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THE STATE OF PREPAREDNESS FOR CLIMATE CHANGE-INDUCED ENERGY INFRASTRUCTURE DISASTERS IN SLOVAKIA

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1. Introduction

Climate change has ceased to be an abstract environmental concern for Central European energy systems. It has become a measurable operational variable affecting the physical integrity of overhead lines, the cooling capacity of thermal and nuclear power plants, the stability of slopes relevant to gas pipelines, and the seasonal profile of electricity and gas demand.

The Slovak Republic is a useful case study because it combines: (i) a compact territory with strong topographic contrasts, (ii) a highly interconnected energy system, and (iii) a generation mix dominated by nuclear and hydropower—making water-related constraints especially important. Together with Slovakia's historical gas transit role (now ended), these factors concentrate both hazard exposure and preparedness needs within a relatively small system.

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2. Geographic and Energy Profile of Slovakia

2.1 Two climatic regimes within one small territory

Slovakia lies at the boundary between Atlantic maritime and continental climatic influences, and its topography amplifies the result. The consequence is that two different hazard profiles coexist within a territory of only ~49,000 km²:

- Northern and central Slovakia (Carpathian region): dense forests, narrow valleys and flysch bedrock prone to erosion and landslides. Dominant hazards for infrastructure include icing, heavy wet snow, windstorms, falling trees onto 22 kV lines, and flash floods in steep catchments.
- Southern and eastern lowlands: agricultural and urbanised plains increasingly exposed to prolonged heatwaves, tropical nights, drought, declining river flows, and intense convective storms that cause local flooding of substations and cable routes.

2.2 A low-carbon but water-dependent electricity mix

Slovakia's electricity generation is among the least carbon-intensive in the EU. Nuclear power provides almost 70% of generation, and hydropower (Váh cascade and Gabčíkovo) contributes 14–18% depending on the hydrological year. The remainder comes from solar, biomass and high-efficiency gas-fired cogeneration. [17], [25]

This profile has a direct bearing on climate resilience. A system dominated by nuclear and hydro is structurally dependent on water: nuclear units require stable cooling water, while run-of-river hydropower plants depend on instantaneous river flow. Drought and high water temperatures therefore translate into generation constraints. [17], [25]

2.3 Network and gas infrastructure

The transmission system operator SEPS (wholly state-owned) operates the 400 kV and 220 kV backbone and is a member of ENTSO-E's Continental Europe synchronous area. [21], [22] Distribution is handled by three regional operators: Západoslovenská distribučná, Stredoslovenská distribučná and Východoslovenská distribučná.

In gas, eustream operates a major transmission system and Slovakia's historical corridor for transit ended on 1 January 2025 when the Ukrainian transit agreement expired. [24] Underground storage facilities in western Slovakia are operated by NAFTA and POZAGAS with a combined working capacity close to 4 billion cubic metres. [23]

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3. The Legal Framework: From Brussels to Bratislava

3.1 Why an "all-hazards" approach matters

The 2022 EU legislative package shifted critical infrastructure policy toward an all-hazards resilience doctrine, where natural hazards, climate change, technical failures, cyberattacks and hybrid threats are assessed within a single framework. For an energy operator, the practical meaning is that a flood or ice storm is treated with comparable planning discipline as a sabotage scenario.

Table 1. Key EU instruments and their Slovak transposition

EU instrument	Core requirement relevant to climate resilience	Slovak transposition / application
Directive (EU) 2022/2557 (CER) [1]	Risk assessments covering natural hazards; resilience and business-continuity measures for critical entities	Act No. 367/2024 Coll. on critical infrastructure (in force 1 January 2025), replacing Act No. 45/2011 Coll. [8]
Directive (EU) 2022/2555 (NIS2) [2]	Cybersecurity risk management for essential entities, including energy networks	Amendment of Act No. 69/2018 Coll. on cybersecurity, effective 2025
Regulation (EU) 2019/941 [3]	National electricity crisis scenarios and risk-preparedness plans; regional coordination; no unjustified cross-border restrictions	Slovak Risk-Preparedness Plan prepared by the Ministry of Economy with SEPS
Regulation (EU) 2022/1032 (gas storage) [4]	Mandatory filling trajectories before winter	Applied directly; monitored by Ministry of Economy and ÚRSO
Regulation (EU) 2017/2196 (Emergency & Restoration code) [5]	System defence plans, restoration plans, black-start arrangements	SEPS Defence Plan and Restoration Plan approved under the Act on Energy
Directive 2007/60/EC (Floods) [6]	Flood hazard and risk maps; flood-risk management plans	Act No. 7/2010 Coll. on flood protection; Flood Risk Management Plans [12], [18]
Regulation (EU) 2021/1119 (European Climate Law) [7]	Binding duty to strengthen adaptive capacity	Adaptation Strategy (NAS SR) and Action Plan (NAPZ) [14], [15]

3.2 The Critical Entities Resilience Directive (CER)

Directive (EU) 2022/2557 requires Member States to identify "critical entities" in eleven sectors (energy first among them) and obliges those entities to carry out risk assessments at least every four years, adopt resilience measures, and notify significant incidents. [1] Article 5 and Annex I explicitly list natural hazards and climate change as risks to be assessed. [1] Slovakia transposed the directive through Act No. 367/2024 Coll., in force from 1 January 2025, replacing the earlier critical infrastructure act. [8]

3.3 NIS2 and cyber-physical interdependence

NIS2 emphasizes that physical and digital failures compound each other. Modern grids rely on SCADA and energy management systems whose telemetry largely travels via

optical infrastructure embedded in overhead-line-related assets. A storm-induced line outage can therefore also impair communications. NIS2 requires redundancy in communications, backup power for control sites and tested recovery procedures—requirements relevant to both natural hazards and cyber incidents. [2]

3.4 Electricity risk preparedness and the regional dimension

Regulation (EU) 2019/941 was adopted because national crisis planning in a synchronously interconnected system becomes self-defeating if neighbours restrict exports precisely when help is needed. It requires ENTSO-E to identify regional crisis scenarios, obliges Member States to prepare risk-preparedness plans, and prohibits unjustified curtailment of cross-border capacity during a crisis. [3], [22]

3.5 National institutions

Three national instruments structure preparedness and crisis response in the electricity sector:

Act No. 251/2012 Coll. on energy: Section 20 allows SEPS/distribution operators to declare a state of emergency in the electricity system in defined situations (e.g., natural disasters, severe weather, sudden capacity shortfall), enabling load restriction, directed control of generation and priority supply to hospitals and emergency services. [9]

Act No. 250/2012 Coll.: establishes the independent Regulatory Office for Network Industries (ÚRSO) which approves grid codes, assesses SEPS's ten-year network development plan, and—crucially for adaptation—determines which investment costs are recognised in regulated tariffs. [10], [19]

Act No. 387/2002 Coll. on crisis management: governs the Central Crisis Staff (chaired by the Minister of the Interior) and district crisis staffs coordinating the Fire and Rescue Service during large-scale events. [11], [16]

Meteorological and hydrological warnings are supported by SHMÚ, river and dam management by SVP, and adaptation strategy frameworks by national policy documents. [14], [15], [18], [20]

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4. Climate Reality in Practice: 2024 and the Summer of 2025

4.1 The warmest year on record and the September 2024 floods

According to SHMÚ, 2024 was the warmest year in Slovakia's instrumental record and continued a pattern where the ten warmest years occurred since 2000. [20] The year also brought the most significant flood event in a decade: between 13 and 17 September 2024, the low-pressure system "Boris" brought 200–400 mm of rain to parts of Central Europe.

In Slovakia, the Danube at Bratislava peaked at approximately 9.7 m (highest level since 2013), inundating the Devín district and parts of Záhorie; the Morava river flooded agricultural land and threatened distribution infrastructure. Distributors used pre-

emptive de-energisation of low-lying transformer stations in Devín and Devínska Nová Ves. [18], [20]

4.2 Summer 2025: heat, drought and convective storms

Summer 2025 illustrates the compound nature of climate stress. Three phases were observed:

(a) Dry spring and hydrological deficit: By June, SHMÚ's drought monitoring classified large parts of southern and eastern lowlands as severe to extreme agricultural and hydrological drought, with flows on the Hron, Ipeľ and lower Váh below long-term averages. [20]

(b) Early-July heatwave: Around 1–4 July 2025, maxima of 37–38°C were recorded at southern lowland stations; tropical nights occurred, with maxima above 24°C in the urban cores of Bratislava and Košice. SHMÚ issued the highest-level heat warnings for several districts. [20]

(c) Convective storms and a second heat episode: The heatwave broke with severe thunderstorms producing localised rainfall of 50–100 mm in a few hours, flash flooding in small catchments and wind damage to distribution lines; another hot spell followed in mid-August. [20]

4.3 Hydrological stress on nuclear and hydro generation

Mochovce draws cooling water from the Hron via the Veľké Kozmálovce reservoir; Bohunice draws from the Váh via the Sínava reservoir. Both use cooling towers, so their consumptive water demand is evaporation rather than once-through discharge—making them less vulnerable than once-through plants elsewhere. Nevertheless, low flows required close coordination between Slovenské elektrárne and SVP on reservoir releases, and thermal discharge limits became binding during the July heatwave. [18], [25]

5. Vulnerability by Subsector

Table 2. Climate vulnerability matrix of Slovak energy infrastructure

Subsector (operator)	Dominant hazard	Damage mechanism and operational impact
Transmission 400/220 kV (SEPS)	Windstorms, icing, heat	Tower and conductor damage; OPGW fibre loss; thermal de-rating; loss of transit capacity
Distribution 22 kV / 0.4 kV (ZSD, SSD, VSD)	Tree falls, wet snow, flash floods	Broken poles and conductors in forest corridors; flooded 22/0.4 kV stations; multi-day outages in mountain valleys
Nuclear generation (Slovenské elektrárne)	Drought, high water temperature	Cooling-water and thermal discharge constraints; potential output reduction
Hydropower (Vážska kaskáda, Gabčíkovo)	Drought, altered flow regime	Lower output; reduced balancing and black-start availability
Gas transmission (eustream)	Landslides, river scour	Pipeline stress on flysch slopes; exposure of river crossings
Gas distribution (SPP – distribúcia)	Floods, high groundwater	Flooded pressure-regulating stations; failure of cathodic protection units
District heating (MH Teplárenský holding)	Local floods	Flooded heat-pipe chambers; pump and heat-exchanger failures

5.1 Distribution networks: where most outages happen

The transmission backbone is designed to meet high reliability requirements and rarely fails. Most customer outages originate in the 22 kV distribution network, running thousands of kilometres through forested terrain in central and north-eastern Slovakia.

The single most important storm-related cause is not wind loading on the line itself but trees standing outside the statutory protection corridor that are uprooted and fall across the conductors. Removal requires landowner consent and, in protected areas, nature-conservation permissions under Act No. 543/2002 Coll., which becomes an administrative bottleneck. [13]

5.2 Gas pipelines: buried but not immune

Buried pipelines are protected from wind and ice, but climate-sensitive failure mechanisms remain. At river crossings, flood-driven scour can strip gravel cover and expose the pipe to hydraulic loading and debris impact. On flysch slopes, prolonged rainfall can trigger slow ground movement imposing bending stress. eustream monitors these segments through geodetic surveys, strain gauges and satellite radar interferometry (InSAR). [24]

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6. Winter Preparedness and Security of Supply

6.1 The end of transit and the new storage calculus

The expiry of the Russia–Ukraine transit agreement on 1 January 2025 ended flows through Veľké Kapušany that had defined Slovak gas policy for five decades. For winter

2025/2026, Slovakia relied for the first time entirely on westward and southern routes plus domestic storage. [24]

EU gas storage regulation (EU) 2022/1032 originally set a binding 90% filling target by 1 November; later amendments extended the regime to 2027 and introduced flexibility, including a 35% threshold serving as a protection limit for countries with exceptionally large storage capacity relative to domestic consumption. [26] Current and historical filling levels are published daily on the AGSI+ transparency platform. [26]

6.2 Withdrawal dynamics

At the start of winter, the storage system can deliver more than 40 million m³/day, comfortably above the roughly 35 million m³/day consumed on the coldest days below –15°C. As stocks deplete, deliverability declines towards half that level by late February; therefore, a long cold tail is more dangerous than a cold start and import routes must remain available throughout the season. [23]

6.3 Electricity interconnection and the Ukrainian dimension

Slovakia's electricity system is connected by 400 kV lines to neighbours. Two Hungary–Slovakia lines commissioned in 2021 removed a long-standing bottleneck on the southern profile. [21]

The Veľké Kapušany–Mukachevo line has served as a corridor for emergency and commercial exports to Ukraine since Ukraine's emergency synchronisation with Continental Europe in March 2022. A weather-induced outage on this line can therefore have humanitarian consequences beyond Slovakia's borders. [22]

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7. Operational Defence and Restoration

7.1 Defence and Restoration Plans

Under regulation (EU) 2017/2196, SEPS maintains a System Defence Plan and a Restoration Plan. The defence plan includes automatic under-frequency load shedding, disconnecting pre-defined blocks of demand as frequency falls below thresholds to prevent generator trips. The restoration plan designates black-start sources—hydro plants that can start from internal diesel generators without grid supply. [5]

In Slovakia, primary black-start units are at Gabčíkovo and on the Váh cascade near Žilina, with the Čierny Váh pumped-storage plant supporting island operation in the north. Restoration paths enable re-establishing off-site power to nuclear units; nuclear units also rely on their own emergency diesel supplies. [21], [25]

7.4 Flood protection of substations

Following the major floods in 2010 and 2013, strategic substations near the Danube, Váh and Hornád were retrofitted with permanent flood walls, mobile barriers and pumping capacity, and control/battery rooms were relocated above design flood levels.

The September 2024 event was a real test of several measures; limited transmission-level damage compared to significant distribution-level flooding in Devín indicates where protection investment has and has not yet reached risk levels. [18]

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8. Gaps and Recommendations

8.1 Strengths, weaknesses, opportunities, threats

Strengths	Weaknesses
• Robust N-1 400 kV backbone; strong interconnection • Storage capacity ≈ annual gas demand • Hydro black-start capability • EU-aligned legal framework (CER, NIS2, 2019/941)	• Thousands of km of 22 kV overhead lines in forest • Permitting barriers to preventive tree removal • Fragmented data across SHMÚ, SVP, SEPS, DSOs • Regulatory recognition of resilience CAPEX
Opportunities	**Threats**
• CER/NIS2 implementation as a driver of investment • Modernisation Fund and REPowerEU financing • DLR, InSAR and AI-based forecasting	• More frequent 38 °C+ heatwaves and tropical nights • Declining summer river flows for cooling • Loss of transit revenues; exposure of Ukraine corridor

8.2 Three structural gaps

1. Regulatory treatment of resilience investment: ÚRSO's methodology for the 2023–2027 regulatory period caps recognised distribution capital expenditure; undergrounding in mountainous terrain costs multiple times the overhead equivalent. Without explicit recognition of resilience benefits in the regulated asset base, operators postpone such projects. [19]

2. Vegetation management vs nature protection: Act No. 543/2002 Coll. requires permits for felling outside the protection corridor, including in Natura 2000 sites covering much of the Carpathian forests where distribution lines run. The primary cause of storm outages is therefore also the hardest to address administratively. [13]

3. Data integration: SHMÚ forecasts, SVP hydrological data and operator SCADA information are not combined into a shared real-time situational-awareness platform. Each institution acts on its own view; none has the full picture.

8.3 Recommendations

- Introduce a resilience allowance in regulation: Regulator should recognise undergrounding in high-risk corridors, relevant sensors, and substation flood protection as priority eligible costs, with performance-based incentives linked to outage duration metrics.

- Create a fast-track permitting procedure for hazard-tree removal triggered by meteorological agency severe-weather warnings, including compensatory planting obligations protecting conservation objectives.
- Build a joint energy–weather situational-awareness platform combining meteorological agency, water management company and operator data, and institutionalise joint analysis cells during declared warnings.
- Expand regional exercises under Regulation (EU) 2019/941 to include compound scenarios (e.g., heatwave + low hydro output + cross-border line outage). [3]
- Publish dated preparedness indicators (storage fill vs deliverability, available cross-border capacity, number of priority circuits equipped with monitoring), so partners and the public can distinguish observed performance from planned capability.

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9. Conclusion

Slovakia enters the second half of the 2020s with real strengths: a meshed and well-interconnected transmission grid, storage capacity supporting winter resilience, hydro black-start capability, and a legal framework that has fully absorbed the EU's all-hazards approach.

The experience of 2024 and 2025—record warmth, a once-in-a-decade Danube flood, and a summer combining drought, heat and violent convective storms—confirmed both that the backbone holds and that vulnerabilities lie at the edges: in the 22 kV lines of the Carpathian valleys, in the cooling-water margins of a nuclear-and-hydro system, and in the administrative "seams" between meteorologists, water managers, regulators and operators.

For partner countries, three lessons travel well. First, a low-carbon mix is not automatically climate-resilient; water dependence must be planned for explicitly. Second, the hardest resilience problems are often legal and regulatory rather than technical. Third, in a synchronously interconnected continent, no national preparedness plan is complete without its regional counterpart.

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Annex I. Institutional map of climate-related energy crisis management in Slovakia

Level	Body	Role in climate-related energy disruption
Government	Central Crisis Staff (chaired by Minister of the Interior)	Overall coordination of nationwide emergencies
Ministry	Ministry of Economy	Energy policy, Risk-Preparedness Plan, declaration of gas crisis levels
Ministry	Ministry of the Interior	Integrated rescue system; Fire and Rescue Service; district crisis staffs
Ministry	Ministry of the Environment	Adaptation strategy; supervision of SHMÚ and SVP
Regulator	ÚRSO	Grid codes, network development plan assessment, tariff recognition of investment
Agency	SHMÚ	Meteorological and hydrological warnings, drought monitoring
Enterprise	SVP	River and reservoir management, flood defence
Operator	SEPS	Transmission; Defence and Restoration Plans; black-start coordination
Operators	ZSD, SSD, VSD	Distribution; field restoration; pre-emptive de-energisation
Operators	eustream, SPP – distribúcia, NAFTA, POZAGAS	Gas transmission, distribution and storage
Generator	Slovenské elektrárne; Vodohospodárska výstavba (Gabčíkovo)	Nuclear and hydro generation; cooling-water coordination; black-start units