CIGRE contributions to “Power System Resilience”

SEERC Workshop Rom, 23rd January 2025

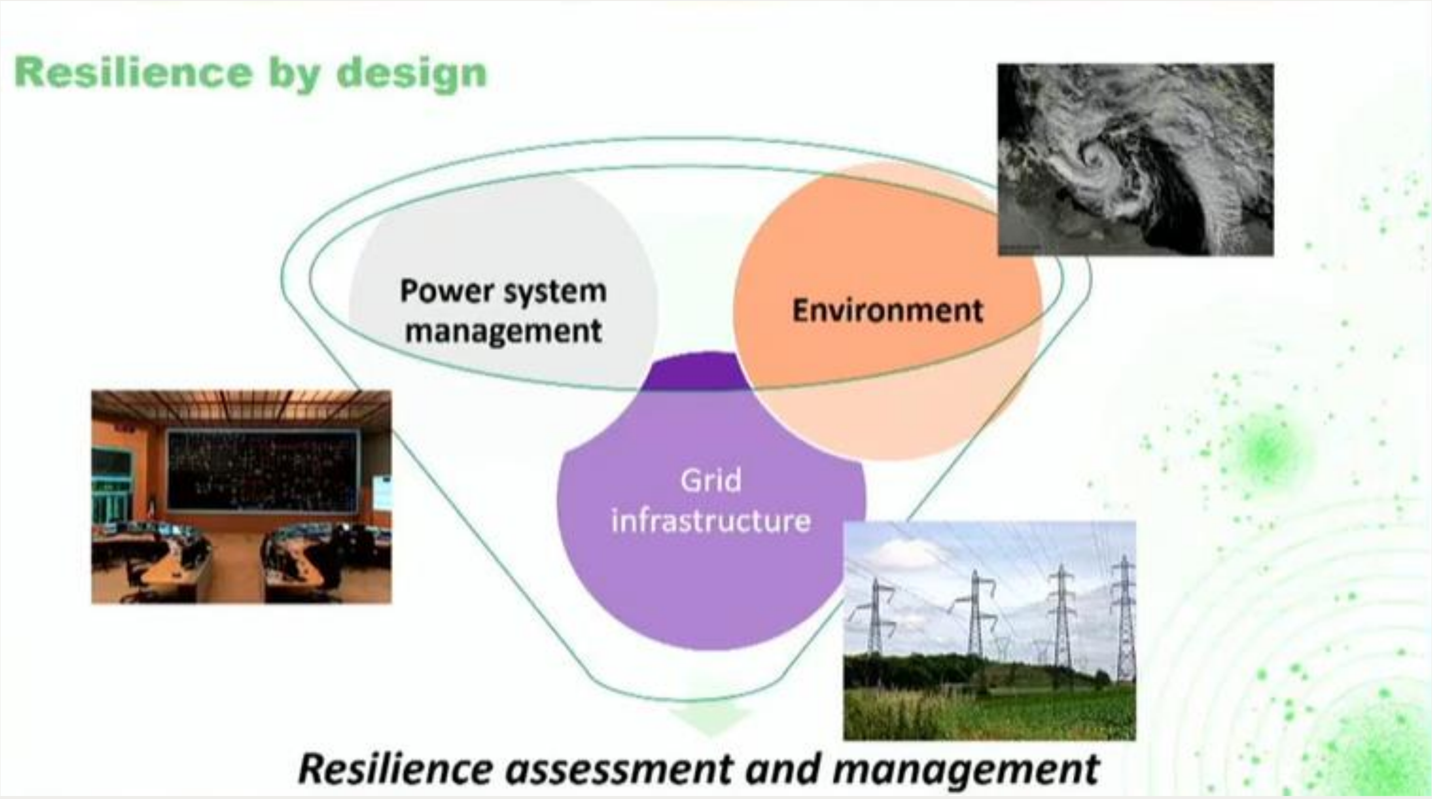
Konstantin O. Papailiou

CIGRE President

For power system expertise

ELECTRA N320 – Februar 2022

- WG C4.47 Resilience of interdependent critical infrastructure



ELECTRA N316 – June 2021

- WG C2.25 (TB 833) Operating strategies and preparedness for system operational resilience

Figure 2 - General resilience framework

ELECTRA N334 – June 2024

- Evaluation of grid operational resilience stressed by energy transition and by climate change: new metrics (SIRI) and countermeasures

Figure 1 -Vaia WindStorm (2018) and SnowStorm (2019) in Alpine Italian region (Trentino Alto-Adige)

CIGRE WG C4.47 “Power System Resilience”

CIGRE Paris Session 2024

27 August 2024

For power system expertise

Mathaios Panteli

Dr Mathaios Panteli (panteli.mathaios@ucy.ac.cy)

Assistant Professor, KIOS Center of Excellence, University of Cyprus

Honorary Lecturer, Department of Electrical and Electronic Engineering, Imperial College London, UK

Relevant Expertise:
- Chair of CIGRE WG C4.47 “Power System Resilience” and of CIGRE Cyprus National Committee
- Advisor to EU and international organizations (e.g., Ofgem UK and The World Bank)
- >15 years of experience on the topic of resilience, being the coordinator of and contributor to several industrial and research projects in EU and globally on power grid resilience assessment, quantification and enhancement

Resilience Definition

the ability to limit the ***extent, severity*** *and* ***duration*** *of* ***system degradation*** *following an* ***extreme event****.*

- In CIGRE definitions, the generic term "*magnitude*" usually used in resilience definitions is replaced by the two terms "*extent and severity*", which respectively refer to the *geographical extension* and the *intensity of the effects* of the event on the system.
- "*Severity*" in the present definition refers to the "*severity of the event consequences*", which must be kept separate from the "*severity of the event*" which in general does not imply any system degradations.
- The term "*degradation*" is intended as "*deviation from specified target performances*", both in system planning and operation as well as infrastructural and operational resilience.
- The term "*extreme event*" refers to high impact low probability (HILP) events, going beyond the "ordinary events" and referring to the "out of range type of contingencies" (ENTSO-E).

Climate Adaptation and Resilience

What's Coming

Though its projections typically lag observed reality due to its conservative, consensus-driven approach, the Intergovernmental Panel on Climate Change (IPCC), in its sixth round of reports published in 2021 and 2022, almost-entirely removed qualifying language about what the world can expect to experience in coming years and decades. A few takeaways:

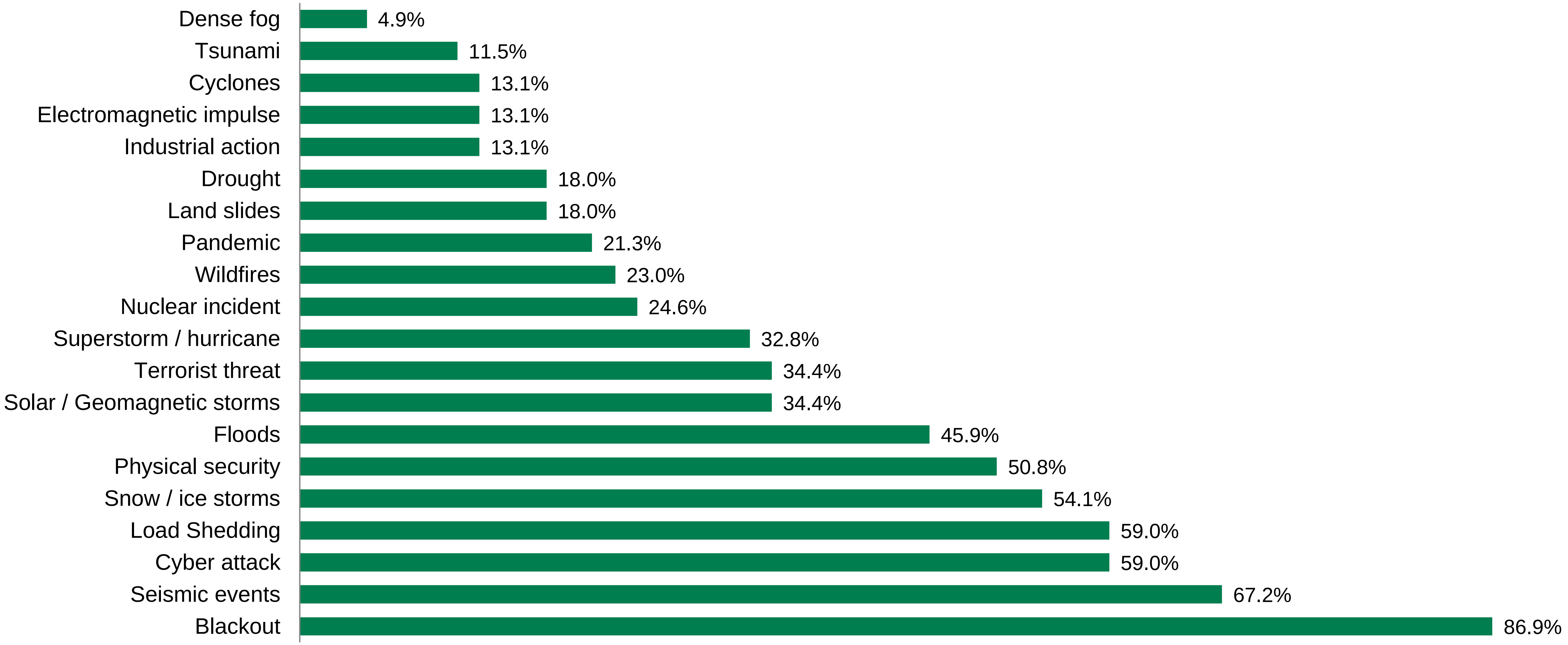
- The world will likely officially reach or exceed 1.5 degrees C (2.7 degrees F) of warming above the industrial baseline within the next two decades. 2023 achieved this milestone every month.
- No region will be left untouched by the impacts of climate change, with enormous human and economic costs that far outweigh the costs of action. Southern Africa, the Mediterranean, the Amazon, the western United States and Australia will see increased droughts and fires, which will continue to affect livelihoods, agriculture, water systems and ecosystems.
- Changes in snow, ice and river flooding are projected to impact infrastructure, transport, energy production and tourism in North America, the Arctic, Europe, the Andes and more.
- Many consequences of climate change will become irreversible over time, most notably melting ice sheets, rising seas, species loss and more acidic oceans.

International Survey

- The results of this survey on the current practices of resilience within the electricity infrastructure will inform and assist the CIGRÉ C4.47 PSR working group in achieving the goals as stated in the terms of reference and will be shared with all the participating entities.
- The working group will develop technical brochures, tutorials, position papers and articles and journal publications to describe the trends on the adoption and application of resilience concepts within the electricity sector.
- The initial international survey will inform the enhancement of the next survey before the development of an international power system resilience index that can be utilised to benchmark the maturity of the utility resilience programme.

Introduction

Which of the extreme threats/scenarios are actively being evaluated to boost resilience of electricity infrastructure?

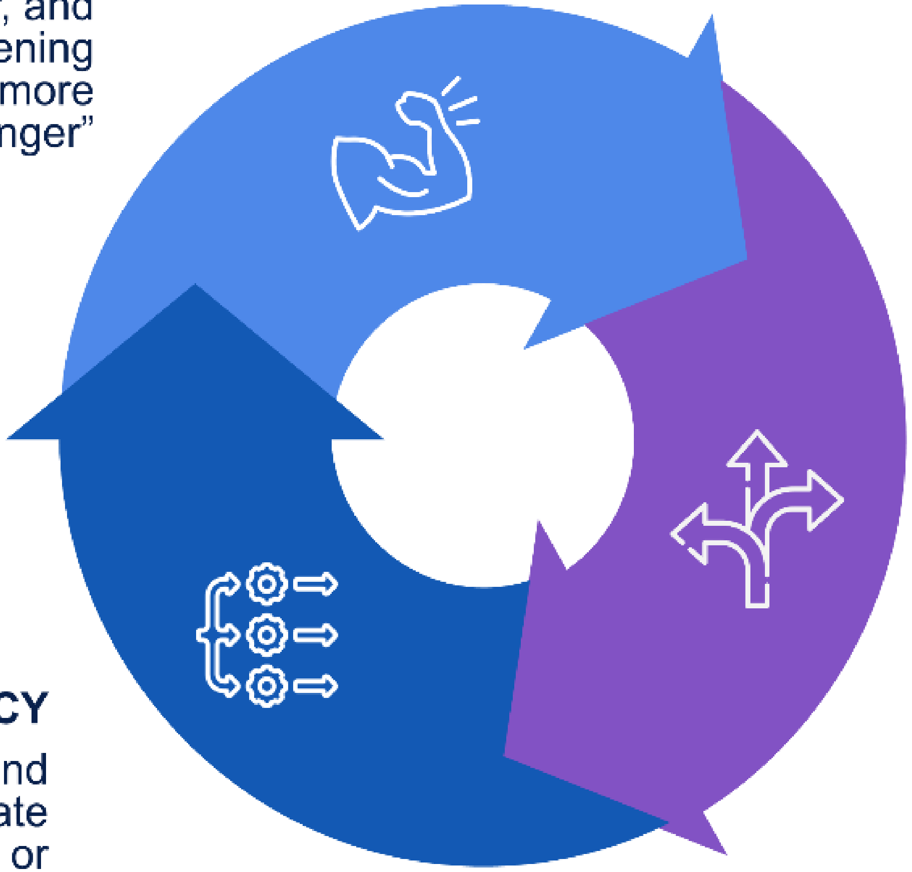


Resilience Decision-Making and Planning

The Resilience Trilemma

ROBUSTNESS

Substation, tower, and other equipment hardening to make the system more robust and “stronger”



FLEXIBILITY AND RESPONSIVENESS

New flexible network technologies, e.g., special protection schemes, FACTS and HVDC lines

Distributed energy resources, e.g., microgrids and distributed generation

Shorter response times, e.g., by increasing expenditure in enhanced stocks of network assets and equipment, more repair crews, and more online monitoring and control solutions.

REDUNDANCY

New assets (e.g., lines and transformers) to create alternative “routes”, or additional reactive power to operate the network under “weaker” conditions

In CIGRE, through SC D2, we have observed critical trends and insights from over forty member countries' annual cybersecurity reports. These include the following:

1. **Increasing Use of AI and Machine Learning:** Advanced technologies such as AI and machine learning are being widely adopted to detect cybersecurity threats and protect power systems and utility assets. As cyber threats grow in complexity and frequency, these technologies play a pivotal role in keeping pace with emerging challenges.
2. **Greater Exposure in the Energy Transition Era:** The shift towards distributed and interconnected power systems has heightened exposure to cybersecurity risks. With more entities connected to the grid, the attack surface for malicious actors has expanded, demanding robust security measures.
3. **Strengthened Regulations:** In recent years, regulators worldwide have significantly enhanced cybersecurity requirements for critical infrastructure. However, there is a pressing need to address gaps in smaller systems, such as Distributed Energy Resources (DERs), by developing compliance frameworks to ensure secure grid integration.
4. **Role of Standards and Architectures:** Standards like IEC 62443 and cybersecurity architectures provide a vital foundation for power utilities. They help establish a cybersecurity baseline and guide continuous improvement, ensuring resilience against evolving threats.
5. **Growing Importance of Supply Chain Security:** Supply chain vulnerabilities are increasingly critical. Compromises in software and hardware—such as malware implants or tampered firmware at manufacturing or during transit—underline the need for rigorous checks to ensure component integrity before deployment.
6. **Cyber-Physical Risks:** Real-world examples have shown how cyberattacks on computer systems can lead to physical damage to power plants. These incidents emphasize the interconnected nature of cybersecurity and physical system protection.
7. **Collaborative Research and Recommendations:** With the escalating risks tied to interconnected power systems, CIGRE, along with other international bodies, are prioritizing research and collaboration. These efforts aim to provide actionable recommendations to strengthen cybersecurity in the power sector.

Current CIGRE SC D2 Working Groups on Cybersecurity

- Working Groups:
- D2.51: Security Operations Center (SOC) for power utility
- D2.54: Regulatory approaches to enhance power utility cybersecurity frameworks
- D2.63: Inter-Control Center Communications Protocol (ICCP) Security for grid reliability (undergoing approval)

Floodings in Valencia (Spain) 2024

Damages in the electric transmission grid

cigre
For power system expertise

Event 29th October 2024

- Massive floodings in Valencia region (Eastern Coast of Spain)

  In some areas ~200 litres/m2 in 2 hours

  Creates massive river overflowing

- The bad condition of river beds and constructions in floodable areas provokes the worst natural disaster in Spain:

  222 deaths, 10 dissapeared;

  Damages in buildings, roads, railways, telecommunications...

  Hundreds of thousands of vehicles lost

  The global damages expected to overcome € billions

The worst natural disaster in Spain

Damages to the electric grid

- Major damages in the distruibution grid in some areas
- Telecommunications importantly affected
- Transmission grid affected but not so severely:

  Flooding of 2 substations (1 GIS 220 kV out of service)

  Micro-tornados destroyed some towers (cascade effect)

  23 towers down, 12 damaged (400 & 220 kV)

  7 circuits lost (400 & 220 kV)

  Some cicuits fell over distribution lines creating local problems

  The rest of the system remained unaltered
- The system responded well: nuclear, hydro and gas generation avoided blackout in the region. Coordination TSO-DSO and generators.

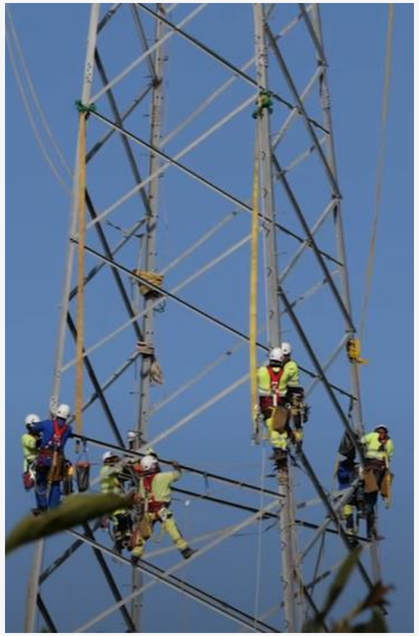
Damages in the Transmission system (micro-tornado)

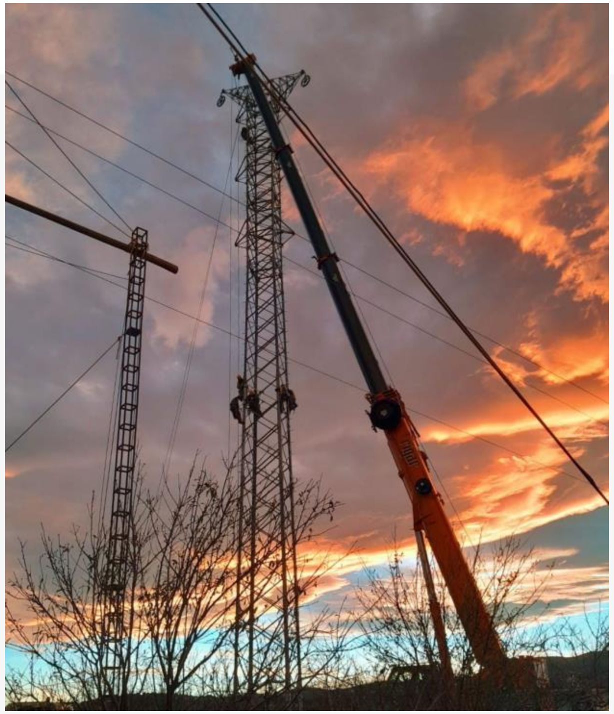

grupobou.com

cigre
For power system expertise

Flooded substation

Reconstruction





https://www.youtube.com/watch?v=QPrJd_qWzpk&t=5s

Recovery

- Main Challenges and response:

  Quick assesment of the damages: coordination with Army. Use of Helicopters/Drones

  Centralized coordination. Experienced personnel and contingency plans.

  Temporary solutions to feed certain areas

  Access to sites (heavy machinery). Coordination with other operators (DSO, teleco…)

  Lack of communications. Use of sattelite and fixed infrastructure in substations

  Sufficient spare materials and tools

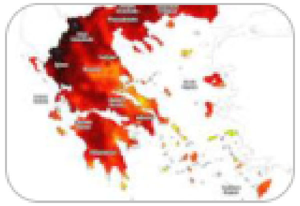
  Commitment of personnel. Increadible response of all the companies: contractors, manufacturers, etc.

  Record time for recovery: all circuits rebuilt within 1.5 months, except one (400 kV), expected in less than 3 months.

cigre
For power system expertise

Main risks for HEDNO

- The increase in the frequency and intensity of extreme weather events in recent years is a major challenge for HEDNO.
- Risks from climate change can be divided into short-term events (capable of causing shocks to equipment) and long-term stresses.
    - **Shocks**: floods, fires, storms, heat waves, strong winds, snowfall, frost.
    - **Stresses**: humidity, increased temperature, drought, landslides, sea level rise and coastal pollution.



Extreme Heat

Wildfires

Snowstorms

Floods

	Natural Disasters						Long-term stresses				
Climatic Risks	**Floods**	**Wild-fires**	**Strong winds**	**Storms (thunder, heavy rainfall, hailstorm**	**Snow-storms, frost**	**Heat-waves**	**Increased Temper-ature**	**Humidity**	**Drought**	**Soil instability, landslides, subsidence**	**Sea level rise, marine pollution, salinization**
Equipment											
Outdoor substations	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Indoor substations	✓	✓						✓			
Overhead line network (poles, conductors, insulators)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Switches/ disconnectors	✓	✓		✓	✓		✓	✓			
Transformers (MV/LV)	✓	✓	✓				✓	✓	✓		
Underground cable network				✓			✓			✓	✓
Comm-unications		✓	✓	✓						✓	

Most vulnerable equipment to climate change risks (Outdoor substations, Overhead line network)

Shocks – Extreme heat

Characteristics of the phenomenon

- Extreme temperatures, with values much higher than season normal (>40ºC)
- Extremely high minimum temperature values (>28ºC)
- Long duration (>10 days in a row)
- Very often accompanied by African dust storms
- Combined with wildfires turns into a complex crisis

Most affected assets of the distribution network

- Underground cable network
- Outdoor and indoor substations
- Overload due to high demand and reduced heat dissipation cause more frequent faults in the equipment during the heatwaves
- Overhead line network
- The African dust creates surface pollution and causes insulator leakage, wear and eventually failure.

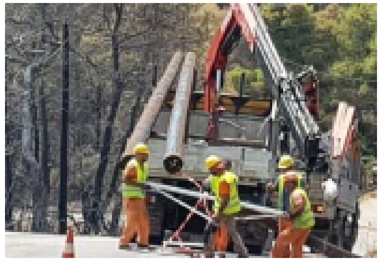
Recent experience

- On 01/07/2021, the island of Crete during covid-19 pandemic and tourist season experienced a major heatwave (44.3ºC in Hania city) that led to a fault in a gas turbine disconnector and 52,16 MVA total interrupted power.
- Indicatively, in 2023 for July alone, more than 150 faults in underground cables were recorded in Attica Region.
- Every summer from 2021 to 2024 had extreme heat episodes followed by large wildfires that caused massive damage on HEDNO's network.

Intense and long heatwaves tend to become the new normal

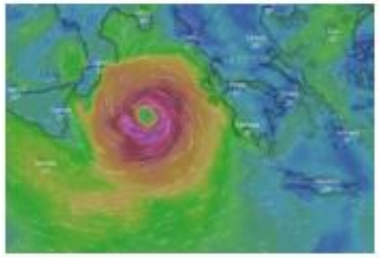
Shocks – Wildfires

	Affected areas	Description	Damages	Immediate response
Mainland fires	North Attica, North Evia and Peloponnesus	In the summer of 2021, the extreme heatwave (43-44°C in the mainland for more than 10 days) was followed by multiple forest fires.	More than 4,000 wooden poles burnt, over 285km of MV & LV overhead network needed replacement and over 16M € total restoration cost	Load shedding was performed in Attika, in order to ensure the smooth operation of the mainland's electrical system. Outages were short (only in a few cases exceeding two hours), while the total interrupted power was approximately 680 MW. Twelve (12) mobile generators of 2.12 MW total power were used to serve critical needs in some locations, until the full recovery of the grid.
Samos	the small islands of Fournoi and Thymaina	On 13.07.2022 they experienced an outage due to a wildfire in Samos	Damages in the connection on the underwater cable that supplies both islands.	The restoration began on the morning of July 15, through the installation of an emergency generator of 1.5 MW total power on Fournoi island and was complete the next day by the replacement of the damaged overhead network in Samos.
Evros	Evros, Alex/polis, Samothraki	A Megafire took place in Ebros region between 19/08/2023 and 03/09/2023	On 21/08/2023 a MV line in Alex/polis was destroyed and as a result the underwater cable of Samothraki lost its supply and the island's electricity was interrupted (while it was fighting its own forest fire).	The corrective actions to relieve the clients' inconvenience started the same day by sending 4 generators 200kW each and 8 more on the following day to cover local needs. The island's electricity was fully restored with the dispatch of a 5MW generator to cover the entire load on 25/08/2023



Shocks – Floods

	Affected areas	Description	Damages	Immediate response
Cyclone Ianos	Ionian Islands, Evia, Karditsa	On 18-21 of September 2020 the Mediterranean Cyclone "Ianos" hit Greece	• >450 faults due to fallen trees (broken poles and/or conductors) in the islands Kefalonia, Zakynthos and Ithaca • 1,148 km of MV network and 1,771 km of LV network affected • 63,500 clients' supply interrupted • 114 underground MV/LV substations flooded	• 11 emergency generators (6.5MVA in total power) were transferred in Karditsa city for client relief until the total recovery of the network • Over 97% of the major damage in the Distribution Network had been repaired by 22 September
Storm Daniel	Larissa, Volos, Trikala, Karditsa	Storms "Daniel" in September of 2023	• 14 MV lines were damaged severely • >16,000 poled needed to be replaced • >80M € estimated cost of network restoration and adaptation • 148 underground MV/LV substations required equipment replacement	• Cooperation with Coast Guard and Hellenic Army to transport generators to the affected areas to supply critical infrastructures • The personnel was reinforced from the other HEDNO Regions in order to restore the damages. The maximum number of technical personnel that worked in the restoration of damages reached 600 people among with 350 construction vehicles.



Shocks – Snowstorms

	Affected areas	Description	Damages	Immediate response
MEDEA	Central Greece, Peloponnese,Ipeiros, Attika	"MEDEA" Winter Storm 13-20 February 2021	• Broken poles and/or conductors due to fallen trees • The inaccessible road network did not allow the timely repair of faults and led to long-term outages • 150,000 clients disrupted at the peak of the storm	800 technicians were mobilized and 100% of repairs was complete by 22th of February
ELPIS	Attika	"ELPIS" Winter Storm 22-30 January 2022	• The rare event of snow thunderstorm caused more faults than expected • 79 MV lines in total were affected • 657 faults were recorded in Mainland and 448 in Aegean islands	• 17 emergency generators were rented and distributed in various areas • 756 people of technical personnel and 233 construction vehicles were mobilized and 95% of the disrupted points of supply was restored by 26th of January

Climate Risk Management

Focus areas	Actions taken
1 **Guidelines, communication & response mechanisms**	**HEDNO Guidelines for Environment and Climate Change** Climate change adaptation is part of HEDNO's Environmental Policy and is based on the following pillars: • Anticipation of future impacts both on its organization and on its asset base, with thorough assessment and analysis of Climate Change projections and scenarios. • Deployment of effective disaster risk management strategies and resilience engineering initiatives. • Maintenance of the operational capability of the network during extreme weather events. • Rapid recovery following an event through the application of an effective crisis response plan. • Implementation of targeted network-strengthening adaptations based on performance indicators, lessons learned, and best practices. **Communication Material for Climate Resilience** • Infographic for vegetation management and climate resilient network materials • Climate Change e-flyer in terms of Climate Change Awareness Week 2023 • Crisis management infographic, including guidelines at all stages of the disaster management cycle: prevention / preparation, increased readiness, response and recovery. • Posters for safety considerations in emergency situations due to extreme weather. **HEDNO liaison in the National Coordination Center for Operations & Crisis Management (ESKEDIK)** • Geospatial data of MV networks and substations have been delivered to the Ministry of Climate Crisis and Civil Protection. **Best Practices Guide for Managing Climate Risks, Disasters & Crises** ***Explained next***
2 **Data collection & assessment studies**	**Database for Severe Climate Incidents** **Internal Survey for Climate Risk Perception** **Adaptation to 5C Study** • An assessment study has been completed for the climate change adaptation of network's infrastructure assets in case of the Global Warming scenario of the temperature's rise by 5°C **Climate Vulnerability Assessment Study** ***Explained next***
3 **Preparation** (e.g., workshops)	**Climate Crisis Workshop** **Emergency Drill – Tabletop Exercise THESEUS 2024** ***Explained next***

Recent CIGRE Work

CIGRE Technical Brochure 809 (June 2020)

Dynamic Loading Effects on Overhead Lines : Impact on Structures (WG B2-24)

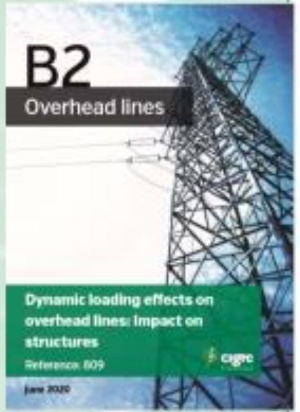
Salient Findings

- Most tower failures attributed to narrow high wind gusts exceeding design wind velocity. Narrow high wind gust can affect a single tower, or both the structure and its spans simultaneously.

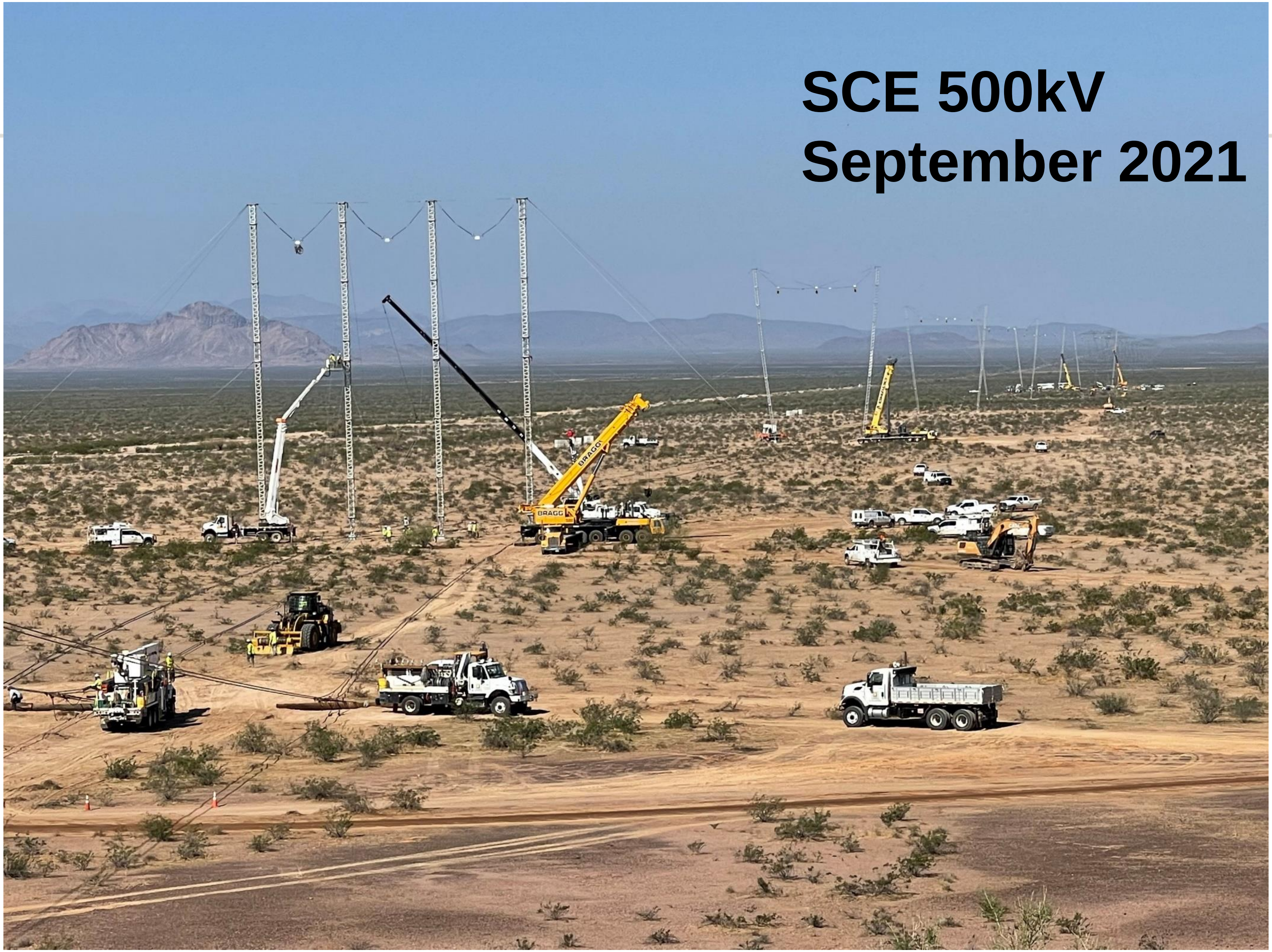
- Lack of understanding of the characteristics of localized high intensity winds caused by downbursts, thunderstorm winds.

- Current industry practice of design do not explicitly apply structural dynamic analysis to predict response of time varying loads.

- Equivalent static analysis methods of dynamic loading events have provided reliable tower designs under typical conditions. However, dynamic analysis is important in situations which are beyond typical boundary conditions.



SCE 500kV September 2021



SCE ERS video link https://lnkd.in/gFS7sibt

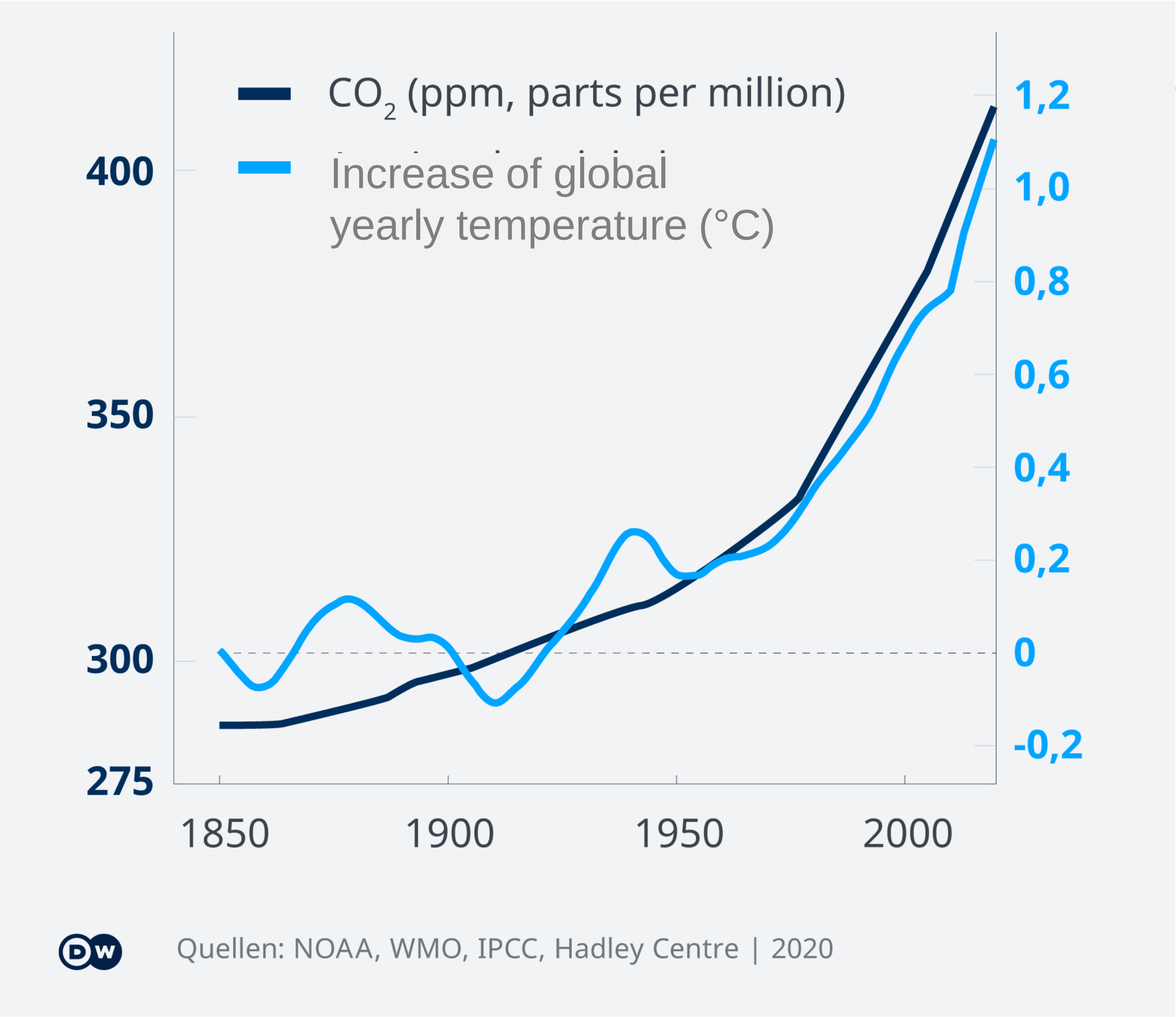
Automatically GPS-operated tractors mown down 400 kV towers!

CIGRE and the Energy Transition

World Energy Outlook (IEA) 2022

cigre
For power system expertise

- Approximately 20% of the world's population has no access to electrical power.
- Global electricity demand rises between 6000 and over 7000 TWh by 2030, equivalent to adding the current level of demand in the United States and the European Union. Global electricity demand in 2050 is 150% higher in the Net Zero Emissions by 2050 (NZE) Scenario.
- **Electricity networks are the backbone of electricity systems and need to expand and modernize to support energy transitions**. Total grid lengths more than double from 2021 to 2050. Annual investment rises from around USD 300 billion in recent years to around USD 600 billion by 2030 and averages USD 800 billion per year to 2050.



CO2 (ppm, parts per million)
Increase of global
yearly temperature (°C)
400
350
300
275
1,2
1,0
0,8
0,6
0,4
0,2
0
-0,2
1850
1900
1950
2000
DW
Quellen: NOAA, WMO, IPCC, Hadley Centre | 2020

How much electric power is needed to electrify the planet?

- The global electricity power demand for the zero emissions scenario is about 25000 - 40000 GW.
- The installed capacity of all energy sources today is about 10700 GW.
- This means that an additional 21700 - 36700 GW are required, i.e. more than 1000 GW of power plants per year would have to be brought on stream by 2050!

And how many new transmission lines?

- The global, largely overhead, transmission grid is estimated to be around 8 - 10 million circuit km.

- The energy transition requires 1.1 - 2.5 million km of new lines (mainly high voltage), of which about 300000-500000 km HVDC.

- Of the 8 - 10 million km of existing lines, about 40 - 60%, i.e. about 3.2 - 6.0 million km will have to be replaced or refurbished by 2050.

- This means that the total requirement for overhead lines by 2050 is about 4.3 - 8.5 million km.

The role of CIGRE in the energy transition

- Raise its voice and point out the problem also to non-technical audiences, in particular politicians
- Attract and educate young people
- Utilize better the human capital at its disposal

The future belongs to electricity and CIGRE will be there!