

HOLISTIC RISK ASSESSMENT FOR NATIONAL POWER GRID FACING EXTREME WEATHER EVENTS AND NATURAL HAZARDS

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Abstract: National Power Grid are increasingly exposed to extreme weather events and natural hazards whose frequency, intensity, and unpredictability have grown under changing climatic conditions. Traditional risk assessment methods – often focused on individual assets or isolated hazard types – are no longer sufficient to capture the complex, interconnected vulnerabilities of modern power networks. This study proposes a holistic risk assessment framework that integrates multi-hazard characterization, systemwide vulnerability analysis, and probabilistic impact modeling to evaluate the resilience of national-scale power infrastructures. The framework considers cascading failures, interdependencies with other critical sectors, spatial variations in infrastructure exposure, and the dynamic adaptation of grid operations. Using recent extreme weather events and geophysical hazards as case studies, the analysis reveals key system weaknesses and prioritizes resilience-enhancing interventions. The results demonstrate the importance of comprehensive risk metrics and cross-sector coordination in guiding national energy policy, infrastructure investment, and emergency preparedness. Ultimately, the proposed approach supports decision-makers in strengthening the robustness and adaptability of power systems facing an evolving landscape of natural hazards.

Keywords: risk assessment, National Power Grid, extreme weather, natural hazard.

1. INTRODUCTION

National Power Grid (NPG) form the backbone of modern societies, enabling essential services such as healthcare, transportation, communication, and industrial operations [26], [29]. However, these systems are increasingly challenged by extreme weather events – including heatwaves, storms, floods, droughts, and wildfires – as well

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as geophysical hazards such as earthquakes, landslides, and volcanic activity [15], [18], [23]. Climate change has intensified many of these hazards, amplifying their impacts and complicating long-term planning for infrastructure resilience. As disruptions to power systems can propagate rapidly through interconnected networks, even localized events may trigger widespread outages and economic losses [7], [10], [16], [22].

Historically, risk assessments for power systems have relied on deterministic models or single-hazard evaluations that do not fully capture the complexity of real-world conditions [32], [34]. Such approaches overlook key factors such as compound hazards, interdependencies with other critical infrastructures (e.g., water supply, telecommunications, gas networks), and the nonlinear behavior of grid components under stress. Recent large-scale outages – from hurricanes and polar vortices to severe flooding and wildfires – have illustrated the need for a more integrated perspective.

A holistic risk assessment approach addresses these challenges by combining physical hazard modeling, infrastructure vulnerability analysis, system operation dynamics, and probabilistic risk estimation [24]. This multidimensional perspective enables the identification of not only direct physical risks but also operational, organizational, and cascading risks within and beyond the power sector. Moreover, it supports scenario analysis, enabling policymakers and planners to evaluate potential future climates, evolving demand patterns, and emerging technologies such as distributed energy resources and smart-grid controls [11], [14], [17], [33].

This paper presents a comprehensive framework for holistic risk assessment tailored to national-scale power systems. The approach integrates multi-hazard exposure mapping, advanced vulnerability modeling, and system-level impact analysis with decision-oriented risk metrics [21], [25], [27]. Through empirical case studies and model simulations, we demonstrate how the framework can guide strategic planning, enhance emergency response capacities, and inform long-term investments in resilient infrastructure. By adopting holistic, data-driven methodologies, nations can better prepare for the growing threats posed by extreme weather events and natural hazards, ensuring reliable and sustainable power supply in an increasingly uncertain world [28].

The NPG from National Power System, functions as an interconnected system to the European Power System – ENTSO-E, which represents the European Network of Transmission System Operators for Electricity [12], [13], [19], [31].

Romania, through the national electricity transmission company, Transelectrica, which is a national transmission and system operator (TSO), has an active and essential role within ENTSO-E, being a full member [20]. It manages and operates the electricity transmission system, ensuring electricity exchanges between Romania and the countries of the European Union and the neighbouring countries that are not part of the European Union (Serbia, Ukraine and the Republic of Moldova) [].

The NPG, is composed of the following critical energy infrastructures, fig.1:

- *82 power substations*: 1 power substation in a gauge of 750 kV, but functioning at 400 kV; 38 power substations of 400 kV; 43 power substations of 220 kV [35];
- *8834.4 km overhead power lines*: 3.1 km – 750 kV; 4915.2 km – 400 kV; 3875.6 km – 220 kV; 40.4 km – 110 kV (interconnection Serbia, Ukraine and the Republic of Moldova) [30];

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- 216 transformation units totaling 38 058 MVA;
- 1 National Energy Dispatch – NED;
- 5 Territorial Dispatchers – TED [1], [2], [3].

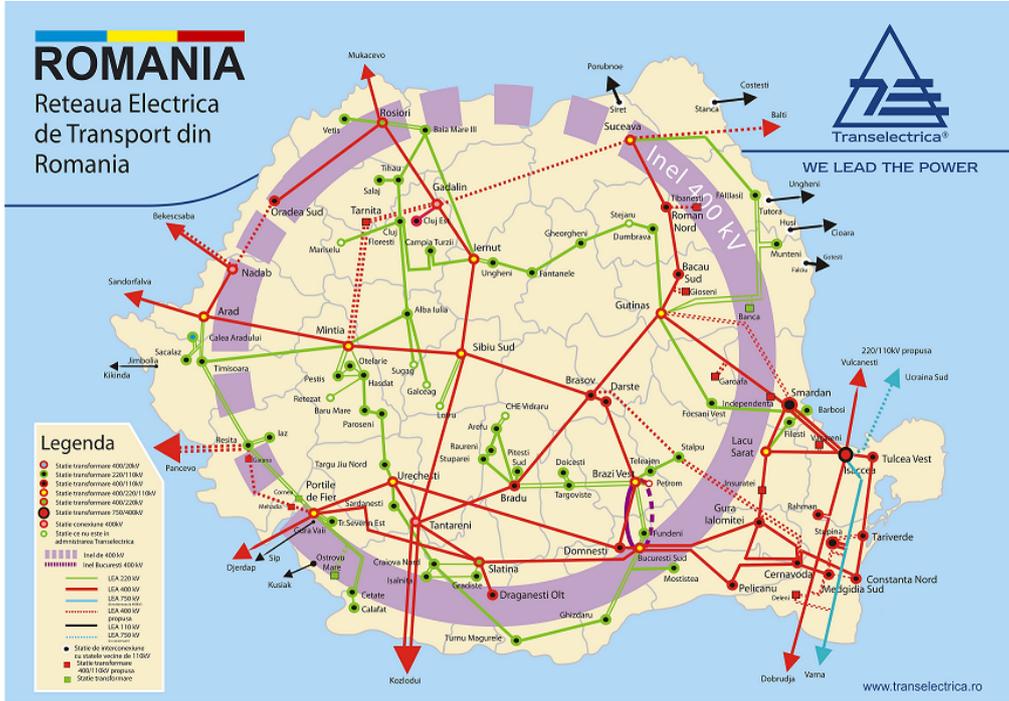


Fig.1. National Power Grid map (source: Transelectrica)

2. ASSESSMENT AND MANIFESTATION

2.1. Extreme weather events

The identification, assessment and manifestation are shown in Table 1 [4], [5], [6], [36].

Table 1. Extreme weather events

Risk scenario: EXTREME WEATHER EVENTS					
1	Extreme temperature (cold)	low	Likelihood	3 Medium	<ul style="list-style-type: none"> • Difficulties arise in ensuring the adequacy of the NPS due to a reduced level of production in power plants, this causes the limitation or total loss of reserves; • In conditions of very low temperatures, accidental events occur that lead to the unavailability of equipment in the transmission and distribution network;
			Gravity/Impact	5 Very high	
			Risk level	15	
			Scenario type	13– 16 Bad	

			<ul style="list-style-type: none">• Under these conditions, interconnection capacities are required to the maximum, which can limit the level of electricity imports;• Disturbances occur in the electricity market through large variations in the electricity trading price or an insufficient level of offers;• Low production in certain plants leads to large power movements to deficient areas, overload of some grid elements and results in voltage deviations and difficulties in compensating reactive power;• For certain time intervals problems arise in ensuring that the N-1 safety criterion is met.• Low production level and loading of certain lines can lead to the impairment of the static and dynamic stability of the NPS;• The impossibility of intervention in some areas appears and increases the time needed for intervention and remediation actions;• In conditions of extreme low temperatures, accidental triggers of electrical equipment (power lines, transformers or autotransformers) may occur, which may lead to the overload of other equipment and to the increase of grid congestions;• There is a risk of the impossibility of operating some switching equipment, in the event of interventions or maneuvers necessary to maintain the safe functioning of power grids;
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			<ul style="list-style-type: none"> • There is a high media pressure, as well as from the public opinion and the political environment, regarding the rapid resolution of the crisis situation and the provision of energy needs for the population and the stopping of exports; • The low temperature can affect the entire region which leads to the impossibility of receiving or providing support to other countries in the region; • Low level of domestic production as well as large power movements to deficient areas can lead to congestion on interconnecting lines and even the impossibility of ensuring electricity exports; • In conditions of insufficient production in power plants and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers. 								
2	Storm	<table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>Likelihood</td> <td style="background-color: yellow;">3 Medium</td> </tr> <tr> <td>Gravity/ Impact</td> <td style="background-color: red;">5 Very high</td> </tr> <tr> <td>Risk level</td> <td>15</td> </tr> <tr> <td>Scenario type</td> <td style="background-color: orange;">13– 16 Bad</td> </tr> </table>	Likelihood	3 Medium	Gravity/ Impact	5 Very high	Risk level	15	Scenario type	13– 16 Bad	<ul style="list-style-type: none"> • Line triggers occur due to electrical discharges, conductor breaks, trees falling on lines, conductor galloping; • The triggers can be simultaneous for lines located on the same corridor, the same pillars or on lines located very close together; • Damage to insulators, conductors or falling trees can lead to long-term unavailability of lines; • Some pillars may fall due to the galloping phenomenon; • Triggers occur in substations due to faults in busbar fields
Likelihood	3 Medium										
Gravity/ Impact	5 Very high										
Risk level	15										
Scenario type	13– 16 Bad										

			<p>caused by materials/branches brought by the wind;</p> <ul style="list-style-type: none"> • Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of the lines; • Production in wind power plants is decreasing sharply due to wind intensification; • Problems arise in ensuring that the N-1 safety criterion is met; • Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace destroyed/damaged assets; • Low level of domestic production as well as large power movements to deficient areas can lead to congestion on interconnecting lines and even the impossibility of ensuring electricity exports; • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers. 								
3	Heavy rainfall and flooding	<table border="1"> <tr> <td>Likelihood</td> <td>3 Medium</td> </tr> <tr> <td>Gravity/ Impact</td> <td>5 Very high</td> </tr> <tr> <td>Risk level</td> <td>15</td> </tr> <tr> <td>Scenario type</td> <td>13– 16 Bad</td> </tr> </table>	Likelihood	3 Medium	Gravity/ Impact	5 Very high	Risk level	15	Scenario type	13– 16 Bad	<ul style="list-style-type: none"> • Equipment triggers occur due to flooding of substations; • Triggers or unavailability of some lines occur, caused by landslides or floods affecting the stability of the pillars; • There is a reduction in production in the affected hydro power plants; • Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of the lines; • Problems arise in supplying
Likelihood	3 Medium										
Gravity/ Impact	5 Very high										
Risk level	15										
Scenario type	13– 16 Bad										

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			<p>some grid areas for a very long period, correlated with the time required to repair/replace damaged infrastructures;</p> <ul style="list-style-type: none"> • Congestions can occur on interconnection lines and even the impossibility of securing electricity exports; • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers. 								
4	Winter weather conditions (snow, ice, frost)	<table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>Likelihood</td> <td style="background-color: yellow;">3 Medium</td> </tr> <tr> <td>Gravity/ Impact</td> <td style="background-color: red;">5 Very high</td> </tr> <tr> <td>Risk level</td> <td>15</td> </tr> <tr> <td>Scenario type</td> <td style="background-color: orange;">13- 16 Bad</td> </tr> </table>	Likelihood	3 Medium	Gravity/ Impact	5 Very high	Risk level	15	Scenario type	13- 16 Bad	<ul style="list-style-type: none"> • Several line triggers occur, caused by snow, ice or frost, or falling trees on the lines; • Production in wind power plants is decreasing or stopping altogether due to ice deposits on turbine blades; • Damage to insulators, conductors or falling trees can lead to long-term unavailability of lines; • Some pillars may fall due to the galloping phenomenon; • Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of the lines; • Problems arise in ensuring that the N-1 safety criterion is met; • Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace damaged infrastructures; • Large power movements to deficient areas can lead to congestion on interconnecting lines and even the impossibility of ensuring electricity exports; • There is a risk of extensive
Likelihood	3 Medium										
Gravity/ Impact	5 Very high										
Risk level	15										
Scenario type	13- 16 Bad										

			<p>damage to the NPS leading to the failure of supplying electricity to a large number of consumers.</p>								
5	Heat wave	<table border="1"> <tr> <td>Likelihood</td> <td>3 Medium</td> </tr> <tr> <td>Gravity/ Impact</td> <td>5 Very high</td> </tr> <tr> <td>Risk level</td> <td>15</td> </tr> <tr> <td>Scenario type</td> <td>13– 16 Bad</td> </tr> </table>	Likelihood	3 Medium	Gravity/ Impact	5 Very high	Risk level	15	Scenario type	13– 16 Bad	<ul style="list-style-type: none"> Line triggers occur due to the expansion of OHL conductors, equipment triggers due to sealing faults (oil/SF6 gas leaks), incorrect functioning of numerical terminals due to excessive heating of switchbox, shutdown of computer and process systems and communication systems; Vegetation fires may occur in transformer substations correlated with the production of short circuits in the grid and by melting some materials when passing the fault current through equipment with imperfect contacts; Vegetation fires may occur in the safety corridor of power lines, leading to equipment triggers or damage; At peak times, the energy consumption from internal resources is not covered and it is necessary to import a significant amount of energy. Under these conditions, interconnection capacities which may limit the level of electricity imports are maximised; The appropriate level of voltage in certain grid areas is not ensured due to a reactive power deficit caused by the widespread use of air conditioners (coolers); Difficulties arise in ensuring the adequacy of the NPS due to a reduced level of production in power plants, which causes the limitation or total loss of reserves;
Likelihood	3 Medium										
Gravity/ Impact	5 Very high										
Risk level	15										
Scenario type	13– 16 Bad										

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				<ul style="list-style-type: none"> Disturbances occur in the electricity market through large variations in the electricity trading price or an insufficient level of offers; Reduced production in certain plants leads to large power movements to deficient areas and results in voltage deviations and difficulties in compensating reactive power; For certain time intervals problems arise in ensuring that the N-1 safety criterion is met; The low level of production and loading of certain lines may lead to the impairment of the static and dynamic stability of the NPS; The drought can affect the entire region which leads to the impossibility of receiving or providing support to other countries in the region; Low level of domestic production as well as large power movements to deficient areas can lead to congestion on interconnecting lines and even the impossibility of ensuring electricity exports; In conditions of low production in power plants and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers. 								
6	Drought	<table border="1"> <tr> <td>Likelihood</td> <td style="background-color: yellow;">3 Medium</td> </tr> <tr> <td>Gravity/ Impact</td> <td style="background-color: red;">5 Very high</td> </tr> <tr> <td>Risk level</td> <td>15</td> </tr> <tr> <td>Scenario type</td> <td style="background-color: orange;">13– 16 Bad</td> </tr> </table>	Likelihood	3 Medium	Gravity/ Impact	5 Very high	Risk level	15	Scenario type	13– 16 Bad		<ul style="list-style-type: none"> At peak times, the energy consumption from internal resources is not covered and it is necessary to import a significant amount of energy. Under these conditions, interconnection capacities
Likelihood	3 Medium											
Gravity/ Impact	5 Very high											
Risk level	15											
Scenario type	13– 16 Bad											

			<p>which may limit the level of electricity imports are maximised;</p> <ul style="list-style-type: none">• The appropriate level of voltage in certain grid areas is not ensured due to a reactive power deficit caused by the widespread use of air conditioners;• Difficulties arise in ensuring the adequacy of the NPS due to a reduced level of production in power plants, which causes the limitation or total loss of reserves;• Disturbances occur in the electricity market through large variations in the electricity trading price or an insufficient level of offers;• Reduced production in certain plants leads to large power movements to deficient areas and results in the overload of some grid elements and voltage deviations and difficulties in compensating reactive power;• For certain time intervals problems arise in ensuring that the N-1 safety criterion is met;• Low production level and loading of certain lines can lead to the impairment of the static and dynamic stability of the NPS;• The drought can affect the entire region which leads to the impossibility of receiving or providing support to other countries in the region;• Low level of domestic production as well as large power movements to deficient areas can lead to congestion on interconnecting lines and
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			<p>even the impossibility of ensuring electricity exports;</p> <ul style="list-style-type: none"> • In conditions of low production in power plants and large power movements to deficient areas, there is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers. • Under the action of heat, accidental triggers of electrical equipment (power lines, transformers or autotransformers) may occur, which may lead to the overload of other equipment and to the increase of grid congestions; 								
7	Forest /vegetation fires	<table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>Likelihood</td> <td style="background-color: yellow;">3 Medium</td> </tr> <tr> <td>Gravity/ Impact</td> <td style="background-color: red;">5 Very high</td> </tr> <tr> <td>Risk level</td> <td>15</td> </tr> <tr> <td>Scenario type</td> <td style="background-color: orange;">13– 16 Bad</td> </tr> </table>	Likelihood	3 Medium	Gravity/ Impact	5 Very high	Risk level	15	Scenario type	13– 16 Bad	<ul style="list-style-type: none"> • Large areas are covered by fires, and in certain areas violent storms are produced, accompanied by electric discharges that increase the number of fire outbreaks; • Line triggers occur, caused by fire flames and line disconnections are required to allow staff to intervene to extinguish or stop the spread of fires; • Fires can also spread across substation territory leading to equipment triggers and damage; • There is a reduction in production in wind power plants due to wind intensification; • Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of affected/damaged equipment; • Problems arise in ensuring that the N-1 safety criterion is met; • Problems arise in supplying
Likelihood	3 Medium										
Gravity/ Impact	5 Very high										
Risk level	15										
Scenario type	13– 16 Bad										

			<p>some grid areas for a very long period, correlated with the time required to repair/replace destroyed/damaged assets;</p> <ul style="list-style-type: none"> • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
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2.2. Natural hazards

The identification, assessment and manifestation are shown in Table 2 [7-9]

Table 2. Natural hazards

Risk scenario: NATURAL HAZARDS			
1	Solar storm		<ul style="list-style-type: none"> • The solar (geomagnetic) storm generates the appearance of the Carrington effect, which leads to widespread damage to transformer units and line insulators; • Protection malfunctions occur; • All computer systems are affected; • Major and long-term disturbances occur in communication systems that significantly hinder the response in a crisis situation; • Equipment triggers take place and some equipment becomes unavailable for a very long period of time; • Controlled disconnects occur to prevent the transformation units from being overloaded; • A controlled blackout may occur due to the evolution at European level; • Coordinated action is taken at ENTSO-E level as the situation has been anticipated and some organizational crisis response measures have been taken.
		Likelihood	1 Very low
		Gravity/ Impact	5 Very high
		Risk level	5
		Scenario type	4–6 Low

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			<ul style="list-style-type: none"> Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace destroyed/damaged assets; 								
2	Earthquake	<table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>Likelihood</td> <td style="background-color: #008000; color: white; text-align: center;">1 Very low</td> </tr> <tr> <td>Gravity/ Impact</td> <td style="background-color: #ff0000; color: white; text-align: center;">5 Very high</td> </tr> <tr> <td>Risk level</td> <td style="text-align: center;">5</td> </tr> <tr> <td>Scenario type</td> <td style="background-color: #fff2cc; text-align: center;">4–6 Low</td> </tr> </table>	Likelihood	1 Very low	Gravity/ Impact	5 Very high	Risk level	5	Scenario type	4–6 Low	<ul style="list-style-type: none"> Damage/ triggers of equipment in substations and damage/falls of pillars on lines occur; Accidental shutdowns of production groups in power plants located in the area affected by the earthquake may occur; Industrial accidents may occur accompanied by fires, production shutdowns, gas emissions or leaks of hazardous substances; Damage occurs to GIS buildings in power substations, electrical equipment foundations or transformers; Disturbances occur in the road transport network, which leads to delays in carrying out the faults remediation work/repair of lines and transformation units; The functioning of communication systems is disrupted due to the phenomenon of generalized panic; Rescue or fire fighting teams are required; Difficulties may arise in carrying out faults remediation work in substations, caused by the large number of equipment of the same type affected and the lack of equipment in security stocks; Problems arise in ensuring that the N-1 safety criterion is met;
Likelihood	1 Very low										
Gravity/ Impact	5 Very high										
Risk level	5										
Scenario type	4–6 Low										

		<ul style="list-style-type: none"> • Problems arise in supplying some grid areas for a very long period, correlated with the time required to repair/replace damaged assets; • Congestions can occur on interconnecting lines and even the impossibility of securing electricity exports; • There is a risk of extensive damage to the NPS leading to the failure of supplying electricity to a large number of consumers.
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2.3. Risk scenarios estimation and assessment algorithm

2.3.1. Likelihood Estimation

LEVEL	LIKELIHOOD	Time
1. Very low	It has a very low likelihood of occurring. Normal measures are required to monitor the evolution of the event.	over 20 years
2. Low	The event has a low likelihood of occurring. Efforts are needed to reduce the likelihood and/or mitigate the impact produced.	16 – 20 years
3. Medium	The event has a significant likelihood of occurring. Significant efforts are needed to reduce the likelihood and/or mitigate the impact produced.	11 – 15 years
4. High	The event has a likelihood of occurring. Priority efforts are needed to reduce the likelihood and mitigate the impact produced.	6 – 10 years
5. Very high	The event is considered imminent. Immediate and extreme measures are required to protect the objective, evacuation to a safe location if the impact so requires.	1 – 5 years

2.3.2. Gravity Estimation

LEVEL	GRAVITY / IMPACT
1. Very low	The event produces a minor disturbance in the activity, without material damage
2. Low	The event causes minor material damage and limited disruption to activity
3. Medium	Injuries to staff, and/or certain losses of equipment, utilities and delays in providing the service.
4. High	Serious staff injuries, significant loss of equipment of installations and facilities, delays and/or interruption of service provision.

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5. Very high	The consequences are catastrophic resulting in deaths and serious injuries to staff, major losses in equipment, installations and facilities and termination of service provision.
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2.3.3. Risk Level Calculation

LIKELIHOOD	Very high 5						
	High 4						
	Medium 3						
	Low 2						
	Very low 1						
	0	Very low 1	Low 2	Medium 3	High 4	Very high 5	
GRAVITY / IMPACT							
Note: The risk is given by the product between Likelihood and Gravity / Impact							

2.3.4. Risk Scenario Type

Risk level: 1 – 3	Risk level: 4 – 6	Risk level: 7 – 12	Risk level: 13 – 16	Risk level: 17 – 25
Very low	Low	Moderate	Bad	Very bad

3. CONCLUSIONS

Integrated Risk Perspective is Essential – A holistic risk assessment demonstrates that evaluating the national power grid solely from an engineering or operational standpoint is insufficient. Extreme weather events and natural hazards require integration of meteorological, geological, infrastructural, and socio-economic data to fully understand vulnerabilities and interdependencies. **Critical Vulnerabilities Identified** – The assessment reveals that key components – such as transmission lines, substations, and distribution networks—are particularly susceptible to high-impact events like hurricanes, floods, heatwaves, and earthquakes. Cascading failures from a single point of vulnerability can result in widespread outages, highlighting the need for strategic redundancy;

Dynamic and Probabilistic Approaches Improve Resilience – Traditional deterministic assessments are inadequate in capturing the uncertain nature of extreme events. Incorporating probabilistic risk models allows for scenario-based planning, enabling grid operators to anticipate a range of potential threats and prioritize mitigation measures effectively. **Interdependency with Other Critical Infrastructures** – The study underscores that the power grid does not operate in isolation; disruptions can cascade to water supply, telecommunications, transportation, and healthcare. Holistic assessment must therefore account for cross-sector dependencies to prevent systemic failures.

Preventive and Adaptive Measures Are Key – Risk mitigation strategies, such as grid hardening, decentralized energy systems, smart grid technologies, and emergency response planning, are critical. Investments in early warning systems and adaptive infrastructure significantly reduce both the likelihood and impact of power outages during extreme events. **Policy, Planning, and Stakeholder Engagement** – Effective risk management requires coordination among government agencies, utility companies, and local communities. Policies supporting infrastructure resilience, real-time data sharing, and climate-informed planning are crucial for enhancing national energy security. **Continuous Monitoring and Updating of Risk Assessments** – Climate change and evolving hazard patterns mean that past risk assessments may become obsolete. A dynamic, continuously updated risk management framework ensures the power grid remains resilient against emerging threats.

A holistic risk assessment reveals that safeguarding a national power grid against extreme weather and natural hazards requires an integrated, proactive, and adaptive strategy. By combining engineering solutions, probabilistic risk modeling, cross-sector collaboration, and policy support, national energy infrastructure can achieve resilience, reliability, and sustainability in the face of growing environmental uncertainties.

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