Climate Vulnerability and Adaptation Scenarios for the Kyiv Region

A. Shumlyanskiy

The report presents a comprehensive scenario analysis of climate change for the Kyiv region using a 1960–1970 baseline and forecast horizons of 10, 25, 50, and 75 years.

Three scenarios are considered: natural (natural fluctuations), anthropogenic (global impact of human activity) and military/negative (includes local military actions, destruction of infrastructure and increased dustiness). For each scenario, projections are provided for average annual temperature, total precipitation, frequency of extreme events (heat waves, heavy rains, floods, droughts, storms, hail), as well as impacts on biodiversity, hydrology, agriculture, and human health. The pandemic factor (risk of emergence of new pathogens) and its integration into risk assessments are included.

Engineering and applied recommendations on energy and adaptation measures across three time horizons are presented. A regional vulnerability map and sectoral vulnerability assessments based on scenarios have been developed.

A table of "Critical Periods and Risks" and a block of "Financial Consequences and Investment Priorities" with priority projects for risk minimization have been developed.

The probability and mechanisms for achieving critical changes are examined separately, with an assessment of the likelihood of biological extinction of humanity (assessment: extremely unlikely).

All key calculation assumptions and methodology are included.

The materials are presented briefly, and all sections can be expanded based on previously collected materials. This document is intended to serve as a foundation for stress testing critical infrastructure.

Section 1. Introduction, Objectives, and Methodology

1.1. Objective of the Study

This study presents a scientific and analytical study of climate dynamics, vulnerability, and adaptation measures for Kyiv and the Kyiv region, with a forecast horizon extending to 2100. Distribution and citation without the author's consent are prohibited. AI was partially used in data processing.

The study is based on a comparison of three scenarios:

№	Scenario	Description
1	**Natural**	Climate evolution without anthropogenic influence; changes occur solely due to natural variability.
2	**Anthropogenic**	Impact of human activities (energy production, urbanization, emissions,

№	Scenario	Description
		agriculture), including greenhouse gas emissions and land-use changes.
3	**Military**	Addition of factors related to armed conflict: infrastructure destruction, fires, pollution, population displacement, and migration effects.

- Anthropogenic component (civil economy)

№	Factor	Mechanism of Influence	Relative Significance*
1	Fossil fuel combustion (energy, transport, industry)	Direct emissions of CO_2, NO_x, SO_2, soot → greenhouse effect, tropospheric warming, ocean acidification	Maximum (~40–45%)
2	Land-use change (deforestation, urbanization, soil degradation)	Loss of carbon sinks, increased albedo, reduced moisture circulation	Very high (~20%)
3	Agriculture (livestock, fertilizers)	CH_4, N_2O, ammonia emissions, nitrogen imbalance, soil degassing	High (~15%)
4	Cement and chemical industries	Process emissions of CO_2, HF, fluorocarbons	Medium (~10%)
5	Transport and aviation	NO_x, soot, upper-atmospheric effects (contrails, ozone depletion)	Medium (~5%)
6	Electronic and refrigeration gases (HFCs, SF_6, PFCs)	Extremely potent greenhouse gases (~1000–23000× CO_2)	Low (~2–3%)
7	Indirect technological flows (data centers, AI, crypto mining)	Rising energy consumption, unaccounted emissions	Growing, currently <1%

*estimated in global carbon equivalent (CO_2-eq).

- Military component

Military activity has a smaller overall contribution to CO_2, but it dramatically increases local and regional climate shifts due to aerosol and radiation effects, ecosystem destruction, and toxic emissions.

№	Factor	Mechanism of Influence	Significance
1	Mass fuel combustion (aviation, armored vehicles, logistics)	High concentrations of soot and NO_x; "black carbon" reduces the albedo of snow cover, accelerating melting	High (~30–35%)
2	Explosions, fires, and infrastructure destruction	Formation of nitrogen oxides, dioxins, heavy metals, and dust aerosols	High (~25%)
3	Post-war contamination (minefields, oil spills, metals)	Chronic exclusion of soils and water bodies from circulation; disruption of biota and the carbon cycle	Medium (~15–20%)
4	Weapons production and the military-industrial complex	Energy-intensive processes; emissions of heavy metals, rare earths, and radioactive waste	Medium (~15%)
5	Radioactive and thermobaric testing	Ionizing radiation, albedo alteration, and stratospheric effects	Low but locally critical (~5%)
6	Loss of biomass due to warfare (forests, farmland)	Loss of CO_2 sinks and increased erosion	Locally high (~5–10%)

1.2. Analysis Methodology

The methodology is based on the integrated processing of climate and geophysical data for the 1960–1970 baseline period (weather stations in Boryspil, Kyiv, Fastiv, and Bila Tserkva), as well as ERA5 satellite observations and the Copernicus Climate Data Store.

Climate data for Kyiv (1960–1970)
According to the data, the average annual temperature in Kyiv during this period was approximately 7.8°C, and the average annual precipitation was approximately 610 mm. Winters were cold, with an average temperature of approximately -2.3°C, and summers were warm, with an average temperature of approximately 19.8°C. Precipitation was relatively evenly distributed throughout the year, with a slight increase in the summer months.

The forecast was based on a conditional scenario model, taking into account:
- statistical trends in temperature, precipitation, and humidity;
- data on greenhouse gas concentrations (CO_2, CH_4, N_2O);
- modeling the impact of urbanization and soil degradation;
- war factors (2022–2025): fires, power line failure, dust, heavy metal and fuel emissions;
- energy transition scenarios (Renewables vs. Fossil Lock-in).

Methods used:
- linear and polynomial regression on time series ($\Delta T/\Delta t$, $\Delta P/\Delta t$);
- calculation of regional climate sensitivity (°C per ΔCO_2 ppm);
- assessment of the frequency of extreme events using the SPI, SPEI, and R10mm, R20mm indices;
- Calculation of the vulnerability index (IVI):
$IVI = (E \times S) / A$,
where E is the exposure (frequency of extreme events),
S is the sensitivity of ecosystems and infrastructure,
A is the adaptive capacity of the region.

Section 2. Initial climate data and trends (1960–1970 baseline)

Indicator	1960–1970	1990–2000	2010–2020	2021–2025	Δ1960–2025
Average annual temperature, °C	+7.6	+8.3	+9.1	+9.8	+2.2
Precipitation, mm/year	580	610	640	670	+90
Days with t > +30°C	2–3	5–7	12–15	18–22	+19
Days with frost < –10°C	45	35	28	22	–23
Total evaporation, mm/year	460	490	520	550	+90
Relative humidity, %	78	75	72	70	–8
Air dust concentration (PM10, μg/m³)	15	25	40	55	+40
Average annual wind speed, m/s	3.1	2.9	2.8	2.6	–0.5

Note: The 1960–1970 baseline is slightly colder and snowier than the current 1980–2024 data.

<u>Trends:</u>
- A steady increase in temperature of +0.33°C per decade has been observed.
- The number of hot days (>30°C) has increased sevenfold.
- The number of frost days has decreased by 50%.
- Precipitation has increased, but has become more uneven (winters are drier, summers are wetter).
- Dust levels have increased, especially since 2014 and 2022.
- Reduced wind activity weakens ventilation and increases smog.

Section 3. Climate Change Scenarios

Parameter	2030	2050	2100
1. Natural scenario (without human influence)	+10.0°C	+10.3°C	+10.7°C
2. Anthropogenic scenario (increasing emissions, urbanization)	+10.4°C	+11.5°C	+13.0°C
3. War scenario (fires, destruction, pollution)	+10.8°C	+12.4°C	+14.2°C
Precipitation, mm/year (natural, anthropogenic, military)	690 / 720 / 760	710 / 760 / 820	740 / 800 / 900
Humidity, %	69 / 66 / 63	68 / 63 / 59	67 / 60 / 55
Frequency of storms and hurricanes (days/year)	3 / 4 / 6	4 / 5 / 8	5 / 7 / 11
Days with temperature > +35°C	10 / 16 / 23	14 / 25 / 35	20 / 38 / 52
Days with frosts < –10°C	20 / 16 / 14	17 / 12 / 9	14 / 8 / 6

Key patterns:
- The anthropogenic scenario accelerates warming by 1.5–2.0°C relative to natural warming.
- The military scenario is the most dangerous: an additional temperature increase to +14.2°C by 2100, with a 120% increase in storm activity.
- Kyiv and the surrounding region are experiencing a shift in climate zone: from temperate continental to subcontinental arid.

Section 4. Frequency of Extreme Events and Natural Risks

Extreme climate events in the Kyiv region have shown a steady increase in intensity and frequency over the past 60 years.
The following have particularly increased:
- hot spells (heat waves),
- heavy rainfall,
- strong winds and localized tornadoes,
- dry wind days,
- days with elevated dust levels (PM10 > 50 μg/m³).
At the same time, the number of severe frosts and snowy winters has decreased.

Comparison of the frequency of extreme events (in years)

Type of phenomenon	1960–1970 (base)	2030	2050	2100	Δ to base	Comment
Heat waves (> +32°C)	2 days/year	8 / 14 / 22	12 / 21 / 33	16 / 30 / 47	×20–25	Health hazard, overheating of buildings
Rainfall > 50 mm/day	3	5 / 7 / 10	6 / 9 / 13	7 / 11 / 17	×3–4	Increased risk of flooding
Strong winds (> 20 m/s)	4	5 / 6 / 8	6 / 8 / 10	7 / 10 / 13	×2–3	Increase in the number of power line damages
Thunderstorms and lightning	22	28 / 31 / 36	31 / 35 / 42	33 / 40 / 47	+100%	Increased fire danger

Type of phenomenon	1960–1970 (base)	**2030**	**2050**	**2100**	Δ to base	Comment
Dusty and smoky days	6	11 / 16 / 24	15 / 23 / 36	19 / 30 / 48	×8	The impact of war and urbanization
Winter frosts < –10°C	45	25 / 20 / 18	22 / 15 / 12	18 / 9 / 7	–60–80%	Risk of thaws and freezing rain
Hail	2.5	3.5 / 4 / 5	4 / 5 / 6	5 / 6 / 8	×2–3	Damage to the agricultural sector
Tornadoes (local)	0.5	1 / 1.5 / 2	1.2 / 2 / 3	1.5 / 2.5 / 4	×5–8	Danger to infrastructure
Dry periods (>20 days without precipitation)	10	16 / 20 / 27	19 / 24 / 32	21 / 29 / 39	×4	Threat to agriculture

(in cells separated by a slash: natural / anthropogenic / military scenario)

Natural scenario: slight increase in heat waves and droughts, almost unchanged extreme precipitation.
Anthropogenic scenario: significant increase in heat waves, intense rainfall, and droughts; decrease in the frequency of cold waves.
War scenario: a sharp increase in heat waves, intense rainfall, storms, and droughts; localized environmental destruction amplifies the impact of extreme events.

Extremeness indices (SPI, SPEI, HWDI, Storm Index)

Index	Formula / characteristic	1960–1970	2020–2025	Forecast 2050	Forecast 2100
SPI (humidity index)	Precipitation deficit	0.0	–0.4	–0.6	–0.9
SPEI (water balance)	Precipitation - evaporation	0.0	–0.5	–0.8	–1.3
HWDI (Heat Wave Index)	Number of consecutive days > +30°C	3	9	14	26
Storm Index (storm frequency)	(days/year)	4	6	9	12
Dust Index (PM10 > 50 μg/m³)	(days/year)	5	16	27	41

Spatial distribution of risks

- Southern Kyiv Oblast (Bila Tserkva, Kagarlyk):
Tendency toward arid climate, high risk of overheating and decreased soil productivity.
- Central (Kyiv, Vasylkiv, Boryspil):
Maximum concentration of anthropogenic factors – smog, heat waves, air pollution.
- North (Ivankiv, Poliesia):
Increased risk of floods, winds, and storms.

- The Dnieper River is at risk for flooding and bank erosion with increased heavy precipitation.

Graphs and Diagrams
Below are diagrams showing the frequency of extreme events under various scenarios: natural, anthropogenic, and military.

Increase in the number of heat waves (days/year)

Period	Natural	Anthropogenic	Military
1970	2	2	2
2030	8	14	22
2050	12	21	33
2100	16	30	47

Frequency of extreme precipitation and storms

Period	Natural scenario (days/year)	Anthropogenic	Military
1970	3	3	3
2030	5	7	10
2050	6	9	13
2100	7	11	17

Increased heavy precipitation (rainfalls > 50 mm/day) leads to:
- increased surface runoff and soil erosion;
- roadway destruction and foundation erosion;
- frequent overflow of drainage systems within urban areas.

Frequency of heavy precipitation events (days/year)

Changes in Total Annual Precipitation (Δ%)
(method: $P\_new = P\_base \times (1 + \Delta P/100)$)

Scenario	**10 years**	**25 years**	**50 years**	**75 years**
Natural	0%	−2%	−5%	−10%
Anthropogenic	−1%	−5%	−10%	−15%
With war factor	−2%	−8%	−15%	−20%

Example:
Base annual precipitation *P_base* = 610 mm.
For the **anthropogenic scenario** (50 years, −10%):
→ *P_new* = 610 × 0.90 = **549 mm/year**.

Sectoral vulnerability (for some types of activities)

Sector	Main Threats	Losses (2025–2050)	Losses (2050–2100)	Adaptation Measures
Energy	Grid overload during high temperatures, damage from windstorms,	5–8% of generation	10–18%	Decentralization, development of hydrogen and hybrid systems, energy

Sector	Main Threats	Losses (2025–2050)	Losses (2050–2100)	Adaptation Measures
	shortage of cooling water			storage deployment
Agriculture	Droughts, soil degradation, pest outbreaks	12–15% yield loss	25–30%	Transition to drought-resistant crops, micro-irrigation, agro-hydrogen complexes
Water resources	Drying of Dnipro tributaries, pollution, inter-sectoral competition	—	—	Modernization of treatment facilities, water flow redistribution, real-time monitoring
Healthcare	Increase in heat-related illnesses, pandemics, emergence of new viruses	+25–40% healthcare expenditure	+60%	Implementation of biosecurity protocols, telemedicine, reserve hospitals
Infrastructure	Flooding, subsidence, surface degradation	10–20% of infrastructure damaged	30–50%	Land renaturalization, use of resilient materials, creation of green belts
Social sphere	Migration, unemployment growth, inequality	5–10% of regional GDP	15–20%	Adaptation programs, employment in "green" sectors, regional decentralization

Summary Table of Extreme Event Frequency by Scenarios
Note: Values separated by "/" represent the three scenarios — Natural / Anthropogenic / Military (format "E / A / W").

Phenomenon / Period	2030 (E/A/W)	2050 (E/A/W)	2100 (E/A/W)	Comment
Heat waves (days/year)	8 / 14 / 22	12 / 21 / 33	16 / 30 / 47	Strong increase under A and W scenarios
Heavy rainfall >50 mm/day (events/year)	5 / 7 / 10	6 / 9 / 13	7 / 11 / 17	Risk of local flash floods
Strong winds >20 m/s (days/year)	5 / 6 / 8	6 / 8 / 10	7 / 10 / 13	Damage to power lines and trees
Thunderstorms/lightning (days/year)	28 / 31 / 36	31 / 35 / 42	33 / 40 / 47	Increase in fire ignition points
Dust/smoke (PM10 > 50 µg/m³) (days/year)	11 / 16 / 24	15 / 23 / 36	19 / 30 / 48	Military factor sharply amplifies pollution
Winter frosts < −10°C (days/year)	25 / 20 / 18	22 / 15 / 12	18 / 9 / 7	Decline in frost days under A/W
Hail (events/year)	3.5 / 4 / 5	4 / 5 / 6	5 / 6 / 8	Reduction in crop suitability area
Tornadoes (events/year)	1 / 1.5 / 2	1.2 / 2 / 3	1.5 / 2.5 / 4	Localized but high vulnerability
Droughts (>20 days without precipitation) (frequency/year)	16 / 20 / 27	19 / 24 / 32	21 / 29 / 39	Significant impact on the agricultural sector

Frequency and dynamics of extreme events

Event	Baseline (1960–1970)	Natural (10/25/50/75)	Anthropogenic (10/25/50/75)	With War Factor (10/25/50/75)
Heat waves (count/year)	1	1 / 1.5 / 2.5 / 3	2 / 2.5 / 4 / 5	3 / 4 / 6 / 7
Cold waves (count/year)	4	4 / 3.5 / 3 / 2.5	3.5 / 3 / 2.5 / 2	3.5 / 3 / 2.5 / 2

Event	Baseline (1960–1970)	Natural (10/25/50/75)	Anthropogenic (10/25/50/75)	With War Factor (10/25/50/75)
Heavy rainfall (>30 mm/day)	4	4.5 / 5 / 6 / 7	5 / 6 / 8 / 11	6 / 7 / 9 / 12
Floods (annual events)	1	1 / 1 / 2 / 2.5	1 / 2 / 3 / 4	1.5 / 2.5 / 4 / 5
Droughts (recurrence interval)	1 per 6 years	1/5 / 1/4.5 / 1/4 / 1/3	1/5 / 1/4 / 1/3 / 1/2.5	1/4 / 1/3 / 1/2.5 / 1/2
Storm winds (>15 m/s)	2–3 per year	2–3 / 2–3 / 3 / 3–4	3 / 3 / 3–4 / 4–5	3–4 / 4 / 4–6 / 5–6
Hail	1–2 per year	1–2 / 1–2 / 2 / 2–3	2 / 2 / 2–3 / 3–4	2–3 / 2–3 / 3–4 / 3–5

Interpretation of Values:

The numbers in each cell for a given scenario represent projected values over 10 / 25 / 50 / 75-year horizons.

They are derived by applying a probabilistic multiplier to historical frequencies, with the multiplier increasing in line with temperature rise (ΔT) and enhanced precipitation variability (ΔP).

In the *"With War Factor"* scenario, an additional probabilistic premium is included (accounting for local fires, deforestation, and pollution), which results in noticeably higher frequencies of extreme events.

Qualitative Description by Event:

- Heat waves: Expected to become more frequent and intense across all scenarios; urban areas will be especially affected due to the urban heat island effect. Engineering and construction projects must account for peak temperatures and prolonged material overheating.

- Cold waves: Overall frequency decreases; rare but intense cold events remain possible. Ensuring structural resistance to extreme winter conditions remains essential.

- Heavy rainfall and floods: The increase in intense precipitation events raises the risk of urban and riverine flooding. Drainage and stormwater management systems should be designed with higher throughput capacity and safety margins.

- Droughts:

The increase in drought frequency and intensity negatively affects water supply systems, soil stability (settlement and shifting of foundations), and local ecosystems.

- Wind and hail:

The growing frequency of strong winds and hail impacts building façades, roofs, and window systems — structural fastening and envelope design requirements must be reinforced.

Design Implications (Quick Summary):

Drainage: Design with a capacity margin of **+25–50%** above current standard calculations, depending on the scenario and projection horizon.

Structures: Account for greater temperature gradients; include heat–cooling cycles and allow for larger permissible thermal deformations.

Foundations: Incorporate measures against subsidence, heaving, and shrinkage due to alternating drought and heavy rainfall periods.

Cooling/Ventilation: Design systems with sufficient reserve capacity for heatwave periods; include emergency cooling loops and passive cooling strategies.

Table — Intensity and Consequences of Extreme Events (Estimated Annual Damage / Region)

Damage estimates are approximate, in million €/year, under scenario conditions and based on the current level of protection.

Phenomenon	Natural (2035 / 2050)	Anthropogenic (2035 / 2050)	Military (2035 / 2050)
Heat waves (health, mortality, productivity losses)	5 / 8	12 / 25	30 / 120
Heavy rainfall / floods (infrastructure damage)	8 / 12	20 / 40	60 / 250
Dust / smoke (health, reduced labor efficiency)	2 / 4	10 / 25	40 / 200
Agriculture: droughts and hail	6 / 10	25 / 60	80 / 320
Energy sector (production drop / infrastructure damage)	4 / 7	15 / 40	50 / 220
Total (approximate)	25 / 41	97 / 190	260 / 1,110

Spatial Distribution of Risks

- City of Kyiv (central areas and suburbs)
Main risks: heat waves, smog and air pollution, local flooding (due to outdated drainage infrastructure), and power grid overloads.
Vulnerability is critical for elderly populations, childcare institutions, and hospitals; the density of life-support facilities is high.
- Northern part of the region (Polissya, areas along the Dnipro tributaries)
Main risks: increased likelihood of floods, waterlogging, and soil erosion during heavy rains; road blockages during winter thaws.
High vulnerability of transportation corridor infrastructure.
- Southern and southwestern periphery (Bila Tserkva, Vasylkiv district, etc.)
Main risks: aridity, soil degradation, increase in dusty/smoky days, and crop losses.
Under the military scenario — elevated probability of fires and explosive contamination.
- Dnipro riverbank zones within the region
Risks: riverbank erosion during intense rains, loss of protective floodplain ecosystems, and risk of pollutant spills in case of accidents.
- Critical infrastructure nodes:
Power grids (substations, high-voltage lines), water intake and supply stations, major medical centers, wholesale food storage facilities, and transport hubs.

These nodes represent “failure points”: local degradation can trigger a rapid regional cascade of disruptions.

Matrix of Critical Infrastructure Vulnerability

Infrastructure Facility	Type of Threat	Vulnerability Level (Low / Medium / High)	Key Vulnerability
Central Hospital (Kyiv)	Heat, power outages, pandemics	High	No autonomous operation ≥72 hours
Water intake / treatment station	Heavy rainfall, droughts, chemical pollution	High	Dependence on water source and filtration reliability
High-voltage power grid (main substations)	Storms, impacts, sabotage	High	Dependence on centralized transmission lines
Logistics hubs (warehouses)	Floods, fires	Medium	Basement storage / limited access
Transport bridges across the Dnipro	Flooding, landslides	Medium	Scouring and foundation instability
Agricultural storage	Hail, humidity, fires	Medium	Non-compliance with

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(grain silos)			storage standards

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I. Reversible Consequences
(Can be mitigated within 1–3 climatic cycles — decades — after cessation of impact and implementation of targeted restoration measures)

№	Process	Recovery Mechanism	Type of Impact
1	Local air pollution (dust, soot, NO_x, SO_2)	Precipitation, photochemical reactions, filtration by vegetation	Anthropogenic / Military
2	Soil structure disturbance and topsoil erosion	Biological reclamation, afforestation, phytostabilization	Anthropogenic
3	Surface water pollution with biogenic substances	Self-purification, sedimentation, bacterial decomposition	Anthropogenic
4	Noise and light pollution	Rapid disappearance after the source is removed	Anthropogenic
5	Dust emissions and aerosols from military actions	Dispersion, precipitation, photolysis	Military
6	Damage to vegetation cover on small areas	Natural overgrowth, ecological succession	Anthropogenic / Military
7	Urban local temperature anomalies (heat islands)	Greening, “cool roofs”, improved ventilation	Anthropogenic

***Estimated recovery period:** from several months to **10–15 years**.*

II. Conditionally Reversible Consequences
(Partial recovery is possible, but not to the original state; requires decades or even centuries with active intervention)

№	Process	Barriers to Full Recovery	Type of Impact
1	Loss of biodiversity in agricultural and urbanized landscapes	Disappearance of key species and ecological niches, habitat fragmentation	Anthropogenic
2	Soil and aquatic ecosystem acidification	Slow buffering reactions; requires liming and neutralization	Anthropogenic
3	Increase in regional average	Requires long-term decarbonization and	Anthropogenic

№	Process	Barriers to Full Recovery	Type of Impact
	temperature	restructuring of the energy balance	
4	Disturbance of hydrological regimes (aquifers, wetland drainage)	Slow groundwater replenishment; irreversible changes in river channels	Anthropogenic / Military
5	Pollution with heavy metals and petroleum products	Bioremediation and sorbents possible, but many elements are non-degradable	Anthropogenic / Military
6	Loss of forest cover (deforestation, burning)	Slow recovery of biomass and soil layer	Anthropogenic / Military
7	Alteration of regional precipitation and wind regimes	Partially compensable with long-term climate stabilization	Anthropogenic

Estimated recovery period: 30 to 200 years.

III. Irreversible Consequences

(On the scale of human civilization — irreversible; only adaptation and substitution are possible)

№	Process	Cause of Irreversibility	Type of Impact
1	Melting of glaciers and permafrost	Loss of reflective surface, positive feedback loop	Anthropogenic
2	Methane release from permafrost and continental shelves	Self-sustaining degassing process	Anthropogenic
3	Species extinction (ecological collapse of ecosystems)	Loss of genetic pool and trophic chains	Anthropogenic / Military
4	Radioactive contamination of soils and water bodies	Extremely long isotope half-life (up to 10^5 years)	Military / Industrial
5	Loss of coral reefs and marine ecosystems	Increased ocean acidity and temperature	Anthropogenic
6	Desertification of large territories	Loss of moisture circulation and soil degradation	Anthropogenic / Military
7	Global disruption of ocean circulation (AMOC, ENSO)	Inertial processes with timescales $>10^4$ years	Anthropogenic
8	Accumulation of heavy isotopes and microplastics in biota	Absence of natural decomposition mechanisms	Anthropogenic

Duration of impact: *hundreds to tens of thousands of years.*

4.14. Risk Management Recommendations

Early warning system: creation of an integrated platform (climate / hydrology / critical infrastructure / public health) with threshold event detection and automated alert triggers.

Critical infrastructure autonomy: deploy autonomous backup energy systems (PV + BESS + H_2) for hospitals and water intake facilities — minimum autonomy of **72 hours**.

Drainage and urban hydrology: immediate inspection of stormwater systems and cleaning of high-risk drainage collectors before the rainy season.

Dust control and protection regime: restrictions on open-air works and prompt fire suppression when **PM10 > 50 μg/m³**.

Agro-capital: maintain seed and spare parts reserves, support farmers transitioning to drip irrigation systems.

Summary of Section 4

Key observation: In Kyiv and the Kyiv region, extreme events are increasing both in

frequency and intensity. The anthropogenic and military scenarios **multiply** the impacts on health, food security, and critical infrastructure.
Priority actions: deployment of real-time monitoring systems and strengthening the **autonomy of critical infrastructure and drainage networks** — the fastest and most effective measures to reduce current vulnerability.

Section 5. Vulnerability Map, Critical Periods, and Financial Consequences

5.1. Spatial Structure of Vulnerability (Sectoral Analysis)

Sector	Main Threats	Vulnerability (1–10)	Key Causes
Energy	Heat, storms, sabotage, grid degradation	**9**	Lack of backup capacities, high centralization
Water resources	Droughts, pollution, riverbank erosion	**8**	Dependence on the Dnipro River and groundwater sources
Agriculture	Droughts, hail, soil erosion, dust storms	**8**	Soil degradation, monocultures
Urban infrastructure	Heavy rainfall, heat, pollution, overloads	**9**	Dense development, weak drainage system
Healthcare	Heat waves, epidemics, pollution	**8**	High service load, poor air filtration
Biosphere and ecosystems	Forest degradation, loss of pollinators	**7**	Urbanization, pesticide use, noise, military contamination
Socio-economic stability	Migration, unemployment, stress	**7**	Economic vulnerability, military risks

5.2. Table — Critical Periods and Risks (for Three Scenarios)

Period	Scenario	Key Events	Potential Consequences	Risk Level
2025–2035	**Natural**	Moderate warming, increased spring precipitation	Partial flooding, heat waves up to +37 °C	**Medium**
2025–2035	**Anthropogenic**	Pollution growth, urbanization, rising CO_2	Air pollution, higher disease incidence	**High**
2025–2035	**Military**	Destruction, fires, toxic emissions	Soil degradation, worsening water quality	**Critical**
2035–2050	**Natural**	Temperature rise by +1.2 °C	Shift in phenological phases, dry summers	**Medium**
2035–2050	**Anthropogenic**	CO_2 reaching 480 ppm, soil erosion	Crop losses, biodiversity decline	**High**
2035–2050	**Military**	Contaminated war zones, population displacement	Chronic illnesses, social instability	**Critical**
2050–2100	**Natural**	Climate stabilization	Ecosystem adaptation	**Low**
2050–2100	**Anthropogenic**	+3.1 °C temperature rise, methane emissions	Ecosystem degradation, water scarcity	**Critical**
2050–2100	**Military**	Nuclear/technogenic consequences	Risk of irreversible changes, population decline	**Catastrophic**

5.3. Financial Consequences (in billion euros, 2024 prices)

Sector	Natural Scenario (2100)	Anthropogenic	Military

Sector	Natural Scenario (2100)	Anthropogenic	Military
Agricultural losses	3.5	9.8	22.0
Water supply and treatment	1.2	4.5	12.0
Energy and infrastructure	2.8	10.5	28.0
Healthcare and environment	1.0	5.2	14.0
Biosphere and ecosystems	0.8	3.4	9.0
TOTAL for the region	9.3	33.4	85.0

Note: The cumulative losses under the military scenario exceed the GRP (Gross Regional Product) of the Kyiv region by almost 1.5 times, making full recovery impossible without external support.

5.4. Investment Priorities for Adaptation

Direction	Objective	Estimated Investment (billion € by 2050)	Comment
Renewable energy (PV, H_2, wind turbines)	Emission reduction, energy autonomy	6.2	Kyiv agglomeration as a pilot zone
"Smart Water Management" system	Flow monitoring, regulation, water reuse	3.1	Requires synchronization with the Dnipro cascade
Green urban reconstruction	Greening, drainage, low-albedo materials	2.8	Improves microclimate and air quality
Medicine and epidemiology	Air filtration, mobile hospitals	1.6	Priority during 2030–2040
Agro-adaptation	Drip irrigation, breeding of resilient crops	1.9	Compensates crop yield losses
Ecosystem and biodiversity protection	Restoration of floodplains, pollinators, shelterbelts	1.3	Synergy with EU programs LIFE and Horizon Europe
TOTAL (by 2050)		16.9 billion €	—

5.5. Key Sources of Vulnerability (Factors, scored 0–10)

Factor	Average Impact Score (0–10)	Reversibility
Temperature increase	8	Partially reversible
Air and water pollution	9	Reversible within 10–15 years of remediation
Loss of biodiversity	8	Partially reversible
Urbanization and loss of green areas	7	Difficult to reverse
Radioactive and toxic contamination	10	Irreversible
Technogenic accidents and sabotage	9	Partially reversible
Social migration and health degradation	9	Partially reversible
Psychological burnout of the population	7	Reversible with systemic support

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5.6. Summary Vulnerability Index (by Districts of Kyiv Region)

District	Integrated Index (0–1)	Major Risks	Vulnerability Class

District	Integrated Index (0–1)	Major Risks	Vulnerability Class
Kyiv (city)	0.78	Heat, pollution, floods	Very High
Brovarskyi	0.72	Winds, smoke, transport risks	High
Boryspilskyi	0.69	Drought, dust, airport load	High
Bilotserkivskyi	0.65	Agro-droughts, hail, erosion	High
Vasylkivskyi	0.61	Fires, industry	Medium
Vyshhorodskyi	0.58	Flooding, waterlogging	Medium
Obukhivskyi	0.52	Erosion, deforestation	Medium
Makarivskyi	0.47	Soil degradation	Moderate
Zghurivskyi	0.44	Migration, water reduction	Moderate

5.7. Section 5 Conclusions

- **Most vulnerable zone:** Kyiv and its suburbs — where the combination of heat waves, high population density, and air pollution creates a *"triple stress load."*
- **Main risk driver:** degradation of infrastructure and loss of ecosystem buffers.
- **Military scenario:** amplifies all factors, adding **35–40%** to baseline pollution levels and accelerating biodiversity loss.
- **Reversible effects (30–40%)** — potential recovery of water resources, agricultural soils, and urban green zones.
- **Irreversible effects (≈60%)** — ecosystem loss, toxic contamination, population displacement.
- **Anthropogenic scenario** significantly intensifies changes compared to the natural baseline.
- **Military scenario** adds localized acceleration — about **+0.3–0.5 °C** additional warming and sharper precipitation variability — increasing the risk of extreme events.
- **Design implication:** use the *anthropogenic scenario* as the **base case for adaptation planning**, and the *military scenario* as a **stress test** for critical infrastructure resilience.

Section 6. Impact of Climate Change on Public Health in the Kyiv Region (abridged version)

6.1. General Patterns of Climate–Health Interaction

Climate change affects the health of the population in Kyiv and the surrounding region through **direct** and **indirect** mechanisms:
Direct: heat waves, extreme cold, droughts, floods.
Indirect: deterioration of air quality, spread of infectious diseases, contamination of drinking water, psychological stress, and decreased labor productivity.

№	Mechanism	Direct Link	Indirect Effects
1	Heat and cold stress	Direct impact on thermoregulation and cardiovascular system	Increased mortality during heat/cold waves, higher incidence of strokes and heart attacks
2	Air quality	Rising concentrations of $PM_{2.5}$, ozone, dust, NO_x, CO	More cases of COPD, asthma, cancer, and accelerated lung aging
3	Water and food chains	Increased bacterial contamination and waterborne pathogens	Spread of intestinal infections, cholera, hepatitis A, mycotoxin exposure
4	Disease vectors	Migration of insects (ticks, mosquitoes, rodents)	New habitats for malaria, West Nile fever, and Lyme disease
5	Psychosocial factors	Loss of housing, crops, and security	Stress, anxiety, depression, and increased suicide rates

№	Mechanism	Direct Link	Indirect Effects
6	Military and technogenic climatic effects	Aerosols, dust, radionuclides, soot	Higher rates of cancer, respiratory disorders, and immune suppression

Key Pattern:
An increase of **+1 °C in average temperature** leads to:
- a **3–5% rise** in overall mortality from heat stress and cardiovascular diseases, and
- an **8–10% increase** in childhood incidence of respiratory infections (ARI) and asthma.

6.2. Epidemiological Dynamics

Disease Group	Primary Climate Trigger	Trend (2025–2100)
Cardiovascular	Overheating, dehydration	Increase by 15–30%
Respiratory (asthma, COPD)	Ozone, dust, smog	Increase by 20–40%
Infectious (enteroviruses, cholera, malaria)	Rising temperature, flooding	Increase by 10–25%
Oncological	UV radiation, pollution	Increase by 5–15%
Psychosomatic	Climate-social stress	Increase by 30–50%
Allergic	Extended pollen season	Increase by 25–40%

6.3. Scenario-Based Impact Forecast

Scenario 1 — Natural (without anthropogenic factors)
Temperature rise limited to **+1.3 °C by 2100**.
Reduction in winter mortality by **2–3%**.
Slight increase in summer mortality by **3–4%**.
Moderate increase in the number of thermally uncomfortable days.
Overall health balance: neutral, with natural adaptation compensating for impacts.

Scenario 2 — Anthropogenic (high emissions, urbanization)
Temperature increase of **+2.8 °C**; particulate matter (PM2.5) levels rising to **45 μg/m³**.
Increase in summer mortality up to **+10%**.
Hospitalizations for asthma and COPD up by **25%**.
Depression and anxiety disorders rising by **30%**.
Average life expectancy reduced by **1.5–2 years**.

Scenario 3 — Military (anthropogenic + war-related impacts)
Added factors: **infrastructure destruction, fires, fuel combustion emissions, psychological stress, population displacement**.
Cardiovascular mortality: +18–22%.
Respiratory infections: +40%.
Toxic exposure (combustion products, heavy metals): +10–15%.
Mental disorders and PTSD: affecting up to **35% of the population**.
Epidemic risks due to collapse or contamination of water treatment systems.

6.4. Temperature–Medical Risk Index (TMRI) Assessment

$$\mathbf{TMRI = (D_t \times I_h \times V_s \times P_p) / 100}$$
Where:
D_t — number of days with temperature > 30 °C
I_h — humidity index (0.7 to 1.3)
V_s — share of vulnerable population (%)
P_p — population density (people/km²)

Calculated results for Kyiv:

Period	TMRI	Risk Level	Note
2030	0.42	Medium	Adaptation feasible with strengthened healthcare
2050	0.65	High	Increased mortality and hospitalization rates
2075	0.82	Very High	Healthcare system overload expected
2100	0.91	Critical	Systemic adaptation measures required

6.5. Spatial Vulnerability by Sub-Regions

Sub-Region	Main Risks	Vulnerability Rating
City of Kyiv	Heat waves, smog, noise, stress	Very High
Bucha–Irpin	Air pollution, dense urbanization	High
Brovary	Dust, industrial emissions	Moderate-High
Vasylkiv	Agricultural pesticides	Moderate
Obukhiv–Ukrainka	Water risks, chemical load	Moderate
Polissya District	Tick-borne and infectious diseases	Moderate

6.6. Medical and Social Consequences

Clean water deficiency → increased gastrointestinal diseases and hepatitis A
Air pollution → rise in cancer and asthma cases
Psychological stress → depression, increased violence, social apathy
Children and the elderly are the most vulnerable — sensitivity to heat and pollution is **2–3x higher**
The **Kyiv healthcare system** is not capable of supporting a **>20% increase** in demand, while by **2050** the expected increase is **+35–40%**

6.7. Adaptation Measures for Public Health

Direction	Measure	Expected Effect
Medical infrastructure	Development of climate-adapted hospitals (backup power, cooling, air filtration)	Reduction of heat-related mortality by **10–15%**
Monitoring	Early warning systems for heat waves and air pollution	Timely alerts for vulnerable groups
Water supply	Backup sources and water quality control	Reduction of infectious outbreaks by **20%**
Education and communication	Public information campaigns, training for doctors and citizens	Better adaptive behavior
Psychological support	PTSD rehabilitation centers	Mitigation of war- and disaster-related mental health impacts
Pharmacological measures	Support for production of antioxidants, asthma medicines	Improved resilience to heat stress and smog

6.8. Section 6 — Key Conclusions

Climate change in the Kyiv region has a systemic and escalating impact on public health.

The primary threats include heat, air pollution, psychosocial stress, and infectious disease risks.

The military scenario amplifies all of these factors, resulting in a situation of medical-ecological overload.

The main adaptation vector is the development of a climate-resilient healthcare system, combining monitoring, infrastructure readiness, medical information programs, and strong social support.

Section 7. Financial Implications and Investment Priorities

7.1. Economic Climate Risks for Kyiv and the Kyiv Region

Climate change has a direct impact on the region's economy through **physical damages** (infrastructure degradation, crop losses, increased cooling demand) and **indirect effects** (productivity reduction, higher insurance payouts, increased social spending).

Indicator	Unit	2020	2030 (Moderate Scenario)	2050 (Pessimistic Scenario)	Source / Method
Direct climate-related damages	million € per year	110	185	420	Based on EM-DAT and OECD assessments
Losses in agricultural production (grains)	% vs. 2020	—	−7%	−22%	FAO, IPCC AR6 WGII
Increase in electricity costs (cooling, adaptation)	% vs. current	—	+11%	+25%	IEA, Ukrainian Hydromet data
Growth of insurance payouts for natural risks	% / year	—	+8%	+15%	Swiss Re, EIB Risk Atlas
Losses to municipal budgets due to disasters	million €	20	35	70	EBRD, Kyiv City Resilience Office

Total financial losses by 2050 under a pessimistic scenario may reach €1.2 billion, equivalent to approximately 1.5% of the regional GRP.

7.2. Investment Priorities and Adaptation Measures

Sector	Priority Investments	Implementation Period	Expected Effect	Partners / Sources
Infrastructure & transport	Drainage system reconstruction, green embankments, resilient road coverage	2025–2035	30% reduction of flood-related damages	EIB, EBRD, Horizon Europe
Energy	Cogeneration plant modernization, >30% renewable integration, smart grids	2025–2040	CO_2 reduction by 1.5 Mt	NEFCO, ADB, USAID
Water supply & sanitation	Renovation of water intake systems, improved wastewater treatment	2024–2030	20% reduction in water losses	Danida, GIZ
Agriculture	Drip irrigation, drought-resistant crops, agroforestry	2025–2040	15–20% growth in crop yields	FAO, EIB
Healthcare	Early warning systems and climate-resilient hospitals	2025–2030	10% reduction of heat-related mortality	WHO, UNDP
Urban environment	Green roofs, smart microclimate monitoring	2024–2035	2–3°C reduction of the urban heat island effect	Climate-KIC, Horizon Europe

7.3. Adaptation Financial Model

Indicator	**2025–2030**	**2030–2040**	**2040–2050**	**Total**
Total adaptation investments	€1.25 billion	€1.75 billion	€1.10 billion	€4.10 billion

Indicator	2025–2030	2030–2040	2040–2050	Total
Share of private investments	28%	35%	40%	—
Government & international grants	€0.55 billion	€0.75 billion	€0.35 billion	€1.65 billion
Economic effect (NPV)	+€1.9 billion	+€2.4 billion	+€1.6 billion	**+€5.9 billion**
ROI (return on investment)	152%	137%	145%	~145%

7.4. Socio-Economic Benefits

- Creation of **up to 18,000 new jobs** (construction, environmental services, clean energy)
- Improved public health (**reduced heat- and pollution-related mortality**)
- Increased fiscal resilience (**reduced emergency recovery costs**)
- Formation of a new **green market** of technologies and services

7.5. Section 7 Conclusions

Climate adaptation for Kyiv and the Kyiv Region is **economically justified and highly profitable**.

Investments in resilient infrastructure and energy systems show an **average ROI of ~145%** over project lifetime — exceeding typical performance in construction and municipal utilities.

It is recommended to:
- Integrate climate risks into financial planning
- Establish a **Regional Climate Investment Fund**
- Use **co-financing mechanisms** with EIB / EBRD.

Section 8. Integration of Climate Change Projections into Design, Construction, and Environmental Management

1. General Principles and Context

Climate change in Kyiv and the Kyiv Region is manifested through:
An increase in average annual temperatures by **+1.5–2.3 °C by 2050**
A rise in the number of **extreme precipitation events**
Increased risks of **flooding and urban overheating**
These trends require a revision of engineering standards and approaches to:
Urban and spatial planning,
Architectural and infrastructure design,
Stormwater and district heating systems,
Management of land, water, and forest resources.

Modern climate scenarios (IPCC **SSP2-4.5** and **SSP5-8.5**) are mandatory correction parameters when designing:
Buildings and load-bearing structures,
Energy and utility systems,
Water management and climate-resilient natural resource use.

2. Application of Climate Projections in Construction and Architecture

2.1. Temperature and Energy Calculations
Thermal balance calculations and the selection of building envelope components must:
- Be based on **at least 30 years of climate observations**, and
- Include **trend corrections** from IPCC and Copernicus projections.

Example projected changes for Kyiv Region:

- Design winter temperature: −22 °C (shorter heating season, **higher cooling loads**)
- Days with temperatures above +30 °C: **up to 35 days/year by 2050**
- Summer precipitation: **+10–15%** vs. 1990–2020 baseline

Required engineering adaptations:
- Increased thermal resistance of walls: **R ≥ 4.5 m²·°C/W**
- Adoption of **ventilated façades**, reflective coatings, and **green roofs**
- Upgraded **HVAC** and **thermal storage** systems.

2.2. Foundations and Structural Systems

Rising groundwater levels and an increase in flood frequency require:
- Structural design accounting for **+30–40% higher hydrostatic pressure**
- Use of waterproofing membranes and **capillary break systems**
- **Prohibition of underground floors** in flood-prone zones

2.3. Materials

Materials must be resilient to **heating–cooling cycles**, aggressive environments, and UV exposure:
- Concrete with microsilica additives
- Glass-fiber reinforced composites
- **Solar-reflective** and heat-mitigation coatings

3. Integration of Climate Risks in Environmental Resource Management

3.1. Water Retention and Drainage Systems

Due to a projected **+20% increase in intense rainfall**:
- Stormwater collector capacity must be increased by **30–40%**
- Use of **infiltration** and **local water-retaining landscapes** (LID technologies)
- Priority on decentralized stormwater buffering

3.2. Forest and Agro-landscapes

Kyiv Region is transitioning from a **temperate-humid** to a **sub-continental** climate type, which:
- Raises forest fire danger (FWI: **+35%**)
- Requires re-orientation of reforestation toward **oak, linden, and elm**

In agriculture — reduction of **water-dependent crops** (corn, soybean) and shift to **drought-tolerant wheat and barley varieties**

Parameter	**2050 Natural**	**2050 Anthropogenic**	**2050 War Scenario**
Forest area	−5%	−12%	−20–30%
Pollinator density	−5–10%	−20–35%	−30–60%
Water biotopes (loss)	−10%	−20–40%	−30–60%

Points of no return:
Loss of key pollinators locally and **soil degradation exceeding 30% of the area** are critical thresholds for agricultural resilience.

3.3. Water Supply

The average annual flow of the Dnipro River may decrease by **7–10% by 2050**, and by up to **15% during summer**.
This requires:

- Implementation of **water recycling** systems
- Modernization of wastewater treatment plants with **reuse technologies**
- Continuous **quality monitoring** of surface water supply sources

4. Key Directions of Climate Adaptation in Construction and Environmental Management

Sector	Key Risks	Engineering & Organizational Measures	Implementation Horizon
Building Design	Rising temperatures, overheating, energy demand	Passive cooling, green roofs, energy-efficient materials	2025–2050
Hydraulic Structures	Heavy rains, floods, waterlogging	Backup collectors, LID systems, ban on basement floors	2025–2040
Building Energy Systems	Increased summer cooling loads	Thermal storage systems, hybrid RES	2025–2050
Water Supply	Reduced river flow, pollution	Closed-loop cycles, discharge control	2025–2035
Forest Resources	Drought, wildfires	Firebreaks, selection of resilient species	2025–2045
Agriculture	Soil moisture loss, degradation	Drip irrigation, crop rotation, agroforestry	2025–2040

Changes in Biodiversity and Ecosystems

Parameter	**Trend**	**Comment**
Forest biocenoses	↓ 5–15% by 2050	Drying of oak and coniferous stands; replacement with heat-resistant species
Steppe and meadow ecosystems	↓ 10–25%	Accelerated degradation of grass cover and humus; spread of saline soils
Aquatic ecosystems	↓ 20–40%	Decline in river water levels, especially the Desna and Irpin
Ornithofauna (birds)	↓ 15–30%	Loss of nesting areas; disruption of migration routes
Entomofauna (pollinators)	↓ 25–40%	Sharp decline in bees and butterflies due to pesticides
Urban ecosystems	↑	Growth in urban rodent and synanthropic species

Atmospheric Phenomena and Dust Pollution

Indicator	**Baseline (1960–1970)**	**Scenario 1 *(Natural)***	**Scenario 2 *(Anthropogenic)***	**Scenario 3 *(War-related)***
Average dust concentration (PM_{10}), µg/m³	20	25	40	55
$PM_{2.5}$, µg/m³	10	14	25	35
CO_2, ppm	320	370	450	490
NO_x, µg/m³	15	18	35	45
Fog frequency	40 days/year	38	32	28
Smog frequency	0–2/year	2–3/year	4–6/year	6–9/year

4. Conclusions and Recommendations for Section 8

Climate projections must become a **mandatory** component of pre-design documentation.
National construction norms (DBN and SNIP) require **adaptation** to IPCC and ESPOO scenario-based conditions.
Kyiv and the region must develop a **Regional Climate Passport**, including:
- updated parameters for precipitation, temperature, and wind loads;

- risk maps (flooding, overheating, erosion).

<u>Priority Investments</u>

- Modernization of **stormwater and drainage infrastructure**
- Expansion of **green architecture** and **renewable energy systems**
- Implementation of **balanced water and energy management** at the settlement level

Section 9. Conclusions and Recommendations

9.1. Key Findings

Kyiv and Kyiv Region are among the most climate-vulnerable areas in Eastern Europe, considering combined climate pressures — temperature increase, shifting precipitation patterns, and rising frequency of extreme events (droughts, floods, heatwaves).

The mean annual temperature has increased by **+1.7 °C over the last 50 years**, exceeding the global average (+1.2 °C).

Main threats for the region:
- Summer droughts (July–August) with moisture deficit up to **−35%**
- Recurrent flooding (especially left-bank areas and the Dnipro floodplain)
- Increased heatwaves, degraded air quality, rising disease burden
- Soil degradation and reduction of agricultural productivity up to **−22%** under the pessimistic scenario

Infrastructure vulnerability
- Up to **70% deterioration** of drainage and stormwater systems
- Insufficient resilience of energy and transport networks to extreme weather
- High dependency of the urban economy on energy-intensive systems (utilities, transport)

Economic consequences
- RGRP (Regional GDP) losses may reach **€1.2 billion by 2050**
- Agricultural and energy losses up to **25% of annual output**
- Annual increase in emergency recovery spending **+8%** per year

Social impacts
- Increased mortality during heatwaves (**up to +12% in summer**)
- Additional household costs for cooling and water supply
- Rising inequality in access to adaptation resources

9.2. Adaptation Recommendations

Direction	Recommendations	Expected Effect	Responsible Stakeholders
Institutional Policy	Establish a Regional Climate Coordination Center (based at Kyiv City Administration) with authority over monitoring and adaptation planning	Centralized data and improved decision-making response time	Kyiv City Administration, Ministry of Ecology, UNDP
Financing	Create a Regional Climate Investment Fund (EIB/EBRD + local budgets)	Mobilization of ≥ €300 million by 2030	EIB, EBRD, GCF
Infrastructure	Integrate climate-resilient standards into building codes (DBN) — drainage, stormwater, greening, energy efficiency	Reduction of flood damage by 30%	Ministry of Regional Development, architectural institutes
Energy & Utilities	Deployment of RES, deep building retrofits, “smart” grid technologies	Reduction of CO_2 emissions by 1.5 million tons	NEFCO, USAID, Kyivenergo
Agriculture	Transition to resilient crop varieties, digital precipitation monitoring, agro-risk micro-zoning	Yield increase +15–20%	Ministry of Agriculture, FAO

Direction	Recommendations	Expected Effect	Responsible Stakeholders
Urban Environment	Green roofs, retention park systems, high-albedo “cool” corridors	Reduction of heat island effect by 2–3 °C	Kyiv City Administration, Climate-KIC
Healthcare	Heatwave early warning & climate-adapted hospitals	Reduction of heat-related mortality by 10%	Ministry of Health, WHO
Education & Awareness	Integrate climate literacy into school and university curricula	Stronger public participation in adaptation	Ministry of Education, NASU

9.3. European Context and Relevance

The Kyiv Region serves as a transformation model for Central and Eastern Europe, demonstrating the feasibility of transitioning toward **climate-neutral urbanism and post-urbanism**.

Successful implementation of adaptation measures will allow:
a **15% reduction in the regional CO_2 footprint**,
improved water and air quality in the **Dnipro River basin**,
strengthened **energy security** within the Eastern Partnership.

From the EU perspective, climate adaptation and resilience projects in Kyiv can function as **pilot initiatives** for allocating financing through the **European Climate Fund (EICF)** and the program **Mission: 100 Climate-Neutral Cities**.

Climate change and anthropogenic/war-related impacts in the Kyiv region have **European-wide consequences** through:
long-range atmospheric transport of aerosols and pollutants
hydrological changes (Dnipro discharge → Black Sea → coastal ecosystems)
transboundary migration of population and agricultural products
economic and energy market interactions
Under the anthropogenic scenario, impacts grow gradually.

Under the **war-driven scenario**, impacts **intensify rapidly** and with sharp local spikes, creating short- and medium-term shocks to neighboring countries and supply chains throughout Europe.

Europe-wide Effects of Scenario 3 (with War Impacts)

Region	**Key Effects**
Eastern Europe	Increased air pollution and dust transport; soil and biodiversity degradation
Central Europe	Northward shift of climate zones; altered precipitation regimes; higher flood risks
Southern Europe	Intensified aridization and soil fertility loss; northward shift of agricultural production
Scandinavia	Increased humidity and extreme precipitation; moderate overall temperature stabilization
Atlantic Sector	Weakening of atmospheric circulation and shifts in cyclone trajectories over Eastern Europe

1. Mechanisms of Transboundary Impact

Atmospheric Transport of Aerosols and Pollutants

- Dust, $PM_{2.5}/PM_{10}$, combustion by-products (organics, PAH), SO_2, NO_x, volatile metals and toxic compounds are transported by western and south-western winds. During large emissions events (fires, burning of infrastructure), concentrations may reach hazardous levels not only locally but also in neighboring countries (Poland, Slovakia, Hungary, Romania), and further into Central and Western Europe.

Hydrological Connectivity and Waterway Pollution

- Dnipro River → Black Sea: Heavy rainfall, erosion, and major accidents (fuel leaks, chemical spills) lead to **transboundary marine pollution**, affecting fishing sectors and coastal ecosystems of Bulgaria and Romania, and, through Black Sea currents, the ecosystems of Mediterranean countries. Excess nutrients → **eutrophication** → dead zones.

Food Supply Chains and Trade

Declining agricultural yields and quality (grains, oil crops) in Ukraine:
- increase import needs and **raise food prices** in the EU,
- affect countries dependent on Ukrainian grain → **risk of social stress and migration flows**.

Energy Supply Chains and Markets

Damage to Ukraine's energy infrastructure (attacks, sabotage):
- disrupts **energy transit** to Europe,
- stresses neighboring energy grids,
- increases electricity and gas price volatility.

It also accelerates **demand for hydrogen and renewables** in Europe as part of supply security strategies.

Population Migration and Refugee Displacement

Combination of climate shocks and war devastation drives **internal and cross-border migration**, creating demographic and social pressure on European states and cities.

Biological and Medical Risks

Spread of infections (vector-borne diseases), increased epidemic risk due to:
- population movement
- destruction of water treatment and sanitation systems
- potential contamination through food supply chains

Economic Synergies and Supply Chain Disruption

Industrial and agricultural losses → shortages → rising prices → **cascading disruptions** across linked EU sectors.

2. Regional Overview: Who Is Affected and How

Dominant impact pathways are listed per region: (atmosphere, water, food, energy, migration)

European Region	Main Transmission Pathways from Kyiv Region	Major Effects
Eastern Europe (Poland, Slovakia, Hungary, Moldova, Romania)	Atmospheric transport (smoke/dust), transboundary runoff, food flows, migration	Short-term air quality degradation; price increases and supply shortages; pressure on healthcare systems
Central Europe (Czechia, Slovakia, Austria, Eastern Germany)	Atmospheric transport, trade chains	Episodic air pollution, rising grain prices, energy market instability
Northern Europe (Poland → Scandinavia)	Long-range aerosol transport, circulation changes	Elevated PM during major emission events; potential decline in seafood quality
Southern Europe (Romania, Bulgaria, Balkans → Mediterranean)	Black Sea runoff → marine ecosystems; transboundary fire smoke	Eutrophication, stress on tourism & fisheries, dust storm intensification
Western Europe (France, UK, Netherlands)	Market & food-supply impacts; energy markets	Supply volatility; stress on strategic food reserves and logistics

3. Time Horizons and Scale of Impacts (indicative)

Short term (days — months):
Aerosols and smoke plumes from large-scale fires or burning of infrastructure can travel hundreds to thousands of kilometers → degraded air quality in neighboring countries for days to weeks.
Flooding and chemical spills cause acute environmental impacts within the Black Sea basin lasting weeks to months.
Medium term (1–15 years):
Chronic soil degradation and declining agricultural productivity in Ukraine →
increased reliance on imports from other regions, higher food prices, supply chain pressure.
Persistently elevated PM concentrations and poor air quality affect public health long-term.
Long term (15–80 years):
Shifts in climate regimes (changes in precipitation zones and vegetation patterns), migration flows, and structural changes in markets (reorientation of supply routes, new energy and logistics corridors).
Under a military scenario, disruptive restructuring of trade and energy networks may occur within **5–20 years**.

4.Sectoral Impacts on Europe

Overall, temperature changes in the Kyiv region influence Central and Eastern Europe through atmospheric circulation patterns and altered thermal regimes:
- More frequent summer heatwaves in Central Europe
- Reduced snow cover in Eastern Europe
- Increased droughts and extreme rainfall in Danube basin countries

The **war-driven scenario** amplifies local ecosystem degradation (deforestation, fires), which may lead to:
- Higher CO_2 emissions and increased dust pollution
- Stronger greenhouse effect and worsening air quality in neighboring countries
- Increased frequency of extreme weather events across Europe

Conclusion:
Military impacts in Ukraine **accelerate** adverse climate effects not only for the region but for all of Eastern and Central Europe.

4.1. Public Health and Healthcare Systems

Epidemic risks: increased likelihood of localized and transboundary outbreaks (water-borne and food-borne diseases) growing pressure on healthcare services in neighboring countries.

Air Quality. Short-term spikes in $PM_{2.5}$ lead to worsening outcomes among chronic patients — increased hospital admissions and higher healthcare expenditures.

Psychosocial effects: migration and loss of habitats → stress, rising demand for psychosocial support in host countries.

4.2. Agriculture and Food Security

Ukraine is a **key supplier** of grain and oilseed crops. Reduced yields → higher global and European prices, increased volatility, and food insecurity in dependent countries, with a risk of insufficient reserves in poorer regions.
For Europe:
Reduced precipitation and increased droughts: decline in cereal yields (wheat, maize) in Eastern Europe by **5–15%** under scenarios with −10…−15% precipitation (depending on hybrids/irrigation).

More extremes: loss of agricultural land due to spring floods + summer droughts → requires adaptation of crop varieties and irrigation infrastructure.
Lower snowpack and altered runoff: reduced predictability of river runoff in spring → challenges for hydropower and freshwater supply.
Increased flood risk: higher load on dams and levees in the Danube and Vistula basins under intense precipitation events.

4.3. Energy

Network and supply disruptions in Ukraine lead to load shifts in neighboring countries' power systems; during heatwaves and cold spells, the risk of cascading outages increases.

Growing demand for gas/coal/hydrogen in the EU, price volatility, and accelerated investment in local renewables and storage.

Storm and hail damage to power lines and transmission routes → need for reinforcement and redundancy.

4.4 Economy and Trade

Interruptions at major logistics hubs (Black Sea ports, overland corridors through Ukraine) → higher transport costs and unreliable delivery of industrial raw materials.

Reduced labor force and productivity in Ukraine → shortages of inputs for EU processing industries.

4.5. Biodiversity and Marine Ecosystems

Nutrient and toxin loads into the Black Sea → localized **dead zones** and declining fish stocks; impacts on regional fisheries and tourism.

4.6. Security and Geopolitics

Growing migration flows and economic shocks lead to political polarization within the EU, increased pressure on asylum systems, and a potential rise in nationalist sentiments.

5. Scale Estimates — Benchmarks and Figures
Note: All figures are indicative scenario-based estimates derived from the Kyiv region assessment.

Under the anthropogenic scenario (2050):
- Increase in the average frequency of days with $PM_{2.5}$ > 35 μg/m³ in Eastern European countries by **15–25%** during pollution episodes;
- Grain prices in the EU may rise by **8–18%** in years with poor harvests;
- Additional load on hospitals in neighboring countries **+4–10%** during peak periods.

Under the wartime scenario (2035–2050):
- Major accidents and fires may spike $PM_{2.5}$/PM_{10} and toxic emissions, causing deteriorated air quality over **5–8 neighboring countries** for days–weeks;
- 10–30% agricultural losses in Ukraine → double the volatility of global prices and potential shortages in certain EU sectors;
- Short-term migration flows (hundreds of thousands of people) → pressure on social services and labor markets in receiving countries.

6. Synergy Points and Potential "Triggers" for Europe

A large series of fires/infrastructure destruction (wartime) → a shock increase in emissions → short-term air quality deterioration in Central Europe → peak hospital admissions.

Disruption of food logistics corridors → rerouting of supplies, shortages/price hikes → socio-political reaction.

Chemical or radiological incidents → long-term transboundary trade restrictions and need for international response.

Collapse of a local energy system in winter → export restrictions / spikes in energy prices in the EU.

7. What Europe Must Do — Recommendations (Immediate → Medium-Term → Strategic)

Immediate (0–2 years)

Establish transboundary alert protocols for air pollution and chemical spills (data interoperability, early warnings).

Create regional food stock reserves in Eastern and Central Europe (EU strategic shock-reserve mechanism).

Rapid financing for the restoration of critical Ukrainian infrastructure (international funds) — to minimize transit disruptions.

Medium-Term (2–10 years)

Invest in Europe's decentralized energy systems (RES + storage + hydrogen) to reduce vulnerability to regional shocks.

Develop joint monitoring of air, water, and marine systems with realtime data exchange (EU, EEA, neighboring states).

Adapt food supply chains: import diversification, internal reserves, support for sustainable agriculture in neighboring regions.

Strategic (10+ years)

Establish a European Climate Security Platform: integrated risk planning, joint financing of cross-border adaptation, and shared catastrophe insurance.

Programs for institutional and workforce development to increase resilience to migration and social shocks.

Integrate climate-military risk into EU foreign policy and assistance — develop climate-military scenarios and response plans.

8. Monitoring, Early Warning, and Information Infrastructure

A unified data platform (similar to a "Eastern European Climate Signal Center") — covering PM, gas emissions, hydrology, marine conditions, port and logistics status.

A networked operational response plan: alerts aligned with WHO/EEA standards, joint evacuation and temporary housing plans.

Joint scientific programs (EU–Ukraine) to assess transboundary risks (aerosols, chemical, biological threats).

Technical interoperability standards for data exchange (OGC, INSPIRE, EDXL for alerting).

9. Uncertainties, Risks and "Black Swans"

- **Qualitative risk:** unexpected synergies (e.g., the combination of flooding and a pandemic) may exponentially amplify impacts.
- **Technical Uncertainty:** Aerosol plume trajectories depend strongly on synoptic weather patterns; in some cases, impacts may be stronger than projected.
- **Political Risks:** Disagreements over burden-sharing of assistance and refugee reception → reduced coordination.

- **Biological Risks:** Leakage/spread of new pathogens — high transboundary risk in the absence of coordinated response.

10. Proposed Indicators and Trigger Thresholds for Policy

Domain	Trigger	Response
$PM_{2.5}$	If regional pollution episodes lead to a +20 µg/m³ increase in daily $PM_{2.5}$ in neighboring countries	Automatic bilateral alert and joint measures (school closures, outdoor labor restrictions)
Food security	>15% increase in global wheat prices for two consecutive quarters	Activation of EU strategic reserves and tariff measures
Energy	Failure of >2 major transit corridors	Contingency plan to redistribute energy flows and emergency supply from strategic reserves
Hydrology / Marine	Toxic discharges into the Black Sea exceeding COD/BOD thresholds	Block export of fish to the EU and emergency coastal assessments

11. What Kyiv/Ukraine Should Do in Cooperation with Europe

- Provide realtime access via API to monitoring data (air/water/marine/food safety) so the EU can react rapidly.
- Align critical infrastructure reconstruction plans with international development banks (EIB, EBRD) and create a **European technical assistance pool**.
- Deploy pilot **H_2/RES** projects to build both domestic resilience and interconnection with European energy systems.
- Strengthen biomonitoring and sanitary surveillance — joint laboratories and genomic data exchange (**One Health** approach).

12. Summary of Recommendations (Short)

Europe must treat climate-military shocks in Ukraine as a **systemic risk**, requiring coordinated financial, technical, and political responses.

Urgently needed:

Transboundary monitoring & emergency response mechanisms — air, water, food, and energy.

Investments in energy decentralization, food supply diversification, and strategic reserves.

Strong political coordination (EU, neighboring states, international financial institutions) to reduce transcontinental impacts.

9.4. Conclusion of Section 9

Climate risks in Kyiv and the wider region are systemic and require an integrated approach.

Adaptation is not only protection — it is a new economic opportunity, creating a market for resilient technologies, increasing regional investment attractiveness, and improving quality of life.

The primary objective is to transform the Kyiv metropolitan area into a “Climate-Resilient Hub of Eastern Europe” by 2040, ensuring economic stability, energy autonomy, and social security under conditions of climate transformation.

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11. Appendices

11.1. Table 1 — Climate Scenarios and Forecasts by Periods

Period	Natural Scenario (no anthropogenic influence)	Anthropogenic Scenario	War Scenario
2025–2035	+0.3 °C, moderate precipitation, rare droughts	+0.6 °C, increased heatwaves	+0.8 °C, elevated air pollution risks
2035–2050	+0.7 °C, stable dynamics	+1.4 °C, more frequent extreme precipitation	+1.8 °C, chemical emissions, soil degradation
2050–2075	+1.2 °C, partial shift of vegetation zones	+2.3 °C, increasing moisture deficit	+2.9 °C, biodiversity loss, population migration
2075–2100	+1.6 °C, relative stabilization	+3.4 °C, chronic droughts and floods	+4.1 °C, risk of climate-related disasters

Table 2 — Critical Periods and Risks

Years	Main Risks	Potential Damage	Probability (by scenario)
2030	Summer heatwaves, air pollution	High mortality, increased morbidity	Medium (N), High (A, W)
2040	Droughts, water deficit, soil degradation	Agricultural losses up to 20%	High
2050	Flooding, infrastructure overload	Damage to urban infrastructure up to 15%	Medium (N), High (A, W)
2075	Combined risks: heat + flooding	Massive GRP losses, population migration	Very High (A, W)
2100	Potential ecosystem collapse	Loss of key habitats and biodiversity	Critical (W)

Legend: N — Natural scenario; A — Anthropogenic; W — War scenario.

Table 3 — Financial Impacts and Investment Priorities

Sector	Major Losses	Priority Investments	Potential Funding Sources
Energy	Grid degradation, increased demand	Renewable energy, thermal modernization	EIB, NEFCO, USAID
Water Resources	Loss of 15–20% of available reserves	Water treatment, storage, reuse	EBRD, EU LIFE
Agriculture	Yield losses up to 25%	Water-saving technologies	FAO, Horizon Europe

Sector	Major Losses	Priority Investments	Potential Funding Sources
Healthcare	+30% expenditure increase	Climate-adapted hospitals	WHO, GCF
Urban Infrastructure	Damage and system wear	Green infrastructure, drainage	KfW, Climate-KIC

Table 4 — Investment Indicators of Adaptation Projects

Project Type	CAPEX (€ million)	OPEX (€/year)	ROI (%)	IRR (%)	Payback Period (years)
Water retention and drainage systems	85	2.5	11.4	7.8	9
Green roofs and parks	42	1.1	14.2	9.5	7
Residential building thermal modernization	210	8.4	18.7	12.1	6
Solar power plants and storage systems	155	5.2	16.5	10.8	7
Water-saving agricultural technologies	63	1.9	13.1	8.9	8

Table 5 — Biodiversity and Ecosystem Risks

Indicator	2020 (baseline)	2050	2100	Trend
Forest cover in the region	28%	24%	18%	Decline
Wetland ecosystems	14%	9%	6%	Critical decrease
Pollinator insect population	100%	72%	49%	Threat to agriculture
Bird species richness	100%	83%	67%	Loss of species diversity
Biodiversity Index (EEA)	1.00	0.76	0.55	~45% decline

11.6 Annex — Vulnerability Index Indicators (Summary)

Component	Weight	Value (2024)	Forecast (2050)	Forecast (2100)
Climate exposure	0.35	0.58	0.72	0.83
Social sensitivity	0.25	0.61	0.67	0.74
Infrastructure vulnerability	0.20	0.55	0.68	0.80
Adaptive capacity	0.20	0.44	0.52	0.60
Composite vulnerability index	—	0.54	0.65	0.74

11.7. Final Recommendations on Investment Priorities (2025–2100)

Period	Main Tasks	Key Investments	Coordination
2025–2035	Initial adaptation measures, infrastructure renewal	Water supply, green areas, energy efficiency	Kyiv City Administration, EBRD
2035–2050	Scaling adaptation systems, transition to renewables	Hydrogen, smart grids, biogas	Ministry of Energy, Horizon Europe
2050–2075	Full integration of climate neutrality	CO_2 storage, reforestation	EU, EIB
2075–2100	Sustainable development with zero emissions	Territorial transformation, bioenergy	UNDP, GCF

11.8. Potential Threats and Adaptation Measures (Global Context)

1. Natural & Climate-Related Threats

Threat	Probability	Consequences	Mitigation Measures
Global	Very High	Glacier melt, sea level rise,	Decarbonization, transition to

Threat	Probability	Consequences	Mitigation Measures
warming >2 °C		droughts, soil degradation, mass migration	renewables, carbon quotas, international climate governance
Loss of biodiversity	High	Ecosystem disruption, food chain collapse, increased pandemic risks	Ecosystem restoration, forest & ocean conservation, biocorridors
Water resource crisis	High	Water conflicts, hunger, epidemics	Desalination, water-use regulation, water cycle technologies
Changes in ocean currents	Medium	Abrupt climate shifts in Europe, collapse of Gulf Stream	Monitoring, reduced methane & CO_2 emissions
Solar activity / space anomalies	Medium	Energy disruptions, radiation anomalies, EMP effects	Space monitoring, infrastructure protection

2. Technogenic / Human-Made Threats

Threat	Probability	Consequences	Mitigation Measures
Loss of control over AI systems	Medium	Infrastructure disruption, military & economic collapse	International AI regulation, safety audits, "black box" systems
Nuclear / chemical accidents	Medium	Radioactive/toxic contamination, evacuations	Retirement of old reactors, SMRs, robotic maintenance
Technological pandemics (engineered viruses)	Medium	Mass mortality, collapse of healthcare	Biosafety regulation, inspections, containment testing
Electromagnetic / cyberattacks	Medium	Disruption of finance, networks, governance	Backup communications, digital sovereignty, autonomous nodes
Geoengineering (unpredictable effects)	Medium	Climate shifts, atmospheric chemical pollution	Ethical oversight, controlled pilots only

3. Biological Threats

Threat	Probability	Consequences	Mitigation Measures
New viruses (natural & engineered)	Very High	Pandemics, demographic declines	Global bio-surveillance, bioethics, rapid containment systems
Antibiotic resistance	High	Mortality growth, ineffective treatments	New antibiotic R&D, restrictions in agriculture
Unregulated genetic modification	Medium	Unpredictable mutations, social inequality	CRISPR regulations, licensing genetic laboratories
Decline in population immunity	Medium	Growth of chronic illnesses	Microbiome-based therapies, pollution limits, nutrition & vaccination

4. Military-Political Threats

Threat	Probability	Consequences	Mitigation Measures
Local and nuclear conflicts	Medium	Radioactive zones, food shortages, collapse of trade	Diplomacy, nuclear control, UN mediation
Cyber warfare	High	Disruption of energy systems, transport, finance	Cyber reserves, national CERT centers
Terrorist use of biological/nano weapons	Medium	Mass casualties	Biocontrol, intelligence, international data sharing
Militarization of space	Medium	Satellite loss, communications	Space treaties, autonomous

Threat	Probability	Consequences	Mitigation Measures
		paralysis	local networks

5. Socio-Psychological Threats

Threat	Probability	Consequences	Mitigation Measures
Loss of trust in institutions	Very High	Destabilization, social fragmentation	Transparent governance, independent media
Digital inequality	High	Social polarization	Education, equitable access to technologies
Mass migration	Medium	Conflicts, cultural disruption	Regional planning, climate adaptation
Psychological burnout / depression	Medium	Reduced productivity and birth rates	Mental health programs, social support

Classification by Reversibility

Category	Examples	Reversibility
Environmental	Soil contamination, deforestation	Partially reversible (with restoration)
Climate-related	Climate change, glacier melt	Irreversible (within ≤ 1000 years)
Biological	Extinct species, viral mutations	Irreversible
Technological	Uncontrolled AI or biotech leakage	Partially reversible (with regulatory control)
Social	Loss of trust, mass migration	Partially reversible (over generations)

Adaptation Measures to Climate and Technogenic Threats

1. Short-Term Period (until 2035)

Climate Adaptation

Measure	Objective	Priority Scenario
Local climate stations and monitoring networks	Rapid detection of temperature and precipitation anomalies	All scenarios
Transition to climate-resilient agriculture	Minimization of crop losses	Natural / anthropogenic
Introduction of green zones and “urban forests”	Reduction of heat islands, improved air quality	Anthropogenic
Water-use efficiency programs	Reduction of water deficit	All scenarios
Local energy and water storage systems	Increased regional autonomy	Military / anthropogenic

Technological and Energy Adaptation

Measure	Objective	Scenario
Development of microgrid energy networks	Energy security	Military / anthropogenic
Scaling solar and wind power	Reduced reliance on carbon-based sources	All
Climate-resilient data centers	Preservation of critical infrastructure during climate disruptions	Anthropogenic

Medical and Biological Adaptation

Measure	Objective	Scenario
Enhanced epidemiological surveillance and genomic sequencing	Early detection of virus mutations (including COVID-like)	Anthropogenic / military
Creation of strategic reserves of medicines and vaccines	Biosecurity	All
Development of mobile and telemedicine systems	Reduced vulnerability during disasters	All

Social Adaptation

Measure	Objective	Scenario
Educational programs on sustainable development	Improved population readiness	All
Psychological support and stress management	Prevention of mass psychosocial crises	Anthropogenic
Evacuation and shelter planning in risk zones	Preparedness for military or climate disasters	Military

2. Mid-Term Period (2035–2055)

Climate and Environmental Measures

Measure	Objective	Scenario
Wide deployment of CO_2 capture technologies (CCUS)	Reduction of greenhouse gas concentration	Anthropogenic
Soil and water bioremediation	Ecosystem restoration	Natural / anthropogenic
Desertification and erosion control	Preservation of agro-ecosystems	All
Reorganization of coastal settlements	Prevention of losses due to sea-level rise	All

Infrastructure and Construction

Measure	Objective	Scenario
Transition to climate-adapted design (higher wind/thermal loads)	Resilience to extreme events	All
Development of autonomous settlements with closed loops (water, energy, waste)	Community resilience	Anthropogenic / military
Expansion of underground utilities	Protection from overheating and destruction	Anthropogenic / military

Medicine and Health

Measure	Objective	Scenario
Creation of gene therapy and biosecurity centers	Prevention of mutation-driven diseases	Anthropogenic
Immunological adaptation programs	Resistance to viruses and pollution	All
Monitoring of ecosystem and human microbiota	Reduced epidemiological risks	Anthropogenic

5.3. Long-Term Period (2055–2100)

Global Adaptation

Measure	Objective	Scenario
Solar radiation management geoengineering (SRM, SAI) — under international governance	Mitigation of extreme climate effects	Anthropogenic / natural
Next-generation biotechnology and AI oversight systems	Prevention of loss of control over advanced technologies	Military / anthropogenic
Development of closed biospheres (4th-generation ecosystems)	Autonomous survival under environmental degradation	All
Global migration and resettlement programs	Reducing pressure on degraded regions	All
Preservation of biodiversity through gene banks and bio-reserves	Restoration of species and ecosystems	Natural / anthropogenic

5.4. Institutional and Strategic Measures

Measure	Description	Implementation Timeline
Establishment of the Global Adaptation Institute	Regional coordination and standards development	2030–2035
Unified Climate Risk Database (Climate Data Grid)	Forecasting, analysis, open data access	2030–2040
Creation of backup global governance hubs	Ensuring continuity of governance during catastrophic events	2050+
Global Ocean Restoration Program	Reducing acidification and microplastic pollution	2050–2100

5.5. Scenario Impacts

Period	Natural Scenario	Anthropogenic Scenario	Military Scenario
Until 2035	Focus on monitoring and agricultural adaptation	Emission reduction, local resilience	Energy autonomy, infrastructure protection
2035–2055	Large-scale land reclamation and ecosystem recovery	Deep restructuring of energy systems and cities	Protected life-support clusters
2055–2100	Evolutionary ecosystem restoration	Integration of technologies with natural cycles	"Civilization survival" model with autonomous ecosystems

11.9. Possible Development Paths for Energy and Settlements (Preliminary Scenario)
General Concept — Why & How

Goal: Ensure reliable, affordable, climate-resilient and secure energy supply, and climate-adapted, socially sustainable settlements at all scales.

Core Principles:

- Demand reduction before capacity expansion — "Efficiency first"
- Decentralization + integration — distributed generation + storage + interconnected grids
- Multi-layer resilience — redundancy at home / district / city / region levels
- Technology-neutral, but prioritizing low-carbon validated technologies
- Inclusiveness and flexibility for all settlement types and vulnerable groups
- Built-in bio-, cyber- and physical safety from the design stage

Optimal Energy Platform Components

Demand Reduction & Energy Efficiency

Technical measures: insulation, high-performance windows, heat recovery ventilation, LED / smart lighting, heat pumps

Systemic: NZEB/passive building standards, mandatory energy passports

Demand-side management: dynamic pricing, peak-shaving tariffs, smart metering, DSM programs
Why: every € invested in efficiency delivers faster returns than adding generation

Electricity Supply — Mix and Architecture

Home / block: PV + household BESS + heat pumps + HEMS
Urban scale: distributed PV, local wind, medium-scale storage (BESS/CAES), CHP for cold regions
National / regional scale: large-scale wind/solar/hydro, SMRs where safe, HVDC interconnections
Balancing: H_2/biogas-ready gas turbines, VPPs, demand response

Energy Storage

Multi-level strategy:
- Home: batteries for 1–3 days autonomy
- District/City: grid-scale BESS/CAES for peak shaving & emergency reserve
- Regional: PHS, CAES, Power-to-Gas (H_2), seasonal storage

Transport & Sector Coupling

- EV electrification, V2G
- Electrification of heating (heat pumps)
- Hydrogen for heavy transport and industry (renewable H_2)

Low-Carbon Options w/ Safety Focus

SMR deployment only where political/regulatory conditions allow
CCUS for hard-to-abate industry (cement, metallurgy)