[40] Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC: Member States will have to identify the critical entities for the secto rs set out in the CER Directive by 17 July 2026. They will use this list of essential services to carry out risk assessments and to th en identify the critical entities.

[41] For example, if a T&D network is designed with a fully underground cable grid, its sensitivity to cold waves is significantly reduced.

TABLE 2.9 • Sensitivities of T&D network components.

<table>
<tr><th>Climate Hazard</th><th colspan="4">Sensitivities</th></tr>
<tr><td>Extreme wind (including storm, lightning, hurricane, tornado)</td><td colspan="4">• Physical damage on transformers, overhead lines, and connection equipment (insulators, earth wire and phase conductors) due to lightning-induced electricity voltage spikes. Lightnings may also ignite bushfires, leading to further physical infrastructure damage.
• Extreme wind conditions may cause physical damage on transmission towers and poles (assets are blown over) and overhead transmission lines due to flying debris or falling tree branches.
• Windy and stormy conditions may slow repair and maintenance due to safety issues and difficulties in accessing assets (e.g., due to blockages of access roads).
• Physical damage on the grid may lead to sudden (and potentially lengthy) power outages (i.e., loss of electricity).</td></tr>
<tr><td>Global Score: High</td><td>On-site assets & processes</td><td>Inputs</td><td>Outputs</td><td>Interdependent systems</td></tr>
<tr><td>Flood
Storm surge
Heavy precipitation</td><td colspan="4">• Ground-located T&D assets (e.g., substations, transformers, and circuit breakers), critical IT systems and electrical instrumentation are physically damaged by inundation. Subsequent repairs may be costly and time-consuming.
• Heavy rainfall that causes flash flooding can result in mudslides and soil erosion, exposing underground transmission cables.
• Water ingress may cause faults to steel structures, fittings, conductors, and earth wires, leading to power outages.
• Flooding can disrupt access for maintenance and repair, resulting in increased operational costs and lengthy supply outages.</td></tr>
<tr><td>Global Score: High</td><td>On-site assets & processes</td><td>Inputs</td><td>Outputs</td><td>Interdependent systems</td></tr>
<tr><td>Wildfire</td><td colspan="4">▪ Wildfires may inflict damage to all physical infrastructure of a T&D network, and especially to overhead lines and conductors located in remote areas, susceptible to fires.
▪ Physical damage may lead to power outages.
• Access roads may become inaccessible during a wildfire event, inhibiting repairs works on the network.</td></tr>
<tr><td>Global Score: High</td><td>On-site assets & processes</td><td>Inputs</td><td>Outputs</td><td>Interdependent systems</td></tr>
<tr><td>Heat wave</td><td colspan="4">• Extreme temperatures may cause thermal expansion of conductors, sagging of overhead lines, and overheat of transformers. They also cause soils to dry, reducing their ability to conduct heat away from underground cables, leading to cables overheating. Dry soils also increase the risk of ground movements, which may damage underground cables and joints.
• Operating a higher temperatures over sustained periods may accelerate asset degradation and shorten the lifespan of the equipment, thus leading to increased operational costs. For example, empirical studies on transformer lifespans have found that an increase of 7°C in the hotspot temperature (a 30°C ambient temperature can correspond to a 120°C hotspot temperature) can double the aging acceleration factor[42].
• Increased temperatures may result in the de-rating of equipment for lines and substations, and, hence, to the reduction of network capacity. In general, it has been shown that the average power output decreases 0.7% to 1% per 1°C increase in air temperature above a reference temperature (usually taken to be 20°C)[43].</td></tr>
</table>

[42] Dumas, M., Kc, B., & Cunliff, C. I. (2019). Extreme weather and climate vulnerabilities of the electric grid: A summary of environmental sensitivity quantification methods (No. ORNL/TM-2019/1252). Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States).

[43] Martikainen, A., Pykälä, M. L., & Farin, J. (2007). Recognizing climate change in electricity network design and construction. Espoo. VTT Research Notes, 2419.

	• Extreme temperatures increase demand for air-conditioning and ventilation units, which may overload network elements (e.g., transformers, switchgear) and lead to burnouts, failures, and loss of supply.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Cold wave (snow, hail, ice)	• Physical damage to overhead lines and transmission towers (due to gravitational loads), leading to power outages. • Reduced access to facilities for repairs, due to access road blockages.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Landslide Avalanche Subsidence	• Physical damages and stability issues to the towers/pylons and critical equipment (substations, transformers, etc.) as well as to the interdependent infrastructure i.e., access roads. • Ground movements may result to foundation issues and stability issues to any structures built on landslide-prone areas (the movement of the structure is amplified by its height). Overhead line structures are more vulnerable to this movement, but it can also impact ground mounted structures such as transformer bases.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing temperatures Temperature variability	• The average power output decreases 0.7% to 1% per 1°C increase in air temperature above a reference temperature (usually taken to be 20°C). Long-term temperature changes may affect the long-term performance of the project. • Higher summer temperatures cause sagging.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Coastal erosion Soil erosion	• Ground movements may cause physical damage to underground network cables and joints, potentially leading to power outages. • Reduced access to facilities for repairs, due to access road blockages.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Permafrost thawing	• Freeze-thaw ground movements may cause physical damage to underground network cables and joints or cause foundation issues to any structures built on this ground.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Drought	• Ground drying and shrinkage may result to foundation issues and movement issues to any structures built on this ground (the movement of the structure is amplified by the height of the structure). Overhead line structures are more vulnerable to this movement, but it can also impact on ground mounted structures such as transformer bases and switch house foundations. • Ground movement caused by drying and shrinkage may exert tensile forces on cables. Whilst cables have an inherent tensile strength, joints in the network are more vulnerable and can fail by being effectively pulled apart. • As moisture in the soil reduces, the soil resistivity increases reducing the effectiveness of network earthing systems. Where earthing design parameters are exceeded, system and public safety issues can arise with reduced touch potential distances, failure to fully dissipate fault current, exposed metal components.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Sea level rise Saline intrusion	• Potential gradual chemical damage to pipe-type cable systems from increased tidal flooding, which will affect asset integrity and could lead to water ingress. • Ingress of saline groundwater may also impact the buoyancy of pipes and cause structural damage, further translated to operational and supply issues.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

T&D networks are distributed systems with significant spatial variability, and therefore, may exhibit variations in hazard exposure depending on the assets' location. Hazard and project component maps should be superimposed to identify the maximum system exposure.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts in combination with the network's criticality, readers are referred to the **Introductory Chapter** (Module 5). To assist users with the scoring procedure, an overview of potentially significant impacts to T&D networks across various risk areas (RA) is provided in the tables below

TABLE 2.10 • Potentially significant climate impacts on T&D networks (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damage to On-Site Infrastructure**: This includes substations, towers, overhead lines, underground cables, and equipment. Such damage, often caused by extreme weather events or chronic stresses, has the potential to lead to asset failures and lengthy power outages.
RA2: Safety and Health	**Fire and Electrocution Impacts**: Overheated equipment within the T&D network can pose fire risks. Damaged power lines increase the risk of electrocution for both personnel and the public. **Drought-Induced Impacts:** Drought conditions can increase soil resistivity, reducing the effectiveness of network earthing systems. This results in public safety issues, including reduced touch potential distances, failure to fully dissipate fault current, and exposed metal components.
RA3: Environment	**Fire Triggers and Habitat Disruption:** Damaged or overheated assets within the T&D network can ignite fires, leading to vegetation loss and habitat destruction. Such incidents can have ecological impacts on local ecosystems. **Pollution:** Damaged substations or equipment can leak insulating fluids, oils, or other pollutants into the soil and water, causing environmental harm. Power outages often lead to the use of backup diesel generators, which emit greenhouse gases and air pollutants. **Wildlife Impacts:** Damaged power lines can increase the risk of electrocution for birds and other wildlife, potentially harming local fauna.
RA4: Social	**Critical Facilities Impact:** Power outages can disrupt operations in critical medical facilities, jeopardising patient care and essential medical services. This has a direct impact on public health and safety. **Vulnerable Populations:** Heat or cold waves, combined with power outages, pose significant risks to vulnerable populations, including the elderly, sick, and very young, who rely on temperature-controlled environments for their well-being.
RA5: Financial impacts	**Increased O&M cost & claims:** The rising cost of repairs/restoration of damaged assets and equipment, the increased maintenance cost (e.g., for the more frequent replacement of weathered spare parts) and possible compensation claims from affected businesses and households (in case of prolonged power outages) may curtail revenues destabilising the financial viability of the T&D operator.
RA6: Reputation	**Customer Trust:** Frequent or prolonged service interruptions can lead to dissatisfaction among customers, eroding trust and confidence in the T&D network. Dissatisfied customers may seek alternative service providers. **Investor Confidence:** Repeated failures, high repair costs, and environmental damages can diminish investor confidence, potentially impacting the network's financial stability and attractiveness to investors.

Module 6: Climate risk assessment

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 2.11 presents potential adaptation solutions to mitigate physical climate risks to electricity grids, if and where required. The suitability of each measure is linked to the encountered level of risk and the uncertainty of climate projections, while the timing of implementation is aligned with specific project stages. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 2.11 • Transmission & Distribution (T&D) networks: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. In any case inform decision-making along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Extreme wind (including storm, lightning, hurricane, tornado)	▪ Move overhead lines underground. ▪ Promote a flexible grid design scheme that allows redundancies into the system by providing rerouting options to avoid loss of supply during times of disruption. ▪ Invest in redundant equipment such as backup power systems or mobile substations that can be quickly deployed to restore power to critical areas in the event of damage to fixed substations.	▪ Design the grid with islanding capabilities that enable segments of the grid to be isolated and powered separately to minimise disruptions. ▪ Install lightning protection (earth wires, spark gaps, lightning rods). ▪ Use covered and/or insulated conductors. ▪ Implement wind-proofing measures for towers/poles (e.g., guy wires).	▪ Employ monitoring systems that will allow assessing climate performance throughout the project's lifetime. If certain thresholds are being surpassed, plan the application of additional engineering measures (e.g., reinforce the transmission towers to withstand higher wind loads). ▪ Proactively switch out specific parts of the network to avoid water ingress causing faults and uncontrolled shutdowns. ▪ Trim trees occasionally to reduce the risk of them falling on power cables.
Flood Storm surge Heavy precipitation	▪ Avoid low-lying and other type of flood-prone areas for the development of the grid network. ▪ Integrate data from flood risk maps into the T&D planning process to identify and avoid vulnerable areas.	▪ Waterproof substations, ensuring that there is sufficient drainage. ▪ Utilise sealed enclosures and watertight connections for sensitive electrical components to prevent water intrusion. ▪ Elevate water-sensitive electrical equipment. ▪ Use wetlands and other natural flood barriers as a flood buffer zone. ▪ Conduct field testing on buried cables and pipelines to assess their resilience to heavy precipitation and floods. ▪ Use flood maps to inform the selection of grid infrastructure locations and land use planning.	▪ Plant/Maintain vegetation along the network track to prevent flood-induced scouring.
Wildfire	▪ Move overhead lines underground. ▪ Avoid constructing critical infrastructure in high-risk wildfire zones. ▪ Invest in mobile substations that can be quickly deployed to restore power to critical areas affected by wildfires.	▪ Use fire-resistant materials for utility poles, insulators, and other critical equipment. These materials are designed to withstand high temperatures and reduce the risk of ignition. ▪ Design the grid with segmentation capabilities, allowing for isolation of affected areas in the event of a wildfire. ▪ Install fire extinguishing systems. ▪ Consider prescribed burns as part of a proactive fire management strategy to reduce fuel buildup in the vicinity of power infrastructure and create	▪ De-energising lines to prevent potential fires. ▪ Develop comprehensive emergency response plans that outline protocols for responding to wildfires, including coordination with firefighting agencies and evacuation plans for staff. ▪ Install remote fire detection and monitoring systems, such as cameras and sensors, to quickly detect and report wildfires in their early stages.

		fuel breaks and managed zones around critical infrastructure, including substations and power lines, to reduce the risk of wildfires spreading.	
Cold wave (snow, hail, ice)	▪ Move overhead lines underground. ▪ For distribution systems and lower-voltage lines adjust the thermal ratings of conductors and equipment for extreme cold temperatures. This allows for more accurate calculations and reduces the risk of overloads during cold waves. ▪ Plan for redundancy in critical grid components, allowing for swift restoration in case of equipment failures during cold waves.	▪ Reinforce poles, towers, and overhead lines to sustain higher/more extreme ice loads. ▪ Design substation buildings with proper insulation and heating systems to maintain operational temperatures. ▪ Install heaters on transformers to prevent the freezing of transformer oil, ensuring they remain operational during cold waves. ▪ Utilise heated enclosures for cable splicing and termination points to prevent ice buildup and maintain connectivity during cold weather.	▪ Obtain timely weather forecasts and combine them with robust emergency response procedures (e.g., rapid de-icing of lines). ▪ Use remote sensing technologies to assess ice and snow accumulation on power lines and substations, enabling timely response and maintenance. ▪ Develop load shedding protocols that can be activated during extreme cold events to reduce the demand on the grid, preventing overloading and ensuring critical loads are maintained. ▪ Establish agreements with local road network operators to guarantee prompt snow clearance in the aftermath of an event, ensuring continuous access to the grid for inspections and repairs.
Landslide **Avalanche** **Subsidence**	▪ Avoid landslide areas and consider project relocation in extreme risks. ▪ Perform a comprehensive geotechnical investigation and conduct a topography survey to assess any stability issues. ▪ Plan for grid redundancy (e.g., isolation of risk-prone areas, plan for mobile substations).	▪ Design and install retaining walls, barriers, or slope and erosion stabilisation measures (e.g., riprap, gabions, etc.) to prevent landslides or erosion from reaching and damaging critical T&D infrastructure. ▪ Implement debris flow diversion structures, such as basins or catchment systems, to redirect debris and sediments away from critical components.	▪ Early warning systems that correlate rainfall intensity with landslide risk (in the case of active landslides. ▪ Install slope movement sensors and monitoring systems that can detect changes in the landscape, such as shifts or erosion.
Changing temperatures Temperature variability	▪ Conduct a comprehensive analysis of historical and projected temperature trends to identify areas susceptible to temperature change.	NA	▪ Implement continuous monitoring systems to assess the efficiency of the project under varying temperature conditions. ▪ Periodically review and adjust maintenance practices based on observed changes in temperature-related impacts. ▪ Establish performance contracts that account for temperature-related variations. Set performance expectations and incentives based on actual project output under different temperature scenarios.
Coastal erosion **Soil erosion**	▪ Avoid erosion prone areas and consider project relocation in extreme risks. ▪ Develop a long-term plan that considers future coastal dynamics and erosion scenarios.	▪ Design and install retaining walls, barriers, or slope and erosion stabilisation measures (e.g., riprap, gabions, etc.).	▪ Early warning systems that monitor the coastline and soil movements. ▪ Implement vegetation and soil conservation programs along the T&D corridors to reduce soil

		▪ Implement flexible and adaptive designs that can accommodate changes in coastal and soil conditions over time.	erosion. Regularly inspect and maintain vegetative cover.
Permafrost thawing	▪ Conduct permafrost surveys and geotechnical investigations to identify the extent of permafrost and its characteristics in the project area. ▪ Avoid building critical infrastructure on unstable permafrost or areas with high thaw susceptibility.	▪ Design foundations and structures with permafrost considerations, using technologies like thermosyphons or thermally insulated foundations to prevent permafrost thaw beneath substations and other critical infrastructure. ▪ Apply cover materials such as gravel or other thermally conductive materials to insulate and protect the permafrost under infrastructure components.	▪ Install permafrost monitoring sensors that track ground temperature and subsurface conditions. Real-time data can help in identifying early signs of thawing. ▪ Implement vegetation management practices to encourage vegetation growth in permafrost areas. Vegetation can act as an insulating layer, reducing the rate of thaw.
Drought	▪ Conduct geotechnical assessments and soil testing during the feasibility stage to identify areas with a high risk of ground drying and shrinkage. Avoid building critical infrastructure in these high-risk zones.	▪ Design foundations to be more resilient to ground movement (e.g., deep foundations and pilings), reducing the impact of ground shrinkage. ▪ Utilise flexible joint designs that can accommodate minor movement without compromising their integrity.	▪ Adopt drought-tolerant landscaping practices around substations and power lines to reduce the need for irrigation and water consumption for vegetation maintenance.
Sea level rise **Saline intrusion**	▪ Prioritise the selection of sites that are at a higher elevation.	▪ Incorporate flood barriers, seawalls, and levees to protect substations, switchgear, and other critical infrastructure from rising sea levels. ▪ Use corrosion-resistant materials for power lines, poles, and equipment to withstand the effects of saline intrusion.	▪ Monitor sea level and act proactively in case of predefined warning thresholds.

2.2 Wind Farms (onshore/offshore)

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of wind farms to climate hazards are provided in **Table 2.12** along with indicative scores per component category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.1** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical wind farm infrastructure (onshore and offshore) under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities.

TABLE 2.12 • Sensitivities of wind farms components.

Climate Hazard	Sensitivities			
Flood Storm surge Heavy precipitation	• Extreme waves introduce severe stressing to the tower and the turbine foundation (which exceed safety limits) – for offshore farms. • Potential foundation scouring creating serious stability issues for the wind-tower. • Physical damage to submerged cables, substations, and interdependent infrastructure (access roads, T&D grid, etc.)			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Wildfire	• Physical damage to onshore wind farm assets and the T&D network affecting power generation and transmission. • Power outages affecting control and communications systems. • Potential facility access restrictions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Cold wave	• Structural damage to blades due to icing. Damaged/broken blades create imbalances and bending of shafts. • Icing (even light icing) reduces the aerodynamic efficiency of blades, which reduces the amount of power the wind-turbine can produce. • Very low temperature may create malfunctions to sensitive E&M equipment. • Faster corrosion of metallic components causing increased maintenance costs. • Temporarily blockage of access/auxiliary roads due to excess snow coverage, obstructing inspections and repairs. • Measurement and control errors.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing wind patterns	• Lower wind speeds resulting in lower wind energy production. • In the opposite case (stronger wind speeds), the business case is rather improved provided the wind farm size can exploit the increased wind energy potential.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Extreme wind (including storm, lightning, hurricane, tornado)	• Severe stressing of turbine blades, tower and foundation. • Mechanical or electrical failures of sensitive E&M equipment. • Physical damage to interconnected infrastructure (including transmission lines and access roads. (in the case of onshore wind farms).			

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems
Landslide Avalanche Subsidence	• Physical damage to onshore wind farm assets and the interconnected infrastructure. • Blockage of access roads due to fallen soil/rock masses. • Landslides and shoulder failures of access roads obstructing inspections and repairs.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Sea level rise Saline intrusion	• Potential physical damage to onshore farms located in coastal areas (typically in the form of permanent foundation deformations/instabilities) as a result of inundation or coastal erosion. • Increased stressing on the wind-turbine as a result of increased wave heights (due to higher sea levels). Possible failure modes: tower tilting, foundation failures.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Permafrost thawing	• Freezing/thawing of the ground is subjecting the turbine foundations to heave or subsidence. • Permafrost thawing increases the coverage of drifting sea ice in polar regions. Ice-loads from drifting sea-ice can be threatening for the stability of the tower.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Heat wave	• Increased temperatures could lead to the failure of electrical equipment and gear boxes. • Heatwaves increase the risk of thermal runway for batteries (i.e., energy leakage in the form of heat), which may result in explosions and/or fires. • Power output undermatching peak energy demand (which increases during heatwaves due to air conditioning and refrigeration) leading to supply shortages.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing temperatures Temperature variability	• Reductions in air density (as a result of increased mean temperature reduce the energy output of the park. • Warmer waters encourage sea life growth (e.g., algae) causing faster corrosion of submerged parts.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Drought	• Dry soil may impact the electrical conductivity of the ground affecting the grounding systems of wind turbines.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Coastal erosion Soil erosion	• Differential foundation settling, affecting the overall stability of the turbine. • Underground cables may become exposed, increased risk of electric shock accidents.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts in combination with the project's criticality, readers are referred to the **Introductory Chapter** (Module 5). Below, an overview of potentially significant impacts to wind farms across various risk areas (RA) is provided, to assist users with the scoring procedure.

TABLE 2.13 • Potentially significant climate impacts on wind farms (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Extensive Physical Damages**: Wind turbines are susceptible to damage from extreme weather conditions such as hurricanes, high winds, and lightning strikes, which can result in operational downtime and increased repair costs. **Turbine Component Wear**: Mechanical components of wind turbines, including gearbox and bearings, are subject to wear and tear over time.
RA2: Safety and Health	**Maintenance and Inspection Risks**: Wind turbine maintenance, repair, and inspection activities may pose safety risks for workers if precautionary measures are not taken to account for all hazards, electrical hazards, and the remote nature of offshore turbines.
RA3: Environment	**Manufacturing of Turbine Components**: The production of wind turbine components, including the manufacturing of blades, towers, and nacelles, contributes to embodied carbon. The energy-intensive processes involved in producing materials such as steel and composites release greenhouse gases, adding to the overall carbon footprint of wind farms and contributing to climate change. **Transportation and Installation**: The transportation of turbine components to construction sites and the subsequent installation involve additional carbon emissions. The logistics of transporting large and heavy components over significant distances contribute to the embodied carbon of wind farms.
RA4: Social	**Energy Accessibility & Social Acceptance**: Communities relying on wind energy may face energy accessibility challenges if turbines experience frequent downtime or failures, impacting energy supply and the overall social acceptance of the wind park. Note that this is quite unlikely in the European interconnected system.
RA5: Financial impacts	**Energy Supply Disruptions:** Wind farm downtime can disrupt energy supply to the grid, leading to potential financial losses for farm owners/operators utilities and energy consumers. **Supply Chain Disruptions:** Delays in component replacements due to failures or extreme weather events can further increase loss of revenues, or maintenance and repair costs.
RA6: Reputation	**Reliability and Safety:** Maintaining a positive reputation relies on demonstrating reliability and safety. Frequent turbine failures, operational downtime, or accidents can damage the reputation of wind farm operators.

Module 6: Climate risk assessment

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 2.14 presents potential adaptation solutions for climate hazards that could impact wind farms. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 2.14 • Wind farms: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. In any case inform decision-making along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Flood Storm surge Heavy precipitation	▪ Perform in-depth flood risk analysis (for current and future climate) during the site selection. ▪ Implement redundancy measures for electrical components (e.g., redundant power distribution units).	▪ Install Cable Protection System (CPS) and scour protection to withstand the hydrodynamic forces and the consequent scouring. ▪ Apply terracing, erosion blankets and drainage on slopingground to mitigate soil movements during heavy precipitation events. ▪ Consider eco-friendly scour protection measures for the foundation of offshore wind-turbines.	▪ Apply erosion protection measures to prevent excessive runoff and water erosion of hillsides (popular locations for onshore wind-turbines). ▪ Protect and restore wetlands to use them as a buffer zone for offshore-wind parks (located at the immediate shoreline). ▪ Restore vegetation to prevent erosion of slopes.
Wildfire	▪ Avoid high-risk wildfire zones.	▪ Install fire extinguishing systems. ▪ Develop fire zoning and proactively manage vegetation (tree trimming and pruning) to reduce fire risk.	▪ Develop comprehensive emergency response plans that outline protocols for responding to wildfires, including coordination with firefighting agencies and evacuation plans for staff). ▪ Apply graduated protection concepts (i.e., turbines can be selectively disconnected from the grid before causing a surge risk). ▪ Install fire detectors and monitoring systems.
Cold wave	NA	▪ Apply anti-icing or de-icing techniques (e.g., active blade heating, passive hydrophobic coating). ▪ Use materials with greater fatigue life.	▪ Install ice sensors and integrate ice detection systems with early warnings.
Changing in wind patterns	▪ Consider project relocation (e.g., migrate to a different site to deeper waters). ▪ Consider possibility of extending the wind park in case of projected increased wind patterns. ▪ Integrate considerations in the business model for lower wind yield due to climate change.	▪ Optimise the wind-farm layout. ▪ Apply aerodynamic design enhancements (advanced blade profiles). ▪ Implement wake steering systems.	▪ Utilise computer control and tracking systems to monitor wind speed/direction and optimise blade orientation.

Extreme wind (including storm, lightning, hurricane, tornado)	▪ Consider project relocation (in case the wind-park is at a tornado hot zone). ▪ Adjust design specifications beyond the code thresholds to increase stability/safety of the wind turbine.	▪ Build offshore breakwaters to reduce surge impacts on wind turbines. ▪ Implement enhanced lightning protection and grounding. ▪ Upgrade/reinforce foundations to withstand increased loading. ▪ Use turbine models of a higher specification than necessary in view of current/historic wind pattern.	▪ Install a weather monitoring system. ▪ Install an early warning system for early detection of extreme wind conditions to prevent wind turbine overspeed or reduce loads. ▪ To reduce the risk of falling branches/uprooting on access roads prefer seasonal timing of tree trimming that avoids disturbance to protected species.
Landslide Avalanche Subsidence	▪ Avoid landslide areas and consider project relocation in extreme risks. ▪ Perform a comprehensive geotechnical investigation to confirm landslide risks.	▪ Implement slope stabilisation measures such as soil nailing and anchoring, retaining walls, etc. ▪ Design effective drainage systems, such as subsurface drains and surface water diversion channels to improve stability conditions of landslide-prone regions. ▪ Design deeper/stronger foundations for wind turbines.	▪ Monitor prone areas to landslides/avalanches/subsidence. ▪ Promote the growth of vegetation, such as grasses, shrubs, and trees, to help stabilise soil and slopes by increasing root strength and improving water absorption.
Sea level rise Saline intrusion	▪ Plan subsea power cables at appropriate depth levels.	▪ Design for increased wave loads and water depths. ▪ Install Cable Protection System (CPS). ▪ Construct wave-absorbing structures around the turbine foundations. ▪ Use anti-corrosive materials and coatings for sensitive metal parts. ▪ Insulation of submerged cables to protect from salt water.	▪ Implement a real time monitoring system to measure displacements and material strains (to early detect fatigue issues). ▪ Increase frequency of maintenance actions.
Permafrost thawing	▪ Conduct geotechnical investigations to map permafrost regions. ▪ Perform risk assessments for thaw settlement hazard.	▪ Incorporate drifting sea ice loads in the design and select appropriate foundation size and type. ▪ For onshore wind-turbines: increase foundation size or mitigate risk of foundation settlements using geotextiles etc.	NA
Heat wave	NA	▪ Apply thermal coatings and thermal insulation to minimise heat stress on critical components. ▪ Implement advanced air conditioning and cooling systems for substations and transformers.	▪ Perform regular maintenance of lubrication systems and proactive repairs.

Changing temperatures Temperature variability	NA	▪ Optimise the geometry of the blade and the tip speed ratio based on the air density.	▪ Increase the frequency of regular maintenance and clearance to mitigate sea life growth (e.g., algae).
Drought	NA	▪ Apply stringent criteria in the design of grounding systems.	▪ Monitor grounding resistance of soil and perform correction actions if deemed necessary. ▪ Implement and maintain vegetative cover along the turbine corridors to reduce soil drying and erosion.
Coastal erosion Soil erosion	▪ Avoid coastal sites and erosion-prone areas.	▪ Increase the trench depth of underground cables.	NA

2.3 Solar Parks (PV)

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of solar parks to climate hazards are provided in **Table 2.15** along with indicative scores per component category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.1** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical solar park infrastructure (Concentrated Solar Power parks and Photovoltaic Parks) under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities.

TABLE 2.15 • Sensitivities of solar park components.

Climate Hazard	Sensitivities			
Extreme wind (including storm, hurricane, tornado)	• Physical damage to the park's components and equipment from wind gusts and flying debris: broken panels, destabilised racking systems, inverter damages/failures. • Damages to transmission and distribution lines, line cascades and risk of prolonged power outages with costly repercussions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Flood Storm surge Heavy precipitation	• Short-circuit damages of the solar panels and other electrical equipment if the site becomes inundated; Cracking and shattering of panels in severe hailstorms. • Damages to transmission and distribution lines, line cascades and risk of prolonged power outages with costly repercussions. • Flooded/inundated access roads obstructing inspections and repairs.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Landslide Avalanche Subsidence	• Solar panels can be heavily damaged by landslides or any sort of massive ground displacements (subsidence, levy collapse, etc). • Damages to the racking systems in case of soil subsidence. • Physical damage to transmission and distribution lines, blockage of access roads (obstructing maintenance operations).			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Wildfire	• Physical damages to the solar park's assets (if directly exposed to fire). • Damages to the interconnected T&D network. • Heavy smoke from wildfires reduces the amount of solar radiation reaching the panels impairing the performance of the solar park.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Drought	• Low-performing cooling systems that rely on water. • Reduced solar power output due to air pollution and panel soiling (which absorb and scatter sunlight). • Rising water usage conflicts may restrict water availability, impacting cleaning and cooling operations and hence the efficiency of the panels.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Cold wave	• Damages on the panels, e.g., cracks (especially when shifting from hot to cold temperatures). • Heavy snow cover can damage panels.			

	• Freezing temperatures and ice may corrode metal components of the inverter causing malfunctions. • Power output reduction due to ice formation on panels.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Sea level rise Saline intrusion	• Temporary or permanent inundation of the park (for coastal facilities) potentially causing electrical malfunctions. • Damages to the racking systems in case of soil subsidence (triggered by increased groundwater level in coastal facilities).			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing precipitation patterns and types (reflecting increased cloudiness)	• Reduced energy power output due to prolonged cloudiness. • Increased dust accumulation (caused by the reduced frequency of natural cleaning with rainwater) reduces the energy output of the park. • Increased requirements for manual cleaning (case of less often rain) increase the O&M cost.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Heat wave	• Power output undermatching peak energy demand (which increases during heatwaves due to increased air conditioning and refrigeration needs). • Significant deviations from optimal temperature[44] reduce performance and energy output. • Prolonged exposure to extreme heat can contribute to material fatigue and degradation, potentially affecting the structural integrity of the solar park			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing temperatures Temperature variability	• Low-performing solar panels[44], produce less energy; energy supply shortages may arise. • Increased cooling demands for solar equipment resulting in increased O&M cost. • Faster degradation of solar panel material resulting in increased O&M cost. • Colder temperatures increase the power output.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Coastal erosion Soil erosion	• Soil erosion increases water run-off and hence the risk of ground movements and landslides impacting the PV panels and the interconnected infrastructure (transmission lines and access roads).			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Permafrost thawing	• Freezing/thawing cycles are subjecting the structures built on the ground to heave or subsidence.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing in wind patterns	• In general, wind reduces the PV module temperature, improving their electrical production. Changes in the wind patterns can be either beneficial or detrimental depending on whether the change is increasing or decreasing.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

[44] The performance of the photovoltaic panels drops by about 0.5% for every 1 °C increase in temperature.

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts in combination with the project's criticality, readers are referred to the **Introductory Chapter** (Module 5). Below, an overview of potentially significant impacts to solar parks across various risk areas (RA) is provided, to assist users with the scoring procedure.

TABLE 2.16 • Potentially significant climate impacts on solar park (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical damage to on-site infrastructure:** This includes PV panels, mounting racks, cabling system, inverters and other relevant critical electrical equipment (e.g., batteries). Damage from extreme weather events or accidents can lead to asset failures, prolonged power supply outages, and increased maintenance costs.
RA2: Safety and Health	--
RA3: Environment	**Deforestation:** Construction of large-scale solar power plants can lead to soil degradation and destruction of vegetation, which may result increase the risk of flooding of the broader region. **Water Resource Concerns:** Water may be required for cleaning solar panels to maintain efficiency. In regions experiencing water scarcity due to climate change, water resource usage for cleaning may raise environmental concerns.
RA4: Social	**Energy Supply Impact:** Power interruptions due to damage or outages in the solar park can affect the overall energy supply of the community. This can impact essential services, including healthcare facilities, water treatment plants, and other community services.
RA5: Financial impacts	**Economic impacts for the Operator:** Increased O&M cost for repairs/replacement of damaged/dysfunction equipment and increased needs for cleaning, Reduced energy output, reduces cash inflows and the economic attractiveness of the investment. **Business and Consumer Losses:** Disruptions in solar energy production can affect downstream businesses and customers who rely on consistent solar-generated electricity. Businesses may face financial losses, and alternative energy sources may be needed, resulting in increased energy costs for consumers.
RA6: Reputation	**Reliability and Trust:** The reputation of solar parks relies on demonstrating reliability and safety. Consistent failures, accidents, or underperformance can erode trust among customers and investors. **Environmental Responsibility:** Commitment to environmental responsibility is vital for maintaining a positive reputation. Accidents or environmental violations can damage an operator's image as an environmentally responsible entity.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 2.17 presents potential adaptation solutions for climate hazards that could impact solar parks. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9)

TABLE 2.17 • Solar parks: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. In any case inform decision-making along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Extreme wind (including storm, hurricane, tornado)	▪ Consider project relocation in case of extreme risk.	▪ Design and construct wind-proofing measures for the panels and the mounting structures to withstand extreme weather. ▪ Install reinforced glass for the panels. ▪ Increase mounting specifications of solar panels to withstand extreme winds. ▪ Install lightning protection (earth wires, spark gaps, lightning rods). ▪ Design a decentralised power generation system to spread the risk (e.g., installation of micro-inverters to each panel). ▪ Apply anti-soiling coatings.	▪ Adjust panel tilt angle to reduce wind load – manual or automatic system. ▪ Proactively switch out critical electrical equipment to avoid water ingress. ▪ Consider disaster clauses in the contractual provisions with the owner of the T&D network (i.e., Public Authority).
Flood Storm surge Heavy precipitation	▪ Avoid flood-prone areas. ▪ Increase battery storage provisions to minimise dependence on grid infrastructure.	▪ Waterproof transformers and wiring. ▪ Elevate water-sensitive electrical equipment.	▪ Proactively switch out critical electrical equipment to avoid water ingress.
Landslide Avalanche Subsidence	▪ Avoid landslide/erosion prone areas. ▪ Perform a comprehensive geotechnical investigation to confirm landslide risks. ▪ Relocate park in case of extreme risks.	▪ Implement slope stabilisation measures such as soil nailing and anchoring, retaining walls, etc. ▪ Design effective drainage systems, such as subsurface drains and surface water diversion channels to improve stability conditions of landslide-prone regions.	▪ Monitor areas that are prone landslides/avalanches/subsidence. ▪ Restore vegetation to mitigate landslide risks.
Wildfire	▪ Avoid high-risk wildfire zones.	▪ Install fire extinguishing systems.	▪ Develop fire zoning and proactively manage vegetation (tree trimming and pruning) to reduce fire risk. ▪ Develop comprehensive emergency response plans, including coordination with firefighting agencies and evacuation plans for staff. ▪ Install fire detectors and monitoring systems.
Drought	▪ Plan for water redundancies (e.g., water tanks) during drought periods. ▪ Explore dry cooling systems that do not rely on water.	NA	▪ Perform more frequent maintenance cleaning to protect panels from soiling. ▪ Adopt drought-tolerant landscaping practices around the solar park to mitigate soiling.

Cold wave	NA	▪ Apply ice-repellent coatings for PV panels to reduce ice-adhesion.	▪ Establish dense rows of bushes or shrubs to act as shelterbelts. ▪ Ensure availability of cleaning equipment to avoid snow piling up.
Sea level rise **Saline intrusion**	▪ Prioritise locations with higher elevation. ▪ Consider project relocation in case of extreme risk.	▪ Increase elevation of critical components. ▪ Elevate levy structures to protect PV panels from inundation. ▪ Use of anti-corrosive materials.	▪ Restore/ maintain coastal vegetation (e.g. salt marshes) to dissipate waves and protect back-lying areas from flooding and erosions.
Changing precipitation patterns and types (including increased cloudiness)	NA	▪ Use PV panels with textured glass and antireflective coatings to capture sunlight from multiple angles (for increased cloudiness). ▪ Use monocrystalline solar panels for higher efficiency in cloudy condition..	▪ Utilise advanced tracking and control system to rotate the panels. ▪ Harvest rainwater for PV cleaning. ▪ Explore manual cleaning alternatives to natural cleaning with rainwater.
Heat wave	▪ Plan for a robust cooling system. ▪ Explore the feasibility of innovative technologies such as nanomaterial coatings for improved panel performance.	▪ Enhance the cooling system of the solar park (e.g., using fans or blowers to circulate air around the panels or using water-based cooling systems such as sprinklers or misting systems). ▪ Use temperature-resistant materials. ▪ Use of heat-resistant cells. ▪ Optimise the design layout (spacing, orientation) to improve air circulation.	▪ Apply automated cooling mechanisms based on real-time temperature readings.
Changing temperatures **Temperature variability**	NA	▪ Enhance the cooling system of the solar park (e.g., using fans or blowers to circulate air around the panels or using water-based cooling systems such as sprinklers or misting systems). ▪ Optimise the design layout (spacing, orientation) to improve air circulation. ▪ Use of air or waterless cooling systems such as passive airflow beneath mounting structures. ▪ Explore innovative technologies for improving PV performance (e.g., micro-mirrors, nanomaterial coatings). ▪ Use temperature-resistant materials and heat-resistant cells.	▪ Perform sustainable landscaping to improve the microclimate around the solar park.
Coastal erosion **Soil erosion**	▪ Avoid coastal sites and erosion-prone areas.	▪ Elevate levy structures to combat coastal erosion and protect PV panels from inundation. ▪ Build retaining walls, terraces, or embankments to control soil erosion and reduce soil drift. ▪ Install geotextiles and erosion control blankets in eroded slopes.	▪ Restore/Maintain coastal vegetation (e.g., salt marshes) to dissipate waves and protect back-lying areas from flooding and erosions.

Permafrost thawing	▪ Conduct geotechnical investigations to map permafrost regions.	▪ Apply soil remediation practices (e.g., geotextiles) to mitigate permafrost-induced settlements.	NA
Changing in wind patterns	NA	NA	▪ Promote sustainable landscaping to manage wind patterns and improve the microclimate around the park.

2.4 District Heating – Networks and biomass-based Heat Generation

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of biomass-based DH systems to climate hazards are provided in **Table 2.18** along with indicative scores per component category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.1** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical biomass-based DH systems under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities[45].

TABLE 2.18 • Sensitivities of biomass-based DH system components.

Climate Hazard	Sensitivities			
Flood Storm surge Heavy precipitation	• Short circuit or electronic damages when on-ground equipment gets wet. • Uplift failure/upheaval buckling of underground pipes creating operating issues. • Increased heat-losses in the distribution grid, due to increased moisture of the surrounding soil. • Increased biomass moisture (especially if stored in open space) reduces its energy value leading to decreased energy production. • Flooded biomass storages may disrupt heating/cooling operations.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (Medium)	**Outputs** (Medium)	**Interdependent systems** (High)
Sea level rise Saline intrusion	• Chemical corrosion of underground pipes from the infiltration of saline groundwater. • Ingress of saline groundwater may create unfavourable buoyancy conditions for buried pipes causing structural damages. • Water input for thermal energy generation may be significantly affected by saline intrusion, impacting the overall efficiency of the system and the cost of energy.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (High)	**Outputs** (No sensitivity)	**Interdependent systems** (Medium)
Wildfire	• Physical damage to the central plant and equipment when directly exposed to wildfire. • Shortages in biomass materials, either due to an on-site fire damaging the fuel stored at the facility, or indirectly, from wildfires harming dedicated energy crops or croplands supplying bioheat production. • Availability and quality of water may be affected by wildfires.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (High)	**Outputs** (No sensitivity)	**Interdependent systems** (Medium)
Landslide Avalanche Subsidence	• Physical damage by the moving soil/rock (for landslides) or snow (for avalanches) masses on critical infrastructure components (structural components of the heating plant) and access roads. • Underground pipes are highly vulnerable to damage from landslides, avalanches, or subsidence, potentially disrupting the heat distribution network. • Increased maintenance activities may be required due to potential structural issues. • Supply chain may be impacted affecting transportation routes and biomass availability.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (No sensitivity)	**Outputs** (No sensitivity)	**Interdependent systems** (Medium)

[45] Biomass district heating systems can take various forms based on the type of biomass used, the scale of the system, and the technology employed. For example, straw-fired biomass systems, wood chip and wood pellets systems, organic waste or agricultural residues used in anaerobic digestion systems, pyrolysis and gasification systems, etc.

Changing temperatures Temperature variability	• Lower temperatures decrease annual forest production, and by extension biomass production. • Temperature variations affect crop yields and hence the availability of agricultural residues for biofuel production. • Higher air temperatures increase the efficiency of the combustion leading to savings on fuel costs and cheaper production of energy. • Higher temperature may increase water usage for biomass production and operations. • Weather-related variability in peak energy demand: when temperatures are milder, the demand for district heating may decrease, during colder-than-average winters, higher energy demands may strain the system.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Permafrost thawing	• Freeze-thaw ground movements may cause physical damage to the underground pipes. • Stability and alignment of flue gas cleaning systems may be influenced. • Foundation instabilities and structural damages/dysfunction of key components (boilers, condensers, storage structures, etc).			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Drought	• Irrigation water requirements for large-scale biomass production may substantially increase, increasing water competition with other potential users. • Reduced availability of biomass feedstock, such as wood, agricultural residues, or dedicated energy crops. • Potential reduction of the biomass moisture content could enhance its calorific value (energy content) leading to increased thermal energy production (favourable effect).			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Coastal erosion Soil erosion	• Stability issues and physical damages to the infrastructural components (especially underground pipes) and critical equipment or to the interdependent infrastructure: access roads and railways.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Cold wave	• Cold waves can impact the moisture content and combustion characteristics of biomass, leading to reduced system efficiency and increased fuel costs. • Increased heat losses in the distribution grid and heat storage tanks. • To meet the increased demand for heating during very cold days the system will be running at higher temperatures (potentially activating system's reserve power) creating more heat loss and increased production cost. • Accelerated structural component deterioration, leading to increased maintenance costs.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Heat wave	• Overheating of electrical components. • High ambient temperatures can increase the rate of decomposition of biomass materials due to accelerated microbial activity, leading to loss of dry matter and energy content. • Increased risk of biomass self-ignition, especially when stored in large piles. • Elevated temperatures can affect the integrity of components of the district heating system. For instance, prolonged exposure to high temperatures may lead to material degradation. • Higher energy consumption driven by increased demand for cooling.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Extreme wind (including storm, hurricane, tornado)	• Physical damages to the facility by high winds and debris carried by storms. Particularly vulnerable are slender metal components such as suspended pipes, chimneys, elevated tanks, etc. • Business disruption/discontinuous operations if critical components are severely damaged (e.g., feeder pipeline). • The biomass supply chain may be affected (e.g., damaged transportation routes).			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

The biomass DH system, specifically its piping network, is distributed with notable spatial variability. As a result, hazard exposure can vary based on the location of system assets. To comprehensively assess risks, overlaying hazard and network/asset maps is essential. This process helps pinpoint areas with the highest system exposure, ensuring a thorough understanding of potential hazards across the system.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts in combination with the project's criticality, readers are referred to the **Introductory Chapter** (Module 5). Below, an overview of potentially significant impacts to biomass-based DH systems across various risk areas (RA) is provided, to assist users with the scoring procedure.

TABLE 2.19 • Climate impacts for to biomass-based DH systems (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Infrastructure Damages:** This area encompasses the potential impact on the integrity of key components within the district heating system, including boilers, condensers, heat exchangers, pipes, and biomass storage facilities. Any compromise to these components can result in asset failures, prolonged heating system downtime, and associated direct and indirect costs for the heating provider.
RA2: Safety and Health	**Operational Safety:** Health and safety consequences on operational personnel. This includes the potential for fire hazards, particularly in biomass storage and handling areas, as well as the effects of exposure to high temperatures and potential emissions.
RA3: Environment	**Degradation of freshwater ecosystems:** Expanded feedstock production (e.g. corns) poses risk to water quality and quantity (depending on the hydrological setting of the production fields). **Pollution:** Air temperature and humidity variations affect the efficiency of the conversion as well as the emissions of pollutants arising from combustion.
RA4: Social	**Water competition:** Increased irrigation water requirements for large-scale biomass production during drought periods can increase water competition among users. **Social Dynamics:** The influence of biomass-based district heating systems on local communities' quality of life and relationships. Consideration of factors such as noise, visual impact, and land use that can affect community well-being and social interactions. **Energy Accessibility:** Potential challenges in energy accessibility for communities relying on the heating supply, especially during downtime or failures, impacting energy provision.
RA5: Financial impacts	**Financial losses:** Including damage to equipment, loss of feedstock and supply-chain shortages, reduced efficiency and increased fuel cost when operating at very low temperatures.
RA6: Reputation	**Image and Credibility:** Consistent breakdowns or environmental incidents can harm the provider's reputation. Being perceived as an environmentally responsible and reliable service provider is pivotal for maintaining customer trust and investor confidence.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 2.20 presents potential adaptation solutions for climate hazards that could impact biomass-based DH systems. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 2.20 • Biomass-based DH systems: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. In any case inform decision-making along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Flood **Storm surge** **Heavy precipitation**	▪ Consider overground heat distribution pipelines instead of below the ground. ▪ Avoid low-lying area and other type flood-prone areas for the distribution grid development. ▪ Consider insurance schemes to reduce external risks due to flood (e.g., potential biomass fuel shortages arising from the restricted access to the heating plant due to flood damage in the immediate transport network).	▪ Waterproof of the heating plant, i.e., raise the elevation of significant electrical/mechanical equipment, implement flood barriers and levees to prevent water ingress. ▪ Increase of indoor fuel storage capacity to protect the on-site stored biomass from precipitation-induced changes in moisture content. ▪ Design effective stormwater management systems to handle increased precipitation.	▪ Use of wetlands and other natural flood barriers as a flood buffer zone. ▪ Implement real-time monitoring of water levels in surrounding areas to provide early warnings triggering emergency responses. ▪ Conduct regular inspections of flood defences and critical infrastructure.
Sea level rise **Saline intrusion**	▪ Avoid coastal areas. ▪ Optimise for elevated locations to minimise the risk of flooding and saline intrusion. ▪ Consider alternative water sources that are less susceptible to saltwater contamination.	▪ Waterproof the plant and ensure that there is sufficient drainage. ▪ Design critical system components, such as boilers and storage tanks, on elevated platforms to minimise exposure to potential flooding and saline intrusion. ▪ Use of anti-corrosive pipe protection. ▪ Consider technologies like screening and filtration to safeguard against saline intrusion.	▪ Protect and restore natural flood barriers such as flood plains, salt marshes, fresh-salt water transitions. ▪ Conduct regular inspections of system components to identify signs of corrosion. ▪ Implement continuous water quality monitoring, especially for water sources susceptible to saline intrusion.
Wildfire	▪ Choose sites with lower wildfire risk, considering factors such as proximity to flammable vegetation and historical fire data. ▪ Incorporate defensible space planning into the site design to create a buffer zone that reduces the risk of wildfire encroachment.	▪ Install fire extinguishing systems. ▪ Increase of indoor fuel storage capacity, to protect the on-site stored biomass material. ▪ Use fire-resistant construction materials for critical system components and buildings. ▪ Implement firebreaks and barriers around the biomass district heating system to prevent the spread of wildfires: this involves creating cleared zones or installing physical barriers to impede the progress of fires.	▪ Regularly maintain firebreaks and cleared zones to ensure their effectiveness and proactively manage vegetation (tree trimming and pruning) to reduce fire risk. ▪ Prepare fire management plans, protocols and keep up communication with local fire authorities. ▪ Diversify the biomass suppliers to avoid the risk of fuel shortage. ▪ Implement continuous monitoring systems for early detection of wildfires. This may include the use of remote sensing technologies, cameras, or other monitoring tools to detect smoke or flames in the vicinity.

Landslide **Avalanche** **Subsidence**	▪ Conduct comprehensive geotechnical assessments during the planning phase to identify areas prone to landslides, avalanches, or subsidence. ▪ Implement site zoning strategies to designate safe areas for critical infrastructure. ▪ Employ advanced modelling techniques to predict landslide risk based on factors such as slope, soil type, and historical events. Use this information to inform site selection and design decisions.	▪ Design reinforcements (structural supports, protective barriers, retaining walls) for the critical system components and buildings to withstand potential impacts from soil movements.	▪ Implement continuous monitoring systems to detect early signs of ground movement, subsidence, or increased landslide risk. Automated monitoring can trigger alerts for proactive responses. ▪ Conduct regular inspections of critical infrastructure for signs of stress, movement, or damages. ▪ Implement vegetation management strategies in landslide-prone areas to stabilise slopes.
Changing temperatures **Temperature variability**	▪ Consider systems with flexibility to accommodate variations in heat demand resulting from temperature fluctuations. ▪ Ensure scalability to adjust capacity based on changing climate conditions and evolving energy needs.	▪ Incorporate thermal energy storage systems into the design to manage temperature variability. This enables the storage of excess heat during periods of high demand and its release during periods of lower demand or extreme temperatures. ▪ Design systems that can efficiently utilise a diverse range of biomass feedstock.	▪ Implement advanced control systems that can dynamically adjust the operation of the biomass district heating system based on real-time temperature conditions, including optimising combustion parameters for different biomass types and adjusting heat distribution. ▪ Regularly analyse monitoring data to identify trends and proactively address potential issues.
Permafrost thawing	▪ Perform a permafrost analysis for the distribution grid (including future projection scenarios). ▪ Perform a comprehensive geotechnical investigation. ▪ Choose sites with minimal permafrost susceptibility.	▪ Design ground stabilisation measures (e.g., geotextiles) to avoid potentially harmful ground displacements. ▪ Design foundations with consideration for permafrost conditions (e.g., prefer piles). ▪ Optimise the design of ground heat exchange systems and incorporate insulation strategies for buried components to minimise heat transfer to permafrost layers. This involves controlling the temperature of fluids circulating in the ground to prevent accelerated thawing.	▪ Monitor risk zones and areas prone to soil movements. ▪ Conduct regular inspections of the ground surrounding critical infrastructure to identify signs of permafrost thawing. Implement preventive measures and repairs as needed to maintain the stability of the system.
Drought	▪ Integrate water conservation strategies into the planning phase, e.g., assessing alternative water sources, implementing water recycling systems, and optimising water use efficiency.	▪ Design ground stabilisation measures to avoid potentially harmful ground displacements. ▪ Incorporate alternative water sources, such as rainwater harvesting or treated wastewater, into the design.	▪ Perform regular inspections of the distribution network and proactive management (e.g., prioritisation of the repair of pipe sections to avoid significant damage). ▪ Develop water recycling and treatment protocols to reuse and treat water within the system.
Soil erosion **Coastal erosion**	▪ Identify areas prone to soil and coastal erosion by utilising geological surveys, topographic mapping, and coastal studies to evaluate vulnerability. ▪ Choose sites with minimal erosion risk and establish buffer zones.	▪ If applicable, engage in coastal engineering to implement protective structures such as seawalls or revetments to defend against coastal erosion.	▪ Implement vegetative stabilisation measures, such as planting native vegetation. ▪ Implement continuous monitoring systems to detect early signs of soil and coastal erosion. This includes the use of sensors, surveys, or satellite imagery to track changes in topography.

Cold wave	▪ Consider historical temperature data and climate projections to understand the severity and frequency of cold waves in the region. ▪ Plan for enhanced insulation of critical system components and buildings to minimise heat loss during extreme cold conditions.	▪ Increase of pipe insulation thickness/upgrade of pipe insulation material in the distribution grid and heat storage tanks (if existent). ▪ Incorporate backup heating systems or alternative heat sources into the design (e.g., supplementary heating or circulation systems). ▪ Use materials that are resistant to the effects of extreme cold temperatures for critical system components. This includes selecting materials that can withstand low temperatures without becoming brittle or compromised.	▪ Implement weather monitoring systems to predict increases in heat demand, thereby informing operations in advance (e.g., by pre-loading the DH network, the anticipated rise in demand can be levelled out). ▪ Develop strategies for snow management, including the removal of snow from critical components and access points. ▪ Optimise combustion parameters, adjust heat distribution, and implement measures to prevent freezing of water-based components.
Heat wave	▪ Choose locations that minimise the impact of extreme heat, considering factors like shading and natural cooling. ▪ Explore options for systems with flexibility to accommodate variations in energy demand during heat waves. ▪ Plan for increased cooling needs.	▪ Use equipment with higher temperature operating limits. ▪ Design redundancy into ICT systems. ▪ Consider supplementary cooling for critical components and thermal energy storage for managing peak loads. ▪ Enhance the insulation of pipelines.	▪ Avoid storage of large quantities of biofuel materials for long periods. ▪ Plan fuel redundancies (i.e., ensure that fuel is delivered in a continuous, just-in-time manner from a set of diversified suppliers). ▪ Establish emergency cooling procedures to prevent system overheating during extreme heat events. ▪ Develop and implement protocols for adjusting combustion parameters based on temperature conditions.
Extreme wind (including storm, hurricane, tornado)	▪ Choose sites with minimal vulnerability to storms and limit exposure to high winds. Assess the terrain to identify potential wind corridors and optimise site layout to minimise the impact of extreme weather events.	▪ Reinforce critical system components and buildings. Consider wind-resistant construction materials and structural designs that can withstand high winds. ▪ Install emergency power backup systems to ensure continuous operation during power outages.	▪ Implement continuous monitoring systems to track meteorological conditions and detect signs of approaching storms. ▪ Develop a comprehensive emergency response plan that outlines procedures for shutting down critical components.

2.5 Green Hydrogen (H2) Electrolysers

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of green H2 electrolysers to climate hazards are provided in **Table 2.21** along with indicative scores per component category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.1** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical green H2 electrolysers infrastructure under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities[46].

TABLE 2.21 • Sensitivities of green H2 electrolysers components.

Climate Hazard	Sensitivities			
Flood Storm surge Heavy precipitation	• Inundation of electrolyser building and physical damages to the electrical equipment (e.g. switchgears and transformers) or other critical equipment (e.g., compressor, storage facilities) as well as to the interdependent infrastructure: renewable plants, transmission and distribution lines, access roads, etc. • Floating/ruptured pipelines buried in waterlogged areas, risk of explosion. • Flood exposes pipelines to debris and other threats. • Interruption/contamination of water source increases the need for water treatment resulting in increased operational cost.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (Medium)	**Outputs** (No sensitivity)	**Interdependent systems** (High)
Extreme wind (including storm, hurricane, tornado)	• Electric damages to the electrolyser and other electrical equipment (e.g., switchgears and transformers). • Structural bucking or overturning of storage tanks when exposed to extreme wind gusts. • Significant stressing due to extreme winds can cause rupture of disks and pressure relief valves potentially leading to sudden hydrogen release increasing the risk of fire or explosion or asphyxiation (in closed environments). • Interruption/contamination of water source increases the need for water treatment resulting in increased operational cost.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (Medium)	**Outputs** (No sensitivity)	**Interdependent systems** (Medium)
Sea level rise Saline intrusion	• Temporary or permanent inundation of the H2 plant (for coastal facilities). • Short circuit damages of electrodes, risk of oxygen-hydrogen gas explosion. • Saline intrusion directly affects the input water and the water purification process. • Operational issues to the interdependent coastal infrastructure e.g., port and harbours for the shipping of ammonia and methanol, or the interdependent water supply system.			
Global Score: High	**On-site assets & processes** (Medium)	**Inputs** (High)	**Outputs** (No sensitivity)	**Interdependent systems** (Medium)
Water stress, Drought	• Increased water demand and water usage conflicts. • Operational issues due to lack of available water (especially for large-scale electrolysers that require significant water quantities). • Increased desalination of saline or brackish water (to compensate for the lack of fresh water) resulting in significant environmental impacts due to brine discharge. • Reduced water quality requiring increased water treatment affects the water purification process and the operation of the hydrogen generator. • Ground drying and shrinkage may create foundation issues.			

[46] For example, the source of the renewable energy used for the H2 production may have different levels of inherent sensitivities, e.g., wind farms vs solar parks.

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems
Wildfire	• Hydrogen's wide flammable range makes it prone to quick ignition when mixed with air, resulting in fires, invisible flames, high-velocity jet fires, thermal radiation, and explosions. • Fire leading to physical damages to the assets. • Damages to the access roads resulting in limited or no accessibility to the H2 facility during or right after the fire events.			
Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems
Heat wave	• Overheating and increased risk of failures and malfunctions of electric equipment when normal operating temperatures are exceeded. • Higher temperatures may impact water quality and the efficiency of water purification systems. • From a thermodynamic standpoint the performance of electrolysis can be improved by functioning at high temperature, but require elaborate heat management modifications.			
Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems
Coastal erosion Soil erosion	• Stability issues and physical damages to electrolysis unit and storage facilities. • Soil erosion may expose transmission pipelines to other threats as corrosion and excavation damage.			
Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems
Landslide Avalanche Subsidence	• Physical damage by the moving soil/rock (for landslides) or snow (for avalanches) masses to electrolysis unit, storage facilities and ither critical equipment. • Underground pipes are highly vulnerable to damage from landslides, avalanches, or subsidence, potentially disrupting the natural gas distribution and water supply.			
Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems
Cold wave	▪ Deviations from the optimal temperature may affect the performance of green hydrogen production. ▪ Freezing water in the stack obstructing operations. ▪ Ice formation on solar panels or wind turbines may obstruct the electrolysis process.			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems
Changing temperatures Temperature variability	• Temperature variations affect the variability and intermittency of renewable energy input which affects the efficiency of the electrolyser (i.e., minimum load for operation, frequent cold starts, time to ramp up to the operating power) and by extension the cost of hydrogen production.			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems
Permafrost thawing	• Freeze-thaw ground movements may cause physical damage to the underground pipes. • Electrolysis unit, hydrogen storages may experience excessive settlement and tilting.			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts in combination with the project's criticality, readers are referred to the **Introductory Chapter** (Module 5). Below, an overview of significant impacts to green H2 electrolysers across various risk areas (RA) is provided, to assist users with the scoring procedure.

TABLE 2.22 • Climate impacts for green H2 electrolysers (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damages**: including the electrolysis units, electrical components, and supporting infrastructure, with the potential to lead to asset failures and extended downtime. This can result in direct and indirect costs for the hydrogen production facility.
RA2: Safety and Health	**Operational Safety Concerns**: Overheating or malfunctioning of electrolysis equipment may pose fire risks within the hydrogen production facility. Additionally, safety risks may arise from electrical faults or hydrogen leaks, potentially leading to harm for personnel working at the facility or the nearby community if precautionary measures are not taken.
RA3: Environment	**Pollution:** Equipment malfunctions or hydrogen leaks can have environmental consequences, including the release of greenhouse gases or other pollutants. **Water Quality**: Green hydrogen production facilities require water for the electrolysis process, and water scarcity or pollution could impact operations. **Desalination:** Increased brine discharge generated during extensive desalination affects soils' capacity to produce crops and forage. Improper treatment of brine may pollute water bodies and groundwater aquifers.
RA4: Social	**Social Ripple Effect**: Disruptions in green hydrogen production can affect industries and services that rely on clean hydrogen as an energy source such as transportation and manufacturing affecting mobility and logistics. The broader economy could also be affected, particularly if hydrogen is a key enabler of decarbonisation strategies.
RA5: Financial impacts	**Operational Cost**: Intermittency of renewable energy input may reduce the efficiency of the electrolyser resulting in increased operational cost for hydrogen production. Extreme climate events are expected to increase repair and O&M costs.
RA6: Reputation	**Investor Appetite:** Frequent equipment failures, extended downtime, or high maintenance costs can make the facility appear unreliable and risky to investors and customers. **Industry image:** Environmental issues such as hydrogen leaks or pollution can tarnish the image of green hydrogen as a clean and sustainable energy source.
RA7: External risks	**Energy Input:** The availability of renewable energy sources (e.g., wind and solar power) directly influences the production capacity of electrolysis units. **Downstream distribution:** Transportation and logistical challenges in distributing green hydrogen can affect the supply chain.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 2.23 presents potential adaptation solutions for climate hazards that could impact green H2 electrolysers, if and where required. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 2.23 • Green hydrogen (H2) electrolysers: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. In any case inform decision-making along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Flood Storm surge Heavy precipitation	▪ Perform in-depth flood risk analysis (for current and future climate) during the site selection stage. ▪ Avoid flood-prone sites. ▪ Optimise site elevation and layout to minimise susceptibility to flooding. ▪ Place critical infrastructure on higher ground and avoid constructing in flood-prone areas.	▪ Design multiple layers of protection for electrical components to provide redundancy in the event that one or more of the measures fail. ▪ Design flood protection measures, e.g., increased drainage capacity (larger trenches, underground pipes), elevation of critical equipment (especially electrical components). ▪ Install silt traps to prevent heavy silt runoff. ▪ Use flood-resistant materials and coatings. ▪ Consider eco-friendly scour protection measures.	▪ Install early warning systems and combine them with temporary flood defence measures (e.g., temporary flood walls). ▪ Use of wetlands as a buffer zone. ▪ Conduct regular inspections of infrastructure to identify and address vulnerabilities. ▪ Consider relocatable or modular systems that can be temporarily moved to higher ground during flood events. ▪ Ensure backup power systems are flood-resistant and located in areas less prone to flooding.
Extreme wind (including storm, hurricane, tornado)	▪ Consider project relocation. ▪ Incorporate wind-resistant design principles into the facility layout. ▪ Invest in comprehensive insurance coverage for storm-related damages.	▪ Consider a robust structural design for the electrolyser building (e.g., foundation reinforcements). ▪ Adjust design specifications beyond the code thresholds to increase stability/safety. ▪ Select structural materials with greater fatigue life. ▪ Design protective measures for the critical equipment (e.g., wind-proofing with anchoring). ▪ Implement effective stormwater management systems to prevent flooding and control water runoff during storms. ▪ Incorporate permeable surfaces to reduce the risk of surface flooding.	▪ Install advanced weather monitoring and early warning systems to track approaching storms. ▪ Perform proactive shutdowns based on the early warnings. ▪ Implement and maintain natural windbreaks, i.e., strategically planted rows of trees, shrubs, or other vegetation that serves as a barrier to reduce the impact of strong winds. ▪ Implement routine inspections of infrastructure to identify and address vulnerabilities.
Sea level rise Saline intrusion	▪ Conduct a detailed assessment of projected sea level rise in the region and consider relocation if necessary. ▪ Incorporate sea level rise projections into the facility's long-term planning. ▪ Optimise site elevation and layout to mitigate the risk of saline intrusion.	▪ Desing coastal protection measures (seawalls, breakwaters, revetments). ▪ Design critical infrastructure, including electrolyser units and storage facilities, with elevated foundations. ▪ Consider subsea power cables and pipes at appropriate depth levels. ▪ Desing wave-absorbing structures (wave breakers).	▪ Use early warning system and integrated coastal monitoring. ▪ Restore and protect the natural buffer zones, such as mangroves or wetlands. ▪ Monitor the condition of protective coatings and materials to ensure effectiveness. ▪ Develop contingency plans specific to saline intrusion events, including protocols for water source switching or temporary shutdowns.

		▪ Install pumping systems to counteract saline intrusion. ▪ Use anti-corrosive materials and coatings.	▪ Stay informed about advancements in desalination and water treatment technologies.
Water stress, Drought	▪ Plan for contractual water use provisions. ▪ Engage all stakeholders and listen to community needs. ▪ Establish partnerships with local authorities for access to diversified water supplies. ▪ Consider the feasibility of a water supply system based on desalination instead of use of fresh water and select appropriate treatment and discharge methods (e.g., discharge into the sea, disposal into sewers, deep well injections, evaporation ponds). ▪ Explore alternative water sources such as treated wastewater or brackish water.	▪ Implement advanced cooling systems that optimise water usage and reduce waste (e.g., dry cooling systems instead of wet). ▪ Perform detailed assessment of the water management at watershed scale and at local scale. ▪ Analyse in depth the effects of brine discharged to different ecosystems and organisms. ▪ Plan for increased water storage capacity to withstand periods of water scarcity.	▪ Utilise advanced sensors and data analytics to optimise water consumption during operation. ▪ Incorporate greywater recycling systems to reuse water from non-potable sources for cooling and non-critical processes. ▪ Implement real-time monitoring systems for water usage and availability. ▪ Develop and regularly update drought contingency plans to ensure operational continuity. ▪ Establish collaborative relationships with local water authorities. ▪ Invest in research and development for innovative water-saving technologies.
Wildfire	▪ Avoid wildfire high-risk zones. ▪ Integrate firebreaks and non-combustible zones into the site layout. ▪ Collaborate with local fire authorities and communities to understand wildfire response plans.	▪ Install fire extinguishing systems. ▪ Install hydrogen gas and flame detectors for timely identification of gas leakage or resulting flames. ▪ Perform a detailed fire and explosion risk assessment. ▪ Incorporate fire-resistant coatings and insulation. ▪ Design and construct buildings and facilities to withstand an explosion with isolated/limited damage.	▪ Prepare firefighting plans including continuous monitoring and early warning systems. ▪ Monitor and manage vegetation growth to prevent the accumulation of flammable materials. ▪ Train properly the staff. ▪ Proactively manage vegetation (tree trimming and pruning) to reduce fire risk while maintaining their ecological value. ▪ Ensure an adequate and reliable water supply for firefighting purposes.
Heat wave	▪ Choose sites with consideration for local climatic conditions, aiming to minimise heat-related risks. ▪ Optimise facility orientation and layout to mitigate the impact of extreme temperatures.	▪ Select appropriate cooling technology, wet, dry or hybrid systems (e.g., air fin cooler, open cooling towers, fogging systems, etc). ▪ Design critical infrastructure with materials that can withstand high temperatures. ▪ Incorporate heat-resistant coatings and insulation to enhance the resilience of structures. ▪ Design the facility for energy efficiency to minimise heat generation during operations. ▪ Incorporate shading and insulation strategies to reduce heat absorption.	▪ Monitor temperatures and perform operational scheduling with protocol shutdowns. ▪ Consider sustainable landscaping to improve the microclimate around the H2 facility. ▪ Develop heat stress protocols for workers, including regular breaks, hydration measures, and shaded rest areas. ▪ Implement emergency cooling measures, such as backup or supplementary cooling systems, to manage extreme heat events.
Coastal erosion Soil erosion	▪ Choose sites with lower susceptibility to erosion, avoiding areas with unstable soils or high coastal erosion rates.	▪ Design landscaping features that enhance soil retention and reduce the risk of coastal erosion. ▪ Install erosion control structures, such as silt fences, geotextiles, and retaining walls, to mitigate soil erosion.	▪ Implement real-time monitoring systems for soil conditions and erosion rates. ▪ Conduct regular inspections of soil conditions and erosion control measures to identify signs of degradation.

	▪ Optimise facility layout and infrastructure placement to minimise soil disturbance and coastal exposure.	▪ Design coastal protection structures, like breakwaters or revetments, to reduce coastal erosion. ▪ Design drainage systems that redirect water away from vulnerable areas. ▪ Increase the trench depth of buried pipelines.	▪ Implement routine vegetation maintenance. ▪ Consider beach nourishment projects to replenish sand and restore coastal resilience. ▪ Stay informed about advancements in erosion control and coastal protection methods.
Landslide Avalanche Subsidence	▪ Perform in-depth landslide risk analysis (for current and future climate) during the site selection stage. ▪ Avoid landslide-prone sites (e.g., steep slopes, unstable geological formations). ▪ Optimise facility layout and infrastructure placement to minimise the risk of triggering landslides.	▪ Select foundation types that can incorporate large differential settlements. ▪ Design landslide protection measures, e.g., retaining walls, vegetation, underwater drainage, reducing slopes. ▪ Install effective drainage systems to manage water runoff and prevent saturation of soil, a common trigger to landslides. ▪ Implement surface water diversion measures to reduce the risk of soil erosion. ▪ Engage specialised geotechnical engineers during the design.	▪ Continuously monitor geological conditions in and around the site to identify potential landslide triggers. ▪ Remote monitoring of risk zones (satellite mapping methods, remote field instrumentation) integrated with early warning systems. ▪ Maintain slope greening and vegetative reinforcement. Choose native plants with deep root systems that contribute to soil stability. ▪ Conduct regular inspections of slopes, retaining structures, and critical infrastructure to identify signs of erosion or instability.
Cold wave	▪ Consider local climate data to understand the severity and duration of cold waves in the region. ▪ Incorporate winterisation planning into the project. ▪ Consider insulation strategies for critical infrastructure to prevent freezing.	▪ Design critical infrastructure using materials that can withstand low temperatures. ▪ Implement cold-resistant coatings and insulation. ▪ Implement insulation measures for pipes and water storage facilities to avoid water freezing.	▪ Implement real-time temperature monitoring systems to track ambient and equipment. ▪ Regularly inspect and treat surfaces prone to ice accumulation. ▪ Implement emergency heating measures, such as backup or supplementary heating systems.
Changing temperatures Temperature variability	▪ Diversify the renewable energy sources to minimise the variability and intermittency of energy input.	▪ Incorporate energy storage systems into the design to manage energy variability. ▪ Design the electrolyser system with the capability to handle a range of loads efficiently, this includes considering the minimum load requirements and the ability to handle frequent cold starts without compromising efficiency.	▪ Implement continuous optimisation strategies based on real-time performance data, including adjusting operational parameters dynamically to maximise efficiency under changing temperature conditions. ▪ Regularly analyse monitoring data to identify trends and proactively address potential issues.
Permafrost thawing	▪ Conduct permafrost surveys and geotechnical investigations to identify the extent of permafrost and its characteristics in the project area and consider relocation if necessary.	▪ Select foundation types that can incorporate large differential settlements.	NA

2.6 Battery Energy Storage Systems (BESS)

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of BESS to climate hazards are provided in **Table 2.24** along with indicative scores per component category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.1** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical BESS under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities.

TABLE 2.24 • Sensitivities of BESS components.

Climate Hazard	Sensitivities			
Heat wave	• Acceleration of chemical reactions leading to degradation and reduced lifespan of battery cells. • Increased risk of self-ignition due to overheating of batteries. • Higher temperatures may impact the discharge characteristics of batteries, affecting the efficiency of electricity output.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (No sensitivity)	**Outputs** (Medium)	**Interdependent systems** (No sensitivity)
Flood **Storm surge** **Heavy precipitation**	• Submersion of batteries and electronics in water can lead to short circuits and corrosion. • Flood water contamination with active battery chemicals can be a significant environmental threat to water ecosystems. • Electrical failures leading to thermal runaway events causing battery fires. • Severe damages to the T&D grid or power generation facilities that feed the BESS.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (No sensitivity)	**Outputs** (No sensitivity)	**Interdependent systems** (Medium)
Wildfire	• Exposed to very high temperatures and flames battery cells may explode. • Dysfunction/failure of the air-filtration engine when air-filter are clogged with wildfire smoke. • Smoke residue accumulated to sensitive electromechanical parts may cause malfunctions. • Physical damage to T&D infrastructure may disrupt the operation of the BESS facility. • Facility access restrictions.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (No sensitivity)	**Outputs** (No sensitivity)	**Interdependent systems** (Medium)
Cold wave	• Extremely low temperatures slow down chemical reactions in batteries and limit their ability to deliver power. • Water ingress into the BESS (from thawing snow) can trigger electrical failures. • Disruption of service in case of power shortages or blackouts (caused by power grid overload during cold spells).			
Global Score: Medium	**On-site assets & processes** (Medium)	**Inputs** (No sensitivity)	**Outputs** (Medium)	**Interdependent systems** (Medium)
Landslide **Avalanche** **Subsidence**	• BESS units can be translated/overturned/distorted when subjected to massive ground displacements. • The BESS units (being relatively heavy structures) can trigger landslides when founded in landslide -prone areas. • Physical damage to transmission and distribution lines may disrupt operations of the BESS facility. • Blockage of access roads obstructing personnel accessibility.			

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems
Extreme wind (including storm, hurricane, tornado)	• Structural damage of BESS components and their support structures. • Impact failures/damages of sensitive electromechanical equipment. • Water ingress into the BESS unit triggering electrical failures. • Electrical equipment damages (e.g., paralleling switchgear, transfer switches) caused by lightning or power surge (after a power outage). • Disruption of service in case of power shortages or blackouts (caused by power grid damages during storms).			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems
Coastal erosion Soil erosion	• Soil erosion increases water run-off and hence the risk of ground movements impacting the BESS facility and other interconnected infrastructure (transmission lines and access roads).			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems
Sea level rise Saline intrusion	• Submersion of batteries and electronics in water can lead to short circuit failures and corrosion. • Foundation failures and soil subsidence of BESS units (triggered by increased groundwater level). • Increased salinity accelerates corrosion effects of metal parts and electronics.			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems
Drought	• Prolonged drought periods create ground drying conditions and shrinkage which may impede foundation issues/instabilities (especially when followed by severe rainfalls). • Reduced availability of water for cooling systems may affect efficiency and thermal management off BESS.			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems
Permafrost thawing	• Freeze-thaw ground movements may cause physical damage to underground network cables and joints. • Excessive settlements and subsidence of on-ground structures.			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts in combination with the project's criticality, readers are referred to the **Introductory Chapter** (Module 5). Below, an overview of significant impacts to BESS across various risk areas (RA) is provided, to assist users with the scoring procedure.

TABLE 2.25 • Climate impacts for BESS (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damages:** Battery cells, inverters, and control systems may fail or dysfunction when subjected to extreme temperature or water. The structural cell of BESS can be heavily damaged when exposed to extreme wind gusts and large ground movements (case of landslides/subsidence).
RA2: Safety and Health	**Personnel:** Risk of explosion can pose a direct threat to personnel working with or near the systems. Health risks may arise from exposure to hazardous chemicals or gases released during a thermal event (e.g. a wildfire), affecting both workers and nearby communities.
RA3: Environment	**Pollution:** The release of pollutants and toxic materials from damaged batteries during thermal events can result in soil and water contamination, posing risks to ecosystems and local water sources. **End-of-life Concerns:** Temperature extremes can curtail the design life of batteries exacerbating the environmental concerns with regard to their disposal and recycling.
RA4: Social	**Social Implications:** Disruptions in battery energy storage systems can affect critical services and industries that rely on stable and resilient energy supply. This includes healthcare facilities, data centres, and emergency services, where interruptions can jeopardise patient care, data integrity, and public safety.
RA5: Financial impacts	**O&M Cost:** Extreme weather events will increase repair costs (for damaged components). Increased operational cost may arise from: (i) chronic changes in the weather patterns curtailing the design-life of batteries resulting in increased frequency of replacements; (ii) increased air conditioning and server maintenance requirements, (iii) charging cost fluctuations.
RA6: Reputation	**Reliability and Trust:** Repeated disruptions or safety incidents in battery energy storage systems can damage the reputation of the facility's operators. Investors and customers may lose trust in the reliability and safety of energy storage solutions. **Environmental Responsibility and Public Perception**: Environmental concerns, such as battery disposal and recycling practices, can also affect the reputation of the technology and its manufacturers as well as the brand image.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 2.26 presents potential adaptation solutions for climate hazards that could impact BESS. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 2.26 • Battery Energy Storage Systems (BESS): Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. In any case inform decision-making along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Heat wave	▪ Ensure scalability to adjust capacity based on changing climate conditions and evolving energy needs.	▪ Implement advanced thermal management systems, such as liquid cooling or passive cooling solutions, to regulate temperatures within the BESS. ▪ Design and construct robust, sealed enclosures for critical components like battery modules, inverters, and control systems. ▪ Use heat-resistant materials for components exposed to high temperatures. ▪ Incorporate landscaping and shading structures to reduce the direct impact of sunlight on the BESS.	▪ Conduct routine inspections to identify wear and tear, especially in components sensitive to heat. ▪ Install monitoring systems to continuously track temperature variations and provide real-time data. ▪ Develop and implement specific operational protocols for high-temperature conditions, including adjustments to discharge rates and cooling system optimisation.
Flood **Storm surge** **Heavy precipitation**	▪ Avoid flood-prone areas.	▪ Construct BESS components on elevated foundations or platforms. ▪ Design and build waterproof enclosures for critical components such as battery modules, inverters, and control systems. ▪ Seal cable entry points with watertight fittings to prevent water infiltration into electrical components. ▪ Install flood barriers and levees around the BESS site to divert or contain floodwaters.	▪ Conduct regular flood risk assessments to identify changes in risk factors and update emergency response plans accordingly. ▪ Install automatic water-level controllers and shutdown operations when critical thresholds are met.
Wildfire	▪ Consider proximity to wildfire high-risk zones during site selection.	▪ Install fire extinguishing systems. ▪ Design defensible spaces around BESS installations by minimising vegetation and incorporating firebreaks. ▪ Construct fire-resistant enclosures for critical components, such as battery modules, to protect against radiant heat and direct flame exposure. ▪ Integrate firebreaks into the site layout.	▪ Prepare firefighting plans including continuous monitoring and early warning systems. ▪ Plan coordination & training for firefighting forces to deal with large BESS-based electrical/chemical fires. ▪ Monitor and manage vegetation growth to prevent the accumulation of flammable materials. ▪ Ensure an adequate and reliable water supply for firefighting purposes. ▪ Implement remote shutdown capabilities to allow for the safe shutdown of BESS systems during wildfire threats.

Cold wave	▪ Ensure scalability to adjust capacity based on changing climate conditions and evolving energy needs. ▪ Select sites that are better protected from cold conditions.	▪ Use materials resistant to cold temperatures or incorporate thermal insulation for critical components, including battery modules and electrical systems. ▪ Install heating systems if necessary.	▪ Establish cold weather protocols for operational activities, including adjustments to discharge rates and maintenance schedules. ▪ Implement remote monitoring systems to continuously track temperature variations and provide real-time data. ▪ Develop strategies for snow management, including snow removal plans for access points and critical equipment.
Landslide **Avalanche** **Subsidence**	▪ Avoid landslide/erosion prone areas and consider project relocation in extreme risks.	▪ Implement slope stabilisation measures. ▪ Prefer deeper foundations. ▪ Design effective drainage systems, such as subsurface drains and surface water diversion channels to improve stability conditions of landslide-prone regions.	▪ Monitor prone areas to landslides/avalanches/subsidence. ▪ Promote the growth of vegetation, such as grasses, shrubs, and trees, to help stabilise soil and slopes by increasing root strength and improving water absorption. ▪ Enhance natural drainage systems, such as swales, bioswales, and infiltration basins.
Extreme wind (including storm, hurricane, tornado)	▪ Select sites less exposed to cyclones and hurricanes or consider project relocation in case of extreme unmitigated risk.	▪ Design BESS structures to meet or exceed best practices and standards for wind resistance. ▪ Secure critical components such as battery modules, inverters, and control systems to prevent displacement during storms. ▪ Install lightning protection systems to safeguard against potential lightning strikes. ▪ Design and build storm-resistant enclosures for the critical components to protect against wind-driven rain and debris.	▪ Conduct routine inspections to identify wear and tear. ▪ Implement automated monitoring systems for weather conditions to provide real-time data enabling timely responses and interventions in an extreme event. ▪ Ensure the availability of backup power systems to ensure critical operations and communications remain functional during power outages.
Coastal erosion **Soil erosion**	▪ Avoid coastal sites and erosion-prone areas after consulting the broader coastal defence and management solution planned by the Public Authorities.	▪ Build seawalls or revetments to protect BESS facility. ▪ Build retaining walls, terraces, or embankments to control soil erosion and reduce soil drift. ▪ Install geotextiles and erosion control blankets in eroded slopes. ▪ Increase the trench depth of underground cables.	▪ Increase and maintain vegetation to prevent erosion. ▪ Shoreline monitoring and early warning systems.
Sea level rise **Saline intrusion**	▪ Conduct a detailed assessment of projected sea level rise in the region and consider relocation if necessary. ▪ Incorporate sea level rise projections into the facility's long-term planning.	▪ Desing coastal protection measures (seawalls, breakwaters, revetments). ▪ Use anti-corrosive materials and coatings. ▪ Optimise site elevation and layout to mitigate the risk of saline intrusion.	▪ Use early warning system and integrated coastal monitoring. ▪ Restore and protect the natural buffer zones, such as mangroves or wetlands. ▪ Monitor the condition of protective coatings and materials to ensure effectiveness.

Drought	▪ Identify alternative water sources or implement water-saving technologies to reduce reliance on local water supplies. ▪ Assess the potential impact of BESS water use on local water resources during drought conditions.	▪ Implement water-efficient cooling systems, such as closed-loop cooling, to minimise water consumption. ▪ Install water recycling systems to reuse and treat water within the BESS, reducing overall water demand.	▪ Keep up to date with new equipment cooling systems that are optimised for efficiency, reducing water requirements without compromising performance. ▪ Install dry fire suppression systems that do not rely on water, reducing the demand for water during fire emergencies.
Permafrost thawing	▪ Conduct permafrost surveys and geotechnical investigations to identify the extent of permafrost and its characteristics in the project area and consider relocation if necessary.	▪ Select foundation types that can incorporate large differential settlements.	NA

3. Municipal Solid Waste Management Sector Guidance

Introduction

The municipal solid waste management sector faces a twofold challenge posed by climate change, on the one hand being required to reduce greenhouse gas (GHG) emissions and on the other to also adapt to the physical consequences of climate-induced hazards. Encompassing separate waste collection, transport, recovery, and disposal services, the sector is confronted with climate risks associated with chronic climatic stressors, and a rise in extreme weather events. Climatic challenges pose threats to waste management infrastructure and have widespread implications throughout the waste management lifecycle affecting planning, design, construction, operation, and maintenance.

For owners and operators of waste management facilities, the impact of climate change may manifest in direct losses from infrastructure damage or indirect losses due to operational disruptions. Substantial operational hurdles resulting from climate-related incidents can lead to severe disruptions in waste management services, posing risks to public well-being, hygiene, and the environment. Such climate-induced disruptions also have the potential to erode trust and confidence in the waste sector's ability to provide reliable and efficient waste management service, affecting the appetite of private investors and insurability.

In light of this, the present chapter expands on the EC Technical Guidance for climate proofing of infrastructure (outlined in the **Introductory Chapter**), and the specific considerations required for climate resilience assessments within the municipal solid waste sector. The chapter considers the three sub-components of the municipal solid waste management sector currently eligible for EU grant funding:

- Separate waste collection and transport schemes.
- Treatment of separately collected waste (recyclable waste, bio-waste, textile waste, bulky waste) and residual waste in separate waste treatment facilities or integrated waste treatment facilities (also known as 'Recovery and Recycling Facilities' - RRF) , that may include one or more of the following treatment processes:
  - Mechanical separation.
  - Aerobic biological treatment of bio-waste.
  - Anaerobic digestion (AD) biological treatment of bio-waste.
- Dumpsite rehabilitation including biogas collection/utilisation & wastewater treatment.

The relevant climate hazards (chronic or acute) potentially affecting each of the sub-components are listed in **Table 3.1**. The color-coded marks (No sensitivity-Low-Medium-High)[47] indicate the general sensitivity level of each sub-component when considering a typical infrastructure. These marks are only intended as a general indication and do not necessarily reflect the relevance of the hazards to the project's specificities. It is important to note that the project promoter should extend the hazard list if necessary and consider any site- or project-specific hazards that may not be mentioned in **Table 3.1**. The sensitivity scoring of the various sub-components could be adjusted and adequately justified by the project promoter based on the project characteristics and the site's specificities.

Note that the timescale for the climate vulnerability and risk assessment should correspond to the intended lifespan of the investment being financed under the project, the lifespan often being (considerably) longer than the reference period used in the cost-benefit analysis.

[47] Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of the general sensitivity scores.

TABLE 3.1 • Overview of the relevant climate hazards affecting the examined municipal solid waste sub-components[48].

Hazards (in accordance with the EU Taxonomy, refer to Table 1.1 of the Introductory Chapter)	**Sub-component**				
	Separate collection & transport	**Mechanical separation**	**Aerobic treatment**	**Anaerobic digestion treatment**	**Dumpsite rehabilitation**
CHRONIC					
Changing temperatures/ Temperature variability	Low	Low	Medium	Medium	Low
Permafrost thawing	Medium	Medium	Medium	Medium	High
Changing precipitation patterns/ Precipitation or hydrological variability[49]	Medium	Low	Medium	Medium	Medium
Sea level rise/ Saline intrusion	Medium	High	High	High	High
Coastal erosion/ Soil erosion	Medium	Medium	Medium	Medium	Medium
ACUTE					
Heat wave	Medium	Medium	Medium	Medium	Medium
Cold wave	Medium	Medium	Medium	Medium	Low
Wildfire	Medium	High	High	High	High
Extreme wind (including storm, hurricane, tornado)	High	High	High	High	High
Drought	Low	Low	Medium	Medium	Low
Flood/Storm surge/ Heavy precipitation	High	High	High	High	High
Landslide/Avalanche/Subsidence	Medium	High	High	High	High

For waste management projects that are close to residential areas and might have issue with odour, the project promoter may also need to include "Changing wind patterns" in the analysis.

[48] The proposed No sensitivity-Low-Medium-High scoring levels are intended for a typical municipal solid waste project; however, it is advisable for the project team to verify and/or review their relevance to the project and its specific context and adju st them accordingly.
[49] These hazards refer to the chronic changes in the average precipitation, the frequency of rainfall events, the duration and onset of rainy season. Extreme precipitation is covered in the acute hazard of heavy precipitation.

Preparation, Planning & Resources

Project Characteristics

Tables 3.2-3.7 provide lists of indicative project elements that could be included in the climate assessment analysis for the sub-components of municipal solid waste management projects examined herein[50]. The final element list for each project is to be defined by the project team based on project specificities. The typical lifespan[51] of tangible infrastructure assets is also listed on the tables[52]. As observed, physical infrastructure assets may have varying lifespans. In the ensuing steps of the assessment, the selected temporal scale of the exposure analysis should aim to encompass the whole physical life of the project (i.e., the longest lifespan of its main infrastructure elements)[53]. It is noted that the various sub-components (i.e., mechanical separation, aerobic and anaerobic biological treatment) and their associated elements are treated as separate projects within this guidance. The project promoter is to select and combine the relevant project specific elements from each of the various sub-components. For example, a municipal solid waste management project may include both the sub-component separate collection and transport and the sub-component RRF including just one or two of the biologic treatment processes (i.e., aerobic and/or anaerobic treatment).

TABLE 3.2 • Indicative key project elements of **separate collection and transport schemes** to be included in the climate resilience assessment.

Element category	Assets/Processes (non-exhaustive list)	Typical lifespan (years)[52]
On-site assets	▪ Separate waste collection equipment (e.g., bins, containers, etc.)	5-15
	▪ Waste collection and/or transport vehicles and other mobile equipment (linear/rotary press, container carriers, rear/side loaders, hook-lift, etc.)	8-15
	▪ Waste container cleaning vehicles (high-pressure water, brush cleaning, automated cleaning, etc.)	8-15
	▪ Centralised waste collection points[54] (including infrastructure and signage/information boards)	10-20
	▪ Depots and maintenance areas, including civil works and equipment (hoists, lifts, etc.)	15-30
	▪ Waste transfer station[55] civil works, including conveyors and sorting equipment, if applicable	15-30
On-site processes	▪ Collection and transport ▪ Container cleaning ▪ Transport and collection routes optimisation ▪ Maintenance & repair (equipment and fleet) ▪ Monitoring & control ▪ Public awareness and education	-
Inputs	▪ Separately collected and residual waste streams ▪ Energy, fuel, water	-

[50] The terminology used for the element categories is indicative and may vary from sub-component to sub-component as appropriate.
[51] It is proposed to define the lifespan as the design working life (DWL), i.e., as the period for which the structure/equipment will be used with anticipated maintenance but without major repair.
[52] Values are indicative and may differ depending on project characteristics as appropriate. The actual lifetime of assets depends on material, regional context, economic conditions, procurement processes, etc. As such, a quite wide range is observed in the tables. It is noted that lifespan is of particular relevance for defining adaptation measures as result of risk analysis.
[53] Not all elements of an integrated municipal solid waste management project need to be evaluated for the same (long) lifespan. For example, sorting equipment or conveyors may undergo more frequent replacement during routine maintenance compared to the durable structures such as buildings, storage tanks or processing vessels.
[54] Centralised waste collection points (often referred to as 'public amenity centres', 'green islands', 'container parks', 'green points', 'green corners', etc.) are designated areas or stations where citizens can bring their waste for proper management, often strategically located in communities or urban areas.
[55] Built infrastructures, completely or partially enclosed, with or without preliminary sorting & preliminary storage of waste, compaction or non-compaction of wastes, and basic wastewater treatment facilities.

Outputs	▪ Separate collected and residual wastes	-
Interconnected systems (outside the direct control of the project)	▪ Waste generators (i.e., citizens, businesses, industries) ▪ Transport and access roads ▪ Energy grid, fuel, water supplies	-

TABLE 3.3 • Indicative key project elements of **mechanical separation facilities** to be included in the climate resilience assessment

Element category	Assets/Processes (non-exhaustive list)	Typical lifespan (years)[52]
On-site assets	▪ Civil works for waste acceptance facility (e.g., for separately collected waste streams (recyclables and/or bio-waste) and/or residual waste), and for treatment areas.	20-50
	▪ Equipment: sorting equipment (based on material properties, e.g., size, density, shape, and magnetic properties), processing equipment (e.g., balers, shredders, densifiers, crushers), transfer equipment (conveyor belts, air ducts, mobile equipment).	5-25
	▪ Storage building/areas civil works (for processed materials).	20-50
On-site processes	▪ Waste reception and pre-sorting ▪ Mechanical sorting ▪ Shredding and size reduction ▪ Baling and compacting ▪ Monitoring & control ▪ Maintenance & repair ▪ Residue handling and sanitation	-
Inputs	▪ Source separated recyclable waste and residual municipal waste (dependent on project type) ▪ Energy, fuel, water	-
Outputs	▪ Separated materials for re-use and/or recycling ▪ Bio-waste for further treatment ▪ Refuse derived fuels ▪ Rejects for final disposal	-
Interconnected systems (outside the direct control of the project)	▪ Waste collection and transport ▪ Energy grid, fuel, water supplies	-

TABLE 3.4 • Indicative key project elements of **aerobic biological treatment facilities** to be included in the climate resilience assessment.

Element category	Assets/Processes (non-exhaustive list)	Typical lifespan (years)[52]
On-site assets	In addition to the applicable assets of the mechanical separation: ▪ Biosolids mixer	10-15
	▪ Aerobic processing equipment (air blowers, air control, rotating drum vessels, vertical towers, etc.)	15-20
	▪ Civil works for maturation building/area including piping and infrastructure for treatment (e.g., aerated static pile systems, turned windrow systems, etc.)	20-30
	▪ Wastewater treatment facility	20-30
On-site processes	▪ Waste reception ▪ Windrow formation ▪ Aerobic decomposition ▪ Turning or agitation ▪ Maturation and curing ▪ Storage and distribution ▪ Monitoring & control (including odour control and pathogens elimination) ▪ Maintenance & repair	-
Inputs	▪ Source separated bio-waste ▪ Bio-waste component of residual waste (from mechanical separation) ▪ Energy, fuel, water	-
Outputs	▪ Compost ▪ Compost like output (CLO) ▪ Stabilised waste for final disposal ▪ Oversized organic materials for re-use ▪ Rejects for final disposal	-
Interconnected systems (outside the direct control of the project)	▪ Waste collection and transport ▪ Energy grid, fuel, water supplies	-

TABLE 3.5 • Indicative key project elements of **anaerobic digestion treatment facilities** to be included in the climate resilience assessment.

Element category	Assets/Processes (non-exhaustive list)	Typical lifespan (years)[52]
On-site assets	In addition to the applicable assets of the mechanical separation:	
	▪ Digestors	20-30
	▪ Biogas storage	20-30
	▪ Combined heat and power generation (CHP) units	15-20
	▪ Wastewater treatment facility	20-30
On-site processes	▪ Waste reception ▪ Mechanical pre-treatment ▪ Digestion ▪ Biogas collection ▪ Biogas utilisation ▪ Digestate management ▪ Storage and distribution ▪ Monitoring & control ▪ Maintenance & repair	-
Inputs	▪ Source separated bio-waste ▪ Bio-waste component of residual waste (from mechanical separation) ▪ Energy, fuel, water	-
Outputs	▪ Digestate/Compost ▪ Compost like output (CLO) ▪ Stabilised waste for final disposal ▪ Oversized organic materials for re-use ▪ Rejects for final disposal ▪ Biogas ▪ Heat/Electrical power	-
Interconnected systems (outside the direct control of the project)	▪ Waste collection and transport ▪ Energy grid, fuel, water supplies	-

TABLE 3.6 • Indicative key project elements of **dumpsite rehabilitation** to be included in the climate resilience assessment.

Element category	Assets/Processes (non-exhaustive list)	Typical lifespan (years)[52]
On-site assets	▪ Geomembranes	20-30
	▪ Piping and manifold systems (including gas wells)	15-25
	▪ Injection systems and wells	10-20
	▪ Leachate/water storage tanks	20-30
	▪ Gas storage (tanks or vessels) and compressor building	20-30
	▪ Electricity generator building	20-30
	▪ Electrical control equipment	5-20
	▪ Monitoring stations	15-25
On-site processes	▪ Leachate collection ▪ Leachate storage ▪ Recirculation ▪ Gas control ▪ Gas storage ▪ Leachate treatment ▪ Monitoring & control ▪ Maintenance & repair	-
Inputs	▪ Energy, fuel, water	-
Outputs	▪ Landfill gas ▪ Leachate ▪ Electrical power, heat, treated water	-
Interconnected systems (outside the direct control of the project)	▪ Energy grid, water supplies ▪ Access roads	-

Project Criticality

The element of criticality is related to the impact analysis (Module 5) and it is up to the project promoter and its team to decide if they will use it or not in the assessment. In the municipal solid waste management sector, a project's criticality may be assessed based on its significance on the broader waste management network to which it belongs and considering its **waste processing capacity and resilience**, as well as the presence of **adequate redundancies** (see also the Critical Entities Resilience Directive[56]). Indicative criticality levels (in qualitative terms) are suggested in **Table 3.7.**

[56] Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC: Member States will have to identify the critical entities for the sectors set out in the CER Directive by 17 July 2026. They will use this list of essential services to carry out risk assessments and to then identify the critical entities.

TABLE 3.7 • Indicative criticality levels for projects in the municipal solid waste sector.

Criticality Level	Description
Very low criticality	Very low contribution to the overall waste management network.
Low criticality	Low contribution to the overall waste management network. Redundancies and backup systems are in place, ensuring minimal disruptions in waste processing and allowing for the continuation of waste management services.
Moderate criticality	Considerable contribution to the overall waste management network. Above 50% processing capacity can be achieved if the system operates with available redundancies/backup systems/inputs.
High criticality	Significant contribution to the overall waste management network. Reduced processing capacity can be achieved when the (limited) available redundancies/backup systems/inputs are used. The risk of a total system breakdown cannot be excluded.
Very high criticality	Major contribution to the overall waste management network. No redundancies exist, or the waste management system cannot operate using the available redundancies/backup systems/inputs.

3.1 Separate waste collection and transport schemes

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of separate waste collection and transport schemes to climate hazards are provided in **Table 3.8** along with indicative scores per element category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical separate waste collection and transport schemes under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities. It is noted that potential sensitivities of waste collection and transport schemes (which may eventually be impacted by climate-related factors) are dependent on the type of scheme, and therefore, cannot receive a standard score in the table below. For example, heavy rain may pose challenges to a door-to-door collection scheme in the case where a smaller street is flooded, while the same event may have minimal impact on a central collection scheme where the routing passes only through main roads that are less prone to flooding. Following this example it is crucial to recognise that the *transportation routes and roads*, which are regarded as interdependent elements of the project (as shown in Table 3.2), *have a significant impact on the efficiency of waste collection and transportation operations and should therefore always be clearly defined and included in the sensitivity analysis*; The project team should assign justifiable scores based on the project specifics to each element.

TABLE 3.8 • Sensitivities of separate waste collection and transport elements.

Climate Hazard	Sensitivities			
Flood **Storm surge** **Heavy precipitation**	• Containers washed away or damaged. • Submerged vehicles and damage to their mechanical and electrical elements. • Issues on the movement and operations of waste collection vehicles, compromising hygiene standards. • Threats to structural integrity and stability of low-lying infrastructures and equipment (e.g., at centralised waste collection points or depots). • Flooded roads rendering routes impassable or with reduced safety conditions, affecting optimal routing strategies for waste collection vehicles. • Degradation of certain waste materials due to water exposure. • Waterlogged waste increasing bulk weight/density. • Damage or downtime to the energy grid and fuel supply systems, leading to operational disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Extreme wind (including storm, hurricane, tornado)	• Damage to waste containers, leading to full destruction or partial displacements. • Damage to facilities and access roads, leading to operational disruptions and high repair costs. • Need for adjustments to transport logistics and cleaning schedules, leading to hygiene issues in cases of very long delays.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Heat wave	• Accelerated degradation of materials, impacting the longevity and structural integrity of waste containers, e.g., in hot and dry conditions, plastic waste containers may become brittle and prone to breakage, impacting their durability. • Reduced overall performance of waste collection and transport vehicles due to increased temperature-related stress or overheating, leading to reduced effectiveness or reduced lifespan of the vehicles and increased maintenance needs. • Challenges in handling of waste during collection. • Malfunctions to equipment in depots, necessitating increased maintenance. • Malfunctions to sorting equipment in waste transfer stations, affecting sorting efficiency. • Reduced performance of monitoring and control systems, leading to system failures. • Temperature-related changes in the composition of separated waste (input and output), influencing handling and transportation. • Damage or downtime to the energy grid and fuel supply systems, leading to operational disruptions. • Degradation of the condition of access roads, influencing logistics.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Cold wave	• Freezing of moisture within waste containers, causing structural damage and reducing durability. • Reduced performance of waste collection and transport vehicles, causing issues such as engine freezing and reduced efficiency. • Reduced efficiency of cleaning processes when water is freezing and causing equipment malfunctions. • Operational challenges or physical damage to equipment in depots, including hoists and lifts, causing increased maintenance needs and repair costs. • Malfunctions to sorting equipment in waste transfer stations, affecting sorting efficiency.			

	• Dangerous road conditions (black ice, snow cover), affecting optimal routing strategies for waste collection vehicles. • Changes in the characteristics of separated waste (input and output), influencing sorting and processing efficiency, handling and transportation. • Damage or downtime to the energy grid and fuel supply systems, leading to operational disruptions.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Landslide Avalanche Subsidence	• Damage to waste containers, e.g., debris flows from landslides burying waste containers, affecting their functionality. • Road damage impacting the efficiency and safety of waste vehicles. • Facilities (centralised waste collection points, depots, transfer stations, etc.) at landslide/avalanche/subsidence-prone areas at direct risk for severe damage and increased maintenance needs. • Changes in road conditions, influencing optimal routing strategies for waste collection vehicles. • Introduction of contaminants into separated waste streams and increased bulk density of waste materials due to debris. • Damage or downtime to the energy grid and fuel supply systems, leading to operational disruptions.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Permafrost thawing	• Ground instability, impacting the placement and stability of waste containers (especially underground type). • Uneven ground settling, affecting the stability of equipment and fleet vehicles, increasing maintenance needs, influencing transportation logistics, and causing damage to depot infrastructure and equipment. • Damage to infrastructure at centralised waste points, including signage, impacting overall functionality. • Stability issues of waste transfer station structures, including conveyors and sorting equipment, leading to malfunctions. • Shifting of underground pipes and stress connections, leading to disruptions in energy grids and fuel supplies.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Sea level rise Saline intrusion	• Increased corrosion, accelerating wear and tear of waste containers. • Waste collection operational issues, especially in low-lying coastal areas. • Reduced effectiveness of cleaning processes, resulting in reduced hygiene levels. • Inundation and infrastructural damage at the coastal depots and waste transfer stations. • Damage or downtime to the energy grid and fuel supply systems, leading to operational disruptions.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Coastal erosion Soil erosion	• Unstable ground conditions, impacting the stability and placement of waste containers. • Stability issues in depots or any other facilities (centralised waste collection points, transfer stations), causing damage to equipment and infrastructure. • Issues on coastal road conditions, influencing the efficiency and safety of waste vehicles and altering the transportation routes.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing precipitation patterns	• Issues on road conditions, influencing the efficiency and safety of waste vehicles and causing operational challenges.			

Precipitation or hydrological variability	• Changes in waste composition. • Need for adjustments in the scheduling of cleaning operations, impacting hygiene standards. • Increased equipment wear, leading to more frequent maintenance needs for both equipment and fleet vehicles.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Wildfire	• Damage to facilities, infrastructure, equipment and fleet vehicles. • Direct threat to waste containers, causing damage or destruction. • Damage or downtime to routes used by waste vehicles, leading to operational disruptions. • Damage or downtime to the energy grid and fuel supply systems, leading to operational disruptions.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing temperatures Temperature variability	• Structural integrity issues for the waste containers, leading to brittleness or warping. • Reduced vehicle performance, especially for those relying on specific operational temperature ranges. • Reduced cleaning efficiency for high-pressure water or automated cleaning vehicles in frequent freezing temperatures. • Faster degradation of infrastructure at centralised waste collection points. • Issues on road conditions, influencing optimal routing strategies for waste collection vehicles. • Changes in the composition of separated waste (input and output), influencing sorting and processing efficiency, handling and transportation.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Drought	• Limitations of the use of water-dependent cleaning methods, leading to inadequate hygiene levels. • Challenges to overall equipment performance due to lack of water for dust control measures. • Reduced vehicle operativity and efficiency due to reduced vehicle washing, including accumulation of contaminants on vehicle surfaces.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Separate waste collection and transport systems are distributed systems with significant spatial variability, and therefore may exhibit variations in hazard exposure depending on the assets' location (depots, transfer stations, roads, waste containers, centralised points, etc.). Hazard and project element maps should be superimposed to identify the system's exposure.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts (with or without the system's criticality), readers are referred to the **Introductory Chapter** (Module 5). To assist users with the scoring procedure, an overview of significant impacts to waste collection and transport schemes across various risk areas (RA) is provided in the table below.

TABLE 3.9 • Climate impacts for separate waste collection and transport schemes (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damages:** Separate waste collection and transport schemes face the risk of asset damage due to extreme weather conditions. Infrastructure, including the waste collection fleet, may be susceptible to physical damage, leading to operational downtime, increased maintenance and reinvestment costs. **Service Disruptions:** Even in the absence of explicit physical damage, climate-induced events, e.g., floods and storms, can disrupt waste collection and transportation services. Road closures and temporary suspension of waste collection or transport services may be necessary until the environmental conditions stabilise, affecting operational efficiency.
RA2: Safety and Health	**Increased Incidents:** Changes in climate patterns, including extreme weather events, can elevate safety risks for both waste collection and transport operations. Intense storms, flooding, or icy conditions may lead to an increased likelihood of accidents, posing risks to the safety of workers. **Traffic Management Challenges:** Climate impacts, such as heavy precipitation and temperature extremes, may disrupt traffic management systems associated with waste collection and transport. This disruption can pose significant safety risks by affecting the coordination and control mechanisms of these systems.
RA3: Environment	**Equipment Malfunctions and Environmental Consequences:** Climate-induced malfunctions in waste collection and transport equipment can have environmental consequences. Equipment breakdowns may lead to the release of pollutants, contributing to environmental issues. **Energy Demand Increase:** The need for climate control measures, such as heating or cooling , in waste vehicles or facilities related to collection and transport (e.g., depots, transfer stations) resulting in higher energy consumption. This increased energy demand, especially in cases involving fossil fuel usage, contributes to carbon emissions further impacting the environment.
RA4: Social	**Equity Challenges and Access Disparities:** Climate impacts on vulnerable settlements or neighbourhoods worsening existing disparities in access to separate waste and transport services. **Public Comfort and Hygiene Concerns:** Climate-related disruptions affecting public comfort and hygiene, especially in crowded urban areas. For example, interruptions in waste collection services leading to overflowing bins and unattended waste accumulations, creating discomfort and potential health hazards for the public.
RA5: Financial impacts	**Operational Disruptions and Maintenance Costs:** Climate impacts on waste collection and transport assets leading to operational disruptions and increased maintenance and reinvestment costs. Frequent repairs, retrofitting, and adaptations to changing climate conditions contribute to financial challenges for waste management and transport agencies. **Infrastructure Adaptation Costs:** Retrofitting existing infrastructure to withstand climate impacts, such as rising sea levels or extreme temperatures, necessitates substantial financial investments for waste management and transport authorities. **Economic Impact:** Disruptions in waste collection and transport services resulting in widespread economic ramifications.
RA6: Reputation	**Service Reliability and Public Perception:** Frequent disruptions in waste collection and transport services due to climate impacts eroding public trust and satisfaction. Reliability

	issues, delays, and accidents adversely impacting the reputation of waste management and transport providers, as well as the perception of local authorities. **Commitment to Sustainable Practices:** The reputation of waste management and transport systems is linked to commitments to sustainable practices. Neglecting to address climate impacts and implement environmentally friendly measures may lead to reputational damage, particularly in a context where public awareness of climate change and sustainability is on the rise.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 3.10 presents potential adaptation solutions for climate hazards that could impact separate waste collection and transport schemes. The suitability of each measure is linked to the encountered level of risk and the uncertainty of climate projections, while the timing of implementation is aligned with specific project stages. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 3.10 • Separate waste collection and transport schemes: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. Informed decision-making is to be applied along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Flood Storm surge Heavy precipitation	▪ Conduct a comprehensive risk assessment to identify areas prone to flooding. ▪ Consider project relocation for critical facilities to areas less prone to flooding. Assess the feasibility of migrating collection points or transfer stations to higher ground or areas with lower flood risk.	▪ Design waste collection equipment, centralised waste collection points, depots, and transfer stations with elevated foundations. ▪ Implement smart infrastructure features, such as flood sensors and automated gate controls to depots and waste transfer stations. ▪ Integrate green infrastructure elements, such as permeable surfaces and rain gardens, to manage and absorb excess precipitation, reducing the risk of surface runoff and flooding.	▪ Utilise advanced weather monitoring systems to track precipitation patterns and predict potential flooding or storm surges. Implement automated alert systems to trigger preventive measures. ▪ Implement route optimisation software that considers real-time weather data to adapt waste collection vehicle routes in response to changing weather conditions. ▪ Promote public awareness campaigns to educate communities on waste management practices during extreme weather events like securing waste containers and following proper disposal guidelines to minimise environmental impact.
Extreme wind (including storm, hurricane, tornado)	▪ Conduct risk assessments considering extreme winds, heavy rains, tornadoes, and cyclones and consider relocation in case of excessive residual risk. ▪ Evaluate the feasibility of constructing sheltered infrastructure with storm-resistant features.	▪ Design waste collection equipment with aerodynamic features to reduce wind resistance. Consider using weighted containers or containers with low wind profiles to minimise the risk of displacement during storms. ▪ Construct centralised waste collection points and waste transfer stations with reinforced structures, impact-resistant materials, and secure anchoring systems to withstand strong winds.	▪ Utilise advanced weather monitoring systems to track approaching storms, tornadoes, cyclones, hurricanes, or typhoons and issue alerts. ▪ Provide training for waste management personnel on emergency response procedures during storm events, emphasising safety measures. ▪ Develop contingency plans for waste collection routes, considering alternative paths to avoid areas prone to tornadoes or cyclones. ▪ Establish protocols for securing waste collection vehicles during extreme wind events, including designated storage areas or wind-resistant garages.
Heat wave	▪ Site selection to minimise likelihood of exposure to extreme heat and maximises natural shading and ventilation opportunities. ▪ Consider factors such as proximity to urban heat islands, prevailing wind patterns, and local microclimates when selecting the site location.	▪ Implement cooling measures for waste collection vehicles, such as reflective coatings, ventilation systems, or shade structures. ▪ Design waste collection equipment with insulated materials to minimise heat absorption and reduce the risk of odours or heat-related issues associated with certain types of waste.	▪ Adopt flexible scheduling for waste collection operations during heatwaves, to avoid peak temperatures and ensure the well-being of personnel. ▪ Implement real-time monitoring systems for waste collection vehicles to track internal temperatures and alert operators or

	▪ Ensure easy access to cool, potable water within the facility.	▪ Design facility layout and orientation to optimise natural airflow and shading to reduce heat buildup. ▪ Incorporate heat-resistant landscaping around waste collection points and transfer stations to reduce the overall ambient temperature and create a more comfortable working environment.	management if heat levels become unsafe for workers, equipment or waste materials. ▪ Establish and communicate safety protocols for waste management personnel. ▪ Launch public awareness campaigns to educate residents about waste management practices during heatwaves. ▪ Develop heat-specific waste collection route optimisation strategies.
Cold wave	▪ Site selection to minimise likelihood of exposure to extreme cold temperatures and frost-prone areas, avoiding low-lying areas and locations prone to cold air pooling.	▪ Equip waste collection vehicles with winter-ready features, including antifreeze systems, snow tires, and heating systems for critical elements. Ensure that vehicles are capable of operating effectively in cold weather conditions.	▪ Implement snow managment procedures at waste transfer stations and depots to maintain accessibility. This includes snowploughs, de-icing agents, and designated areas for snow disposal. ▪ Establish and communicate safety protocols for waste management personnel, including guidelines for proper clothing, breaks in heated areas, and the use of personal protective equipment (PPE) suitable for extreme cold conditions. ▪ Inform residents about any changes in waste collection schedules. ▪ Develop waste collection routing considering road conditions during icy or snowy weather. ▪ Establish contingency routes and coordinate with local authorities for road maintenance.
Landslide Avalanche Subsidence	▪ Conduct thorough geotechnical assessments prior to site selection to identify and avoid areas prone to landslides, avalanches, or subsidence. ▪ Diversify supply routes and establish alternatives to be used during high-risk periods.	▪ Reinforce the foundations of waste collection infrastructure, including depots, centralised waste collection points, and transfer stations. ▪ Implement slope stabilisation measures (e.g., retaining walls, slope reinforcement) to mitigate the risk of landslides in the vicinity of the site. ▪ Vegetate slopes in the vicinity of the facility to enhance stability. ▪ Construct physical barriers such as retaining walls, deflection structures, or debris nets.	▪ Utilise real-time monitoring systems to track ground movements and potential risks of landslides, avalanches, or subsidence. Implement automated alerts to trigger emergency protocols and reroute waste collection vehicles when necessary. ▪ Collaborate with local authorities and geotechnical experts to stay informed about changing geological conditions.
Permafrost thawing	▪ Consider the geographical extent of permafrost and evaluate the vulnerability of critical facilities. ▪ Evaluate the feasibility of relocating waste collection points, transfer stations, and depots in areas where permafrost thawing poses a significant risk.	▪ Design elevated foundations for waste collection equipment, depots, centralised waste collection points, and transfer stations to minimise ground contact and reduce the risk of structural damage during permafrost thawing. ▪ Implement ground reinforcement measures, such as the use of thermosyphons or gravel	▪ Implement permafrost thaw monitoring systems and establish protocols for responding to accelerated thawing, including potential ground subsidence risks. ▪ Modify waste collection vehicles to operate effectively on thawing permafrost. Consider equipping vehicles with larger, low-pressure tires

		pads, to enhance permafrost stability around waste collection and transfer infrastructure.	to minimise ground disturbance and prevent damage to the thawing surface. ▪ Conduct regular inspections of permafrost-affected areas to identify signs of ground instability and implement measures in time.
Sea level rise **Saline intrusion**	▪ Consider elevating critical facilities, such as depots and transfer stations, to minimise the risk of inundation. ▪ Evaluate the feasibility of relocating waste collection points or transfer stations to higher ground in areas susceptible to sea level rise. ▪ Consider long-term projections for sea level changes in site selection.	▪ Design waste collection depots, centralised waste collection points, transfer stations, and storage areas with elevated foundations to mitigate the impact of rising sea levels. Implement flood barriers and other resilient features to prevent saline intrusion. ▪ Utilise corrosion-resistant materials for waste collection containers, especially in coastal areas experiencing saltwater intrusion. ▪ Integrate green infrastructure elements, such as coastal vegetation and wetlands, to act as natural buffers against sea level rise.	▪ Implement routine inspections of waste collection infrastructure in coastal areas to identify and address corrosion issues. ▪ Explore alternative water sources for cleaning and maintenance purposes in areas affected by ground water saline intrusion.
Changing temperatures **Temperature variability**	NA	▪ Consider materials, construction methods and vehicles that are resilient against both extreme heat and cold conditions.	▪ Consider flexible scheduling, contingency routes, and operational adjustments based on temperature forecasts.
Drought	▪ Explore alternative water sources for cleaning and maintenance purposes during drought conditions. ▪ Assess options for fire prevention systems that do not rely heavily on water.	▪ Implement water-conserving technologies for waste vehicles, such as high-pressure, low-water usage cleaning systems. ▪ Incorporate drought-resistant landscaping around waste collection points and transfer stations to reduce water demand for maintaining green areas.	▪ Implement real-time water monitoring systems to track water usage across waste collection and transfer operations. Set benchmarks for water consumption and implement alerts for efficient water management during droughts.
Coastal erosion **Soil erosion**	▪ Identify areas along coastlines or slopes prone to erosion and assess the potential impact on waste management facilities. ▪ Evaluate the feasibility of relocating waste collection points or transfer stations away from eroding coastlines or unstable soil areas. ▪ Designate buffer zones in the planning between waste collection points and coastlines or areas prone to soil erosion.	▪ Design infrastructure with erosion-resilient features, such as reinforced foundations and erosion-resistant materials. ▪ Implement slope stabilisation measures, such as retaining walls or vegetation and use erosion-control blankets or mats to stabilise exposed soil.	▪ Perform regular site inspections to identify instability issues and utilise alerts to trigger emergency response measures when accelerated erosion is detected. ▪ Modify waste collection vehicles to navigate eroded or unstable terrains. Consider equipping vehicles with features like larger tires or four-wheel drive where necessary.
Changing precipitation patterns	NA	▪ Design waste collection equipment to prevent water ingress during precipitation, reducing the risk of waste contamination.	▪ Conduct regular inspections of drainage systems around waste collection and transfer facilities (depots, transfer stations, collection points).

Precipitation or hydrological variability			
Wildfire	▪ Evaluate the feasibility of relocating waste facilities away from high-risk zones.	▪ Design waste collection and transfer infrastructure with fire-resistant materials and features. Utilise non-combustible materials for structures. ▪ Implement firebreaks or cleared zones to minimise the risk of fire spreading. ▪ Install automatic fire suppression systems at critical areas and include sprinkler systems, foam suppression, or water cannons for rapid response.	▪ Implement vegetation management strategies around waste collection points and transfer stations to reduce the risk of fire spread. Clear combustible vegetation, establish firebreaks, and use fire-resistant landscaping to create defensible spaces. ▪ Utilise real-time fire monitoring systems to track wildfire conditions in proximity to waste collection and transfer facilities. ▪ Enhance periodic maintenance protocols of fire management/extinguishing installations.

3.2 Mechanical separation

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of mechanical separation facilities to climate hazards are provided in **Table 3.11** along with indicative scores per element category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical mechanical separation elements under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities. It is noted that potential sensitivities of a mechanical separation facility to climate-related factors are dependent on the type of the facility and its machinery/equipment (fully, partially enclosed or external), and therefore, cannot receive a standard score in the table below. The project team should score the element categories based on project specifics.

TABLE 3.11 • Sensitivities of mechanical separation.

Climate Hazard	Sensitivities			
Extreme wind (including storm, hurricane, tornado)	• Roof damage, structural integrity issues, and water intrusion causing damage to the facility. • Damage to equipment, leading to material scattering. • Contamination of stored waste or washouts of materials. • Increased need for maintenance and repair due to equipment damage or structural issues. • Damage to energy infrastructure (e.g., electrical lines, transformers, generators), leading to power outages and disruptions in facility operations. • Disruption to supply of incoming waste materials due to road closures, debris blockages, or safety hazards. • Damage or downtime to the energy grid and fuel supply systems, leading to operational disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Flood Storm surge Heavy precipitation	• Inundation of waste facilities, causing structural damage, equipment malfunction (submersion, corrosion, and electrical failures), and contamination, loss or washouts of stored materials. • Health hazards due to contamination of stored waste, leaching of hazardous substances, and increased risks of environmental pollution. • Increased demand for maintenance and repair activities. Corrosion of equipment and structures requires frequent inspections, repairs, and replacement of elements. • Disruption of the waste collection routes, leading to waste input alterations. • Damage or downtime to the energy grid and fuel supply systems, leading to operational disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Sea level rise Saline intrusion	• Inundation of waste facilities, causing structural damage, equipment malfunction (submersion, corrosion, and electrical failures), and contamination, loss or washouts of stored materials. • Health hazards due to contamination of stored waste, leaching of hazardous substances, and increased risks of environmental pollution. • Increased demand for maintenance and repair activities. Corrosion of equipment and structures requires frequent inspections, repairs, and replacement of elements. • Damage to the waste collection routes at coastal or low-lying areas, leading to waste input disruptions.			

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems
Wildfire	• Damage to equipment, structures, and stored materials, leading to facility's full or partial destruction resulting in costly repairs or replacements and operational disruptions. • Electrical lines, transformers, and generators are vulnerable to fire and heat-induced damage. • The heat and smoke can change the material properties of recyclables, rendering them unusable or reducing their market value. • Disruptions to waste deliveries due to road closures, safety hazards, or evacuation orders. • Risk of fire damage to electrical grid infrastructure, substations, and transmission lines, leading to widespread power outages.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Landslide Avalanche Subsidence	• Structural damage, collapse, or blockage of accessibility. • Damage of equipment through impact, burial under debris, or structural destabilisation. • Increased maintenance and repair for damaged equipment and structures. • Contamination or loss of waste materials, affecting processing efficiency and material quality. • Disruptions in waste delivery. • Damage or downtime to the energy grid and fuel supply systems, leading to operational disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Heat wave	• Reduced productivity of workers and health safety issues. • Heat-related expansion and contraction of materials, affecting equipment alignment. • Reduced performance of equipment due to overheating and increased wear of structures and equipment (e.g., bearings, motors). • Increased maintenance requirements, such as more frequent inspections, lubrication, and part replacements. • Increased demand for cooling to maintain optimal operating temperatures, leading to higher energy consumption and potential overload on cooling systems. • Increased overall demand for electricity for cooling and equipment operation can lead to grid instability, potential brownouts or blackouts, and higher electricity costs. • Changes in the composition of separated waste. • Increased risk for heat-related fires in stored wastes (especially refuse-derived fuels). • Operational issues to the energy grid, particularly during peak cooling demand periods or due to heat-related damages to the infrastructure.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Cold wave	• Ice formation on surfaces, causing slip hazards. • Reduced equipment efficiency or malfunctions (reduced flexibility, increased friction, lubrication issues and movement challenges of mechanical parts. • Increased demand for heating for staffed areas, leading to higher energy consumption. • Frozen waste leading to difficulties in processing and causing increased wear on equipment. • RDF with higher moisture content is more susceptible to freezing, resulting in handling, storage, and combustion issues. • Operational issues to the energy grid, particularly during peak heating demand periods.			

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems
Permafrost thawing	• Ground stability and shifting issues, leading to subsidence, uneven settling, and potential structural damage, affecting the alignment and operation of equipment. • Damage to underground pipelines or electrical conduits of the facility's energy system (or the interdependent system), leading to leaks or operational disruptions. • Road damage, closures, and disruptions in waste delivery.			
Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems
Coastal erosion **Soil erosion**	• Land loss, compromising the integrity of facility foundations. • Unstable ground leading to equipment misalignment, increased vibration, increased wear and damage. • Shifting of sensor placements, leading to electrical disruptions, and data inaccuracies. • Road damage, closures, and disruptions in waste delivery.			
Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems
Drought	• Reduced water availability for dust suppression and fire prevention. Dust buildup can affect equipment performance and worker health. • Increased risk of fire hazards in storage areas due to dry waste materials. • Drought conditions can affect the quality of separated materials, especially paper and cardboard.			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems
Changing precipitation patterns **Precipitation or hydrological variability**	• Increased equipment corrosion, electrical malfunctions, and increased wear on moving parts. • Increased moisture levels leading to waste material clumping, equipment clogging. • Material slippage on conveyor belts, increased friction, and material blockages. • Deterioration of stored materials. • Damage to sensors, control panels, and electrical elements. • Waterlogged waste piles, leaching of contaminants, and runoff into surrounding areas. • Road damage, closures, and disruptions in waste delivery.			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems
Changing temperatures **Temperature variability**	• Expansion and contraction of materials, causing cracks or leaks in structures. • Change in material properties of equipment such as conveyor belts and hydraulic systems. • Changes in the thermal conditions within storage buildings and areas. • Reduced efficiency of heating and cooling systems, leading to changes in energy consumption.			
Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

The elements of the mechanical separation may be fully, partially enclosed or external, and therefore, may exhibit variations in hazard exposure depending on the assets' location. For example, if a trommel screen is fully enclosed in the waste facility it will not be exposed to the hazard of storms and extreme winds which is not the case if it is external.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts (with or without the project's criticality), readers are referred to the **Introductory Chapter** (Module 5). To assist users with the scoring procedure, an overview of significant impacts to the mechanical separation facilities across various risk areas (RA) is provided in the table below.

TABLE 3.12 • Climate impacts for the mechanical separation facilities (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damages:** Processing and sorting equipment such as shredders, separators, crushers, balers and conveyor belts, as well as storage facilities are at risk of damage leading to potential breakdowns. **Service Disruptions:** Climate-induced events like floods and storms can disrupt the operation of equipment, resulting in operational downtime. Malfunctions of waste equipment due to extreme weather events may necessitate temporary suspension of facility operations, impacting operational efficiency.
RA2: Safety and Health	**Worker Safety Risks:** Increased safety risks for personnel operating equipment during extreme weather events, such as heat waves or flooding. Increased risk for accidents or injuries among waste management personnel. **Air Quality Concerns:** Malfunctions in equipment due to climate impacts may result in the release of pollutants or hazardous substances into the air. Exposure of workers to airborne particles or pollutants during maintenance or repair activities.
RA3: Environment	**Equipment Malfunctions and Environmental Consequences:** Climate-induced machinery breakdowns causing leaks or releases of gases or liquids leading to unintended releases of pollutants into the environment (e.g., case of a seal failure). **Energy Consumption and Emissions:** Higher energy consumption for climate control measures in mechanical equipment and storage areas. Increased use of energy-intensive processes, such as densifiers or crushers, contributing to carbon emissions and environmental impact.
RA4: Social	**Community Disparities:** Mechanical equipment failures leading to operational disruptions in waste management services affecting the citizens reliant on the facility for waste disposal or recycling. **Cascading Disruptions:** With a waste facility experiencing a shutdown or malfunction, neighbouring operable facilities are often faced with the challenge of handling increased waste load. Consequently nearby communities may face discomfort or inconvenience due to the increased activity and potential impacts associated with this redistribution of waste. Possible discomfort due to odour emissions.
RA5: Financial impacts	**Operational Costs:** Increased operational costs due to repairs or replacement of equipment damaged by extreme weather events. Financial strain on facility operators in addressing frequent breakdowns or retrofitting of machinery to withstand climate impacts. **Infrastructure Investment:** Investment required for upgrading or retrofitting existing facilities to be resilient to floods, storms, or other extreme weather events. Financial burden of implementing climate adaptation measures to ensure the longevity and efficiency of equipment.
RA6: Reputation	**Reliability and Trust:** Frequent disruptions in waste processing operations affecting the reliability and timeliness of services provided by waste service operators. Negative public perception due to delays in waste recycling or recovery services during extreme weather events. **Commitment to Sustainability:** Reputation risks for waste service operators not adapting to climate impacts, affecting perceptions of environmental responsibility. Public scrutiny on waste management practices, particularly regarding emissions and environmental stewardship during extreme weather events.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 3.13 presents potential adaptation solutions for climate hazards that could impact the mechanical separation facilities. The suitability of each measure is linked to the encountered level of risk and the uncertainty of climate projections, while the timing of implementation is aligned with specific project stages. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 3.13 • Mechanical separation facilities: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. Informed decision-making is to be applied along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Extreme wind (including storm, hurricane, tornado)	▪ Consider the feasibility of a fully enclosed facility.	▪ Design equipment with reinforced structures and anchoring systems to withstand high winds. ▪ Implement wind-resistant materials for roofs, walls, and equipment housings. ▪ Install wind-resistant doors, shutters, or covers for equipment openings and access points. ▪ Incorporate lightning protection systems for sensitive equipment and electrical infrastructure.	▪ Implement regular monitoring of storm forecasts and tornado alerts for early warning. ▪ Train staff on storm and hurricane or tornado safety protocols, including evacuation procedures. ▪ Provide backup power sources or generators to ensure continuous operation during power outages.
Flood Storm surge Heavy precipitation	▪ Consider the feasibility of relocating or elevating critical elements.	▪ Design equipment with elevated foundations or platforms to mitigate flood risks. ▪ Implement flood barriers or levees around critical equipment areas to prevent water ingress. ▪ Design stormwater drainage systems with increased capacity to handle heavy precipitation. ▪ Install flood-resistant materials for walls, floors, and equipment housings. ▪ Incorporate waterproof seals and covers for vulnerable equipment openings. ▪ Design storage areas with sloped floors and drainage systems to prevent water pooling.	▪ Implement regular monitoring of weather forecasts and flood alerts for early warning. ▪ Maintain flood barriers, levees, and drainage systems to ensure functionality. ▪ Train staff on flood response protocols, evacuation procedures, and equipment shutdown. ▪ Conduct routine inspections of equipment for signs of water damage or corrosion. ▪ Provide emergency backup power sources or generators to ensure continuous operation.
Sea level rise Saline intrusion	▪ Consider the feasibility of relocating critical elements.	▪ Elevate critical equipment, storage areas, and infrastructure above projected sea levels. ▪ Design coastal protective barriers. ▪ Implement waterproof seals and corrosion-resistant materials or protective coatings for equipment exposed to saline intrusion. ▪ Design processing areas with drainage systems that can handle water runoff.	▪ Monitor sea level rise projections and prepare/implement adaptive measures as needed. ▪ Implement regular inspections of equipment for signs of corrosion or saltwater damage. ▪ Train staff on proper cleaning and maintenance procedures for equipment. ▪ Conduct routine checks of seals and gaskets to ensure integrity.
Heat wave	▪ Site selection to minimise exposure to extreme heat and maximise natural shading and ventilation opportunities.	▪ Design equipment with heat-resistant materials or coatings to withstand high temperatures. ▪ Implement insulation for equipment and storage areas to reduce heat absorption.	▪ Implement regular monitoring of indoor temperatures in equipment areas. ▪ Implement regular inspections of equipment for signs of overheating or wear due to high temperatures.

	▪ Consider factors such as proximity to urban heat islands, prevailing wind patterns, and local microclimates when selecting the site location. ▪ Consider the feasibility of a fully enclosed facility. ▪ Ensure easy access to cool, potable water within the facility.	▪ Install ventilation and exhaust systems to dissipate heat from processing and storage areas. ▪ Design facility layout to optimise natural shade and airflow for cooling. ▪ Incorporate shade structures or awnings over outdoor equipment to reduce direct sun exposure.	▪ Train staff on heat wave safety protocols, including hydration and rest breaks and adjust work schedules as needed. ▪ Schedule equipment maintenance during cooler times of the day to minimise heat stress. ▪ Provide cooling stations or rest areas for personnel working in hot environments.
Wildfire	▪ Conduct wildfire risk assessments to identify areas within and around the facility prone to wildfires.	▪ Implement fire breaks or defensible space around the facility to reduce wildfire risks. ▪ Design facility layout to minimise ignition sources and fuel accumulation. ▪ Install ember-resistant vents and screening to prevent ember intrusion into equipment areas. ▪ Design storage areas with fire-rated walls and barriers to contain potential fires. ▪ Install automatic fire suppression systems at critical areas and include sprinkler systems, foam suppression, or water cannons for rapid response.	▪ Implement regular monitoring of wildfire alerts and weather conditions for early detection. ▪ Consider real time temperature monitoring at the facility (particularly at waste storage areas and equipment susceptible to overheating), capturing the temperature distribution, with automatic detection of hot spots. ▪ Maintain fire breaks and vegetation management around the facility to reduce fuel loads. ▪ Train staff on fire safety protocols, evacuation procedures, and equipment shutdown and perform regular fire drills. ▪ Enhance periodic maintenance protocols of fire management/extinguishing installations. ▪ Provide emergency backup power sources or generators in case of power outages during wildfires.
Cold wave	▪ Consider the feasibility of a fully enclosed facility.	▪ Design equipment with cold-resistant seals, gaskets, and lubricants for operation in low temperatures. ▪ Implement insulation for equipment and storage areas to maintain stable internal operational temperatures. ▪ Design facility layout to optimise heat distribution and minimise cold spots. ▪ Incorporate airlocks or vestibules at entrances to prevent heat loss and cold drafts.	▪ Implement regular monitoring of indoor and outdoor temperatures in equipment areas. ▪ Maintain heating systems and insulation to prevent freezing of critical elements. ▪ Train staff on cold wave safety protocols, including proper clothing and equipment operation. ▪ Conduct regular checks of water lines, valves, and pumps for signs of freezing. ▪ Provide backup heating sources or emergency generators in case of power outages.
Landslide **Avalanche** **Subsidence**	▪ Conduct geological surveys and assessments to identify areas prone to landslides, avalanches, or subsidence. ▪ Consider the feasibility of relocating critical equipment away from hazard-prone areas.	▪ Implement slope stabilisation measures such as retaining walls or soil reinforcement. ▪ Design equipment with sturdy foundations and anchoring systems to withstand ground movement. ▪ Incorporate sensors and monitoring systems to detect early signs of slope instability.	▪ Implement regular monitoring of slope stability and ground movement using sensors. ▪ Maintain slope stabilisation measures and conduct inspections for signs of deterioration. ▪ Train staff on landslide, avalanche, and subsidence response protocols and evacuation procedures.

		▪ Design facility layout to avoid areas prone to landslides or subsidence. ▪ Install protective barriers or deflectors to mitigate avalanche risks in mountainous regions.	▪ Conduct routine inspections of equipment for signs of damage from ground movement. ▪ Develop contingency plans for equipment shutdown, evacuation, and emergency repairs.
Permafrost thawing	▪ Conduct permafrost mapping and geotechnical studies to identify areas affected by thawing. ▪ Consider the feasibility of relocating critical elements to areas less prone to permafrost thawing.	▪ Design foundations and structures with thermal insulation to minimise heat transfer to permafrost. ▪ Utilise elevated structures or pilings to minimise contact with thawing permafrost and construct equipment housings with thermal insulation to prevent ground heat transfer. ▪ Implement flexible piping and conduits to accommodate ground movement caused by thawing.	▪ Monitor permafrost conditions using ground temperature sensors and geotechnical monitoring systems. ▪ Implement regular inspections of foundations, structures, and equipment for signs of permafrost degradation. ▪ Develop emergency response plans for addressing sudden ground subsidence or shifting including contingency plans for relocating equipment and implementing temporary measures.
Coastal erosion Soil erosion	▪ Consider sites less prone to likelihood of erosion during the site selection stage. ▪ Consider the feasibility of relocating critical elements.	▪ Implement erosion control measures such as terracing or riprap to stabilise steep soil slopes. ▪ Utilise erosion-control landscaping and vegetation to stabilise soil and coastal areas. ▪ Incorporate stormwater management systems to prevent soil erosion and sediment runoff. ▪ Design proper equipment foundation types.	▪ Develop contingency plans for emergency response to sudden erosion events. ▪ Conduct routine maintenance of erosion-control landscaping and vegetation.
Drought	▪ Explore alternative water sources for cleaning and maintenance purposes during drought conditions. ▪ Assess options for fire prevention systems that do not rely heavily on water.	▪ Implement dust collection and filtration systems to minimise dust buildup and maintain equipment performance. ▪ Design conveyor systems with self-cleaning features or moisture injection to prevent material buildup.	▪ Implement regular monitoring of drought forecasts. ▪ Implement water-efficient practices, including staff training, for equipment cleaning and dust suppression. ▪ Develop contingency plans for water shortages, including alternative dust suppression methods.
Changing precipitation patterns Precipitation or hydrological variability	▪ Develop a plan to relocate critical equipment or adjust layout to minimise exposure to water accumulation. ▪ Consider the feasibility of implementing water-resistant materials for equipment housings and storage areas.	▪ Install pumps or drainage wells to manage excess water during heavy precipitation events. ▪ Design equipment with waterproof seals and protective covers to prevent water intrusion. ▪ Incorporate raised equipment platforms or stands to elevate critical elements above water levels. ▪ Design processing areas with sloped floors and runoff channels to direct water away from equipment.	▪ Implement regular monitoring of precipitation forecasts. ▪ Conduct regular inspections of equipment for signs of water damage or corrosion. ▪ Implement routine cleaning of drainage systems and gutters to prevent blockages. ▪ Train staff on proper procedures for handling equipment during wet or dry conditions.
Changing temperatures	▪ Consider the feasibility of implementing temperature control measures such as	▪ Design waste processing and storage facilities with insulation materials to regulate internal temperatures.	▪ Regularly monitor equipment temperatures and performance to detect anomalies early.

Temperature variability	insulation, shading, or HVAC systems for critical equipment areas.	▪ Incorporate passive cooling strategies such as natural ventilation in facility design. ▪ Install temperature monitoring and control systems for sensitive equipment, with alarms for temperature deviations.	▪ Utilise data analytics to optimise energy use based on temperature forecasts. ▪ Train staff on temperature control measures and protocols for responding to temperature-related issues.

3.3 Aerobic biological treatment

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of aerobic biological treatment process to climate hazards are provided in **Table 3.14** along with indicative scores per element category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical aerobic biological treatment methods under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities. It is noted that potential sensitivities of aerobic biological treatment (which may eventually be impacted by climate-related factors) are dependent on the characteristics of the technological processes, how the windrows are built and on operational features such as active or passive ventilation, dynamic, semi-dynamic or static windrows with forced aeration, and therefore, cannot receive a standard score in the table below. The project team should score the element categories based on project specifics. Moreover, it is noted that an RRF with aerobic biological treatment may have many common elements (processes and equipment) with a waste facility dedicated only to mechanical separation (e.g., shredding), therefore, to avoid repetition, the project promoter is referred to the mechanical separation section to include and assess all relevant elements applicable to their project.

TABLE 3.14 • Sensitivities of aerobic biological treatment facilities.

Climate Hazard	Sensitivities			
Flood Storm surge Heavy precipitation	• Malfunctions and damage to the electrical elements of the equipment. • Saturation of processing vessels, disrupting aerobic decomposition and slowing down the treatment process, potentially followed by generation of odours and harmful gases due to increase leachate production. • Run-off of waste materials causing contamination of the surrounding environment. • Introduction of contaminants into the curing area, affecting the quality of the end product, e.g., compost, and potentially rendering it unsuitable for beneficial reuse. • Operational downtime due to damages to water supply, temperature control, and chemical control systems.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (Low)	**Outputs** (Medium)	**Interdependent systems** (High)
Extreme wind (including storm, hurricane, tornado)	• Structural damage to processing infrastructure and storage facilities, compromising integrity and leading to operational disruptions and repair needs, additionally potentially causing contamination, leaks, collapses and end product loss. • Damage to infrastructure in curing areas, such as covers or windrow structures, resulting in scattering or displacing windrows, affecting the maturation and curing process, leading to production loss and downtime due to need for repairs. • Introduction of contaminants into curing areas impacting the quality of the end product, e.g., compost, . • Failures of electrical elements and operational disruptions due to flying debris. • Operational downtime due to damage to water supply, temperature control, and chemical control systems.			
Global Score: High	**On-site assets & processes** (High)	**Inputs** (Medium)	**Outputs** (Medium)	**Interdependent systems** (Medium)
Wildfire	• Damage to facility buildings, equipment, and storage structures, leading to structural weakening, collapse, or destruction. • Damage to feedstock and materials stored outdoors, e.g., compost, CLO and/or organic waste piles, resulting in loss of resources and operational disruptions.			

	• Damage to power lines or electrical infrastructure, resulting in power outages that disrupt facility operations, equipment functionality, and critical systems such as ventilation or temperature control. • Smoke and ash can degrade air quality in and around the facility, posing health and safety risks to facility personnel.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Sea level rise Saline intrusion	• Increased corrosion rates reduce the lifespan of metallic elements of processing infrastructure and threaten the structural integrity of pipes and valves, leading to reduced efficiency and increased risk of rupturing, leakage and contamination. • Damage to electrical elements leading to malfunctioning of processing equipment and monitoring and control instruments. • Disruptions to the microbial activity within processing vessels and curing areas, reducing the efficiency of the biological process and the quality of the end product e.g., compost, potentially rendering it unsuitable for use. • Introduction of salt contaminants into incoming waste streams, affecting the composition and quality of the inputs. • Inundation of processing vessels, curing areas and transfer stations, affecting the process time and production. • Increased groundwater tables leading to increased hydrostatic pressure, potentially causing structural damage, leaks, or even failure in containment systems.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Landslide Avalanche Subsidence	• Structural deformations, differential settlements, fractures or collapse of infrastructure, resulting in leakages and contamination, and requiring substantial repair costs and time. • Underground deformations leading to rupture of pipelines associated with energy and water supply, resulting in operational downtime. • Reduced availability of land / area for windrow formation activities, necessitating relocation or reconfiguration of processing areas. • Blocked access roads and transportation routes, impeding the delivery of waste materials to the facility and causing delays in waste processing. • Safety risks to workers, increasing the likelihood of injuries or accidents.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Heatwave	• Structural material deterioration of equipment, especially motors and bearings turning or agitation equipment, reducing their lifespan and requiring more frequent maintenance and replacement. • Increased temperatures and accelerated evaporation within processing vessels, shifting the conditions inside beyond optimal thresholds, affecting microbial activity and the efficiency of the biological process. • Increased energy consumption to maintain optimal operating conditions in the curing areas, to prevent overheating. • Increased water demand for cooling and operational purposes, straining water supply systems and increasing operational costs. • Accelerated decomposition of incoming organic waste materials during storage and transportation. • Health issues for workers and staff due to heat stress and increased odour generation from biological processes.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Cold wave	• Structural and stability issues of processing windrows, leading to compaction, settling, or collapse, affecting the biological process. • Frost-related expansion threatens the structural integrity of containers.			

- Freezing of materials slowing down the biological process and the curation processes.
- Reduced efficiency of mechanical elements, such as motors and pumps.
- Structural damages to buildings and equipment due to differential displacements of the base/ground.
- Damage to stored end product materials, e.g., compost, leading to quality degradation.
- Ice formation within distribution pipes cause water blockages, impacting supply systems, and leading to damage.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems

Permafrost thawing

- Excessive ground deformations, causing instability in the foundations of infrastructures, resulting in structural damage or failure.
- Ground movement resulting in distortion and failure of pipelines, leading to leakages, operational disruption, energy/water loss, and contamination.
- Changes in ground moisture levels impacting moisture content in treated cured materials, necessitating adjustments to storage and curing practices to prevent over-drying or excess moisture buildup.
- Ground subsidence or thawing-induced landslides, affecting access roads and transportation routes, causing delays or disruptions in feedstock reception and end product, e.g., compost, CLO, etc. transport.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems

Changing temperatures
Temperature variability

- Threat to the structural integrity of processing infrastructures, due to brittleness or warping of materials caused by expansion-contraction fatigue, compromising performance and longevity of the equipment.
- Reduced efficiency of pumps and engines involved in treatment processes, especially conveyor belts and any hydraulic systems.
- Changes in the thermal conditions within processing and product storage buildings, impacting the treatment process, microbial activity, and the quality of the end product, e.g., compost,.
- Temperature-induced damage to roads such as potholes, or pavement deterioration, impacting vehicle travel routes and waste supply.
- Reduced efficiency of heating and cooling systems requiring frequent adjustments to heating, ventilation, or insulation to maintain optimal conditions for biological processes and worker comfort.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems

Drought

- Water stress and lower moisture levels slow down decomposition rates and affect end product, e.g., compost, quality.
- Additional watering or irrigation of processing windrows to maintain optimal moisture levels for aerobic decomposition increase operational costs and resource usage.
- Reduced input waste material availability and quality, as water stress affects agricultural activities, leading to decreased waste volumes with potentially higher concentrations of heavy metals or agricultural chemicals.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems

Coastal erosion
Soil erosion

- Destabilisation of the processing infrastructures and storage buildings, causing excessive settlements, tilting, and structural damage, resulting in collapse and loss of containment.
- Exposure to wave action leading to saline-induced material deterioration.
- Exposure of underground pipelines and distribution lines leading to damage, corrosion, leakage, and contamination.

	• Reduced availability of land / area for windrow formation activities, necessitating relocation or reconfiguration of processing areas. • Damage to access roads and transportation routes, causing delays or disruptions in waste delivery operations.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing precipitation patterns Precipitation or hydrological variability	• - • Unpredictable fluctuations in rainfall interfere with the maturation process, causing dynamic changes in moisture content affecting end product, e.g., compost, quality. • Increased contamination infiltrating windrows, compromising the quality of end product, e.g., compost, and requiring additional quality control measures.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts (with or without the project's criticality), readers are referred to the **Introductory Chapter** (Module 5). To assist users with the scoring procedure, an overview of significant impacts to the aerobic biological treatment facilities across various risk areas (RA) is provided in the table below.

TABLE 3.15 • Climate impacts for aerobic biological treatment facilities (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damages**: Extreme weather events such as floods or heavy rains can damage aeration systems, piping and conduits, storage tanks and equipment. **Operational Disruptions**: Increased precipitation or organic loading due to climate events can overwhelm aerobic processes, leading to system overloading. High temperatures or extreme cold can affect the efficiency of aeration systems, reducing oxygen transfer rates. Climate stressors can result in the need for more frequent maintenance, cleaning, or repair of aerobic reactors and associated equipment.
RA2: Safety and Health`	**Worker Safety Risks**: Workers may be at risk of heat stress during periods of high temperatures, especially in enclosed spaces. Wet or icy conditions resulting from extreme weather can create slip and fall hazards around aerobic processing areas. **Health Impacts:** Warm and humid conditions in combination with poor ventilation or aerosolisation of organic matter can lead to the release of airborne contaminants, posing respiratory health risks.
RA3: Environment	**Excessive Nutrient Release:** Heavy rainfall events can lead to the runoff of excess nutrients from aerobic processing areas, contributing to eutrophication of water bodies.

	Contaminant Spread: Contaminants from aerobic reactors or processing areas can leach into surface water sources, affecting aquatic ecosystems. Aerosolisation of organic matter or volatile compounds from aerobic processing can contribute to localised air pollution. Leaching of contaminants from aerobic processing areas can impact groundwater quality, affecting drinking water sources.
RA4: Social	**Odour and Air Quality**: Odours from aerobic processing facilities can impact the air quality and health of nearby communities, especially during warm and humid conditions. **Perceived Health Risks**: Concerns about exposure to pathogens or contaminants from aerobic processing may lead to community health anxieties. Possible discomfort due to odours. **Property Values**: Odours, noise, or perceived health risks from aerobic facilities can affect property values in surrounding areas.
RA5: Financial impacts	**Repair and Maintenance**: Climate-related damage require costly repairs and maintenance, increasing capital expenditure and operational expenses. **Energy Consumption**: Climate control systems for aerobic processing areas may require increased energy consumption during extreme temperatures. **End Product Quality Management and Remediation Costs**: Efforts to manage end product, e.g., compost, quality and reduce contaminants can lead to additional labour and material costs. Addressing soil or water contamination from aerobic processing may require costly remediation efforts. **Insurance and Liability:** Aerobic facilities in high-risk climate areas may require specialised insurance coverage for weather-related damage or environmental liabilities. Inadequate management of risks can result in legal liabilities for facility owners or operators.
RA6: Reputation	**Public Perception Challenges:** Odour issues from aerobic facilities can lead to negative public perceptions and complaints from nearby residents. Concerns about the environmental impact of aerobic processing, such as nutrient runoff or air emissions, can affect public trust. **Stakeholder Relations**: Failure to address community concerns about sustainability and climate resilience while maintaining open communication about the facility's activities can damage the operator's reputation and harm public relations.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 3.16 presents potential adaptation solutions for climate hazards that could impact the aerobic biological treatment. The suitability of each measure is linked to the encountered level of risk and the uncertainty of climate projections, while the timing of implementation is aligned with specific project stages. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 3.16 • Aerobic biological treatment facilities: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. Informed decision-making is to be applied along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Flood **Storm surge** **Heavy precipitation**	▪ Conduct a comprehensive risk assessment to identify areas prone to flooding. ▪ Consider the sensitivity to flooding of the different structures and elements when planning the site development, especially with respect to elevation and relative distance from streams.	▪ Elevate critical storage and processing areas, especially incoming bio-waste and end product, e.g., compost, CLO, etc.,storage areas. ▪ Install flood barriers and drainage systems to prevent run-off within curing areas. ▪ Implement smart infrastructure features, such as flood sensors and automated gate controls to protect storage facilities and curing areas. ▪ Integrate green infrastructure elements, such as permeable surfaces and rain gardens, to manage and absorb excess precipitation, reducing the risk of surface runoff and flooding.	▪ Utilise advanced weather monitoring systems to track precipitation patterns and predict potential flooding or storm surges. Implement automated alert systems to trigger preventive measures. ▪ Establish emergency response plans and procedures to safeguard personnel, minimise impacts, and restore operations following extreme weather events. ▪ Launch public awareness campaigns to offer guidance to the public on proper covering and storage of organic waste materials to prevent water saturation and runoff.
Extreme wind (including storm, hurricane, tornado)	▪ Evaluate the feasibility of constructing sheltered infrastructure with storm-resistant features. ▪ Develop contingency plans for supply routes during extreme wind events, considering alternative paths to avoid areas prone to tornadoes or cyclones. ▪ Develop and implement an emergency response plan that outlines procedures for securing equipment, evacuating personnel, and mitigating damage during extreme weather events.	▪ Strengthen critical elements such as processing infrastructures and curing areas to withstand high winds and impact forces. ▪ Install anchoring systems or tie-downs for equipment and structures. ▪ Strengthen roofs and covers to resist wind uplift and prevent water infiltration into biological processing and curing areas.	▪ Utilise advanced weather monitoring systems to track approaching storms, tornadoes, cyclones, hurricanes, or typhoons. ▪ Establish communication protocols to disseminate weather alerts and emergency instructions to facility staff, stakeholders, and local authorities. ▪ Install backup power systems to maintain essential operations and functionality during power outages. ▪ Utilise remote monitoring systems to track facility conditions and equipment status in real-time.
Wildfire	▪ Select sites of new waste facilities or evaluate the feasibility of relocating existing waste facilities away from high-risk zones.	▪ Use fire-resistant materials or insulation to minimise the risk of ignition or damage. ▪ Install air quality monitoring and smoke detection systems. ▪ Install automatic fire suppression systems at critical areas and include sprinkler systems, foam suppression, or water cannons for rapid response. ▪ Install backup power generators and redundant systems to ensure continuity of essential	▪ Create buffer zones around the facility by clearing vegetation, implementing firebreaks, and reducing fuel loads. ▪ Develop and regularly update emergency preparedness and response plans in coordination with local authorities. ▪ Provide comprehensive training to facility personnel on wildfire safety protocols, evacuation procedures, and firefighting techniques.

		operations, during power outages caused by wildfires.	▪ Enhance periodic maintenance protocols of fire management/extinguishing installations.
Sea level rise **Saline intrusion**	▪ Conduct thorough site assessments to identify coastal hazard risks and consider these in site selection. ▪ Plan the facility layout to minimise exposure of critical elements, where inundation may lead to loss of feedstock and end product, e.g., compost, CLO, etc.. ▪ Incorporate natural features such as wetlands or vegetated buffers to provide natural flood protection. ▪ Restore or enhance salt-tolerant vegetation, such as mangroves or native shrubs.	▪ Elevate vulnerable elements above projected flood levels to minimise exposure to floodwaters. ▪ Construct flood barriers or gates around them to mitigate the risk of inundation. ▪ Use corrosion-resistant materials or install impermeable liners around equipment and infrastructure exposed to saltwater to enhance durability and longevity. ▪ Design drainage systems to effectively manage water runoff and prevent waterlogging.	▪ Develop emergency response plans to use in response to extreme weather or coastal hazard warnings. ▪ Install monitoring systems to track water levels, salinity, and other environmental parameters, enabling early detection of potential hazards.
Heat wave	▪ Site selection to minimise exposure to extreme heat and maximise natural shading and ventilation opportunities. ▪ Consider factors such as proximity to urban heat islands, prevailing wind patterns, and local microclimates when selecting the site location. ▪ Ensure easy access to cool, potable water within the facility.	▪ Design the facility layout and orientation to optimise natural airflow and shading to reduce heat buildup. ▪ Install cooling systems (e.g., misting sprays, evaporative coolers) in processing infrastructure and curing areas to regulate temperatures and prevent overheating. ▪ Apply insulation to equipment and infrastructure to reduce heat transfer and maintain stable temperatures within processing vessels and curing areas. ▪ Implement irrigation systems to supplement moisture levels in processing vessels and windrows. ▪ Construct shade structures or covers for outdoor equipment and work areas to mitigate heat stress for workers.	▪ Adjust operating schedules and process parameters to minimise heat exposure during peak temperatures (e.g., conduct turning or agitation during cooler times of the day). ▪ Utilise remote monitoring systems to track temperature and moisture levels in processing vessels and curing areas and conduct regular inspections of equipment and infrastructure to identify signs of wear, corrosion, or overheating. ▪ Implement water conservation measures, recycling and reusing wastewater, to minimise stress on water supply systems. ▪ Upgrade equipment and systems to improve energy efficiency and reduce heat emissions. ▪ Implement heat stress management protocols for workers, including providing access to shaded rest areas, hydration stations, and regular breaks.
Cold wave	▪ Site selection to minimise likelihood of exposure to extreme cold temperatures and frost-prone areas, avoiding low-lying areas and locations prone to cold air pooling. ▪ Plan enclosed storage and insulated storage bins to protect organic waste, end product, e.g., compost, piles, and feedstock materials. ▪ Establish robust supply chain management protocols to ensure a reliable and uninterrupted supply of feedstock materials and diversify	▪ Install heating systems, such as heat tapes or radiant heaters, to maintain temperatures above freezing levels in vulnerable areas. ▪ Install insulation and use durable materials for critical elements such as processing infrastructure and curing areas to minimise heat loss and prevent freezing. ▪ Insulate water supply lines and install freeze protection devices (e.g., heat trace cables or	▪ Develop cold weather protocols for monitoring temperatures, protecting equipment, and adjusting operations. ▪ Install backup power generators or alternative heating sources to maintain essential operations in case of power outages. ▪ Stockpile emergency supplies for rapid response to cold weather-related emergencies.

	feedstock sources to mitigate the risk of supply disruptions.	circulation pumps) to prevent ice formation and possible blockages.	▪ Monitor temperature-sensitive equipment and systems to detect early signs of malfunction or damage.
Landslide Avalanche Subsidence	▪ Conduct thorough geotechnical assessments prior to site selection to identify and avoid areas prone to landslides, avalanches, or subsidence. ▪ Diversify supply routes and establish alternatives to be used during high-risk periods. ▪ Vegetate slopes in the vicinity of the facility to enhance their stability and resistance to water pressures.	▪ Implement slope stabilisation measures (e.g., retaining walls, slope reinforcement) to mitigate the risk of landslides in the vicinity of the site. ▪ Strengthen the foundations of critical infrastructure to withstand ground movements and enhance the structural integrity of vessels and containers to protect them from impact forces. ▪ Construct physical barriers such as retaining walls, deflection structures, or debris nets to divert or contain displaced soils.	▪ Develop emergency response and evacuation plans for safeguarding personnel, securing equipment, and minimising environmental impacts. ▪ Install monitoring systems (typically inclinometers) for real-time monitoring and early warning. ▪ Implement regular maintenance and inspection programs to assess the condition of surrounding slopes and infrastructure.
Permafrost thawing	▪ Consider the geographical extent of permafrost and evaluate the vulnerability of critical facilities. ▪ Evaluate the feasibility of relocating facilities in areas where permafrost thawing poses a significant risk.	▪ Reinforce foundations to withstand ground movement and implement ground stabilisation measures (grouting, compaction). ▪ Use ground freezing techniques to mitigate thawing. ▪ Install insulation layers to minimise heat transfer from the facility to the underlying permafrost	▪ Use ground temperature sensors, settlement gauges, or slope stability monitors to detect signs of thawing and provide early warning alerts. ▪ Implement regular maintenance and inspection programs to assess permafrost conditions and infrastructure elements.
Changing temperatures Temperature variability	▪ Develop control strategies to adjust heating or cooling systems based on ambient temperature changes. ▪ Identify and plan for alternative feedstock options that are less sensitive to temperature variations.	▪ Design energy efficiency measures to minimise the environmental impact of temperature control and reduce energy consumption during heating or cooling operations. Consider using renewable energy sources. ▪ Reinforce structures to withstand temperature variations using heat-resistant materials, insulation, or protective coatings.	▪ Install temperature monitoring systems throughout the facility to continuously monitor internal temperatures in key processing areas. ▪ Establish temperature thresholds or triggers for adjusting operating parameters, such as airflow rates, mixing intensity, or turning frequency, based on real-time temperature data. ▪ Implement a proactive maintenance schedule for insulation, shading, or ventilation to maintain internal temperatures within optimal ranges for aerobic decomposition processes.
Drought	▪ Explore alternative water sources for cleaning and maintenance purposes during drought conditions. ▪ Assess options for fire prevention systems that do not rely heavily on water.	▪ Design wastewater treatment systems with recycling and reuse capabilities. ▪ Implement rainwater harvesting systems to supplement freshwater supplies. ▪ Optimise biological processes (covering of materials, mulching) to minimise water loss. ▪ Diversify feedstock sources by incorporating drought-resistant or water-efficient organic waste materials.	▪ Use moisture sensors and automated irrigation systems to monitor and control moisture levels in process materials.

		▪ Design waste collection containers with features that minimise water retention. ▪ Upgrade equipment and technologies (e.g., low-flow pumps, energy-efficient motors, water-saving irrigation systems) to reduce water consumption.	
Coastal erosion Soil erosion	▪ Conduct erosion risk assessments to identify areas susceptible to erosion and prioritise adaptive measures to minimise impacts on facility operations. ▪ Establish vegetative barriers using native plantings or grass cover to stabilise soil.	▪ Reinforce the supports of critical infrastructure elements such as processing infrastructure and curing areas to withstand erosion. ▪ Use gabions or geotextiles to enhance the erosion resistance of slopes and levees.	▪ Perform regular site inspections to identify instability issues and utilise alerts to trigger emergency response measures.
Changing precipitation patterns Precipitation or hydrological variability	▪ Integrate climate projections and hydrological modelling into facility planning and develop comprehensive water management plans to account for changing precipitation patterns.	▪ Design stormwater management systems (retention ponds, swales, and drainage ditches) to capture and control runoff. ▪ Design facility layouts to minimise the risk of waterlogging and saturation in processing areas.	▪ Develop protocols for managing feedstock materials during precipitation events, such as covering or sheltering incoming waste to prevent waterlogging and maintain feedstock quality.

3.4 Anaerobic digestion biological treatment

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of AD treatment to climate hazards are provided in **Table 3.17** along with indicative scores per element category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical AD treatment methods under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities. It is noted that potential sensitivities of AD treatment facilities (which may eventually be impacted by climate-related factors) are dependent on the type of the technology (e.g., wet digestion, dry continuous digestion, dry batch digestion, etc.), or the type of digester (e.g., vertical digesters with an agitator, horizontal digester with a slow transport agitator, box or percolation digesters) and its mixing system (e.g., mechanical, hydraulic, pneumatic, etc.) and therefore, cannot receive a standard score in the table below. The project team should score the element categories based on project specifics. Moreover, it is noted that an RRF with AD treatment may have many common elements (processes and equipment) with a waste facility dedicated only to mechanical separation (e.g., shredding), therefore, in order to avoid repetition, the project promoter is referred to the mechanical separation section to include and assess all relevant elements applicable to their project.

TABLE 3.17 • Sensitivities of anaerobic digestion biological treatment facilities.

Climate Hazard	Sensitivities			
Flood **Storm surge** **Heavy precipitation**	• Damage to buildings, equipment, and storage tanks. Exposure to floodwaters containing sediments or chemicals accelerates equipment degradation. • Waterlogging of digestate storage areas. Waterlogged digestate becomes more difficult to pump, leading to slower processing times and reduced efficiency. • Introduction of contaminants into the digestate, affecting its quality and composition, or into the incoming feedstock stored on-site, leading to increased levels of impurities, affecting digestion rates and biogas yields. • Increased risk of storage tank overflow, resulting in spillage and potential environmental contamination. • Power outages disrupting operations. • Damage to access roads or closures and feedstock supply disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Extreme wind (including storm, hurricane, tornado)	• Structural damage to buildings, and equipment. • Damage to biogas storage tanks, biogas piping, valves, and collection systems leading to gas leaks, combustion risks, and reduced energy production. • Introduction of contaminants and debris into feedstock. • Digestate storage overflow or spillage leading to environmental contamination, regulatory violations, and cleanup costs. • Power outages disrupting operations. • Damage to access roads or closures and feedstock supply disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Wildfire	• Heat damage to structures and equipment (e.g., structural weakening, material degradation, equipment failure). • Biogas storage facilities are vulnerable to explosion risk. • Operational disruptions due to evacuation or shutdowns, halting AD processes. • Ash and debris or smoke exposure contaminating incoming feedstock, affecting its quality and microbial populations, resulting in reduced digestion efficiency.			

	• Ash and debris settling on digestate storage areas contaminate the material resulting in reduced digestate quality, potential nutrient imbalance, and handling challenges. • Water runoff from wildfire affected areas contaminating water sources, e.g., water courses and stored processes waters). • Health risks to workers from smoke inhalation and direct fire exposure. • Power outages disrupting operations. • Damage to access roads or closures and feedstock supply disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Sea level rise **Saline intrusion**	• Threats to the integrity and stability of on-site assets such as digesters, storage tanks, and equipment. • Increased groundwater tables leading to increased hydrostatic pressure, potentially causing structural damage, leaks, or even failure in containment systems. • Increased corrosion rates to metal elements of AD systems. • Increased salinity levels in the substrate can inhibit the activity of anaerobic microorganisms responsible for AD, resulting in reduced biogas production rates, altered biogas composition (with higher concentrations of less desirable gases e.g., hydrogen sulphide), and prolonged retention times. • Changes in the composition and reduced quality of feedstock, impacting digestion efficiency. The presence of salt ions in the substrate inhibits the growth and activity of methanogenic bacteria, which are crucial for methane production. Also, higher salinity levels in feedstock can introduce contaminants (salts, heavy metals, and organic pollutants) into the AD system impacting storage and utilisation units. • Localised damage to access roads or closures and feedstock supply disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Landslide **Avalanche** **Subsidence**	• Shifting ground causing cracks, tilting, ruptures or structural damage to buildings, tanks, equipment, and biogas piping and valves, leading to leaks, spills, and environmental contamination. • Changes in feedstock composition and contamination risks due to landslide debris. • Reduced land availability resulting in difficulties in managing and disposing of digestate. • Damage to electrical infrastructure leading to power outages disrupting operations. • Damage to access roads or closures and feedstock supply disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Coastal erosion **Soil erosion**	• Loss of soil support leading to ground subsidence, settlement, or structural damage. • Removal of nutrient-rich topsoil, affecting feedstock quality and impacting digestion efficiency and digestate quality. • Sediment-laden runoff contamination of digestate, affecting nutrient content and resulting in reduced digestate usability and increased maintenance of storage facilities. • Introduction of sediment and contaminants into end products, e.g., compost. • Sedimentation clogging of water management systems, affecting treatment processes. • Damage to access roads or closures and feedstock supply disruptions.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Heat wave	• Decreased biogas production due to inhibition of microbial activity. • Acceleration of digestate drying, leading to increased viscosity and pumpability issues and resulting in clogging, reduced nutrient availability, and handling challenges. • Rapid organic material decomposition, potentially spoiling of feedstock. • Intensification of odour emissions from stored feedstock or waste materials. • Alterations in biogas composition, reducing methane content and therefore calorific value. • Higher cooling demands for equipment increasing energy consumption.			

	• Health risks to workers, leading to heat stress, heat-related illnesses, and reduced productivity. • Power outages disrupting operations.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Cold wave	• Freezing of equipment such as digesters, pumps, and valves resulting in equipment malfunctions, reduced flow rates, and process disruptions. • Slowdown of microbial activity, reducing biogas production rates. • Digestate solidification, leading to flow obstructions and resulting in clogging of process lines, reduced digestate quality. Cold-induced viscosity changes in digestate affect handling and dewatering. • Freezing of feedstock, affecting digestion rates and quality. Higher proportions of solid waste in feedstock alter digestion kinetics and reduce biogas yields. • Changes in biogas composition and quality resulting in fluctuations in methane content, combustion challenges, and reduced energy efficiency. • Increased energy demand for heating equipment and staffed spaces. • Health risks to workers and reduced productivity.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Permafrost thawing	• Ground subsidence or instability, affecting the integrity of digesters, tanks, pipelines, leading to cracks, leaks or more severe structural damage. • Previously frozen feedstock may have altered characteristics, affecting digestion rates. • Changes in ground temperature affect microbial activity in digesters leading to fluctuations in digestion rates and biogas production. • Fluctuations in biogas quality affect energy generation efficiency. • Alterations in the pathways of leachate migration from disposal sites, leading to environmental contamination. • Damage to access roads or closures and feedstock supply disruptions.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing temperatures Temperature variability	• Changes in digestion rates and biogas production. Extreme changes affect the insulation requirements of digesters, leading to heat loss or overheating. • Changes in stored biogas pressure and volume, alteration of composition, impacting energy content and energy generation efficiency. • Need for adjustments based on ambient temperature variations for equipment used in wastewater treatment, such as pumps and aerators. • Changes in the storage conditions of incoming feedstock, particularly if containing moisture-sensitive materials. • Changes in the quality and composition of received source-separated bio-waste. • Effected pre-treatment processes having specific ambient condition temperature requirements, e.g., , thermal hydrolysis. • Cooler temperature slow down of maturation rates. • Higher temperature increase of odour emissions from stored digestate. • Increased energy demand affects the utilisation of biogas for heating and the demand for electricity.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Drought	• With less moisture to dissipate heat, AD systems experience higher operating temperatures. • Reduced water availability for process usage and cooling, resulting in challenges in maintaining optimum moisture levels. • Reduced moisture content in feedstock results in altered digestion rates, lower biogas production, and process inefficiencies.			

	• Impacts to agriculture, reducing availability of organic feedstock. • Drought-induced digestate drying and solidification leading to clogging of pipelines, handling challenges, and decreased nutrient availability. Thicker digestates require more energy for mixing and agitation to maintain homogeneity. • Concentrated pollutants in water sources during droughts lead to impaired water quality, process disruptions, and potential equipment damage.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems

Changing precipitation patterns Precipitation or hydrological variability	• Ground saturation, affecting the stability of digesters, storage tanks, and other infrastructure. • Changes in microbial activity and digestion rates. • Fluctuations in moisture levels influence biogas production rates and composition. • Increased water content in digestate, affecting storage and handling. • Altered hydrological patterns require adjustments in water management systems, affecting process water use and treatment.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts (with or without the project's criticality), readers are referred to the **Introductory Chapter** (Module 5). To assist users with the scoring procedure, an overview of significant impacts to the anaerobic digestion biological treatment facilities across various risk areas (RA) is provided in the table below.

TABLE 3.18 • Climate impacts for the anaerobic digestion biological treatment facilities (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damages to AD Infrastructure**: Extreme weather events such as floods or heavy rains can lead to structural damage, cracks, or leaks in AD digesters and storage tanks or damage pipelines, affecting the collection and transport of biogas and digestate. **Disruptions to AD Operations**: Extreme climate events may require temporary shutdowns of AD operations to ensure worker safety and protect equipment. Changes in temperature and moisture levels can impact microbial activity, leading to reduced biogas production and process efficiency.
RA2: Safety and Health	**Worker Safety Risks**: Workers involved in AD operations are at risk of climate-related illnesses e.g., heat strokes or hypothermia. Climate hazards can also lead to leaks exposing workers to hazardous materials, pathogens, or toxic gases. **Health Impacts:** Improper handling or leaks in biogas collection systems due to climate events can expose workers to methane, hydrogen sulphide, or other harmful gases.
RA3: Environment	**Air Pollution:** Changes in temperature and moisture levels can impact the generation and release of biogas, contributing to air pollution and greenhouse gas emissions. **Contaminant Spread:** Floods or storm surges can transport contaminants from AD facilities into nearby ecosystems, affecting water quality and biodiversity. Leachate from AD facilities may contain heavy metals from waste, leading to soil contamination and impacts on plant growth.
RA4: Social	**Community Concerns:** Emissions from AD facilities, such as odours or volatile organic compounds, can affect the air quality and health of nearby communities. Contamination of local water sources from leachate or runoff can pose risks to community drinking water and aquatic ecosystems. Possible discomfort due to odours. **Livelihood Impacts:** Contaminated soil or water from AD operations can affect nearby agricultural lands, impacting crop yields and food safety. Contaminated soil or water from AD operations can affect nearby agricultural lands, impacting crop yields and food safety.
RA5: Financial impacts	**Repair and Maintenance**: Climate-related damage to AD infrastructure requires costly repairs and maintenance, increasing capital expenditure and operational expenses. **Energy Consumption**: Fluctuations in temperature or process disruptions may require increased energy inputs for heating or cooling AD systems. **Insurance and Liability:** AD facilities in high-risk climate areas may face rising insurance premiums due to the potential for climate-related damage. Contamination events or regulatory fines related to AD operations can result in additional waste management expenses.
RA6: Reputation	**Regulatory Compliance**: Climate-related incidents leading to environmental pollution or non-compliance with regulations can damage the reputation of AD facilities and lead to public scrutiny. Climate-related disruptions or incidents at AD facilities may attract media attention, affecting public perception and stakeholder trust. **Investor Confidence and Stakeholder Trust**: Climate impacts to AD facilities may raise concerns among investors about the long-term viability and resilience of the operations. On the other hand, demonstrating effective climate resilience and sustainable waste management practices can enhance investor confidence and partnerships.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 3.19 presents potential adaptation solutions for climate hazards that could impact the anaerobic digestion biological treatment. The suitability of each measure is linked to the encountered level of risk and the uncertainty of climate projections, while the timing of implementation is aligned with specific project stages. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 3.19 • Anaerobic digestion biological treatment facilities: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. Informed decision-making is to be applied along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Flood Storm surge Heavy precipitation	▪ Conduct a site assessment for flood risk, taking into account future climate projections and evaluate the need for relocation in case of significant unmitigated risk. ▪ Incorporate prearranged contracts or agreements with cleanup crews, waste haulers, and repair services into the project strategy and plans.	▪ Elevate critical equipment and storage tanks above flood levels where possible. ▪ Use flood-resistant materials and sealants for construction in flood-prone areas. ▪ Implement automatic shut-off valves and leak detection systems for safety. ▪ Implement floodwater diversion channels and onsite water storage reservoirs. ▪ Designate areas for temporary water containment to prevent flooding of process areas.	▪ Establish procedures for quickly shutting down systems during flood events. ▪ Monitor weather forecasts and adjust feedstock processing schedules accordingly. ▪ Establish alternative feedstock storage options or agreements for uninterrupted supply. ▪ Train staff on emergency response roles, equipment protection, and safe evacuation. ▪ Install backup power generators or battery storage systems for critical operations.
Extreme wind (including storm, hurricane, tornado)	▪ Conduct risk evaluations accounting for severe winds, intense storms, tornadoes, and cyclones, and consider relocation if the residual risk is deemed excessively high.	▪ Use reinforced materials and construction techniques for critical equipment and structures. ▪ Design biogas storage systems with overflow and pressure release mechanisms for safety. ▪ Implement flood barriers, raised platforms, or drainage systems to protect process areas. ▪ Design digestate storage facilities with overflow containment and runoff diversion features.	▪ Conduct routine inspections of equipment, tanks, and pipelines for signs of wear or damage. ▪ Establish protocols for securing loose equipment, shutting down systems, and safeguarding personnel. ▪ Use backup power generators for critical operations. ▪ Maintain fuel supplies, battery backups, or grid tie-in options for uninterrupted power. ▪ Diversify feedstock sourcing and establish backup feedstock storage options or agreements with multiple suppliers.
Wildfire	▪ Perform assessments for fire risks to identify susceptible zones and assets, potentially considering relocation if needed. ▪ Evaluate and strategise mitigation steps for potential environmental effects caused by fire residues and runoff, creating plans for post-fire cleanup, rehabilitation, and restoration.	▪ Use fire-resistant materials for critical equipment, storage facilities, and structural elements. ▪ Design facility layouts to minimise fire spread risks. ▪ Install automatic biogas shut-off valves and pressure relief systems to prevent explosions. ▪ Implement water treatment and filtration systems to mitigate wildfire runoff contamination. ▪ Implement gas detection and alarm systems for early warning of combustible gas leaks. ▪ Install automatic fire suppression systems at critical areas and include sprinkler systems,	▪ Test and maintain backup systems (e.g., power generators or UPS) regularly to ensure functionality during emergencies. ▪ Identify backup feedstock sources or storage options to mitigate supply disruptions. ▪ Maintain water storage levels in reservoirs or tanks for emergency water supply. ▪ Enhance periodic maintenance protocols of fire management/extinguishing installations. ▪ Provide wildfire safety training for all staff, including evacuation procedures and fire response drills.

		▪ foam suppression, or water cannons for rapid response. ▪ Establish water storage reservoirs or tanks for emergency water supply.	
Sea level rise **Saline intrusion**	▪ Integrate localised sea level rise projections and saline intrusion models into facility planning utilise geotechnical studies to assess soil composition and stability. ▪ Incorporate adaptive design principles into facility planning, such as modular construction and flexible layouts. ▪ Explore partnerships for access to alternative water sources unaffected by saline intrusion, such as reclaimed water or brackish aquifers. ▪ Consider relocation.	▪ Elevate critical infrastructure elements above projected sea levels to minimise direct flood risks. ▪ Implement flood barriers or levees around vulnerable areas to prevent water ingress during extreme events. ▪ Specify corrosion-resistant materials for equipment and infrastructure exposed to saline environments. ▪ Design closed-loop water management systems to minimise reliance on external freshwater sources. ▪ Incorporate pretreatment processes like filtration to remove salts from feedstock and process water. ▪ Apply protective coatings, sacrificial anodes, or cathodic protection systems to mitigate corrosion.	▪ Install real-time monitoring systems for water quality, salinity levels, and groundwater elevation. ▪ Implement automated alerts and alarms for abnormal conditions, allowing for rapid response and preventive maintenance. ▪ Develop protocols for adjusting feedstock mixtures and process parameters to accommodate varying salinity levels. ▪ Optimise nutrient supplementation to support microbial communities in saline conditions and maintain digestion efficiency.
Coastal erosion **Soil erosion**	▪ Conduct detailed erosion risk assessments and restrict development in high-risk areas.	▪ Construct erosion barriers such as retaining walls or riprap along vulnerable slopes or embankments. ▪ Implement stormwater management systems with sediment traps or swales to capture runoff. ▪ Incorporate permeable surfaces or vegetated swales to absorb and slow down surface water flow. ▪ Install sediment traps in runoff areas to capture eroded soil before it enters water systems.	▪ Conduct routine inspections for signs of erosion-induced damage to on-site assets. ▪ Implement monitoring programs for sediment buildup in storage facilities and process equipment. ▪ Modify feedstock management to account for variations in quality due to contaminants. ▪ Identify backup routes or access points to the facility to bypass eroded areas during disruptions.
Heat wave	▪ Site selection to minimise exposure to extreme heat and maximise natural shading and ventilation opportunities. ▪ Consider factors such as proximity to urban heat islands, prevailing wind patterns, and local microclimates when selecting the site location. ▪ Ensure easy access to cool, potable water within the facility.	▪ Design systems with enhanced natural ventilation or airflow cooling mechanisms to prevent overheating and install shading structures or awnings to protect outdoor equipment from direct sunlight. ▪ Incorporate heat-resistant materials for equipment exposed to high temperatures. ▪ Insulate digesters and storage tanks to maintain stable internal temperatures.	▪ Install temperature sensors and monitoring systems for early detection of equipment overheating. ▪ Implement automated controls for adjusting process parameters based on temperature fluctuations. ▪ Develop strategies for digestate management during heat waves, such as increased mixing or dilution.

		▪ Use heat exchangers or thermal storage systems to manage heat fluctuations in biogas production. ▪ Implement water recycling systems to reduce reliance on external water sources. ▪ Explore renewable energy sources such as solar panels or waste heat recovery systems.	▪ Optimise dewatering processes to handle higher viscosity digestate and reduce energy consumption. ▪ Offer adequate cooling stations to workers, hydration resources, and scheduling adjustments.
Cold wave	▪ Site selection to minimise exposure to extreme cold temperatures and frost-prone areas, avoiding low-lying areas and locations prone to cold air pooling. ▪ Plan enclosed storage and insulated storage bins to protect organic waste, and feedstock materials. ▪ Establish robust supply chain management protocols to ensure a reliable and uninterrupted supply of feedstock materials and diversify feedstock sources to mitigate the risk of supply disruptions.	▪ Insulate digesters, storage tanks, and process lines to maintain stable temperatures. ▪ Install heating systems with backup power sources for critical equipment and facilities. ▪ Upgrade to cold-resistant materials for equipment exposed to freezing temperatures. ▪ Retrofit heat tracing systems for process lines susceptible to solidification.	▪ Install temperature sensors and alarms to monitor equipment and process temperatures and implement automated shutdown protocols or equipment adjustments based on thresholds. ▪ Develop protocols for managing cold-induced digestate viscosity changes. ▪ Insulate water supply lines to prevent freezing. ▪ Provide cold weather training for staff on frostbite prevention and ensure availability of warm shelters, protective gear, and regular breaks.
Permafrost thawing	▪ Conduct detailed permafrost mapping and ground stability assessments to understand the extent of permafrost thawing risks. Use future climate projections to anticipate long-term permafrost degradation trends. ▪ Opt for modular design approaches that allow for easy relocation or expansion of AD elements in response to shifting ground conditions. ▪ Consider relocation in case of excessive residual risk.	▪ Design AD infrastructure with raised foundations or pilings to mitigate ground subsidence risks from thawing permafrost. ▪ Use flexible piping systems to accommodate ground movement and prevent damage to biogas collection and distribution systems. ▪ Enhance insulation in digesters, storage tanks, and pipelines to minimise heat loss or gain from fluctuating ground temperatures. ▪ Implement ground stabilisation measures such as soil reinforcement, grouting, or geotextile fabrics to prevent subsidence.	▪ Implement real-time monitoring systems for ground temperature, settlement, and stability and install early warning system with alarms to operators. ▪ Develop protocols to adjust AD process parameters such as retention times or mixing intensity based on ground temperature variations. ▪ Establish protocols for emergency shutdowns or operational adjustments for sudden soil instabilities. ▪ Stockpile essential materials and spare parts to quickly address repairs or replacements necessitated by ground-related issues.
Landslide Avalanche Subsidence	▪ Conduct geotechnical surveys to assess ground stability and landslide risks and use historic data and future projections to inform site planning and infrastructure design.	▪ Implement reinforced foundations, retaining walls, or slope stabilisation measures for critical infrastructure. ▪ Design digestate storage systems with robust liners, berms, or containment structures. ▪ Use modular or portable systems for digestate processing to adapt to changing site conditions. ▪ Use modular or portable systems for digestate processing to adapt to changing site conditions	▪ Install ground movement sensors or monitoring systems to detect early signs of subsidence or landslide activity. ▪ Maintain emergency repair kits, spare parts, and backup systems for critical equipment. ▪ Train staff on rapid response procedures for addressing equipment damage or failures. ▪ Develop contingency plans for digestate disposal, like using alternative storage or

			treatment. Partner with off-site facilities for emergency management.
Changing temperatures Temperature variability	▪ Consider site-specific microclimate conditions during site planning and orientation of AD infrastructure. ▪ Develop control strategies to adjust heating or cooling systems based on ambient temperature changes. ▪ Opt for modular design approaches that allow for scalability and flexibility in AD system expansion or modification and identify and plan for alternative feedstock options that are less sensitive to temperature variations.	▪ Design to incorporate natural shading or ventilation strategies to mitigate temperature variations around AD facilities. ▪ Consider adequate insulation for digesters, tanks, and pipelines to minimise heat loss or heat gain. ▪ Design digesters with materials and construction techniques that can withstand temperature variations. ▪ Ensure CHP units are designed to handle variations in biogas quality due to temperature fluctuations.	▪ Implement real-time temperature monitoring for digesters, storage tanks, and biogas systems. ▪ Install alarm systems to alert operators of temperature deviations beyond set thresholds and train operators to make real-time adjustments to heating/cooling systems based on temperature readings. ▪ Implement a proactive maintenance schedule for insulation in digesters and tanks, for pumps, heaters, and heat exchangers to prevent breakdowns, and for potential seal leaks in pipelines.
Drought	▪ Explore and secure alternative water supplies, such as groundwater wells or water deliveries via tankers. ▪ Establish agreements with nearby facilities for mutual access to water resources (mainly applicable for wet digestion technologies). ▪ Assess options for fire prevention systems that do not rely heavily on water.	▪ Design closed-loop water circuits and process designs to minimise water requirements. ▪ Design digestate storage and handling systems for varying moisture content and consistency. ▪ Implement automated mixing systems to prevent solidification and maintain pumpability. ▪ Implement rainwater harvesting, greywater recycling, and water reuse systems.	▪ Implement real-time monitoring of feedstock moisture levels and digestion rates and adjust process parameters for drought conditions to optimise biogas production and quality. ▪ Diversify feedstock sources to include drought-resistant biomass and alternative inputs. Establish partnerships with multiple suppliers for reliable and varied feedstock availability. ▪ Develop water management strategies to optimise usage and minimise wastage.
Changing precipitation patterns Precipitation or hydrological variability	▪ Integrate climate projections and hydrological modelling into facility planning and develop comprehensive water management plans to account for changing precipitation patterns.	▪ Design AD infrastructure with enhanced drainage systems. ▪ Include adequate storage facilities for process water and digestate to manage fluctuations. ▪ Implement efficient water recycling systems to reduce reliance on external water sources. ▪ Design AD systems with flexibility to adjust process parameters based on changing water availability.	▪ Implement real-time monitoring of water levels, quality, and flow rates within the facility. ▪ Install sensor-based controls for water management to optimise use and minimise wastage. ▪ Develop protocols for adjusting feedstock mixtures in response to changing moisture levels. ▪ Collaborate with local water authorities or agencies to share data and best practices.

3.5 Dumpsite rehabilitation

PHASE 1 • Screening

Module 1: Sensitivity Analysis

The sensitivities of dumpsite rehabilitation facilities to climate hazards are provided in **Table 3.20** along with indicative scores per element category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical dumpsite rehabilitation facilities under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities. It is noted that potential sensitivities of dumpsite rehabilitation facilities (which may eventually be impacted by climate-related factors) are dependent on the type of the facility (e.g., conventional or managed anaerobic landfill, bioreactors, hybrid anaerobic/aerobic landfills, etc.), and therefore, cannot receive a standard score in the table below. The project team should score the element categories based on project specifics.

TABLE 3.20 • Sensitivities of dumpsite rehabilitation.

Climate Hazard	Sensitivities			
Extreme wind (including storm, hurricane, tornado)	• Geomembrane damage such as lifting or tearing, leading to breaches and affecting containment. • Damage to infrastructure due to extreme loading or windborne debris. • Damage or displacement to monitoring equipment and sensors. • Safety risks to personnel. • Scattering of waste across the site. • Damage to electrical systems, wiring, generators disrupting operations. • Damage to gas extraction systems, reducing collection, release of environmentally damaging greenhouse gases and leading to increased risk of gas explosions and fires. • Power outages disrupting operations. • Damage to access roads or closures and supply disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Flood Storm surge Heavy precipitation	• Saturation of geomembranes leading to increased fatigue • Flooding of wells and waterlogging of the manifold systems. • Increased risk of erosion and sedimentation compromising gas well and sealing layer integrity. • Contamination of stored water or leachate, posing environmental risks. • Overwhelming of leachate treatment systems, leading to overflows/spills. • Inundation of waters in recirculation systems, affecting waste treatment processes. • Water ingress in gas control equipment, affecting gas extraction rates. • Electrical malfunctions, short circuits or rusting. • Power outages disrupting operations. • Damage to access roads or closures and supply disruptions.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Wildfire	• Exposure of sealing layer geomembranes to intense heat, causing melting or damage. • Ruptures or leaks in manifold systems, damage to well casings, tanks and piping systems. • Significant risk of gas explosions (particularly for gas storage tanks). • Damage to electrical wiring and other electrical elements in generator buildings.			

- Damage to monitoring infrastructure and equipment, leading to sensor malfunctions.
- Operational disruptions due to evacuation of staff for safety concerns.
- Road closures or evacuation orders affecting site accessibility.
- Damage to power lines or substations, affecting facility energy supply.

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems

Sea level rise
Saline intrusion

- Inundation of the site, leading to environmental issues.
- Increased groundwater tables leading to increased hydrostatic pressure, potentially causing structural damage, leaks, or even failure in containment systems.
- Increased corrosion rates.
- Contamination of leachates increasing salinity, requiring adjustments to treatment processes.
- Reduced gas well efficiency and increased maintenance needs due to rising groundwater levels.
- Changes in waste decomposition rates and microbial activity, impacting gas composition and extraction rates.
- Power outages disrupting operations.
- Damage to access roads or closures and supply disruptions.

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems

Permafrost thawing

- Restrictions to the microbial activity responsible for organic waste decomposition. Frozen conditions inhibiting the breakdown of organic materials.
- Ground subsidence / differential settlement, compromising integrity and causing possible tears or ruptures in geomembranes.
- Ground heave / differential settlement, altering the stability and integrity of well casings, tanks, buildings, and other infrastructure elements, as well as the positioning and alignment of machinery systems (e.g., sprinkler, recirculation systems).
- Shifting of underground pipes and stressing of connections, leading to leaks.
- Threats to the integrity of leachate containment systems and increased risk of groundwater contamination. In some cases, the presence of permafrost can create pathways for leachate to migrate horizontally through the frozen layers.

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems

Landslide
Avalanche
Subsidence

- Damage by displacement or burial of sealing layer geomembranes, compromising containment.
- Debris flow damaging, blocking or destroying manifold systems, leachate storage tanks, gas tanks or other infrastructure elements.
- Contamination of stored waters and leachates.
- Damage to gas wells leading to blockages or leaks affecting gas extraction rates.
- Damage or burials of monitoring stations.
- Power outages disrupting operations.
- Damage to access roads or closures and supply disruptions.

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems

Heat wave

- Reduced flexibility and effectiveness of sealing layer geomembranes as they degrade and become brittle.
- Expansion or contraction of pipes, stressing their connections.
- Increased evaporation rates, affecting injected fluid volumes and stored water.
- Increased gas expansion rates, affecting pressure levels and internal temperatures in gas storage facilities.
- Heat stress on compressor equipment leading to overheating or malfunctions.

	• Increased stress on cooling systems for generators and electrical equipment. • Increased odours and emissions. • Changes in the decomposition rates of organic waste. • Changes in the composition and volume of landfill gas. • Safety issues for personnel.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Coastal erosion **Soil erosion**	• Exposure of geomembrane materials, leading to damage and leaks and compromising stability and effectiveness. • Exposure of underground pipes, leading to damage, leaks, and increased corrosion. • Stability issues of critical structures (e.g., leachate storage tanks injection wells, buildings, manifold system). • Soil erosion near leachate discharge points leading to pollution. • Damage to access roads or closures and supply disruptions.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing precipitation patterns **Precipitation or hydrological variability**	• Increased groundwater levels affecting gas well stability and performance. • Overfilling of storage tanks, increasing the risk of overflow. • More frequent maintenance requirements of machinery to avoid rusting and corrosion. • Moisture content affecting the rate and efficiency of landfill gas production. • Excessive moisture resulting in higher leachate volumes for management and treatment.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Cold wave	• Geomembrane materials becoming brittle and prone to cracking and integrity issues to geomembrane seals and joints. • Ice formation in manifold systems can cause blockages and pressure issues. • Freezing of gas pipes affect flow rates. Ice accumulation on gas wells impact extraction efficiency. • Damage to injection system elements, water hoses and fittings, leading to leaks. • Frozen water or leachate in tanks, inducing storage issues (reduced operationality). • Ice buildup on compressor equipment leading to mechanical failures. • Reduced performance of monitoring and control systems. • Slower decomposition rates of organic waste. • Increased strain to power generation systems (e.g., increased demand for heating) and increased fuel consumption.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Drought	• Reduced effectiveness of geomembranes. • Drying of soils leading to shifting or settling, affecting pipe connections and injection systems • Drying of soils leading to shifting or settling leading to foundation issues for generator buildings, tanks or other critical infrastructure. • Changes in quality of leachate, including its strength, pH, and contaminant levels due to lower moisture content of the waste. • Creation of 'dry pockets' due to low waste moisture hindering gas production and waste breakdown. Impact also on surface and compaction sensors. •			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Changing temperatures Temperature variability	• Differential expansion and contraction of geomembranes, leading to tears or leaks. • Differential expansion and contraction of pipes leading to structural stress affecting the seals and joints. • Reduced flow rates and changes in viscosity of injected fluids. • Tank and hose materials degrading faster, becoming brittle or crack leading to leaks. • Changes in the microbial activity in tanks, impacting leachate treatment efficiency. • Changes in gas pressure affecting flow rates and control mechanisms. • Required adjustment of cooling systems for generators • Fluctuation of leachate flow rates (e.g., colder temperatures lead to thicker leachate), affecting collection and pumping systems. • Fluctuation to biological processes in leachate treatment (e.g., higher temperatures can accelerate decomposition or chemical transformations of contaminants).			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Module 2: Exposure Analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Module 3: Vulnerability Analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For examples on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts (with or without the project's criticality), readers are referred to the **Introductory Chapter** (Module 5). To assist users with the scoring procedure, an overview of significant impacts to the dumpsite rehabilitation facilities across various risk areas (RA) is provided in the table below.

TABLE 3.21 • Climate impacts for dumpsite rehabilitation (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damages**: Extreme climate-related hazards such as landslides, floods, or storm surges can cause severe damage to buildings, storage tanks, and equipment. Chronic stress can lead to increase maintenance and repair needs. **Disruptions to Operations**: Climate events can lead to temporary shutdowns or reduced operational capacity.
RA2: Safety and Health	**Worker Safety Risks**: Extreme weather events may threaten worker safety, especially for those workers involved in outdoor operations. Heat-related illnesses such as heat exhaustion and heat stroke or extreme cold exposure leading to risks of hypothermia, frostbite, and reduced dexterity are some examples. **Hygiene and Health Risks**: Impacts from climate events on the facility may lead to workers coming into contact with hazardous materials, chemicals, and pathogens present in the waste. Increased workload or pressure during emergency response to disasters caused by climate events can lead to stress, anxiety, or trauma from dealing with hazardous conditions or evacuations.
RA3: Environment	**Leachate and Contaminant Release:** Climate events can result in the spread of pollutants from the dumpsite into adjacent ecosystems. Leachate seepage can contaminate soil with heavy metals, toxins, and organic pollutants, impacting soil quality. **Air Pollution:** Increased temperatures and prolonged droughts can enhance the generation of landfill gas, leading to potential air pollution risks.
RA4: Social	**Community Health Concerns:** Poor air quality resulting from landfill gas emissions or wildfire smoke can impact the health of nearby communities. Water contamination due to leachate overflow can jeopardise access to clean drinking water for residents. Possible discomfort due to odours. **Impact on Livelihoods:** Contamination of agricultural lands from leachate or floods can harm livelihoods dependent on farming or livestock. Disruptions to dumpsite operations due to climate hazards can affect employment opportunities for local workers.
RA5: Financial impacts	**Increased Maintenance and Repair Costs:** Climate-related damage to infrastructure and equipment requires frequent repairs and replacements, leading to higher operational costs. Mitigation measures such as slope stabilisation or flood barriers entail significant upfront investments. **Insurance Premiums and Coverage**: Dumpsite facilities located in high-risk areas for climate hazards may face increased insurance premiums or limited coverage. Insufficient coverage for climate-related damage can result in financial burdens for facility owners or operators.
RA6: Reputation	**Regulatory Compliance Challenges:** Climate-related damage and environmental incidents may lead to increased scrutiny from regulatory authorities. Non-compliance with environmental standards due to climate impacts can result in fines, penalties, or operational restrictions. **Investor Confidence and Partnerships:** Negative publicity from climate-related incidents can deter potential investors or partners from engaging with the facility. Lack of resilience to climate hazards may hinder collaborations with sustainable waste management initiatives or green energy projects.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 3.22 presents potential adaptation solutions for climate hazards that could impact the dumpsite rehabilitation facilities. The suitability of each measure is linked to the encountered level of risk and the uncertainty of climate projections, while the timing of implementation is aligned with specific project stages. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 3.22 • Dumpsite rehabilitation facilities: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. Informed decision-making is to be applied along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Extreme wind (including storm, hurricane, tornado)	▪ Conduct risk assessments considering extreme winds, heavy rains, tornadoes, and cyclones and consider relocation in case of excessive residual risk.	▪ Design buildings, tanks, and structures to withstand extreme wind loads and pressures. ▪ Install storm shutters or protective covers for windows, doors, and openings. ▪ Use reinforced materials, anchors, and foundations to enhance structural integrity. ▪ Install barriers, screens, or fencing to deflect windborne debris away from critical assets. ▪ Protect electrical systems with surge suppressors, waterproof enclosures, and elevated installations. ▪ Install backup generators, elevated switchgear, and redundant power supply routes.	▪ Designate and mark evacuation routes, safe assembly points, and shelter areas. ▪ Conduct regular drills and train staff on evacuation procedures and safety protocols. ▪ Implement shut-off valves and emergency venting systems for safety during storms. ▪ Test and maintain backup power generators, pumps, and essential systems regularly. ▪ Establish fuel storage protocols and ensure availability for extended storm events. ▪ Regularly inspect and clear drainage paths to prevent waterlogging and flooding.
Flood Storm surge Heavy precipitation	▪ Perform flood risk site assessment (including future climate projections) and consider relocation in case of excessive unmitigated risk. ▪ Consider in the project's strategy preplanned contracts or agreements with cleanup crews, waste haulers, and repair services.	▪ Design buildings, tanks, and structures to withstand floodwaters and storm surges. ▪ Elevate critical equipment and systems above potential flood levels. ▪ Implement engineered drainage systems, berms, and diversion channels. ▪ Install protective covers, or geomembranes to prevent erosion or breaches. ▪ Implement slope stabilisation techniques to secure sealing layer geomembranes during heavy precipitation. ▪ Designate containment zones for leachate or hazardous materials during floods.	▪ Implement regular debris clearing and vegetation maintenance around facilities and ensure access roads, drainage channels, and culverts are clear of obstructions. ▪ Install and maintain backup generators, pumps, and essential systems for continuity. ▪ Implement automated leak detection systems for early warning and response. ▪ Provide training to staff on flood response and leak containment procedures, including emergency shutdowns.
Wildfire	▪ Conduct fire risk assessments to identify vulnerable areas and assets and if necessary, consider site relocation. ▪ Assess and plan mitigation measures for potential environmental impacts of fire residues and runoff and develop recovery plans for post-fire cleanup, rehabilitation, and restoration.	▪ Use fire-resistant sealing layer geomembranes, piping, and building materials in facility construction. ▪ Design structures with fire breaks, non-combustible materials, and ember-resistant features. ▪ Create and maintain firebreaks around facility perimeters to slow fire spread.	▪ Develop a detailed emergency plan outlining procedures for wildfire evacuation and response and include protocols for equipment shutdown, personnel safety, and emergency communication. ▪ Implement early warning systems for wildfires, such as smoke detectors or heat sensors.

		▪ Install automatic fire suppression systems at critical areas and include sprinkler systems, foam suppression, or water cannons for rapid response. ▪ Design designated fire-resistant storage areas to store fuels and flammable materials.	▪ Install backup power generators to ensure continued operation during power outages. ▪ Enhance periodic maintenance protocols of fire management/extinguishing installations. ▪ Conduct regular drills to practice evacuation procedures and improve response times.
Sea level rise Saline intrusion	▪ Conduct assessments of coastal vulnerability to sea level rise and saline intrusion and identify areas of high risk. ▪ Use topographic surveys to assess site elevation and potential flood risk areas. ▪ Locate critical infrastructure such as storage tanks and buildings away from coastal zones or consider entire project relocation. ▪ Designate buffer areas or green spaces to absorb potential saline intrusions and floodwaters.	▪ Design buildings, storage tanks, and equipment platforms above projected flood levels. ▪ Apply protective coatings and linings to infrastructure exposed to saline water and use corrosion-resistant materials for pipes, tanks, and equipment, e.g., implement cathodic protection systems or sacrificial anodes to prevent metal degradation. ▪ Use cutoff walls or grout curtains around landfill perimeters to limit saline water infiltration. ▪ Install subsurface barriers or impermeable liners to prevent saltwater intrusion.	▪ Conduct frequent monitoring of groundwater salinity levels and trends. ▪ Implement early warning systems for detecting saltwater intrusion into facility areas. ▪ Install sensors and monitoring equipment to assess leachate salinity and composition. ▪ Develop protocols for responding to sudden inundation events due to sea level rise. ▪ Plant salt-tolerant vegetation as natural buffers against saline intrusion. ▪ Conduct regular inspections for signs of corrosion on infrastructure elements.
Permafrost thawing	▪ Conduct detailed geotechnical investigations to understand permafrost distribution and characteristics. ▪ Plan for flexible layouts to accommodate potential ground shifts due to permafrost thawing. ▪ Consider relocation.	▪ Use geophysical methods to map permafrost thickness and depth for informed design. ▪ Incorporate increased safety factors for structural stability in areas prone to permafrost degradation. ▪ Designate critical infrastructure away from areas with high permafrost vulnerability. ▪ Specify flexible materials for pipes and conduits and use expansion joints and flexible connectors in gas and water distribution systems. ▪ Implement slope protection measures to prevent erosion and destabilisation of permafrost slopes.	▪ Implement ground temperature and settlement monitoring networks to detect early signs of permafrost thawing and conduct regular surveys and assessments to track permafrost conditions over time. ▪ Conduct routine inspections of infrastructure foundations for signs of permafrost degradation.
Heat wave	NA	▪ Select materials that can withstand thermal expansion and contraction. ▪ Install cooling systems or fans in critical infrastructure buildings and work areas. ▪ Design shading structures or awnings for outdoor work areas and equipment.	▪ Implement heat exposure limits and rest breaks to prevent heat-related illnesses. Adjust work schedules. ▪ Implement regular inspections of equipment to identify heat-related wear or damage. ▪ Schedule maintenance tasks to ensure optimal performance during heat waves.
Cold wave	NA	▪ Select freeze-resistant sealing layer geomembranes, pipes, and fittings for cover sealing systems.	▪ Implement weather monitoring systems to track temperature drops and cold wave forecasts and utilise alerts and notifications to inform staff of impending cold wave conditions.

		▪ Use materials that can withstand freezing temperatures for critical elements. ▪ Design heated enclosures for pumps, valves, and control systems to prevent freezing. ▪ Use insulated covers or heating elements to prevent water freezing in tanks. ▪ Enclose vulnerable equipment and systems to protect from freezing temperatures.	▪ Develop snow removal and de-icing plans for access roads and work areas. ▪ Install backup heating systems for critical infrastructure and buildings and ensure fuel reserves for generators.
Landslide **Avalanche** **Subsidence**	▪ Conduct geotechnical surveys and slope stability assessments to identify high-risk areas and potential landslide triggers around the facility. ▪ Seek expert advice on landslide mitigation technologies and best practices and consider site relocation in case of excessive residual risk. ▪ Consider the feasibility of including in the project buffer zones or setback distances from unstable slopes.	▪ Implement engineered slope protection systems such as retaining walls or terracing. ▪ Design protective layers or covers for sealing layer geomembrane to resist impact from landslide debris. ▪ Implement barriers or catchment systems to divert debris away. ▪ Ensure stable foundation designs for buildings, tanks, and equipment.	▪ Install slope inclinometers, ground movement sensors, or geophysical monitoring. Also consider remote cameras, alarms, or telemetry systems for landslide detection. ▪ Implement real-time landslide monitoring with automated alert systems. ▪ Establish protocols for prompt removal of landslide debris from critical areas.
Coastal erosion **Soil erosion**	▪ Use geospatial mapping to identify areas at high risk of erosion and establish erosion hazard zones to guide infrastructure placement and development.	▪ Design site layouts to minimise exposure of critical assets to coastal erosion. ▪ Construct protective barriers such as riprap or seawalls to mitigate coastal erosion impacts. ▪ Implement slope stabilisation techniques such as terracing or revegetation. ▪ Ensure foundations are anchored securely to resist erosion and soil movement. ▪ Allow water infiltration in access roads (permeable surfaces) to prevent soil erosion and surface runoff.	▪ Install erosion monitoring devices to track shoreline changes and soil erosion. ▪ Conduct routine inspections of coastal infrastructure for signs of erosion damage. ▪ Ensure leachate and waste containment systems are regularly inspected and maintained. ▪ Implement spill response procedures to prevent contaminants from reaching erosion-prone areas.
Changing precipitation patterns **Precipitation or hydrological variability**	NA	▪ Increase capacity of leachate and water storage tanks to accommodate excess precipitation. ▪ Design overflow and diversion systems to prevent tank overfilling during heavy rainfall.	▪ Inspect and clear drainage channels, culverts, and sumps regularly to prevent blockages. ▪ Maintain pumps and valves in stormwater management systems for optimal performance. ▪ Monitor leachate flow rates and adjust recirculation rates based on precipitation forecasts. ▪ Monitor slopes for signs of instability and take corrective action as needed.
Drought	▪ Explore and secure alternative water supplies, such as groundwater wells or water deliveries via tankers.	▪ Use drought-resistant geomembranes that are less affected by moisture fluctuations. ▪ Implement soil stabilisation measures to prevent erosion and drying of soils.	▪ Include procedures for prioritising water use, reducing non-essential activities. ▪ Maintain emergency water storage tanks or reservoirs for critical operations.

	▪ Establish agreements with nearby facilities for mutual access to water resources. ▪ Assess options for fire prevention systems that do not rely heavily on water.		
Changing temperatures Temperature variability	▪ Consider topography and local microclimates to minimise temperature impacts on facility elements.	▪ Utilise composite sealing layer geomembranes with materials resistant to temperature-induced degradation. ▪ Design geomembranes with flexibility to accommodate expansion and contraction. ▪ Incorporate insulation in gas storage tanks and compressor buildings to minimise temperature fluctuations and insulate pipes and conduits to maintain consistent temperatures in critical systems.	▪ Conduct frequent inspections of sealing layer geomembranes, tanks, and pipes for signs of temperature-induced wear. ▪ Adjust recirculation rates, gas flow controls, and leachate treatment processes based on temperature data. ▪ Use temperature data to optimise energy usage, such as adjusting generator output based on ambient conditions.

4. Transport Sector Guidance

Introduction

Climate change poses a dual challenge for the transport sector, demanding both mitigation of greenhouse gas (GHG) emissions and adaptation to the physical impacts of climate-induced hazards. The sector faces threats from increasing temperatures, sea level rise, and more frequent and more intensive extreme weather events, among others. These events jeopardise transport infrastructure and have far-reaching economic implications, therefore requiring considerations across the entire project cycle: planning and development, design and construction, operation, and maintenance.

For operators or owners of transport infrastructure, climate change may result in direct losses due to asset damage or indirect losses due to downtime. More significantly, it can lead to substantial operational losses and to disruptions in transportation services due to weather-related incidents, impacting first of all users and their confidence in the sector's ability to provide reliable and efficient services and also may result in significant economic losses. These losses may also affect the sector's attractiveness for private investments and the insurance conditions of transport projects. Ripple financial impacts include disruptions to regional supply chains due to transportation service disruptions and increased costs for users and businesses.

The present chapter expands on the EC Technical Guidance for climate proofing of infrastructure (outlined in the **Introductory Chapter**), delving into the specific considerations required for climate resilience assessments within the Transport Sector. The chapter covers projects in four transport sub-sectors:

- Urban transport
- Roads
- Railways
- Ports

The relevant climate hazards (chronic or acute) potentially affecting each sub-sector are listed in **Table 4.1**. The color-coded marks (No sensitivity-Low-Medium-High)[57] indicate the general sensitivity level of each subsector when considering typical infrastructure and the associated services. These marks are only supposed to work as a general indication and do not necessarily reflect the relevance of the hazards to the project's specificities. It is important to note that the project promoter should extend the hazard list if necessary and consider any – potentially affecting – site- or project-specific hazards that may not mentioned in **Table 4.1** but still relevant for the project. The scoring levels to be applied in each Module should be adjusted by the project promoter depending on the project characteristics and the site's specificities.

Note that the timescale for the climate vulnerability and risk assessment should correspond to the intended lifespan of the investment being financed under the project. The lifespan is often (considerably) longer than the reference period (economic life) used in the cost-benefit analysis.

[57] Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of the general sensitivity scores.

TABLE 4.1 • Relevant climate hazards affecting the examined transport sub-sectors[58].

Hazards (in accordance with the EU Taxonomy, refer to Table 1.1 of the Introductory Chapter)	**Sub-sector**			
	Urban Transport	**Roads**	**Railways**	**Ports**
CHRONIC				
Changing temperatures/ Temperature variability				59
Permafrost thawing				
Changing wind patterns				60
Changing precipitation patterns/ Precipitation or hydrological variability[61]				
Sea level rise/ Saline intrusion				
Coastal erosion/ Soil erosion				62
ACUTE				
Heat wave				
Cold wave/ Freeze-thaw cycle				
Wildfire				
Extreme wind (including storm, hurricane, tornado)				
Drought				
Fog				
Flood/Storm surge/ Heavy precipitation				
Landslide/Avalanche/Subsidence				

[58] The proposed No sensitivity-Low-Medium-High scoring levels are intended for a typical transport project; however, it is advisable for the project team to verify and/or review their relevance to the project and its specific context and adjust them accordingly.
[59] including water temperature changes
[60] including wave and current changes
[61] These hazards refer to the chronic changes in the average precipitation, the frequency of rainfall events, the duration and onset of rainy season. Extreme precipitation is covered in the acute hazard of heavy precipitation.
[62] including sedimentation

Preparation, Planning & Resources

Project Characteristics

Tables 4.2-4.5 provide lists of indicative components that could be included in the climate assessment analysis for the transport projects examined herein[63]. The final component list for each project needs to be defined by the project team based on project specificities. The typical lifespan[64] of tangible infrastructure assets is also listed on the tables[65]. As observed, infrastructure components may have different lifespans. In the ensuing, the selected time scale of the exposure analysis should aim to encompass the whole physical life of the project (i.e., the longest lifespan of its infrastructure components)[66]. It is noted that roads and railways and their associated components are treated as separate projects in the ensuing; since an urban transport project may also include urban roads (e.g., BRT lane) or rail-based systems (e.g., tram lines, metros, etc.), also mentioned under the urban transport category.

TABLE 4.2 • Indicative key **urban transport** components to be included in the climate resilience assessment.

Component category	Assets/Operations (non-exhaustive list)	Typical lifespan (years)[65]
Assets	▪ Urban road lanes (including pedestrian and bike lanes), parking areas, pavement and layers until embankment	30
	▪ Urban setup/furniture including road furniture	5-10
	▪ Suburban railways, light rail, metro (tracks and foundations)	50
	▪ Bridges, overpasses	100
	▪ Tunnels, underpasses	100
	▪ Surface drainage	10-20
	▪ Rolling stock - buses, trolleybuses	▪ buses: 12 ▪ trolleybuses: 15
	▪ Rolling stock - metros, trams, and rails	20
	▪ Rolling stock - public bikes	3
	▪ Assets/equipment of traffic management systems (e.g., traffic lights, signalling and monitoring cameras, etc.)	10
	▪ Auxiliary buildings (stations, terminals and depots)	50
Processes	▪ Traffic control and management (traffic signal timing, traffic monitoring) ▪ Transportation operations (scheduling, route planning, ticket/fees collection) ▪ Maintenance ▪ Parking management	-
Inputs	▪ Traffic flow/Vehicles/Road and public transport users ▪ Passengers/Cyclists	-
Outputs	▪ Transport service	-

[63] The terminology used for the component categories is indicative and may vary from sub-sector to sub-sector as appropriate.
[64] It is proposed to define the lifespan as the design working life (DWL), i.e., as the period for which the structure/equipment will be used with anticipated maintenance but without major repair.
[65] Values are indicative and may differ depending on project characteristics as appropriate. The actual lifetime of assets depends on material, regional context, economic conditions, procurement processes, etc. As such, a quite wide range is observed in the tables. It is noted that lifespan is of particular relevance for defining adaptation measures as result of risk analysis.
[66] It is recommended to consider the longest lifespan of the different components and include in the climate resilience assessment the most critical ones in terms of structural integrity, operation and safety and/or of relevance for the project.

Interconnected systems (outside the direct control of the project)	▪ Access to/from medium/long-distance transport services and infrastructures ▪ Power supply (including distribution networks)	-

TABLE 4.3 • Indicative key **road** components considered in the climate resilience assessment.

Component category	Assets/Operations (non-exhaustive list)	Typical lifespan (years)[65]
Assets	▪ Road construction (pavement and layers until embankment)	▪ asphalt: 15 ▪ concrete: 30
	▪ Embankments	50-100
	▪ Bridges, overpasses, and structures/buildings	50-100
	▪ Geotechnical assets (e.g., retaining/supporting walls, etc.)	50-100
	▪ Tunnels, underpasses	100
	▪ Road furniture (e.g., protection walls, safety fences, noise walls, gantries, signage, etc.)	5-10
	▪ Surface drainage	10-20
	▪ Auxiliary facilities (e.g., O&M centres, rest areas and service stations, traffic management centres, etc.)	50
	▪ Horticultural assets (e.g., trees, bushes, grassing, etc.)	10-50
	▪ Electro-mechanical installation equipment (e.g., transformation stations, feeder pillars, ITS equipment, lighting, etc.)	10
Processes	▪ Maintenance & Operation ▪ Traffic management ▪ Safety procedures (i.e., response to crash accidents)	-
Inputs	▪ Vehicles/Road users	-
Output	▪ Transport service	-
Interconnected systems (outside the direct control of the project)	▪ Transport connections (other road sections/networks or other transport infrastructure/services) Power supply/Water supply/ Telematics (communications)	-

TABLE 4.4 • Indicative key **railway** components to be included in the climate resilience assessment.

Component category	Assets/Operations (non-exhaustive list)	Typical lifespan (years)[65]
Assets	▪ Track infrastructure (e.g., rails, sleepers, ballast, rail joints, rail fasteners)	50
	▪ Embankments	50-100
	▪ Bridge, overpasses	100
	▪ Tunnels, underpasses	100
	▪ Geotechnical assets (e.g., retaining/supporting walls, etc.)	50-100
	▪ Furniture (e.g., protection walls, safety fences, noise walls, gantries, signage, etc.)	5-10
	▪ Surface drainage	10-20

	▪ Rollingstock (e.g., locomotives, passenger coaches, freight wagons, high-speed trains)	20
	▪ Station and terminal buildings	50
	▪ Electrification system components (e.g., overhead wires, substations, transformers, current collectors)	▪ electrical equipment: 20 ▪ sub-station buildings: 50
	▪ Signal and control systems (e.g., semaphore, colour light, interlocking system, train control system (ATC[67], ETCS[68]), switches and turnouts, Centralised Traffic Control (CTC))	20
	▪ Horticultural assets (e.g., trees, bushes, grassing, etc.)	10-50
Processes	▪ Train operations (scheduling, dispatching, routing, timetable management, crew management) ▪ Maintenance and inspection ▪ Passenger services (ticketing and fare collection, passenger information systems, accessibility services, security, and surveillance) ▪ Freight operations	-
Inputs	▪ Passengers ▪ Cargo	-
Output	▪ Passenger and freight transport services	-
Interconnected systems (outside the direct control of the project)	▪ Other rail connections or integrations with other modes (bus, metro, bicycle, taxi) ▪ Access roads ▪ Supply chain (energy production and distribution, spare parts)	-

TABLE 4.5 • Indicative key **port** components to be included in the climate resilience assessment.

Component category	Assets/Operations (non-exhaustive list)	Typical lifespan (years)[65]
Assets	▪ Berthing and mooring infrastructure (e.g., quay walls, piers, jetties, dolphins)	50
	▪ Sea defence infrastructure (breakwaters and moles)	70
	▪ Port equipment (e.g., shore to sea (STS) gantry cranes, mobile cranes, rail mounted cranes (RMC), straddle carriers, reach stackers forklifts, tractors and trailers, ship loaders and unloaders, conveyor systems)	▪ STS and RMC cranes: 20 ▪ Mobile cranes:15 ▪ Ship loaders and unloaders, conveyor systems: 25 ▪ Other equipment: 10
	▪ Storage facilities (e.g., warehouses, silos, tanks, cold storage units, open storage areas)	50
	▪ Utilities	30
	▪ Navigation aids (e.g., lighthouses, buoy systems, navigation lights, radar systems)	▪ Lighthouses: 50 ▪ Buoy systems and navigational

[67] Automatic Train Control (ATC) systems are designed to automatically control the speed and movement of trains to ensure safe operation and adherence to signalling conditions. These systems use various technologies to monitor train positions, track conditions, and speed.

[68] European Train Control System (ETCS) is a standardised signalling and control system used in Europe to ensure interoperability and safety across different rail networks. It is designed to replace older, country-specific signalling systems with a unified and modernised approach. The system operates in different levels of complexity, with higher levels offering more advanced features such as continuous speed control and moving block signalling.

		▪ lights: 10 Radar systems: 15
Processes	▪ Cargo handling (loading and unloading operations, containerisation, bulk cargo handling) ▪ Customs and inspections (border control, cargo inspection, customs clearance, security screening) ▪ Vessel operations (berthing and unberthing, pilotage services, fuelling) ▪ Logistics (cargo staging and coordination, intermodal transport management, freight forwarding, inventory management) ▪ Maintenance and repair (port infrastructure, equipment, dredging operations) storage facilities, other buildings ▪ Security and surveillance	-
Inputs	▪ Vessels and shipping lines ▪ Cargo ▪ Passengers	-
Output	▪ Cargo (export/import) ▪ Passengers ▪ Waste from vessels	-
Interconnected systems (outside the direct control of the project)	▪ Access roads ▪ Rail connections Power (energy production and distribution) and water supply ▪ Freight centres/Dry ports	-

Project Criticality

As described in the Introduction analysing the climate impacts at network level requires increased attention. In the transport sector, a project's criticality may be assessed based on the significance of a project at network level in terms of connectivity (local/regional/national/transnational), traffic loads, the existence of sufficient redundancies, and potentially broader roles such as connecting to key and strategic facilities like hospitals, ports, other critical/strategic infrastructures and services (e.g. for civil protection). While these factors are important, criticality may vary depending on the context and could encompass other relevant aspects and considerations such as traffic/service levels, construction/rehabilitation costs, and any other pertinent factors specific to the project's role and context. The criticality definition is particularly crucial for identifying adaptation solutions and should be provided by the project promoter. It's worth noting that the identification and definition of criticality may have already been undertaken by network managers or other relevant institutions, as it is not solely an assessment for climate resilience but also a part of network management (see also the Critical Entities Resilience Directive[69]). The climate vulnerability and risk assessment should be aligned with such definitions (if relevant to the project of interest). Criticality could be taken into account in the Phase 2 Detailed analysis.

[69] Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC: Member States will have to identify the critical entities for the sectors set out in the CER Directive by 17 July 2026. They will use this list of essential services to carry out risk assessments and to then identify the critical entities.

4.1 Urban Transport

PHASE 1 • Screening

Module 1: Sensitivity analysis

The sensitivities of urban transport to climate hazards are provided in **Table 4.6** along with indicative scores per component category (No sensitivity-Low-Medium-High)[70]. Sensitivities may refer to the infrastructure elements and the provided service. The proposed scores shall be treated with caution and shall be critically evaluated by the project team to ensure compatibility with the project specificities. For example, an increased frequency and intensity of heavy rainfalls combined with rising sea levels may pose challenges to the functionality of low-lying subway stations, affecting metro operations, while the same climate threat might have minimal impact on elevated rail networks.

TABLE 4.6 • Sensitivities of urban transport components.

Climate Hazard	Sensitivities			
Extreme wind (including storm, hurricane, tornado)	• Increased structural damage, flooding (due to storm), and debris accumulation, impacting the integrity and functionality of the urban transport network or their interdependent systems. • Temporary loss of serviceability and traffic delays due to physical damage. • Flying objects or falling branches from trees due to extreme winds causing physical damage to the fleet (buses, trams, public bikes) and the infrastructure (e.g., breakage of overhead lines of tram etc). • Damage to auxiliary infrastructure can cause breakage or collapse of objects, posing safety issues. • Power outages affecting communication systems and services. • Reduced passengers due to reduced mobility during stormy/windy conditions. • Unsafety riding conditions for bicyclers. Sidewind can cause instability and severe accidents. • Reduced ridership during high wind conditions. Cycling against strong headwinds can increase fatigue among cyclists, potentially affecting their willingness to bike and impacting overall cycling participation rates. • Risk of destabilisation/derailing of buses/trams. • Increased risk of injuries (from flying objects) for passengers. • Limitation/stop to operations for safety reasons. • Power outages, fuel shortages, and disruptions in energy supply for transport operations.			
Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems
Flood Storm surge Heavy precipitation	• Temporary loss of serviceability and traffic delays due to inundation of roads, railways, bike lanes, stations, terminals, tunnels, parking lots and depots. Transferred debris, fallen trees or collapsed signage can also lead to service loss or delays. This also includes traffic suspension due to emergency warnings for events approaching. • Erosion of surfaces (roads, railways, bike lanes, pedestrian pavements) and scouring of bridge foundations and abutments. • Repetitive flooding and storm surges accelerate infrastructure deterioration, requiring frequent repairs. Continuous exposure to floodwaters weakens roadbeds and culverts, leading to structural instability. • Malfunctions of traffic signals, causing traffic congestion and accidents. • Reduced accessibility due to inundation of the interdependent origin/destination regions and reduced passengers/ cyclists due to reduced mobility during heavy precipitation events. • Flooding can lead to electrical failures in transit systems, posing risks of electrocution.			

[70] Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the definition of sensitivity levels.

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems
Heat wave	• Roads, bike lanes, railways, and pavement deterioration (pavement cracking, concrete pavement blow-ups, rutting on roads/bike lanes, expansion of rails leading to track misalignment and potential derailments, etc.). • Heat-related speed restrictions on railways to prevent track buckling. • Increased need for air-conditioning and cooling systems at the vehicles and stations leading to higher energy consumption for stations and transport vehicles. • Increased temperatures strain engines and cooling systems of buses, trains, and vehicles causing heat-related mechanical failures. • Dry conditions in combination with extreme temperatures during heat waves increase the risk of fires along transport routes. • Increased discomfort and potential health concerns may lead to reduced passengers or cyclists. This affects both in-trip users' conditions and users' accessibility to/permanence in stops. It is relevant also for bikers that might be forced to change mode or give up on their trip. • Employees working on railways, platforms, and roads face risks of heat-related illnesses. • Strain on the electrical grid during heat waves, leading to potential blackouts.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Landslide Avalanche Subsidence	• Embankment instabilities and slope failures lead to road/track/bike lanes blockages, structural damage, prolonged closures, and disruptions (partial or total). • Settlement or sinking of ground can cause roads, bike lanes and rail tracks to shift or break. • Higher maintenance demands for geohazard-induced infrastructure damage require specialised remediation techniques and continuous monitoring to ensure sustained operational reliability. • Cleanup and repair efforts after landslides and subsidence events result in travel disruptions. • Potential disruptions in passenger or cyclist comfort, safety concerns, and altered transportation patterns due to geohazard-induced infrastructure limitations. • Reduced accessibility due to damage to the interdependent origin/destination regions. • Power supply issues.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Sea level rise Saline intrusion	• Temporary loss of serviceability and traffic delays due to inundation of roads, railways, bike lanes or stations and depots. This also includes traffic suspension due to emergency warnings for events approaching. • Safety issues or failures of retaining systems, bridges, embankments, and tunnels. • Increased frequency of coastal flooding disrupts traffic flow and access to coastal transport routes including port-related interlinks. • Saltwater intrusion corrodes road foundations, bridge supports, and rail track ballasts. • Increased exposure to saltwater requires more frequent maintenance of transport infrastructure. • Reduced accessibility due to inundation of the interdependent origin/destination regions. • Potential issues in the energy supply coastal components for urban transport systems.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Coastal erosion **Soil erosion**	• Deterioration of roads, railways, bike lanes (e.g., cracks/holes, misalignment of rail tracks, etc.) resulting in loss of service or reducing the passengers/cyclists' comfort and leading to increased maintenance needs. • Severe erosion may lead to safety issues or complete failures/collapses of infrastructure components (retaining elements, bridges, stations, etc.). • Soil runoff can clog drainage infrastructure, leading to flooding on roads, bike lanes or railways. • Erosion removes vegetation that helps stabilise road shoulders and embankments. • Closure of eroded roads/railways limits accessibility for communities and emergency services leading to less passengers.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems

Cold wave **Freeze-thaw cycle**	• Roads, bike lanes, railways, and pavement deterioration (potholes formation, cracking, frost heave lifting the pavement layers, corrosion due to increased usage of de-icing chemicals, abrasive damage caused by ice and snow removal processes). • Ice conditions on roads/ bike lanes may lead to more traffic accidents due to poor friction. Ice formation on rail tracks leads to reduced traction and potential derailments or buckling. • Rail switches and traffic signals may freeze, impacting traffic flow and train routes. • Slippery conditions may lead to passenger/cyclist safety issues. • Increased need for heating at the vehicles and stations leading to increased energy demand. • Vehicles & equipment experience reduced battery life and engine efficiency in cold conditions. • Freeze-thaw conditions can cause increased slope instabilities and embankment failures, switch malfunctions, operational issues like freezing of catenaries and components, pantograph and brake failures. • Increased discomfort and potential health concerns may lead to reduced passengers or cyclists. • Cold temperatures can disrupt fuel supplies for buses, trains, and maintenance vehicles.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems

Permafrost thawing	• Thawing permafrost causes ground subsidence, leading to uneven road/bike lane surfaces and rail tracks or misalignments. • Infrastructure built on permafrost may crack or deform as the ground shifts and loses stability. • Rail tracks may buckle or warp as permafrost beneath them thaws and shifts. • Thawing permafrost can undermine bridge supports and culverts, risking structural integrity. • Reduced load-bearing capacity of thawed permafrost limits vehicle access and transportation capacity. • Reduced accessibility and traffic delays due to interdependent road closures. • Reduced comfort due to road/bike lane/railway deterioration resulting in reduced passengers/ cyclists.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems

Wildfire	• Wildfires and extreme heat can weaken road surfaces or bike lanes and damage bridge structures, leading to structural damage. • Heat from wildfires can cause warping and damage to rail tracks, affecting train services. • Smoke may lead to reduced visibility, increasing the risk of accidents. • Authorities may close roads due to wildfire proximity or smoke hazards, impacting transport routes and leading to temporary operational disruptions (partial or complete network).

	• Power lines and electrical infrastructure near wildfire zones are at risk of damage or failure leading to power supply issues for the urban transport network. • Reduced accessibility when the fire impacts the interdependent network.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing temperatures **Temperature variability**	• Temperature variability leading to frequent fluctuations may accelerate wear and tear on roads, bike lanes, railways, and other auxiliary infrastructure (e.g., higher average temperature may lead to increased age hardening of asphalt binder or increased moisture-related warping in concrete). • Changes in passengers/cyclists' travel patterns (e.g., more summer days in a year may lead to people traveling more frequently by bike instead of using public transport and vice versa).			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing precipitation patterns **Precipitation or hydrological variability**	• Increased need for shelters at the passenger stations in response to an increase in the frequency of rainy days. • Prolonged exposure to moisture accelerates pavement deterioration and pothole formation and contributes to rusting of rail tracks and bridge components. • Changes in passengers' travel patterns (e.g., more rainy days in a year may potentially lead to people traveling less by bike or public transport and more by their cars).			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Drought	• Increased susceptibility to pavement deterioration and soil instability as prolonged drought causes soil shrinkage, leading to road/bike lane surface cracks and unevenness. • Dusty and dry conditions may lead to higher maintenance costs. • Drought conditions reduce water resources for road/bike lane cleaning, railway maintenance, and dust suppression. • Dry conditions increase the risk of wildfires near transport corridors.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Module 2: Exposure analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Urban transport networks are distributed systems with significant spatial variability, and therefore, may exhibit variations in hazard exposure depending on the assets' location (depots, stations, roads, rails, etc.). Hazard and project component maps should be superimposed to identify the system's exposure.

Module 3: Vulnerability analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For details on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts (with or without the network's criticality), readers are referred to the **Introductory Chapter** (Module 5). To assist users with the scoring procedure, an overview of significant impacts to urban transport systems across various risk areas (RA) is provided in the table below.

TABLE 4.7 • Climate impacts for urban transport (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damages**: Urban transport assets can be susceptible to damage from extreme weather conditions such as hurricanes, high winds, and floods, which can result in operational downtime and increased repair costs. **Traffic Disruptions**: Downtime may occur even in the absence of explicit physical damage to urban transport assets. For instance, during severe flooding, a road closure or temporary suspension of public transport services may be necessitated until the floodwaters recede and the road functionality is restored.
RA2: Safety and Health	**Increased Accidents:** Changes in weather patterns, including intense storms, flooding and icing conditions, pose safety risks for commuters and transport workers. **Disruption of Traffic Management Systems:** Climate impacts, such as heavy precipitation and temperature extremes, can affect the functionality of traffic management systems posing significant safety risks.
RA3: Environment	**Increased Pollution:** Shifting travel behaviours, such as decreased public transport or cycling usage and increased reliance on cars (e.g., during heat waves) will have environmental consequences, including the additional releases of greenhouse gases due to increased utilisation of private vehicles. **Increased Energy Consumption**: The increased need for heating or cooling in the vehicles or at the stations can result in higher energy consumption contributing to carbon emissions in case of fossil fuels usage.
RA4: Social	**Equity and Accessibility:** Climate impacts on urban transport can exacerbate existing disparities in access to transportation services. Vulnerable communities may experience reduced accessibility to public transportation or face challenges in adapting to changes in infrastructure.
RA5: Financial impacts	**Operational Disruptions, Maintenance and Damage Repair Costs:** Climate impacts on urban transport assets can result in operational disruptions and increased maintenance and repair costs. These costs contribute to financial challenges for transport agencies and operators. **Infrastructure Retrofitting Expenses:** The need for retrofitting existing infrastructure to withstand climate impacts, such as rising sea levels or increased temperatures, can lead to substantial financial investments for urban transport authorities or operators. **Economic Impact and Income Loss:** Disruptions in urban transport can have far-reaching consequences, affecting businesses and employees who depend on public transportation for their daily commute. Decreased accessibility may lead to financial losses for businesses, while commuters may encounter significant challenges in reaching their workplaces, impacting their productivity and overall work experience.
RA6: Reputation	**Service Reliability and Public Perception:** Frequent disruptions in urban transport services due to climate impacts can erode public trust and satisfaction. Reliability issues, delays, and accidents may negatively impact the reputation of transportation providers and city authorities. **Sustainability Commitments:** The reputation of urban transport systems is closely tied to sustainability commitments. Failure to address climate impacts and implement environmentally friendly practices may lead to reputational damage, especially in the context of increasing awareness of climate change and sustainability.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 4.8 presents potential adaptation solutions for climate hazards that could impact urban transport systems. The suitability of each measure is linked to the encountered level of risk and the uncertainty of climate projections, while the timing of implementation is aligned with specific project stages. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 4.8 • Urban Transport: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. In any case, inform decision-making along all stages of the project cycle with most up-to-date projections and recent extreme climatel events, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Extreme wind (including storm, hurricane, tornado)	▪ Gather historical weather data and consider future scenarios to identify high-risk areas in the urban environment in order to avoid them or include them in the project's adaptation plan. ▪ Plan by following a 'system of systems' approach in order to understand the connections between the urban network, society, and economy and assess accordingly the impacts of extreme weather events to the urban transport network in order to inform the project's adaptation plan.	▪ Take adequate consideration of future charges in extreme wind and storm events when designing vulnerable and exposed elements such as suspension bridges, supports and anchorages of lightweight furniture (e.g., noise screens, lighting and CCTV posts, signalling and E&M equipment, gantries and Variable Message Signs (VMS), etc.). ▪ Include adequate protection for vulnerable users (e.g., install wind-break panels to protect wind-exposed locations along bicycle routes). ▪ Consider wind-proofing critical areas (e.g., parking lots, depots, terminals, etc.). ▪ Consider developing intermodal hubs with covered waiting areas and emergency shelters. ▪ Implement green roofs, permeable pavements, and rain gardens to manage stormwater and reduce flooding risks. ▪ Design adequate public address systems and if required install additional emergency alert signage at stations and terminals. ▪ Consider integrating existing (or installing new) signalling infrastructure (antennas, signal boosters) to integrate mobile apps and SMS alerts for real-time updates and evacuation instructions.	▪ Collaborate with meteorological agencies for real-time weather monitoring and alerts. ▪ Implement early warning systems for extreme winds or storms and develop emergency response plans for rapid evacuation and sheltering. Train staff accordingly. ▪ Develop protocols for relocating transportation fleet to protected areas ahead of severe weather events. ▪ Stockpile emergency supplies and equipment for post-storm recovery and establish partnerships with neighbouring municipalities for coordinated response and resource sharing. ▪ Review existing power system arrangement (redundancy) to enhance supply reliability. ▪ Establish regular maintenance schedules for wind/storm-proofing infrastructure. ▪ Mitigate collapse hazards.
Flood Storm surge Heavy precipitation	▪ Perform an in-depth flood-risk analysis that utilises historical data and future projections. ▪ Consider multi-modal transport systems to provide alternative options during transport disruptions. ▪ Identify high-level adaptation strategies and develop multi-modal adaptation plans in the urban environment (e.g., risk zoning, land-use changes larger-scale NbS that improve natural	▪ Consider raising roads, bike lanes, railway tracks, charging points/stations and substations in flood-prone areas to minimise inundation. ▪ Consider integrating in the design flood walls or levees to protect transport hubs - in particular entries to subterranean systems - and critical junctions. ▪ Consider integrating in the design permeable pavements, green roofs or other Sustainable Drainage Systems concepts to absorb excess	▪ Install flood sensors and monitoring stations to provide real-time alerts. ▪ Develop evacuation and contingency plans for stranded passengers and flood-affected areas. ▪ Install backup generators for traffic signals, subway systems, and transit stations to ensure continuous operation. ▪ Conduct routine inspections of bridges, culverts, and tunnels for signs of erosion or structural weaknesses.

	permeability, masterplan and relocation of people and/or infrastructure, etc.) ▪ Coordinate efforts among transportation, emergency response, and city planning departments for integrated flood risk management.	rainwater and reduce runoff. Consider “green” solutions to improve natural permeability and control water runoff. ▪ Review design codes and guidelines for new infrastructure and retrofits of existing transport infrastructure to meet climate-resilient standards, including drainage improvements and flood-resistant materials.	▪ Clear storm drains, culverts, and ditches regularly to prevent blockages during heavy rains. ▪ Manage vegetation within the applied Sustainable Drainage Systems to prevent overgrowth that can obstruct drainage pathways and reduce system performance. Pruning, mowing, and selective planting help to optimise vegetation for effective water management.
Heat wave	▪ Identify high-level adaptation strategies and develop multi-modal adaptation plans in the urban environment (e.g., risk zoning, land-use changes that improve natural permeability, masterplan and relocation of people and/or infrastructure, etc.)	▪ Use heat-reflective materials for roads, bike lanes and pavements to reduce surface temperatures. ▪ Enhance the green space of pedestrian paths and bike lanes to mitigate heat. ▪ Install expansion joints on railways to accommodate rail movement during heat expansion. ▪ Construct shelters and covers at bus stops and railway platforms for passenger comfort. ▪ Carefully locate charging stations/points in shady/covered areas. ▪ Install green roofs on bus, tram, cycling stations and stops to reduce heat absorption and provide natural cooling. ▪ Implement solar panels to power cooling systems and reduce reliance on the grid. ▪ Adjust rolling stock to work properly under expected heat waves - in particular electric buses, including correct functioning of air conditioning systems.	▪ Monitor weather forecasts to anticipate heat waves and adjust transport schedules accordingly. ▪ Set up temporary cooling stations at transport hubs for passengers and workers during heat emergencies and ensure availability of drinking water at stations and stops for hydration during heat waves. ▪ Conduct regular inspections of railways for heat-related track buckling and alignment issues. ▪ Implement flexible work hours or schedules during extreme heat conditions to protect worker health.
Landslide Avalanche Subsidence	▪ Conduct geotechnical surveys to identify landslide/avalanche-prone areas, assess slope stability and inform transport route planning accordingly.	▪ Consider retaining structures to stabilise slopes and prevent erosion. ▪ Consider barriers along roads, bike lanes and railways to mitigate the impact of falling rocks and debris. ▪ Use geosynthetic materials to reinforce embankments and slopes. ▪ Consider building protective structures such as snow sheds and avalanche galleries along critical sections. ▪ Assess the need for installing snow fences to control snow deposition and reduce avalanche risk on transport routes.	▪ Install sensors for real-time monitoring of slope movements, snowpack conditions, and ground settlement. ▪ Implement automated alert systems to notify authorities and travellers of imminent landslide or avalanche threats. ▪ Conduct regular inspections for signs of instability. ▪ Establish protocols for swift debris after the events. ▪ Maintain vegetation along transport corridors to stabilise slopes and reduce erosion.

Sea level rise **Saline intrusion**	▪ Identify vulnerable coastal transport routes through sea level rise impact assessments. ▪ Develop scenarios for different sea level rise projections to inform the design and the adaptation strategy. ▪ Consider land use regulations to restrict development in high-risk coastal zones. ▪ Promote development of transport hubs and services away from high-risk coastal areas.	▪ Consider raising the elevation of roads, bike lanes, railways, and bridges to mitigate inundation risks. ▪ Review (and if necessary, extend) the design levels of seawalls and revetments to protect coastal transport infrastructure from erosion. ▪ Assess the options to create coastal green spaces and wetlands to act as natural buffers against sea level rise. ▪ Explore the use of flood-resistant materials in the construction of roads, bridges, and railway tracks. ▪ Consider installing pumps to remove excess saltwater from transport tunnels, underpasses, and low-lying areas.	▪ Install sensors to monitor sea level rise and tidal fluctuations along coastal transport routes. ▪ Use predictive models to anticipate coastal flooding events and plan maintenance activities. ▪ Conduct frequent inspections of coastal infrastructure to detect and address corrosion and degradation. ▪ Implement cleaning procedures to remove salt deposits from road surfaces, rail tracks, and bridges.
Coastal erosion **Soil erosion**	▪ Develop erosion zone management plans in collaboration with local communities and coordinate efforts with coastal management agencies to align transport infrastructure plans with mitigation strategies.	▪ Consider measures such as retaining walls, gabions, or vegetative cover to prevent soil erosion. ▪ Explore options for strengthening existing coastal defences and design coastal roads, bike lanes or railways with elevated sections or bridges to reduce exposure to wave action and erosion forces. ▪ Consider installing erosion control blankets or check dams to manage runoff on transport slopes. ▪ Plant native vegetation along transport corridors to stabilise soil and reduce erosion. Use natural vegetation and bioengineering techniques to stabilise coastal banks.	▪ Implement sensors to detect changes in coastal and soil erosion along transport routes. ▪ Conduct frequent inspections of coastal roads, bridges, and slopes for signs of erosion. ▪ Address erosion-related damage promptly to prevent further deterioration of infrastructure. ▪ Replenish eroded beaches with sand to mitigate wave impact and protect coastal roads.
Cold wave **Freeze-thaw cycle**	NA	▪ Consider installing heating systems in transport hubs to provide warmth for passengers and workers. ▪ Explore de-icing technologies on roads, bike lanes, bridges, and rail tracks to prevent ice buildup. ▪ Check if insulation enhancements of transport stations and shelters are required to retain heat and provide protection from cold winds. ▪ Equip buses and trains with cold-weather packages, including insulated cabins and engine block heaters.	▪ Incorporate real-time weather data into transport management systems for proactive decision-making. ▪ Develop plans for rapid response, including service adjustments and passenger safety measures. ▪ Establish procedures for clearing snow and ice from transport routes, platforms, and parking areas. ▪ Conduct regular inspections of rail tracks, switches, and traffic signals for ice buildup and malfunctions.

		▪ If necessary, use anti-freeze fluids in vehicle systems to prevent fuel lines and engines from freezing. ▪ Consider resistant materials and technologies for pavements and concrete structures (e.g., higher-quality concrete and pavement materials, soil stabilisation techniques to reduce frost action in subgrade soils) and structures. ▪ Review design guidelines as regards freeze-thaw effect and salting. ▪ Adjust rolling stock to work properly under expected cold waves - in particular electric buses, including correct functioning of heating systems.	▪ Set up temporary warming stations at transport stops and hubs for passenger comfort and safety. ▪ Implement flexible work schedules to minimise prolonged exposure to extreme cold conditions. ▪ Install backup generators for critical assets to ensure continuity of operations during power outages.
Permafrost thawing	▪ Conduct detailed permafrost mapping and ground stability assessments to understand the extent of permafrost thawing risks. Use future climate projections to anticipate long-term permafrost degradation trends and consider transport rerouting if necessary.	▪ Explore the use insulating materials to protect roads, bike lanes and railways from permafrost thaw. ▪ Consider installing heating elements or heat pipes to stabilise permafrost beneath infrastructure. ▪ Review designs of roads and bike lanes with flexible pavement layers to accommodate ground movement. ▪ Select suitable foundation designs like deep pile foundations that extend below the active layer of permafrost for stability.	▪ Install sensors to monitor permafrost temperatures, ground movement, and thaw depths. ▪ Use satellite imagery and aerial surveys to assess permafrost conditions along transport routes. ▪ Participate in knowledge-sharing networks to exchange experiences and lessons learned with other regions facing permafrost thaw challenges.
Wildfire	▪ Perform assessments for fire risks to identify susceptible zones and assets and inform transport route planning accordingly.	▪ Consider integrating firebreaks along transport corridors and maintain vegetation to reduce wildfire spread. ▪ At critical transport locations use fire-resistant materials for road surfaces, bridges, and rail infrastructure. ▪ Consider in the design designated lanes for emergency vehicles to access wildfire areas along transport routes. ▪ Consider integrating with the city's air quality monitoring system smoke detection systems along transport routes.	▪ Install wildfire monitoring cameras along transport corridors for early detection and use drones for aerial surveillance of wildfires. ▪ Develop plans for transport operations during wildfires, including evacuations and route diversions. ▪ Coordinate with firefighting agencies to integrate transport routes into wildfire response strategies. ▪ Provide passengers and drivers with real-time wildfire alerts and route information. Develop mobile applications to notify users of road closures, evacuation routes, and safe areas. ▪ Establish safe evacuation points and assembly areas at transport hubs for displaced residents.
Changing temperatures	▪ Conduct studies to assess the impact of changing temperatures on transport infrastructure and mobility patterns.	▪ Review asphalt mixes and rail materials designed to withstand temperature fluctuations.	▪ Install weather monitoring stations along transport routes to track temperature variations.

Temperature variability		▪ Consider designs of roads, bike lanes with multiple layers to accommodate thermal expansion and prevent cracking. ▪ Install rail tracks with floating slab systems to allow for thermal expansion and contraction. ▪ Consider porous pavements that allow water to drain, reducing the risk of freezing and thawing damage.	▪ Utilise real-time temperature data to inform maintenance activities and winter road treatments. ▪ Conduct regular inspections for pavement cracks and seal them to prevent water infiltration and further damage. ▪ Inspect rail tracks for alignment issues and perform corrective maintenance to prevent buckling.
Changing precipitation patterns Precipitation or hydrological variability	▪ Integrate climate projections and hydrological modelling into the urban transport planning and develop water management plans to account for changing precipitation patterns.	▪ In case of increased precipitation events upgrade culverts and drains to handle higher volumes of runoff during heavier or more frequent precipitation. ▪ Instead of hard-engineering measures consider integrating in the design the concepts of Sustainable Drainage Systems.	▪ Clear culverts, drains, and ditches of debris to maintain efficient water flow. ▪ Fill potholes promptly and resurface roads to prevent water penetration and deterioration. ▪ Conduct frequent inspections for rail tracks and bridges to detect erosion and corrosion.
Drought	▪ Identify areas susceptible to drought and assess the drought impacts to transport infrastructure and mobility patterns. Consider historical data of extreme drought events. ▪ Develop water conservation strategies in collaboration with local authorities.	▪ Explore of using pavement and track material options materials resistant to cracking and deformation under dry conditions. ▪ Consider permeable pavements to allow water infiltration and reduce runoff during rare rain events.	▪ Implement water-saving measures for road cleaning, rail maintenance, and landscaping. ▪ Establish systems to recycle greywater for non-potable uses in transport facilities.

4.2 Roads

PHASE 1 • Screening

Module 1: Sensitivity analysis

The sensitivities of roads to climate hazards are provided in **Table 4.9** along with indicative scores per component category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of these scores. The proposed scores in the ensuing reflect the sensitivity of a typical road project; still it is recommended that the project team confirms and/or reviews them as relevant for their specific project and its context.

TABLE 4.9 • Sensitivities of road components.

Climate Hazard	Sensitivities			
Extreme wind (including storm, hurricane, tornado)	• Extreme winds can cause structural damage to road signs, signals, and overhead structures and threaten stability of bridge decks. • Tornadoes and hurricanes may leave debris on roads, cause falling trees and flying objects, obstructing traffic flow. • Road closures and detours due to wind/storm damage impact road operations and transportation routes or lead to power outages, fuel shortages, and disruptions in energy supply for transport operations. • Extreme winds and hurricanes can down power lines, affecting road lighting and traffic signals. • High winds and debris increase the risk of accidents and vehicle damage, especially to high-sided vehicles. • Extreme winds and hurricanes (and the post-disaster repair works) can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of networks and assets. • Health and safety risks to road users and road operators including accidents and vehicle damage.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Flood **Storm surge** **Heavy precipitation**	• Floodwaters can submerge roads, causing structural damage and erosion to road assets, bridges and tunnels (including damage to signs, lighting and electro-mechanical equipment, etc.) also increasing slope instability and landslides. • Storm surges and heavy flows can erode bridge foundations, scouring of bridge supports, compromising stability. • Debris from heavy precipitation can block culverts, leading to localised flooding. • Floodwaters can damage vehicles due to submersion or hidden debris. • Floods and storm surges can damage power lines, affecting road lighting and signals. • Flooding (and the post-disaster repair works) can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of networks and assets. • Health and safety risks to road users and road operators including accidents and vehicle damage.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Landslide **Avalanche** **Subsidence**	• Embankment instabilities and slope failures lead to road blockages, structural damage, prolonged closures, and disruptions. • Erosion and debris from landslides can compromise bridge foundations and supports. • Increased risk of accidents due to sudden road closures and debris on roadways. • Landslide/Avalanche-induced detours, and traffic congestion result in longer travel times and logistical challenges. • Landslides can damage power lines and disrupt road lighting and signals.			

	• Landslides (and the post-disaster repair works) can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of networks and assets. • Health and safety risks to road users and road operators including accidents and vehicle damage.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Sea level rise **Saline intrusion**	• Increased saline content in groundwater and coastal flooding can accelerate pavement deterioration. • Exposure to saltwater can lead to corrosion of bridge decks, girders, and supports. • Saline intrusion can clog stormwater drains and culverts, affecting road runoff management. • More frequent repairs and maintenance due to accelerated degradation of road surfaces and bridge components. • Inundation (and the associated repair works) can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of networks and assets. • Health and safety risks to road users and road operators including accidents and vehicle damage. • Sea level rise and saline intrusion can corrode power lines, transformers, and substations along coastal routes affecting the road's power supply.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Wildfire	• Wildfires can cause heat-related damage to road surfaces, leading to cracking and warping and can weaken bridge structures, compromising load-bearing capacity. • Signs and guardrails along roads may be destroyed or degraded by wildfire flames, impacting safety. • Wildfires often lead to road closures for safety reasons, disrupting transportation routes. • Reduced visibility due to smoke creates hazardous driving conditions, increasing accident risks. • Wildfires can damage power lines and utility poles along road corridors, leading to outages. • Roads serving as evacuation routes may become congested or impassable during wildfires. • Wildfires (and the post-disaster repair works) can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of networks and assets. • Health and safety risks to road users and road operators including accidents and vehicle damage.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Heat wave	• Heat waves can cause asphalt to soften, leading to rutting, cracking, concrete pavement blow-ups, surface deformation, increased age hardening of asphalt binder and shorter construction windows. • Bridges may undergo thermal expansion, leading to deck buckling or joint damage. • Electronic components in control systems may overheat, impacting operational efficiency. • Extreme road surface temperatures increase the risk of tire blowouts for vehicles. • Damage to horticultural assets (drying up) and increased need for watering. • Increased fire risk. • Vehicles may experience overheating issues, especially in traffic congestion during heat waves. • Increased need for cooling (passenger and freight). • Increased demand for cooling systems during heat waves can strain power supply reliability.			

<table>
<tr><td></td><td colspan="4">Heat-related damage (and the associated repair works) can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of networks and assets.</td></tr>
<tr><td>Global Score:
Medium</td><td>On-site assets & processes</td><td>Inputs</td><td>Outputs</td><td>Interdependent systems</td></tr>
<tr><td>Permafrost thawing</td><td colspan="4">Thawing permafrost can lead to uneven settling of roads, causing cracks, potholes, and deterioration. It can also compromise the stability of bridge foundations built on permafrost, leading to structural damage.
Thawing permafrost decreases the load-bearing capacity of roadbeds and bridge supports.
Thawing can alter the natural drainage patterns, leading to waterlogging and erosion.
Decreased road stability may require lower speed limits, affecting transportation efficiency.
Vehicles may consume more fuel due to rough road surfaces and slower travel speeds.
Increased costs of winter maintenance operations.
Increased user safety risks due to hazardous pavement conditions.
Permafrost thawing (and the associated repair works) can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of networks and assets.
Transmission lines supported by permafrost-grounded towers may become unstable with thawing, risking power supply. Also, other interconnected infrastructure buried in permafrost (e.g., pipelines) may be at risk of shifting or breaking as the ground thaws.</td></tr>
<tr><td>Global Score:
Medium</td><td>On-site assets & processes</td><td>Inputs</td><td>Outputs</td><td>Interdependent systems</td></tr>
<tr><td>Coastal erosion
Soil erosion</td><td colspan="4">Soil erosion along road shoulders and embankments may lead to slope failures, with severe erosion potentially resulting in complete failures or collapses of infrastructure components such as retaining elements and bridges.
Weakening of bridge supports leading to reduced loading capacity and overall safety issues.
Roads serving as barriers to protect inland areas from coastal erosion may be compromised.
Instability of coastal road edges and embankments due to wave action and tidal forces.
Erosion-induced road narrowing due to loss of shoulder space and road edge stability.
More frequent repairs needed to address erosion-related damage.
Roadside erosion can expose, and compromise buried utility lines.
Erosion (and the associated repair works) can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of networks and assets.
Health and safety risks to road users and road operators including accidents and vehicle damage.</td></tr>
<tr><td>Global Score:
Medium</td><td>On-site assets & processes</td><td>Inputs</td><td>Outputs</td><td>Interdependent systems</td></tr>
<tr><td>Cold wave
Freeze-thaw cycle</td><td colspan="4">Cold waves can lead to pavement and concrete structures cracking and spalling due to freeze-thaw cycles and frost heave lifting the pavement layers, potholes formation, corrosion due to increased usage of de-icing chemicals, abrasive damage caused by ice and snow removal processes.
Bridges are susceptible to ice formation on decks, reducing traction and safety.
Reduced tire grip on icy roads increases the risk of accidents and skidding.
Cold waves bring snowfall, leading to drifting and road obstructions.
Vehicles may experience difficulties starting in cold temperatures, leading to delays.
Snow accumulation and ice formation affect access roads, hindering connectivity.
Cold waves may cause power outages, affecting road lighting and traffic signals and/or any other electro-mechanical equipment.
Increased slope instability and embankment failures.
Increased costs of winter maintenance operations.</td></tr>
</table>

	• Cold/Frost-related damage (and the associated repair works) can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of networks and assets. • Increased demand for heating systems during cold waves can strain power supply reliability.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Fog	• Reduced visibility causing speed restrictions and temporal malfunctions to monitor equipment (e.g., cameras). • Increased health and safety risks to road users and road operators including accidents and vehicle damage. • Fog conditions can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of networks and assets. • Increased smog.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing temperatures **Temperature variability**	• Fluctuating temperatures can cause expansion and contraction of pavement materials, leading to cracks and surface degradation. • High temperatures soften pavement, leading to rutting under heavy traffic, while low temperatures can cause warping and uneven surfaces. • Temperature variations result in expansion and contraction of bridge decks, stressing joints and bearings. • Extreme temperature fluctuations accelerate the aging of asphalt and concrete, reducing their lifespan.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing precipitation patterns **Precipitation or hydrological variability**	• Increased frequency of rainfall events decreases overall safety of roads. • Changes in precipitation patterns affect surface water runoff, potentially causing ponding in case of rain events followed by long dry periods. • Increased annual precipitation could potentially increase erosion rates, augmenting the maintenance cost of roads constructed in slope areas. • Higher and more frequent water flows can accumulate scouring conditions of riverine bridge foundations making them more susceptible to forthcoming flood events. • More frequent watering of roadside greenery if the climate grows drier.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Drought	• Excessive drought conditions can cause soil shrinkage and subsidence, leading to pavement cracking and stability issues to bridge supports (due to differential settlements) in extreme cases. • Fugitive dust may impair air quality. Dust clouds reduce visibility for drivers/bicyclers, increasing the risk of accidents. • Increased wildfire risk. • Droughts may impact water availability for road maintenance activities (watering of greenery, wetting of dirt roads etc.). • Dying of roadside trees and vegetation.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Module 2: Exposure analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Roads present significant spatial extension, and therefore, may exhibit variations in hazard exposure depending on the road segment location. Hazard and road maps should be superimposed to identify the overall road's exposure.

Module 3: Vulnerability analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For details on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts in combination with the road network's criticality, readers are referred to the **Introductory Chapter** (Module 5). To assist users with the scoring procedure, an overview of significant impacts to roads across various risk areas (RA) is provided in the table below.

TABLE 4.10 • Climate impacts for roads (non-exhaustive list of examples).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damages and O&M impacts**: Climate events can compromise the structural integrity of roads and bridges, leading to increased repair needs and maintenance cost (see RA5). **Traffic Disruptions** (of varying degree depending on the severity of the event). For low impact events: reduced traffic speeds and reduced road capacity causing congestion, delays, and increased user costs. For high impact events: Inundated (or damaged) road segments closed to traffic, disrupted transport services, reduced accessibility, lengthy detours ballooning user costs.
RA2: Safety and Health	**Increased Accidents:** Extreme weather events like heavy storms and snowfall can reduce visibility and create slippery road conditions, increasing the risk for accidents. **Traffic Control Systems Malfunctions:** The impact of climate events such as heavy rainfall and extreme temperature fluctuations can disturb the functioning of traffic management systems, leading to significant safety risks.
RA3: Environment	**Increased Energy Consumption**: The increased time travel due to traffic delays and rerouting in combination with the increased need for heating or cooling in the vehicles can result in higher energy consumption contributing to carbon emissions in case of fossil fuels usage. **Pollution**: Disruptions caused by climate events can result in environmental impacts like soil contamination from spills or leaks from accidents, water pollution caused by runoff from roads carrying pollutants such as oil, debris, and chemicals, noise pollution caused by changes in road surfaces or traffic patterns.
RA4: Social	**Disrupted Access to Services:** Climate events can cut off access to essential services such as hospitals, schools, and markets, particularly in rural areas. **Community Isolation**: Damage to roads during extreme weather events can isolate communities, reducing social connectivity and access to emergency services.
RA5: Financial impacts	**Increased Repair and Reconstruction Costs:** Expensive climate-related damage can strain the operator's budgets, diverting funds from other targets. **Infrastructure Retrofitting Expenses:** The need for retrofitting existing infrastructure to withstand climate impacts, such as rising sea levels or landslide hazards, can lead to substantial financial investments for urban transport authorities. **Increased Maintenance Cost:** More frequent repairs or changes in operational procedures (to maintain a given quality of service under less favourable climate conditions).

	Loss of toll revenues: Often traffic disruptions may curtail toll revenues.
RA6: Reputation	**Negative Public Perception:** Persistent road closures or poor road conditions due to climate impacts can lead to dissatisfaction among road users and increase the risk of losing truistical attractiveness. **Investment and Development Concerns:** Concerns over the risks of road infrastructure to climate events may deter potential investors or developers, impacting growth and economic opportunities.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 4.11 presents potential adaptation solutions for climate hazards that could impact the roads. The suitability of each measure is linked to the encountered level of risk and the uncertainty of climate projections, while the timing of implementation is aligned with specific project stages. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 4.11 • Roads: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures This table may include in-built resilience measures and/or existing operational practices which should be identified and reported for the project. In any case inform decision-making along all stages of the project cycle with most up-to-date projections (and recent climate events), at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Extreme wind (including storm, hurricane, tornado)	▪ Conduct risk evaluations accounting for severe winds, intense storms, tornadoes, and hurricanes for current and future time horizons, and consider appropriate-to-extreme-wind-load structure typologies during the feasibility studies.	▪ Revise road and bridge design to withstand extreme wind loads (e.g., streamlined shapes and profiles for bridges, low-profile design and anchor systems for road signs, traffic lights, and other roadside fixtures, etc.). ▪ Consider using durable materials and storm-proof measures to minimise damage. ▪ Consider installing natural or man-made windbreaks. ▪ Consider wind-proofing critical areas (e.g., rest areas, service areas. etc.).	▪ Develop preparedness plans with protocols for road closures, evacuation routes, and rapid response. ▪ Establish partnerships with meteorological agencies for real-time storm monitoring and alerts. ▪ Establish rapid response teams for clearing debris and restoring access to roads after storms. ▪ Pre-position emergency supplies such as barricades, signage, and sandbags for quick deployment. ▪ Regularly maintain trees and vegetation to prevent hazardous falling branches and debris.
Flood Storm surge Heavy precipitation	▪ Conduct detailed flood risk assessments along road corridors to identify vulnerable areas and inform the adaptation plan accordingly (with climate change considerations).	▪ Road alignment considerations (vertical and horizontal) including possible elevation of road segments, bridges, and culverts above flood levels where feasible/as relevant. ▪ Consider using flood-resistant materials such as concrete, steel, and composite materials for construction. ▪ Adequate drainage system type and capacity including e.g. an allowance for future climate change and retention analysis. ▪ Consider integrating in the design flood barriers, levees, and retention basins along vulnerable road segments. ▪ Review design standards and guidelines (review design rain intensity and frequency values or consider a climate change factor, e.g. 10-20% increase in drainage capacity or increased clearance over 50-(100/200/300/500) year flood levels under bridges).	▪ Conduct regular inspections of bridges, culverts, and drainage systems for signs of deterioration. ▪ Clear debris and sediment from culverts, ditches, and drains to maintain flow capacity. ▪ Install flood monitoring gauges and weather sensors along vulnerable roadways. ▪ Integrate real-time data into traffic management systems to alert drivers of hazardous conditions.

		▪ Implement green infrastructure techniques to reduce runoff (e.g., permeable pavements, bioswales). ▪ Reinforce slopes and road shoulders with erosion-control measures to prevent washouts as well as adequate slope drainage.	
Landslide Avalanche Subsidence	▪ Conduct detailed landslide/avalanche hazard assessments along road corridors to identify high-risk areas and consider rerouting if necessary.	▪ Consider slope reinforcement techniques such as retaining walls, soil nails, and rock bolts. ▪ Utilise bioengineering methods like vegetation planting and erosion control mats on slopes. ▪ Review earthworks design guidelines and/or practices (e.g. strengthen drainage, slopes, protection measures, use of berms, protective measures at the foot of embankments etc.). ▪ Develop landslide risk assessment models. ▪ Consider the design and construction of debris flow channels or catchment basins to divert and contain debris. ▪ Install debris fences and barriers to intercept and control debris movement along roads.	▪ Conduct frequent inspections of slopes, embankments, and drainage systems for signs of instability. ▪ Clear vegetation, debris, and sediment from culverts and channels to maintain flow capacity. ▪ Install slope monitoring devices such as inclinometers and geotechnical sensors for early detection. ▪ Implement real-time weather and rainfall monitoring stations to track potential landslide triggers.
Sea level rise Saline intrusion	▪ Consider coastal zoning regulations to limit development in high-risk areas.	▪ Consider the option of elevating road surfaces and bridge decks when relevant. ▪ Utilise corrosion-resistant materials for road infrastructure and bridge components. ▪ Consider installing larger culverts and stormwater drains to handle increased runoff and saline intrusion. ▪ Investigate the use of permeable pavements to allow water infiltration and reduce surface flooding. ▪ Apply corrosion-resistant coatings on bridges, guardrails, and metal components. ▪ Evaluate the potential benefits of using sealing treatments on road surfaces to prevent saltwater infiltration.	▪ Monitor road surfaces for early signs of deterioration and prioritise maintenance. ▪ Conduct frequent inspections of bridges, culverts, and drainage systems for signs of corrosion. ▪ Use sensors and gauges to monitor coastal water levels and anticipate flood risks. ▪ Develop flood response plans with designated detour routes and emergency access points. ▪ Install backup generators at critical facilities along coastal roads to ensure continuous power supply.
Wildfire	▪ Conduct fire risk assessments to identify vulnerable areas and assets along road corridors and inform the adaptation plan accordingly.	▪ Consider using fire-resistant materials for road construction, such as concrete barriers and fire-retardant coatings. ▪ Explore the use of fire-resistant plant species in roadside landscaping to minimise wildfire ignition risks.	▪ Implement routine maintenance to clear debris and vegetation from roadside areas prone to ignition. ▪ Maintain firebreaks along road corridors to create barriers against wildfire spread. ▪ Forest management considerations and fire risks related to woody areas close to roads.

		▪ Install ember-resistant vents and screens on bridge structures and road infrastructure. ▪ Design culverts and drainage systems to prevent ember intrusion and blockage during wildfires. ▪ Consider possible installation of fire hydrants at exposed locations and highway junctions.	▪ Establish partnerships with firefighting agencies for coordinated firebreak maintenance efforts. ▪ Designate and publicise evacuation routes with clear signage and emergency information.
Heat wave	NA	▪ Design adequately robust pavements resistant to high temperatures (e.g. using more resilient materials and processes with increased heat-resistance properties). ▪ Adequate considerations for concrete pavements (e.g. proper dimensioning of expansion joints, etc.) ▪ Adequate considerations for bridges (e.g. thermal expansion impact on bridge joints). ▪ Consider implementing cool pavement technologies such as reflective coatings or permeable surfaces to reduce surface temperatures. ▪ Explore the use of porous asphalt to enhance heat dissipation and reduce heat island effects. ▪ Consider potential benefits of roadside trees or vegetation to provide shade and reduce heat absorption by road surfaces. ▪ Adequate considerations for horticultural assets resistant to heatwaves. ▪ Design rest areas or shelters with natural shading to offer relief for travellers during heat waves. ▪ Install heat-reflective road signs and markers to minimise heat absorption and maintain visibility. ▪ Consider possible installation of fire hydrants at exposed locations and highway junctions.	▪ Implement pavement temperature sensors to monitor surface temperatures and identify hotspots. ▪ Apply surface treatments such as water spraying or cooling mats during extreme heat events to lower pavement temperatures. ▪ Schedule maintenance activities during cooler periods to minimise heat stress on equipment and personnel. ▪ Establish temporary cooling stations or hydration points for maintenance crews working in high temperatures. ▪ Provide real-time updates on road conditions and closures during heat waves through digital signage or online platforms and educate drivers on the risks of heat-related pavement issues while encouraging proactive vehicle maintenance.
Permafrost thawing	▪ Conduct detailed permafrost mapping and ground stability assessments to understand the extent of permafrost thawing risks. Use future climate projections to anticipate long-term permafrost degradation trends and consider rerouting if necessary.	▪ Consider utilising insulating materials such as foam boards or geofoam beneath roadbeds to reduce permafrost thawing. ▪ Explore the option of constructing roads on raised embankments or gravel pads to elevate the road surface above the active layer of permafrost. ▪ Consider bridge designs with deep foundations reaching below the active layer to prevent thaw-related settlement.	▪ Deploy permafrost monitoring equipment along road corridors to continuously assess ground temperature changes. ▪ Establish a monitoring program to track permafrost thaw rates and detect early signs of instability. ▪ Conduct regular pavement inspections to identify early signs of distress.

		▪ Utilise gravel or coarse materials for road surfaces that allow for better drainage and reduced heat absorption. ▪ Incorporate geosynthetic reinforcements in road construction to distribute loads and minimise permafrost disturbance.	▪ Apply sealants and protective coatings on road surfaces to minimise water ingress and prevent freeze-thaw damage. ▪ Use de-icing agents strategically to reduce the impact of freezing temperatures on road conditions. ▪ Participate in knowledge-sharing networks to exchange experiences and lessons learned with other regions facing permafrost thaw challenges.
Coastal erosion Soil erosion	▪ Consider integrating in the planning vegetative buffers along roadsides to absorb water, stabilise soil, and reduce erosion.	▪ Explore the possibility of constructing seawalls, revetments, or rock armour along coastal road sections to mitigate wave impact. ▪ Consider installing retaining walls, gabion baskets, or geotextiles on road embankments to prevent soil erosion. ▪ Investigate the implementation of bioengineering techniques such as vegetation planting for slope stabilisation and implement beach nourishment projects to enhance natural coastal defences and reduce erosion. ▪ Design roads with adequate drainage systems to minimise water runoff and erosion.	▪ Conduct routine inspections of coastal roads and embankments to identify erosion hotspots. ▪ Monitor slope conditions and erosion indicators to take timely preventive measures. ▪ Perform regular maintenance of drainage systems to prevent water buildup and erosion. ▪ Prepare emergency erosion repair kits (e.g., sandbags, geotextile fabric) for quick deployment. ▪ Identify and establish alternative access routes in advance to ensure connectivity during road closures.
Cold wave	NA	▪ Consider using cold-resistant asphalt mixes and concrete for road construction to withstand freezing temperatures. ▪ Specify frost-resistant bridge materials and coatings to prevent deck icing and corrosion. ▪ Explore the installation of electric or hydronic roadway heating systems to prevent ice formation and promote safe driving conditions.	▪ Develop comprehensive winter maintenance plans detailing snow removal, de-, and anti-icing strategies. ▪ Establish protocols for monitoring weather conditions and deploying resources during cold wave events. ▪ Implement pre-wetting techniques to enhance the effectiveness of salt and de-icing agents in lowering freezing points.
Fog	NA	▪ Incorporate visibility aids such as fog lights, reflective road markings, and signage with high visibility materials to enhance visibility for drivers navigating through foggy conditions.	▪ Use variable message signs for real-time fog updates, aiding drivers to adjust behaviour. ▪ Enforce temporary speed limits in fog using electronic signs or enforcement. ▪ Employ traffic management tactics like lane closures and diversions for safer fog conditions. ▪ Create emergency plans to manage fog-related incidents, coordinating with first responders.

Changing temperatures Temperature variability	NA	▪ Integrate thermal stress considerations in road and bridge design to accommodate temperature-induced expansion and contraction. ▪ Explore the potential benefits of installing thermal insulation layers to minimise temperature differentials within bridge structures. ▪ Consider using high-quality sealants and materials for expansion joints to enhance durability and longevity.	▪ Implement seasonal planning for road treatments and repairs based on temperature trends. ▪ Deploy temperature sensors on critical infrastructure to monitor variations and predict potential issues. ▪ Regularly inspect and maintain expansion joints on bridges to ensure proper functioning and prevent structural damage.
Changing precipitation patterns Precipitation or hydrological variability	▪ Integrate climate projections and hydrological modelling into the road planning and develop water management plans to account for changing precipitation patterns.	▪ Design and implement effective stormwater drainage systems to handle runoff based on climate change projections. ▪ Ensure culverts are appropriately sized to potentially handle increased water flows. ▪ Consider using debris screens to prevent culvert blockages.	▪ Conduct frequent inspections of culverts, bridges, and embankments to detect signs of erosion or damage. ▪ Clear debris from drainage systems and culverts after heavy precipitation events. ▪ Fill potholes promptly and resurface roads to prevent water penetration and deterioration.
Drought	▪ Identify areas susceptible to drought (e.g., steep slopes) in the proximity of the road network to plan mitigation measures in collaboration with public authorities. ▪ Conduct assessments to identify the critical water needs for the road operations and develop water conservation strategies in collaboration with local authorities.	▪ Explore the use of soil stabilisers and binders to mitigate erosion and maintain roadbed stability during dry conditions. ▪ Consider bridge designs with flexible joints and foundations to accommodate soil movement and settlement. ▪ Establish vegetative buffer zones to reduce dust generation and install smart irrigation systems for roadside landscaping. ▪ Adequate considerations for horticultural assets resistant to droughts. ▪ Explore the use of recycled plastics and rubberised asphalt in road construction to reduce reliance on traditional water-intensive materials.	▪ Implement xeriscaping techniques with drought-tolerant plants along roadsides to reduce water usage and use sensors to optimise water usage based on soil moisture levels. ▪ Optimise water use for road cleaning, focusing on high-traffic areas and critical safety zones. ▪ Schedule road maintenance activities during cooler times of the day to minimise water loss from evaporation.

4.3 Railways

PHASE 1 • Screening

Module 1: Sensitivity analysis

The sensitivities of railways to climate hazards are provided in **Table 4.12** along with indicative scores per component category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical railways under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities. It is noted that potential sensitivities of railways (which may eventually be impacted by climate-related factors) are dependent on the type of railway system (e.g., heavy/light rail, underground/elevated, multiple/single/hybrid track configurations, monorail, high/low speed, etc.), and therefore, cannot receive a standard score in the table below. The project team should score each component category based on project specifics.

TABLE 4.12 • Sensitivities of railways components.

Climate Hazard	Sensitivities			
Extreme wind (including storm, hurricane, tornado)	• Extreme winds, and flying objects can cause structural damage to signs, signalling equipment, overhead structures, ballasts, and railbeds or trains (e.g., rail car blow-overs, slippery rails or locking of train wheels in case of fallen leaves, etc.), and threaten the stability of bridge decks. Platforms, waiting areas, and station buildings can also be damaged from extreme winds, storms and hurricanes. • Storms can down power lines or damage substations, affecting power supply and impacting electrified rail operations (including lighting and traffic signals). • Loss of communication systems, affecting train control, scheduling, and safety protocols. • High winds and debris increase the risk of accidents and rolling stock damage. • Service disruptions, route closures, and speed restrictions due to damaged or blocked tracks and infrastructure, or due to wind gusts impacting the safety of circulation (especially in case of high-speed trains, speed is progressively reduced up to a complete stop in extreme events).			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Flood **Storm surge** **Heavy precipitation**	• Heavy rain and floodwaters can submerge rails, cause structural damage and erosion to ground assets (e.g., track washouts), equipment (e.g., damage to signs, lighting and electro-mechanical equipment), bridges and tunnels (e.g., foundation instability and scouring). They also increase slope instability and can trigger landslides and embankment failures. • Debris from heavy precipitation can block culverts, leading to localised flooding. • Floodwaters can damage the rolling stock due to submersion or hidden debris. • Floods and storm surges can damage power lines, substations and electrical equipment, affecting electrified operations, such as lighting and signalling, and affecting train control, scheduling, and safety. • Service disruptions, route closures, and speed restrictions due to flooded tracks and washed-out sections. • Disruptions in freight logistics, storage facilities, and delivery schedules due to infiltration of water into rail facilities, trains, and handling equipment, leading to freight damage and operational delays. • Issues on the interconnected transport systems, such as access road closures, bridge failures, and traffic congestion. • Reduced demand due to limited accessibility or changes in mobility patterns (e.g., use of car instead of train or remote working instead of commuting during extreme flood events).			

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems
Landslide **Avalanche** **Subsidence**	• Embankment instabilities and slope failures lead to track destabilisation, embankment collapses, structural damage, prolonged closures, and disruptions. • Erosion and debris from landslides can compromise bridge foundations and supports. • Potential blockages, collapses, or structural damage to critical infrastructure (e.g., substations, signalling equipment, cable cuts, etc.) from landslides or subsurface movements. • Landslide/Avalanche-induced detours, and traffic congestion result in longer travel times and logistical challenges. • Landslides can damage power lines, substations and electrical equipment and disrupt electrified operations, including lighting and signalling. • Blocked roads of the interdependent network hinder access to stations and connectivity. • Service disruptions, route closures, and speed restrictions due to blocked tracks and safety concerns (e.g. derailment/overturning). • Disruptions in supply chains, freight transport, and logistics due to rail network closures.			

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems
Sea level rise **Saline intrusion**	• Increased saline content in groundwater and coastal flooding can increase corrosion rates to all steel parts of infrastructure and equipment. • Inundation and water-related damage (washouts, erosion, instability, scouring) to platforms, tracks, rail bridges, and station facilities near coastal areas. • Exposure of overhead wires and substations to saltwater, causing electrical malfunctions and outages. • Saline intrusion can clog stormwater drains and culverts, affecting road runoff management. • Service disruptions, route closures, and speed restrictions due to flooded tracks and safety concerns (e.g., due to damaged signalling systems). • Worker safety issues and passenger discomfort due to physical damage or travel disruptions caused by sea level rise-related incidents. • Contamination and degradation of fuel supplies and lubricants stored in coastal rail facilities. • Interruptions in rail connectivity with other modes of transport (roads, ports, airports) due to flooded or damaged rail lines.			

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems
Heat wave	• High temperatures cause expansion of rails leading to track buckling and deformation (and potential train derailments). • Overheating of overhead train lines and electrical equipment lead to disruptions to electrified operations, including lighting and signalling, affecting train control and safety. • Overheating of platforms, waiting areas, and facilities, impact passenger comfort and safety. • Service disruptions, route closures, and speed restrictions due to due to heat-related track maintenance and safety protocols. • Increased demand for cooling systems in trains and stations, impacting energy usage and costs. • Increased risk for fire. • Intensified need for track inspections, equipment checks, and maintenance during and after heat waves. • Reduced demand as extreme heat waves reduce mobility. • Risks to power supply infrastructure from overheating, affecting electrified rail operations.			

Global Score: High	On-site assets & processes	Inputs	Outputs	Interdependent systems
Wildfire	• Track damage, including rail warping, tie burning, and ballast degradation. • Wooden bridge structures or other timber elements are very sensitive to fire damage. • Potential loss of signal equipment and communication lines due to fire-related destruction causing safety concerns. • Reduced visibility due to smoke creates hazardous driving conditions, increasing accident risks. • Overgrown vegetation near tracks act as fuel for wildfires, increasing fire spread risks. • Service disruptions (passenger and freight logistics), route closures, and speed restrictions due to fire-damaged tracks and infrastructure. • Wildfire can cause power outages from damaged electrical lines, impacting electrified rail operations.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Permafrost thawing	• Track settlement, deformation, and instability as permafrost thaws, leading to uneven tracks and rail track damage (e.g. buckling). • Bridge abutments and supports are sensitive to shifting permafrost, affecting their structural integrity. • Thawing permafrost decreases the load bearing and can weaken embankments and cuttings, leading to slope failures and landslides. • Thawing can alter the natural drainage patterns, leading to waterlogging and erosion. • Damage to signal cables, track circuits, switches and communication equipment from ground movement due to thawing. Damage to electricity poles, towers and substations from ground movement, affecting electrified rail operations. • Operational issues (e.g. catenary and components freezing, pantograph failure, brake malfunction, etc.) leading to service disruptions, route closures, speed restrictions, and increased maintenance intervals.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Coastal erosion **Soil erosion**	• Track instability, subsidence, and deformation due to coastal erosion and soil loss. • Stability issues to rail embankments, retaining walls or slopes potentially leading to landslides. • Reduced loading capacity, foundation instability and scouring of bridge supports from erosive forces. • Derailments, track obstructions, and safety hazards from erosion-induced track failures. • Erosion-related damage to signalling systems, track circuits, and communication cables. • Disruptions in train schedules and speed restrictions due to compromised track conditions from erosion affect travel times and freight logistics. • More frequent repairs needed to address erosion-related damage. • Erosion can expose and compromise buried utility lines affecting the power supply of the rail operations. • Eroded access roads limits accessibility to stations.			
Global Score: Medium	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Cold wave **Freeze-thaw cycle**	• As temperatures drops track shrinkage and cracking may occur leading to track misalignments. • Increased slope instability and embankment failures. • Freezing of switch mechanisms and points may cause operational disruptions. • Potential damage to overhead wires, substations, and signalling equipment from icing due to extreme cold can cause issues to electrified operations. Also, potential			

- disruptions in communication systems due to frozen equipment or damaged cables can pose safety issues.
- Impaired performance of train brakes, doors, and couplings in sub-zero temperatures.
- Reduced train speeds, extended braking distances, and increased derailment risk on icy tracks.
- Higher demand for heating systems in trains and stations, impacting energy usage and costs.
- Challenges in conducting inspections and repairs in freezing conditions.
- Risks of fuel gelling and viscosity changes, affecting locomotive performance and maintenance.
- Performance limitations for electrical systems (on-board batteries and related charging infrastructure, increased need for heating stressing batteries).
- Reduced demand as extreme cold waves reduce mobility.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems

Changing temperatures

Temperature variability

- Expansion and contraction of rail tracks, leading to track buckling, joint failure, and alignment issues.
- Thermal stress on bridge decks, bearings, and expansion joints, affecting structural integrity.
- Performance issues, insulation degradation, and power supply disruptions in electrified rail systems and operations.
- Increased wear and tear on track components, rolling stock, and infrastructure elements. For example, deterioration of materials, such as rail ties, ballast, and concrete, from thermal stress.
- Variations in energy demand for heating/cooling systems, traction power, and climate control in trains.
- Passenger discomfort, HVAC system strain and potential demand changes.

Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems

Changing precipitation patterns

Precipitation or hydrological variability

- Increased risk of erosion, subsidence, and track settlement due to prolonged wet periods and soil saturation.
- Changes in precipitation patterns affect surface water runoff, potentially causing flooding and ponding in case of rain events followed by long dry periods.
- Overwhelmed drainage capacity, leading to waterlogging, track submersion, and embankment instability.
- Blocked drainage channels after prolonged drought periods. Increased demand for drainage maintenance, clearing of debris, and management of water accumulation on tracks.
- Increased flow volumes, scouring, and hydraulic pressure affect bridges and culverts during moderate to heavy rainfall events.
- Difficulty in conducting routine maintenance activities, inspections, and repairs during prolonged wet conditions.

Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems

Drought

- Increased risk of track settlement, shifting, and cracking due to soil subsidence from prolonged dry conditions.
- Structural stresses on bridge supports and culverts from decreased water levels and soil stability.
- Drying and die-off of vegetation near tracks, leading to increased fire risks, slope instability, and falling branches on tracks.
- Dust buildup on tracks and ballasts, affecting traction, signalling systems, and safety.
- Reduced availability of water for dust suppression, firefighting, and maintenance activities.

Global Score: Low	On-site assets & processes	Inputs	Outputs	Interdependent systems

Module 2: Exposure analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Railways present significant spatial extension, and therefore, may exhibit variations in hazard exposure depending on the rail segment location. Hazard and rail maps should be superimposed to identify the overall rail's exposure.

Module 3: Vulnerability analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For details on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts in combination with the rail network's criticality, readers are referred to the **Introductory Chapter** (Module 5). To assist users with the scoring procedure, an overview of significant impacts to railways across various risk areas (RA) is provided in the table below.

TABLE 4.13 • Climate impacts for railways (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Rail Damages**: Climate events like heavy rainfall and flooding can cause track bed erosion, leading to track misalignment and potential derailments. **Signal and Communication Disruptions**: Extreme temperatures or severe weather can damage rail signals and communication systems, affecting train operations and safety.
RA2: Safety and Health	**Increased Risk of Accidents**: Slippery rails due to snow or ice accumulation, rail buckling due to heatwaves, reduced visibility from heavy rain and flying objects from extreme winds impact train safety and commuters' comfort. **Health Impacts**: Rail accidents during extreme weather events or climate-related disasters can lead to the release of hazardous materials, such as chemicals or fuels, posing immediate health risks to rail workers and nearby communities.
RA3: Environment	**Contamination of Soil and Water from Climate-Related Accidents**: Climate-related extreme weather events can increase the risk of rail accidents, resulting in spills of hazardous materials that contaminate soil and water resources. **Increased Energy Consumption**: Longer travel times caused by train delays or rerouting, along with commuters opting for personal vehicles, coupled with increased heating or cooling demands within train carriages, can lead to increased energy usage which, in turn, contributes to increased carbon emissions.
RA4: Social	**Disruptions in Commuting and Transport Services:** Extreme weather events or climate-induced track damage can lead to disruptions in rail services, affecting commuters, businesses, and freight transport leading to depreciation of goods (in case of prolonged disruption) and increased transportation cost if re-routing of cargo is required. **Community Isolation:** Rail closures or limited services due to climate impacts can isolate rural communities, reducing access to essential services and economic opportunities.

RA5: Financial impacts	**Cost of Repairs and Maintenance:** Climate-related damage to rail tracks, bridges, and infrastructure require costly repairs and ongoing maintenance. **Loss of Revenue from Service Disruptions**: Rail service interruptions due to weather events result in revenue losses for rail operators, due to reduced passengers or compensations of freight damage.
RA6: Reputation	**Public Perception of Reliability:** Frequent delays or cancellations of rail services due to weather-related issues may impact the public's perception of rail reliability. **Environmental Responsibility Image:** Rail operators with a history of environmental impacts from spills or pollution may face reputation challenges regarding their environmental stewardship.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 4.14 presents potential adaptation solutions for climate hazards that could impact railways. The suitability of each measure is linked to the encountered level of risk and the uncertainty of climate projections, while the timing of implementation is aligned with specific project stages. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 4.14 • Railways: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. In any case inform decision-making along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Extreme wind (including storm, hurricane, tornado)	▪ Select appropriate structure typologies (e.g., avoid sensitive rail assets such as suspension bridges) during the feasibility study.	▪ Consider using durable materials and designs for tracks, embankments, and drainage systems to withstand extreme wind and storm impacts. ▪ Review design standards of foundations, bridges, viaducts, and overhead structures to meet wind load standards and resist storm forces that take into account climate change. ▪ Revise (and renew as relevant) the condition of roofs and canopies.	▪ Install storm/wind monitoring devices, weather stations, and real-time alerts for proactive response (e.g., speed limitations when wind is above certain levels). ▪ Establish rapid response teams and equipment depots for swift track repairs and debris/fallen objects clearance. ▪ Regularly trim and clear vegetation along tracks to prevent tree falls, debris buildup, and obstruction risks and regularly inform the adjacent landowners for their responsibilities.
Flood Storm surge Heavy precipitation	▪ Conduct comprehensive flood risk assessments to identify vulnerable areas, critical infrastructure, and floodplain management strategies. If necessary, consider rerouting.	▪ Consider using flood-resistant materials, elevated track designs, and drainage systems to minimise flood impacts. ▪ Explore the option of raising critical infrastructure, such as substations and signal boxes, above flood levels and install flood barriers or levees. ▪ Review design levels for bridges and culverts considering increased capacity, scour protection, and debris management features based on climate change projections.	▪ Install flood sensors, weather stations, and remote monitoring systems for early detection and response. ▪ Establish protocols for swift track inspections, debris removal, and emergency repairs after flood events. ▪ Develop backup power systems, emergency pumps, and temporary track solutions for immediate post-flood recovery.
Landslide Avalanche Subsidence	▪ Conduct detailed geotechnical surveys and mapping to identify high-risk areas and vulnerable sections and consider rerouting if necessary.	▪ Consider slope protection measures, such as retaining walls, rockfall fences, and soil reinforcement. ▪ Design effective drainage systems and erosion control measures to prevent water-induced landslides. ▪ Consider reinforcing tunnel linings, portals, and bridge foundations (e.g., consider deeper foundations like piles) against ground movements and subsidence.	▪ Install and maintain geotechnical instruments for real-time monitoring of ground stability and slope movements. ▪ Conduct routine inspections of embankments, cuttings, tunnels, and bridges for early detection of potential hazards. ▪ Provide training for rail staff on landslide response procedures, safety protocols, and equipment use.

Sea level rise Saline intrusion	▪ Perform assessments of rail assets for sea level rise and saline intrusion, considering various climate scenarios and create strategies to monitor and adjust rail operations in response to changing sea levels and coastal conditions. ▪ Conduct run-off water management analysis and develop water management strategy and plans.	▪ Consider elevating tracks, platforms, and critical infrastructure above projected sea levels to mitigate flood risks. ▪ Explore the usage of materials that are resistant to saltwater corrosion for tracks, signalling equipment, and station facilities. ▪ Consider flood barriers along vulnerable rail sections and implement efficient drainage systems to manage excess water.	▪ Implement regular inspections and monitoring of tracks, signalling systems, and electrical equipment for signs of corrosion or damage. ▪ Develop protocols for rapid response to sea level rise-related incidents, including evacuation procedures, asset protection measures, designated detour routes and emergency access points. ▪ Install backup generators at critical equipment along coastal areas to ensure continuous power supply.
Heat wave	NA	▪ Explore alternative materials with higher thermal stability for tracks and ballasts to minimise heat-induced deformation and install expansion joints at critical points. ▪ Avoid buckling of railway tracks, by means of increasing the rigidity and weight of the superstructure of the track, including ensuring their fixation with systems that increase their resistance to lateral displacement. ▪ Consider installing reflective or cool roofs on station buildings and facilities to reduce heat absorption. ▪ Design platforms and waiting areas with shading structures or canopies to protect passengers from direct sunlight and try promoting NbS as much as possible (e.g., green roofs).	▪ Implement temperature sensors along tracks and in critical areas for early detection of heat-related issues. ▪ Develop heat wave response plans, including protocols for speed restrictions, service adjustments, and passenger safety. ▪ Increase frequency of track inspections during heat waves to detect buckling or deformation early. ▪ Install or upgrade onboard cooling systems in trains and station facilities to maintain comfortable conditions for passengers and equipment. ▪ Coordinate with energy providers to ensure reliable power supply during peak heat periods for rail operations.
Wildfire	▪ Conduct fire risk assessments to identify vulnerable areas and assets along railways and inform the mitigation plan accordingly.	▪ Avoid timber structures or elements and use fire-resistant materials for tracks, ties, and ballasts to minimise fire damage and track integrity loss. ▪ Consider physical barriers or natural firebreaks, such as gravel strips or cleared areas, to prevent fire spread to tracks. ▪ Install fire extinguisher systems at critical areas along the railway.	▪ Install wildfire detection systems, such as cameras or sensors, along rail corridors for early warning and response. ▪ Establish communication protocols with train operators, staff, and passengers during wildfire events for safe evacuation and response. ▪ Implement regular vegetation clearing and maintenance along tracks to create firebreaks and reduce fuel loads. ▪ Equip maintenance teams and trains with fire extinguishers, hoses, and firefighting equipment for initial response.
Permafrost thawing	▪ Conduct detailed permafrost mapping and ground stability assessments to understand the extent of permafrost thawing risks. Use future climate projections to anticipate long-term	▪ Consider designing tracks with insulated layers to minimise heat transfer to permafrost, reducing thawing rates.	▪ Establish monitoring systems to track permafrost conditions along rail corridors, enabling early detection of thawing.

	permafrost degradation trends and consider rerouting if necessary.	▪ Explore bridge design options with flexible supports and foundations to accommodate ground movement from thawing permafrost. ▪ Review existing power system arrangement (redundancy) to enhance supply reliability. ▪ Investigate ground freezing solutions, soil reinforcement options, or grouting methods to stabilise thawing areas along tracks.	▪ Conduct regular surveys and inspections of permafrost-affected areas to assess stability and identify potential hazards. ▪ Develop protocols for responding to permafrost-related incidents, including track repairs, rerouting plans, and passenger safety measures. ▪ Partner with permafrost research institutions for ongoing studies and data sharing on permafrost conditions and participate in knowledge-sharing networks to exchange experiences and lessons learned with other regions facing permafrost thaw challenges.
Coastal erosion **Soil erosion**	▪ Create the project's adaptation strategy in collaboration with local authorities that monitor erosion hotspots and shorelines and coordinate on mitigation efforts. ▪ Consider incorporation of vegetative buffers to absorb excess water, stabilise the soil, and mitigate erosion alongside railways during the planning and feasibility phase.	▪ Consider using erosion control blankets, geotextiles, and vegetation to stabilise slopes and embankments. ▪ Incorporate erosion-resistant materials for track ballast, embankments, and drainage systems. ▪ Review existing and if necessary, reinforce or build new seawalls, revetments, or riprap along vulnerable coastal sections to mitigate wave impact and erosion.	▪ Conduct frequent inspections of track conditions, embankments, and bridges for signs of erosion-induced damage. ▪ Establish protocols for rapid response to erosion-related incidents, including track closures, repairs, and rerouting plans. ▪ Implement vegetation programs to stabilise slopes, enhance soil retention, and reduce erosion rates along the rail corridor.
Cold wave	NA	▪ Enhance insulation for track components and install heating systems to prevent freezing and maintain track integrity. ▪ Consider designing stations, switches, and signalling equipment with materials and features suitable for extreme cold conditions. ▪ Explore the usage of anti-icing agents and equipment for tracks, switches, and overhead lines to prevent ice buildup. ▪ Prevent the ingress of drifting snow into ventilated, direct current traction motors by designing covered train storage areas.	▪ Install temperature and moisture sensors along tracks to monitor conditions and trigger de-icing operations. ▪ Develop cold wave response plans, including protocols for track de-icing, equipment warming, and passenger safety. ▪ Equip maintenance teams with snowploughs, de-icers, and snowblowers for efficient clearing of tracks and platforms. ▪ Inspect vehicles for overnight weather-related issues, such as frozen couplings, bogies and doors.
Changing temperatures **Temperature variability**	NA	▪ Specify materials with low thermal expansion coefficients, weather-resistant coatings, and UV protection. ▪ Design tracks with thermal expansion joints, ballast systems, and track bed insulation for temperature fluctuations.	▪ Implement predictive analytics, sensors, and monitoring tools to detect early signs of temperature-induced wear. ▪ Prepare seasonal maintenance routines for de-icing, snow removal, track heating, and cooling systems.
Changing precipitation patterns	▪ Integrate climate projections and hydrological modelling into the rail planning and develop	▪ Consider larger culverts, lined channels, and erosion-resistant materials to manage increased	▪ Install rainfall gauges, streamflow sensors, and weather stations for early detection of rising water levels and flood alerts.

Precipitation or hydrological variability	water management plans to account for changing precipitation patterns.	runoff and mitigate erosion based on climate change projections. ▪ Explore slope protection measures, vegetation reinforcement, and gabion walls to prevent slope failures and landslides triggered by hydrological variability.	▪ Conduct frequent inspections of track conditions, embankments, and bridges to identify erosion, subsidence, and structural issues.
Drought	▪ Identify areas susceptible to drought (e.g., steep slopes) in the proximity of the rail network to plan mitigation measures in collaboration with public authorities. ▪ Conduct assessments to identify the critical water needs for the rail operations and develop water conservation strategies in collaboration with local authorities.	▪ Consider using permeable materials for tracks and ballasts to capture and retain water during periods of scarcity. ▪ Prefer drought-tolerant plants and landscaping designs to reduce water demand and maintenance requirements.	▪ Implement water-efficient practices for track cleaning, dust suppression, and vegetation control. ▪ Use dust suppressants, mulching, or track coverings to minimise dust buildup and maintain track integrity. ▪ Install emergency water storage tanks, wells, or reservoirs along rail corridors for firefighting and maintenance.

4.4 Ports

PHASE 1 • Screening

Module 1: Sensitivity analysis

The sensitivities of ports to climate hazards are provided in **Table 4.15** along with indicative scores per component category (No sensitivity-Low-Medium-High). Readers are referred to **Table 1.2** of the **Introductory Chapter** (Module 1) for the description of these scores. The scores reflect the sensitivity of typical ports under the examined threats. They should be, however, critically evaluated by the project team and – if necessary – amended to ensure compatibility with the project specificities. It is noted that potential sensitivities of ports (which may eventually be impacted by climate-related factors) are dependent on the location and the activities of each port (e.g., passenger ports, cargo ports, container ports, multi-purpose ports etc.), and therefore, cannot receive a standard score in the table below. The project team should score each component category based on project specifics.

TABLE 4.15 • Sensitivities of port components.

Climate Hazard	Sensitivities			
Sea level rise **Saline intrusion**	• Increased risk of corrosion and degradation to all metal components of infrastructure and equipment due to prolonged exposure to saline water. • Flooding open storage yards and warehouses, affecting stored goods and structural integrity. • Navigation buoys and lights at lower elevations are at risk of being submerged or damaged. • Challenges in vessel manoeuvring and mooring caused by changes in water levels. • Increased maintenance requirements for assets exposed to saltwater, leading to higher costs and downtime. • Operational disruptions in cargo storage areas and transport links due to flooding or infrastructure damage. • Disruptions in road/rail access from/to the port due to flooding of access infrastructure.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Flood **Storm surge** **Heavy precipitation**	• Inundation, water damage, and foundation erosion to buildings and storage areas. • Damage to equipment and machinery from water intrusion, corrosion, and electrical malfunctions. • Increased sedimentation and debris buildup leading to silt, and contaminated waste. • Power outages or disruptions from inundated electrical substations or infrastructure. • Losses from reduced port activity and business interruptions. • Disruptions in road, rail, and waterway access from flooded infrastructure.			
Global Score: High	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Extreme wind (including storm, hurricane, tornado)	• Wind damage, structural collapse, and roof failure to port structures and buildings. • Extreme wave action causing damage to breakwaters and moles. • Potential flooding or water intrusion to storage facilities leading to cargo damage contamination, or spoilage. • Damage to machinery and equipment from high winds, flying debris, and saltwater exposure. • Risk of crane toppling or structural failure. • Disruptions in berthing and navigation due to hurricanes or tornadoes. • Potential loss of communication infrastructure. • Power outages or disruptions from damaged electrical grids or generators. • Delays or cancellations in shipping schedules due to port closures. • Losses from reduced port activity and business interruptions.			

	• Disruptions in interconnected road, rail, and waterway access from wind/storm-related damage.
Global Score: High	**On-site assets & processes** | **Inputs** | **Outputs** | **Interdependent systems**
Fog	• Reduced visibility causing manoeuvring issues, low speed restrictions and temporal malfunctions to monitoring equipment (e.g., cameras). • Increased health and safety risks to port operators and workers including accidents on land operations. • Fog conditions can disrupt traffic flow, leading to congestion and temporary or permanent inaccessibility of the interconnected transport networks.
Global Score: Medium	**On-site assets & processes** | **Inputs** | **Outputs** | **Interdependent systems**
Permafrost thawing	• Displacement or damage to navigational markers and buoys. • Difficulty to approach berthing and mooring facilities due to ice conditions and challenges in berthing/unberthing procedures caused by changing water levels. • Increased demand for heating systems in storage facilities. • Disruptions in land-based transport interconnections.
Global Score: Medium	**On-site assets & processes** | **Inputs** | **Outputs** | **Interdependent systems**
Heat wave	• Expansion and contraction of materials leading to structural stress. • Overheating and spoilage of temperature-sensitive goods. • Decreased efficiency and potential breakdowns of equipment and machinery due to extreme heat stress, as well as increased maintenance needs due to frequent heat waves. • Reduced visibility due to heat haze affecting navigational markers. • Reduced operational capacity and speed limits due to heat impacts on engines. • Delays in inspections and processing due to heat-related health issues for workers. • Increased demand for cooling systems and electricity during heat waves. • Increased odours and decomposition rates from heat-affected waste. • Risk of interconnected road and rail buckling or damage from heat-affected damages.
Global Score: Medium	**On-site assets & processes** | **Inputs** | **Outputs** | **Interdependent systems**
Cold wave **Freeze-thaw cycle**	• Ice formation can lead to structural damage to quays and berths. • Potential freezing of stored goods, causing spoilage or damage. • Reduced efficiency and potential breakdowns of equipment and machinery in extreme cold. • Impaired visibility due to fog, ice, or frost affecting navigational markers. • Reduced speed and manoeuvrability in icy or frozen waterways. • Health and safety concerns for workers in extreme cold conditions. • Increased demand for heating systems and fuel during cold wave events. • Losses from reduced port activity during cold wave events. • Interconnected road and rail closures or disruptions due to icy conditions.
Global Score: Medium	**On-site assets & processes** | **Inputs** | **Outputs** | **Interdependent systems**
Landslide **Avalanche** **Subsidence**	• Potential coastal cliffs collapses and slope failures leading to physical damages to infrastructure and/or operational disruptions in docking, mooring, and navigational access. • Interruptions in power supply from damaged utility lines or substations. • Disruptions in interconnected road, rail, waterway access from landslide or subsidence damage.

Global Score: Medium	On-site assets & processes	Inputs	Outputs	Interdependent systems
Coastal erosion **Soil erosion** **(including sedimentation)**	• Potential delays or rerouting of shipments due to port accessibility issues due to sedimentation. Also issues with road and rail access from eroded coastal areas. • Contamination from eroded materials entering port areas.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Wildfire	• Damage or destruction from wildfire flames and embers. • Potential damages to stored goods and materials due to fire hazards. • Potential damage to machinery and equipment from smoke exposure and ash accumulation. • Risk of explosions or leaks of fuel storage and tanks due to wildfire proximity. • Disruptions in supply chains due to road closures or evacuations. • Power outages or disruptions from damaged electrical infrastructure.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing wind patterns **(including wave and current changes)**	• Increased stress on structures from wave action or wind load. • Reduced effectiveness of navigation markers in shifting currents. • Challenges in berthing and mooring in strong currents or turbulent waters. • Increased wear on equipment from exposure to salt spray. • Potential delays or rerouting of shipments due to adverse weather conditions. • Delays in inspections and vessel clearance during rough seas. • Reduced port activity during windy conditions.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Changing temperatures **Temperature variability** **(including water temperature changes)**	• Increased water temperature can lead to excessive weed growth, posing to challenges to navigational safety. • Structural stress to infrastructure from thermal expansion and contraction. • Temperature-sensitive cargo degradation or spoilage. • Potential hull damage from ice formation or thawing. • Reduced manoeuvrability in icy or slushy waters. • Higher energy demand for heating or cooling facilities.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**
Drought	• Reduced water availability for port operations including irrigation. • Plant stress, wilt, and loss of greenery or dry vegetation lead to increased risks of ignition and spread of fires. • Increased costs and restrictions on water usage for industrial and operational needs. • Reduced water levels impacting dredging activities and navigational depths. • Concerns over dust emissions, air quality, and heat-related illnesses during drought.			
Global Score: Low	**On-site assets & processes**	**Inputs**	**Outputs**	**Interdependent systems**

Module 2: Exposure analysis

For details on how to conduct the exposure assessment, readers are referred to the **Introductory Chapter** (Module 2) of the present document.

Module 3: Vulnerability analysis

For details on how to conduct the vulnerability assessment, readers are referred to the **Introductory Chapter** (Module 3) of the present document.

PHASE 2 • Detailed Analysis

Module 4: Likelihood analysis

For details on how to conduct the likelihood analysis in the case of extreme or chronic hazards, readers are referred to the **Introductory Chapter** (Module 4) of the present document.

Module 5: Impacts analysis

For details on how to score the severity of climate impacts in combination with the port's criticality, readers are referred to the **Introductory Chapter** (Module 5). To assist users with the scoring procedure, an overview of significant impacts to ports across various risk areas (RA) is provided in the table below.

TABLE 4.16 • Climate impacts for ports (non-exhaustive list).

Risk Areas (RA)	Impacts
RA1: Asset damage/ Engineering/ Operational	**Physical Damages**: Climate extreme events can damage port infrastructure while chronic climate stress can lead to its degradation, leading to increased maintenance and repair needs and potential closures of docks and terminals. **Operational Disruptions**: Extreme weather conditions may halt port activities, resulting in delays in cargo handling, vessel operations, and affecting shipping schedules. Chronic climate stress may lead to reduced throughput.
RA2: Safety and Health	**Worker Safety**: Harsh weather, high winds, and heavy precipitation pose risks to port workers' safety during loading, unloading, and vessel manoeuvring. **Health Impacts:** Port environments may be exposed to air and water pollution originating from climate-induced damages to port's infrastructure or to hazardous cargo, affecting people's health (workers, passengers, nearby residents). Heatwaves may affect people's health as well.
RA3: Environment	**Pollution Incidents**: Accidental spills or leaks due to climate-induced causes can lead to pollution of water bodies, endangering marine life and affecting coastal areas. **Coastal Changes**: Intense storms and sea level rise can accelerate coastal erosion around port areas, leading to loss of land, changes in coastal morphology, and increased sedimentation in navigational channels.
RA4: Social	**Supply Chain Disruptions**: Port closures or limited operations due to climate events can disrupt global and regional supply chains, affecting trade and commerce leading to depreciation of goods (in case of prolonged disruptions) and increased transportation cost if re-routing of cargo is required. **Community Impact and Displacement**: Rising sea levels and coastal erosion may threaten port infrastructure, leading to relocation of port operations causing changes in livelihoods and affecting nearby communities.
RA5: Financial impacts	**Loss of Revenue and Increased Costs**: Weather-related disruptions result in revenue loss from reduced throughput capacity, vessel berthing, and increased expenses for repairs, coastal protection measures and infrastructure upgrades. **Insurance and Risk Management:** Ports face higher insurance premiums and costs to cover climate risks.
RA6: Reputation	**Operational Reliability Perception:** Ports experiencing frequent weather-related closures or delays may face challenges in maintaining a reputation for efficient and reliable services. **Environmental Responsibility Image:** Negative environmental climate-induced impacts from port activities can impact public perception of the port's commitment to sustainability and marine conservation efforts.

Module 6: Climate risk analysis

For details on how to conduct the climate risk assessment, readers are referred to the **Introductory Chapter** (Module 6) of the present document.

Module 7: Selection and appraisal of adaptation options

Table 4.17 presents potential adaptation solutions for climate hazards that could impact ports. The suitability of each measure is linked to the encountered level of risk and the uncertainty of climate projections, while the timing of implementation is aligned with specific project stages. Readers are referred to the **Introductory Chapter** (Module 7) for general guidance on the selection of appropriate measures to avoid maladaptation and suitable appraisal methodologies for their evaluation.

Module 8: Monitoring plans

Readers are referred to the **Introductory Chapter** (Module 8) for general guidance on the features of a climate adaptation monitoring program.

Module 9: Verify consistency with EU, National and relevant regional or local adaptation plans and strategies

For details on how to verify the project's consistency with EU, national and/or regional adaptation plans (whichever relevant), readers are referred to the **Introductory Chapter** (Module 9).

TABLE 4.17 • Ports: Indicative List of Adaptation Solutions, if and where required

Instead of opting for a heavy design based on highly uncertain projections of extreme climate hazards, consider promoting adaptive design strategies that are flexible and can adjust to future conditions, optimising the use of resources and avoiding unnecessary upfront capital expenditures. In any case inform decision-making along all stages of the project cycle with most up-to-date projections, at least for the significant climate hazards.

Climate Hazard	Plan and Feasibility	Design and Construction	Operation and Maintenance
Sea level rise	▪ Develop scenarios for different sea level rise projections to inform adaptation strategies.	▪ Consider raising quay walls, piers, and equipment platforms to higher elevations to reduce exposure to rising sea levels. ▪ Design berths with adjustable heights or floating docks to account for changing water levels. ▪ Specify and use materials that are resistant to saltwater corrosion in the construction of new facilities. ▪ Install flood barriers, seawalls, or pump and retention systems to prevent inundation of storage areas.	▪ Implement real-time monitoring of water levels, and structural integrity of assets. ▪ Increase frequency of inspections and maintenance for assets vulnerable to saltwater corrosion. ▪ Perform regular maintenance and upgrades to pumping systems.
Flood **Storm surge** **Heavy precipitation**	▪ Utilise flood hazard maps for the project area. If such maps do not exist, perform an in-depth flood-risk analysis. ▪ Coordinate planning efforts among port authorities, emergency response, and city planning departments for integrated flood risk management.	▪ Elevate critical infrastructure above projected flood levels. ▪ Consider designing stormwater drainage systems with pumps, culverts, and retention basins for flood control. ▪ Incorporate flood-resistant building materials and waterproofing for structures and equipment. ▪ Install flood barriers, seawalls, or pump and retention systems to prevent inundation of storage areas. ▪ Consider elevated walkways and platforms to provide access during heavy precipitation.	▪ Regularly inspect and maintain drainage systems, culverts, and flood control structures. ▪ Install flood-proof doors, barriers, and seals to prevent water intrusion into buildings. ▪ Develop protocols for rapid shutdown, securing, and evacuation of port facilities during floods. ▪ Train staff on flood response procedures, safety measures, and emergency equipment use.
Extreme wind (including storm, hurricane, tornado)	▪ Gather wind- or storm-related weather data and prepare projections by considering historical destructive events at the proximity of the port facility to inform the port's design and climate adaptation strategy.	▪ Opt for aerodynamic building shapes and profiles to reduce wind resistance and structural stress. ▪ Incorporate reinforced concrete or steel frames for added strength to buildings and install impact-resistant windows, shutters, or protective barriers to safeguard against flying debris. ▪ Consider resilient fendering systems to absorb impact forces from vessels during storms.	▪ Establish partnerships with national/regional meteorological agencies for early warning and forecasting. ▪ Implement advanced early warning systems in the port area. ▪ Install backup power systems and generators to ensure continuity during power outages. ▪ Establish emergency stockpiles of essential supplies, fuel, and emergency response equipment.

		▪ Design mooring points with adequate redundancy to prevent total failure in case of extreme forces. ▪ Explore options for upgrading breakwaters, revetments, or embankments to protect against extreme wave action.	▪ Develop rapid recovery plans for clearing debris, restoring operations, and reopening port facilities. ▪ Designate emergency assembly points with clear signage and access routes (e.g., dedicated shelters or safe havens) for port personnel and visitors.
Fog	NA	▪ Utilise radar systems to monitor vessel movements in and around the port during foggy conditions assisting port operators track vessel positions, detect obstacles, and assess the proximity of vessels to port infrastructure. ▪ Provide navigation assistance to vessels entering and leaving the port during foggy conditions like deploying pilot boats equipped with radar and communication systems to guide vessels safely through restricted visibility areas.	▪ Enforce the use of audible signals, such as fog horns, by vessels navigating in foggy conditions to alert other vessels of their presence and intentions. ▪ Implement speed restrictions for vessels navigating within the port area during foggy conditions to reduce the risk of accidents and collisions. ▪ Require vessels operating within the port to have AIS (Automatic Identification System) transponders activated to improve vessel tracking and monitoring capabilities. AIS data can be integrated with port management systems to enhance situational awareness and coordination during foggy conditions. ▪ Create emergency plans to manage fog-related incidents, coordinating with first responders.
Permafrost thawing	▪ Conduct detailed permafrost mapping and ground stability assessments to understand the extent of permafrost thawing risks. Use future climate projections to anticipate long-term permafrost degradation trends and consider relocation if necessary.	▪ Explore innovative foundation designs resilient to ground shifting and settlement. ▪ Utilise flexible materials for infrastructure to accommodate ground movement. ▪ Consider elevating critical structures above potential thawing zones.	▪ Invest in geotechnical surveys and ongoing monitoring systems. ▪ Regularly inspect and assess infrastructure for signs of permafrost degradation. ▪ Implement efficient drainage systems to manage excess water from thawing. ▪ Establish emergency response protocols for sudden ground instability events. ▪ Participate in knowledge-sharing networks to exchange experiences and lessons learned with other regions facing permafrost thaw challenges.
Heat wave	NA	▪ Incorporate shading structures or canopies in work areas to reduce direct sun exposure. ▪ Integrate in the design of buildings natural ventilation and cooling systems to mitigate heat. ▪ Install cooling stations or rest areas with access to water for workers. ▪ Consider reflective or heat-resistant materials in construction to reduce heat absorption.	▪ Implement heat management protocols for outdoor work, including frequent breaks and hydration. ▪ Monitor health and safety conditions regularly during heat wave events and adjust operations as needed. ▪ Maintain cooling systems for equipment and storage facilities to prevent overheating.

Cold wave **Freeze-thaw cycle**	NA	▪ Consider insulation of critical infrastructure such as storage facilities and equipment to prevent freezing. ▪ Explore de-icing systems for berths, quays, and walkways to maintain accessibility. ▪ Integrate in the design efficient heating systems for buildings and weatherproofing to conserve heat. ▪ Consider installing ice breakers or deflectors along port entrances and channels. ▪ Explore the option of ice booms or barriers to guide ice floes away from critical infrastructure.	▪ Establish cold weather protocols for equipment maintenance and operation, including consideration for storage or diversion channels for the additional snowmelt volume. ▪ Provide adequate protective gear and shelter for workers exposed to cold conditions. ▪ Monitor ice buildup and conduct regular inspections of infrastructure for signs of ice damage or stress.
Landslide **Avalanche** **Subsidence**	▪ Conduct geotechnical assessments and site investigations to identify unstable areas and geological hazards. Develop landslide risk maps and hazard zonation plans for port facilities and surrounding terrain. Consider relocation if necessary.	▪ Consider designs and reinforcements of port structures with deep foundations, retaining walls, or slope stabilisation elements. ▪ Explore different slope protection measures such as rockfall barriers, catch fences, or soil nailing. ▪ Consider drainage systems and erosion control measures to reduce water-induced slope failures. ▪ Incorporate designs for flexible quay walls and berths to accommodate ground movements.	▪ Regularly inspect and monitor coastal cliffs, embankments, and slopes for signs of instability. ▪ Establish early warning systems and monitoring protocols for detecting ground movements and slope instability. ▪ Conduct routine maintenance of drainage systems, surface water diversion, and erosion control. ▪ Engage with geologists, engineers, and experts in landslide mitigation.
Coastal erosion **Soil erosion (including sedimentation)**	▪ Develop coastal erosion zone management plans in collaboration with local authorities and coordinate efforts with the relevant agencies to align the port development plans with existing or planned mitigation strategies. ▪	▪ Consider shoreline stabilisation measures such as seawalls, revetments, riprap or gabion installations. ▪ Integrate in the design of berthing structures with erosion-resistant materials and foundations. ▪ Consider natural coastal buffers like mangroves or dunes to reduce erosion impacts and incorporate in the design soft engineering solutions such as beach nourishment or vegetation planting.	▪ Regularly inspect coastal infrastructure for signs of erosion or instability. ▪ Maintain sediment control systems to prevent runoff and sedimentation in port areas and plan regular dredging activities to improve conveyance. ▪ Renew or replace damaged parts of the port's drainage system.
Wildfire	▪ Conduct fire risk assessments to identify vulnerable areas nearby the port facility or its interdependent infrastructure and inform the mitigation plan accordingly.	▪ Consider using fire-resistant building materials and construction techniques. ▪ Create defensible space around port facilities by clearing vegetation and debris. ▪ Install firebreaks or fire barriers to prevent the spread of wildfires into port areas.	▪ Designate safe zones or refuge areas with fireproof shelters for personnel. ▪ Conduct regular fire drills and training for port staff on emergency procedures. ▪ Maintain firefighting equipment and ensure availability of fire suppression systems. ▪ Establish protocols for securing hazardous materials and fuels during wildfire events.

			▪ Monitor weather conditions and fire risk levels to adjust operations as needed.
Changing wind patterns (including wave and current changes)	▪ Conduct wind and wave modelling studies to assess risks and vulnerabilities to port infrastructure.	▪ Design/Upgrade breakwaters to protect port infrastructure. ▪ Consider flexible mooring systems to accommodate changing patterns. ▪ Explore different wind barrier or windbreak options to shield critical areas.	▪ Integrate wind and wave forecasts into port management systems. ▪ Establish protocols for securing cargo and equipment windy conditions. ▪ Conduct regular inspections of navigation aids for proper functioning.
Changing temperatures Temperature variability (including water temperature changes)	NA	▪ Utilise temperature-resilient materials in construction to withstand temperature variations. ▪ Explore various insulation options in warehouses to maintain stable internal temperatures. ▪ Incorporate natural cooling or heating systems where feasible. ▪ Consider in the design of the drainage systems the runoff from melting snow or ice.	▪ Monitor water temperatures for impacts on marine life and port operations. ▪ Increase the frequency of vegetation cutting and clearance operations. ▪ Explore biological or nature-based approaches for weed control through research initiatives and consider acquiring a larger-scale cutting machine, contingent upon findings that biological control methods are not feasible.
Drought	▪ Conduct assessments to identify the critical water needs for the port operations and develop water conservation strategies in collaboration with local authorities.	▪ Consider retrofitting facilities with water-efficient fixtures, landscaping, and irrigation systems. ▪ Integrating in the design stormwater capture and storage systems for non-potable water use. ▪ Consider Sustainable Drainage Systems to minimise runoff and maximise water infiltration. ▪ Consider additional water storage reservoirs or tanks for emergency water supply during drought.	▪ Explore alternative water sources such as rainwater harvesting, greywater recycling, or desalination. ▪ Conduct regular inspections of water infrastructure for leaks, faults, and efficiency improvements. ▪ Establish drought response protocols for adjusting operations, schedules, and water use priorities.