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Impact Of Climate Change on Transmission System Operator Assets: Experiences from Croatia and Need for Resilience Plan

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***Summary* — The consequences of climate change are felt everywhere, especially on power systems assets, whereby over headlines are one of its most exposed elements. It is expected that the impact of climate change, especially the effects of evident global warming, will be even more expressed in the coming decades, with increased frequency and severity of extreme weather events in the form of storms, winds, snow, ice, high temperatures, fires, etc. Therefore, it is essential to ensure the safe and stable operation of power networks. An experience with two strong storms that appeared within only two days in July 2023, affecting a larger part of the Croatian transmission network, is presented in order to discuss whether it is necessaryto change valid requirements for new overhead lines, and to consider establishment of internal resilience mechanisms for better withstand the impacts of climate change and global warming.**

***Keywords* — climate change, global warming, transmission network, OHLs, resilience, storm, wind**

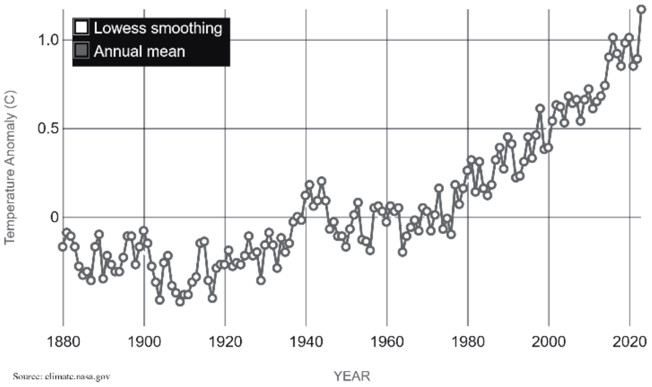
I. INTRODUCTION

Over the past decade, climate change has manifested in various forms, significantly affecting power system infrastructure. Extreme weather conditions are more and more common and they have posed unprecedented challenges to the resilience and reliability of power grids. Rising global temperature shaveled to increased energy demand for cooling, placing additional stress on power generation, transmissionand distribution systems.

The impacts of climate change can reduce efficiency and alter the availability and generation potential of power plants, including both thermal and renewable facilities. For transmission and distribution networks, impacts can result in higher losses, transfer capacity change and physical damage.

These climate-induced disruptions have resulted in widespread power outages, economic losses, and compromised energy security. Infrastructure damage, prolonged downtime, and repair costs have escalated, prompting a re-evaluation of traditional approaches to power system design and maintenance. In response, there is agrowing emphasis on implementing climate-resilient technologies, enhancing grid flexibility, and diversifying energy sources to mitigate the impact of climate change on power systems. Policy makers, utilities, and industry stakeholders are now recognizing the urgency of adopting sustainable practices and investing in innovative solutions to build a more robust and adaptable power infrastructure for the future.

Figure 1 shows the change in global surface temperature compared to the long-term average from1951 to 1980. Earth's average surface temperature in 2023 was the warmest on record since record keeping began in 1880 (source: NASA/GISS). Overall, Earth was about 1.36 degrees Celsius warmer in 2023 than in the late 19th-century (1850-1900) preindustrial average.



Source: climate.nasa.gov

Fig.1. The change in global surface temperature compared to the long-term average from 1951 to 1980

The Mediterranean region is a recognized climate change hotspot, warming 20% faster than the global average, and as such Croatia is subjected to the most extreme climate change, and like in many other regions, they are multifaceted and can affect various aspects of the environment, economy, and society.

This accelerated warming increases the frequency and severity of extreme weather events, such as droughts and heatwaves. Additionally, precipitation is projected to decline by up to 30% in Southern Europe under higher global warming scenarios, exacerbating water scarcity and ecosystem stress. These findings highlight the vulnerability of the region compared to global averages [1-2]. The region is also experiencing ecosystem changes, including biodiversity loss and shifts in marine and terrestrial species due

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to temperature rises and habitat degradation [2-3].

The Mediterranean region is currently dealing with critical challenges, including water scarcity, food and energy insecurity, and ecosystem degradation. Special Report (November 2024) [4] represents a significant step in understanding the complex relationships between water, energy, food, and ecosystems in the Mediterranean.The report offers a comprehensive assessment of the available scientific knowledge on these issues, covering the drivers of change, their cascading impacts, and response options for addressing the region's multiple climate and environmental challenges. Consequently, some notable impacts of climate change in Croatia are already visible in the energy sector. These events can have direct and indirect impacts.

There are numerous scientific and technical papers, reports, and studies that have been performed with a focus on the impact of climate change on the power systems [5-10]. Most of these works are based on real examples of extreme weather conditions and their impact on various parts of the power system, with the conclusion that there is a pronounced need for stronger resilience measures and mechanisms. Power systems need to be able to adapt and withstand different events in climate change patterns, operate under the immediate shocks, and restore the power system's function after an interruption resulting from climate hazards.

According to the IPCC WGI Interactive Atlas, Figure 2 presentsthe global warminglevel(GWL) forCroatiabasedon historical data, starting from 1900, with predictions until 2100. GWL is an analysis dimension alternative to the use of future periods across different scenarios. It translates mean temperature change and can give an answer to how far we are from reaching the global warming imit of 1.5°C (agreed upon under the Paris agreement).

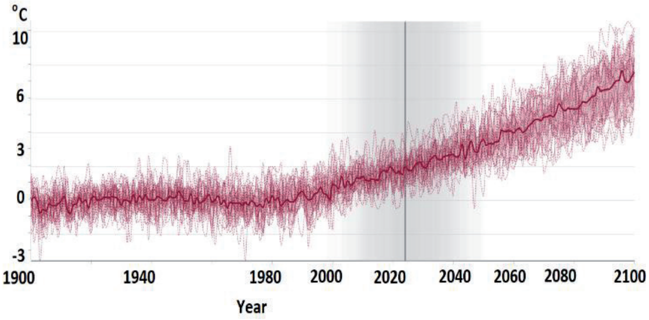

Fig. 2. Mean temperature change for 1.5 °C based on historical data from Croatia

As it can be seen, reaching the 1.5 °C limit is in fact very close. Consequently, every increment of GWL is important because it will directly impact regional changes, with climate and extremes to become more widespread and pronounced. Another evident example of global temperature rise impacting the number of natural disaster events is shown in Figure 3, based on EM-DAT data.

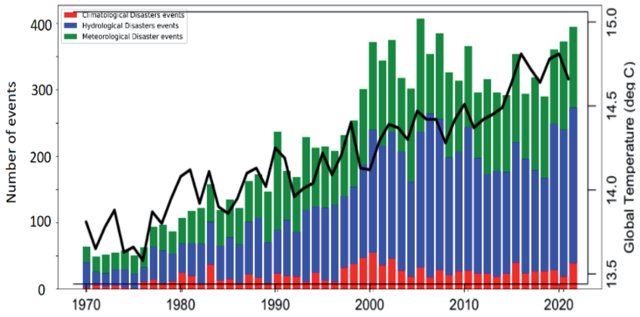

Fig. 3. Global number of events of cilmatological, hydrological and meteorological disasters vs. global temperature

Focusing on the last 20 years (2001-2020), there were 999 natural disaster events in Europe, of which 951 were weather- related, meaning they belonged to the disaster subgroups meteorological, hydrological, or climatological [11].

According to a visualization tool that enables projections of different climate factors for the future (WEMC TEAC), Figure 4 shows predictions of air temperature rise for Croatia.

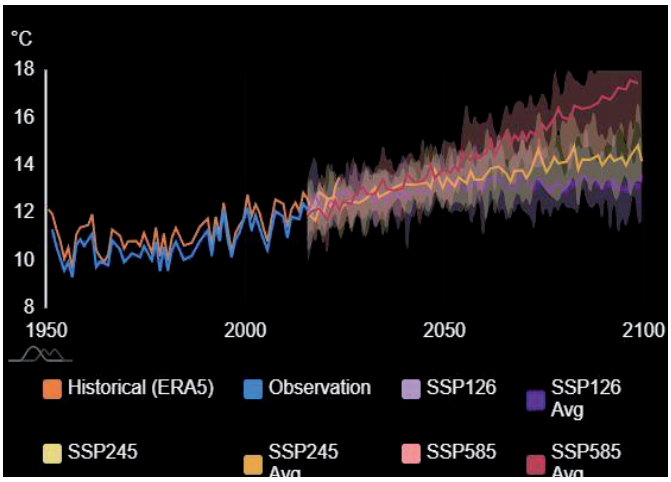

Fig. 4. Prediction of mean annual air temperatures in Croatia according to different scenarios

Temperatures have risen consistently in Europe over the last 40 years. Climate projections into the future show this difference in rates will continue, also for Croatia. Generally, climate model projections for Europe indicate major warming of about 3 to 5°C on average by 2100 for a high greenhouse gas emissions scenario. The projections indicate more frequent high-temperature extremes (e.g., heatwave events, wildfires, strong storms, etc.).

The first part of the paper gives an introtuction on evidences of global warming and climate change, overview of existing national norms and standards related to the designand engineering of OHLs (in this case, parameters related to wind).

As evidence of ongoing changes, the second part of the paper presents HOPS experiences with two strong storms that occurred in July 2023 (on the19th and 21st)on the territoryof central and eastern Croatia and caused unprecedented damage to the transmission network of HOPS, whereby in total 51 transmission line towers were damaged or completely demolished (including six interconnection OHLs with Hungary, Serbia and Bosnia Herzegovina).

For the emergency repair of the transmission network and to ensure reliable electricity supply, a modular emergency restoration towers were installed, with coordination and help provided from neighboring TSOs.

Similar events with significant impact were also recorded earlier, for example in February 2014, when ice caused significant damage to the network, in August 2018, when strong wind damage severely damaged towers and completely demolished one tower on 110 kV OHL [12], or in August 2021 (wind), when three towers of internal 400 kV OHL in a row were completely demolished [13]. The network is also often affected with salt and wildfires in coastal areas, or wind, ice, and floods in continental areas. Also, as a result of the devastating earthquakes in 2020, significant damage occurred in 7 substations in the wider Zagreb and Sisak area.

At the end, it is discussed whether changing of design parameters of OHLs could prevent future damages and their outages due to unpredictable weather phenomena. Also, the need for the establishment of resilience mechanisms is pointed out.

II. Croatian Transmission Network And Overheaed Lines Design Criteria

Croatia is a Mediterranean country located in Southeast Europe. Due to its geographical position, the Croatian power system comprises plants and facilities for electricity production, transmission, and distribution located in different climatic zones and geographical areas. The transmission network is a part of the Croatian power system and comprises transformer substations, switchyards, overhead lines (OHLs), and underground cables. The Croatian Transmission System Operator (further in text HOPS) owns 7778 kilometers of overhead lines at 400 kV, 220 kV, and 110 kV voltage levels and 187 substations.

The Croatian transmission network consists of four different areas, based on four main and biggest cities: the transmission areas are Zagreb (ZG), Split (ST), Rijeka (RI), and Osijek (OS). Each of them is located in different geographical zones with different climatic conditions and possible impacts on power system equipment.

Continental areas (parts of transmissions areas ZG and OS), especially in winter, can experience heavy snowfall and ice. Accumulation of snow and ice on OHLs and towers or substation equipment may lead to increased weight, causing sagging and potential damage. Ice accretion can also increase the risk of conductor breakage. Also, strong winter winds can exacerbate the impact of snow and ice by causing additional stress.

The area of the Adriatic Coast (parts of transmission areas ST and RI) is exposed to strong winds and salt-laden air. Salt corrosion is a significant concern for power system infrastructure, as it can accelerate the deterioration of materials, leading to equipment failure and increased maintenance needs. Also, storm surges associated with coastal storms can lead to flooding, impacting substation equipment and potentially causing electrical failures. In summer, coastal regions may also face the risk of wildfires.

Higher elevations (parts of transmission areas ST and RI), in mountainous regions, receive heavy snowfall during winter. Snow accumulation can affect power lines and transformers, and ice formation on elevated structures poses a risk of conductor breakage and equipment damage.

And, at the end, low-lying areas and river valleys may be susceptible to floodingduring periods ofheavyrainfall, which can damage substation equipment, transformers, and other infrastructure, leading to extended outages.

Understanding these regional climate-related challenges is crucial for TSOs and planners. Mitigation strategies include designing infrastructure to withstand specific environmental conditions, implementing regular maintenance and inspection programs, and employing materials that are resistant to corrosion and environmental stress. Additionally, advanced forecasting and monitoring systems can help anticipate extreme weather events and facilitate timely response and preventive measures to enhance the resilience of the power grid. The existing OHLs at HOPS are designed in accordance with the »Regulation on technical norms for the construction of overhead power lines with a nominal voltage of 1 kV to 400 kV« [14] (hereinafter - Regulation).

The equation of wind load on a conductor or ground wire is defined as (Article 8, Regulation):

$$F_c = P_d \cdot C_{dc} \cdot L \cdot d \cdot G_c \tag{1}$$

where P_d is design wind pressure, C_{dc} is drag coefficient, L is wind span, d is diameter of conductor/ground wire and G_c is gust response factor. Similarly, equation of wind load on towers is defined as:

$$F_t = P_d \cdot C_{dt} \cdot A \cdot G_T \tag{2}$$

where P_d is design wind pressure, C_{dt} is drag coefficient, A is effective area and G_T is gust response factor for towers.

When calculating the wind load, the surface of the object is considered as the actual surface, without additional load, attacked by the wind. For cylindrical columns and for grid columns, only the surfaces facing the wind are taken into account (Article 9, Regulation).

For almost all OHLs in the continental part of Croatia, under the jurisdiction of transmission areas ZG and OS, abasic wind pressure of 600 N/m2 is assumed for design (in accordance with Article 10, Regulation). Based on Art. 10 of the Regulation, the relationship between wind speed and pressure is defined:

$$P_d = \frac{v^2}{16}\ [daN/mm^2] \tag{3}$$

where v is the maximum wind speed [m/s] for the area that appears in the period of the last 5 years (or in the longer observed period for 400 kV lines). According to the regulation, minimal wind pressure is 50 daN/m² (for basic height 40 m above ground).

The coefficients of wind action on individual parts of transmission lines are given in Art. 11 of the Regulations. Therefore, the maximum wind speed for the calculation of wind pressure is determined on the basis of several years of measurements and the application of statistical processing of measurement data.

All new building structures should be dimensioned according to the Eurocodes, and for wind loads, the proposal known also as "NNA" (the Croatian addition to the norm, which is still not approved) was created for HRN EN 1991-1-4:2012, Eurocode 1: Actions on structures - Part 1-4: General actions. - Actions of the wind - National supplement, with a wind map for Croatia [15].

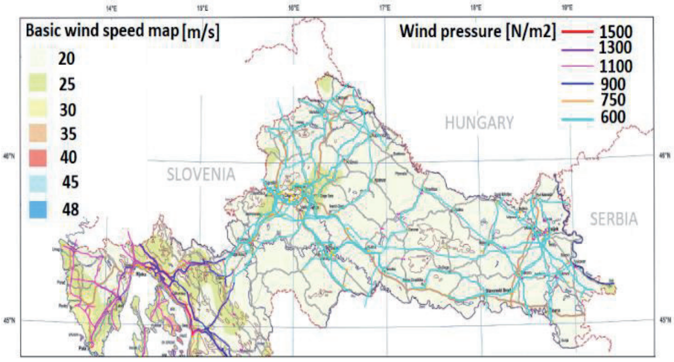

Fig. 5. Basic wind speed map of transmission areas ZG and OS, with the routes of the existing OHLs and the design wind pressures

As can be seen on the map from Figure 5, in the continental area (transmission areas ZG and OS), the basic expected wind speed 10 m above ground is 20-25 m/s, with a maximal wind gust of 40 m/s and the probability of 2% that it will be exceeded in 50 years. Also, an important parameter for the design is the basic wind pressure on sections of 110 kV, 220 kV, and 400 kV OHLs, which is for the observed area 600 N/m2.

In the coastal area, the basic expected wind speed exceeds 25 m/s, with maximal wind gusts greater than 40 m/s. Even nowadays, during the design stage of OHLs (according to the Eurocode), the loads on the structure are calculated differently in the past, it is obvious that nowadays it is more and more possible to experience extreme weather conditions. According to this, it is needed to consider whether the basic wind maps should be updated more frequently, since they present an important input for the calculation at the OHL design stage.

Furthermore, such maps should be correlated with the most critical OHLs from the system operation state of view (according to N, N-1 or similar criteria), and based on this, TSOs can require from OHL designers consideration of stricter requirements (for towers structure and basement).

III. Example Of Climate Change Impact On OHLs In Croatian Transmission Network

On Wednesday, July 19th, 2023, northwestern and eastern Croatia were hit by a strong storm accompanied by hurricane-force winds and thunder, which caused a serious breakdown in the power system [16].

During the afternoon, a convective storm formed west of Slovenia and intensified around the border area of Italy, Slovenia, and Austria. The storm moved towards the affected areas from the west (Slovenia) towards Zagreb and further to the east. Radar images (source: State Hydrometeorological Institute - DHMZ) show the direction of the storm from 15:30 (immediately before the first driving event) until 18:30, in steps of 30 minutes (Figure 6).

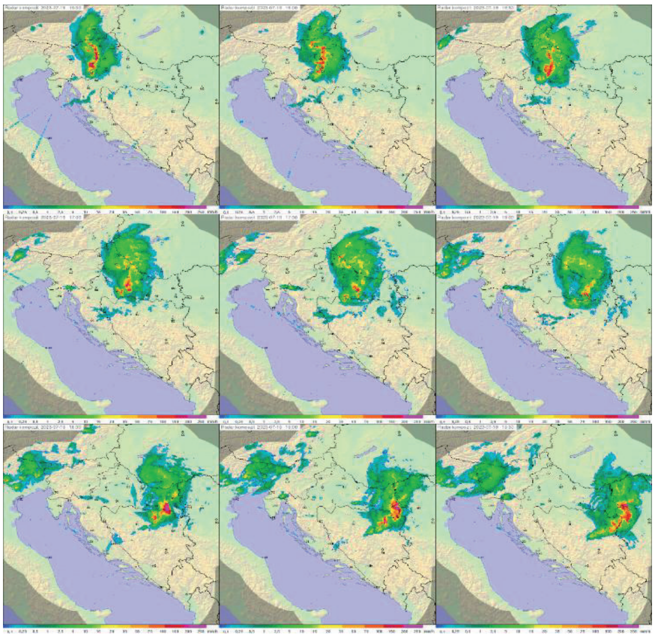

Fig. 6. The storm over Croatia from 15:30-18:30 h on radar

On its way to the east, the storm came over a plain area with ground temperatures of 28-31°C and dew points around 20°C, which enabled further strengthening in a CAPE (Convective Available Potential Energy) environment of over 1500 J/kg, in places even more than 2500 J/kg.

The storm was extremely strong and resulted in its transformation into a supercell that caused serious material damage, including hail with a diameter of about 10 centimeters, extremely strong wind shock fronts, and numerous damaged buildings in the area of Zagreb and Slavonia.

In addition to the hail, the storm was characterized by an extremely strong wind shock front (called a downburst), which, according to measurements, exceeded 20-30 meters per second at the largest number of affected measurement locations. The highest wind speed (44.7 m/s or 161 km/h) and wind gust (52.3 m/s or 188 km/h) were recorded at 17:04 int he area of the city of Kutina—as it is shown on Figures 7 and 8, which are significantly higher values than OHLs are designed for.

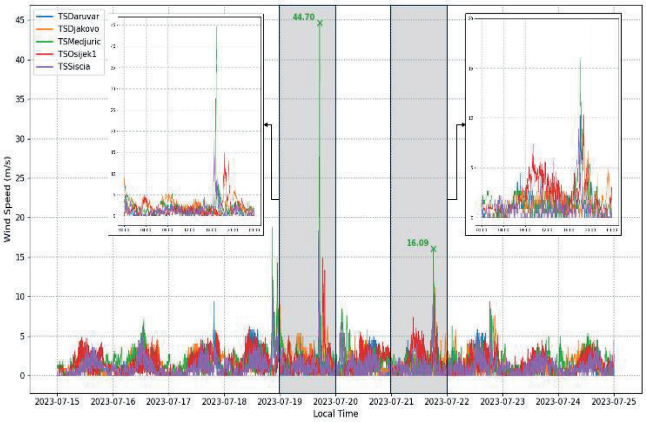

Fig. 7. Wind speed measured at several substations in the area affected by the storm from July 15th to July 24th

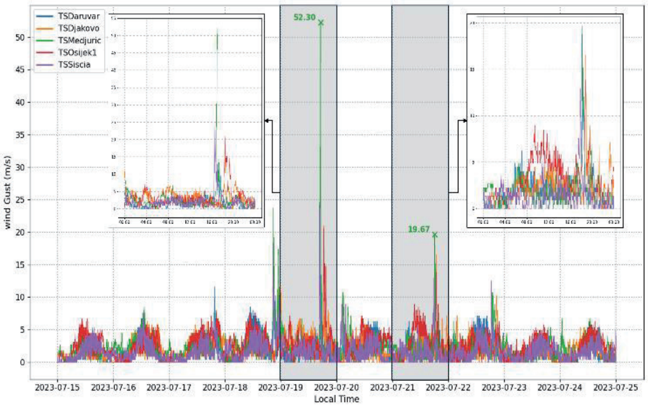

Fig. 8. Wind gust measured at several substations in the area affected by the storm from July 15th to July 24th

In parallel with the ongoing storm, numerous lightning strikes occurred in the mentioned areas of transmission areas ZG and OS, causing direct outages of nine overhead lines (Figure 9). HOPS uses a system for locating atmospheric discharges (SLAP) that provides data on lightning strikes that occurred over the observed area. The SLAP system is connected to the SCADA system and enables the correlationof lightning strikes with the indication of events in thenetwork.

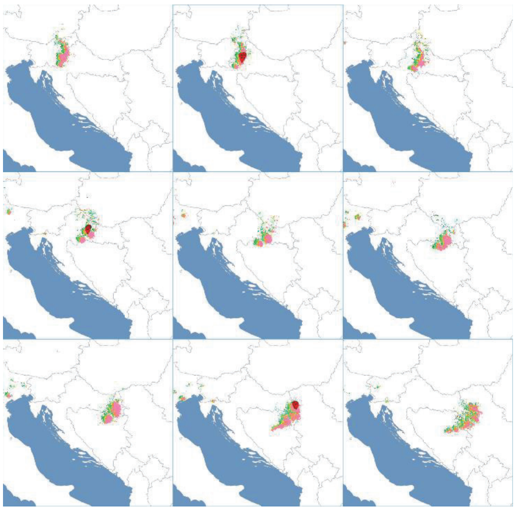

Fig. 9. Lightning strikes recorded during storm with lightning location system SLAP

In addition to the first storm, on July 21st, 2023, another storm further worsened the situation, contributing to new transmission line outages in the transmission area ZG.

An average wind speed during the storm on July 19th, 2023, was 88 km/h, and the storm encompassed a 350 kmwide area, whereby system SLAP recorded 363.872 lightning strikes (from 14:00 until 20:00), which equals 1010 strikes/min, with 9 OHL outages.

Similarly, an average wind speed during the storm on July 21st, 2023, was 94 km/h, and the storm encompassed a 470 km wide area, whereby system SLAP recorded 718.184 lightning strikes (from 14:00 until 20:00), which equals 1994 strikes/min, with 4 OHL outages.

As a consequence, due to the effects of the storm, an outage occurred on 14 overhead lines in the transmission area ZG and 8 in the transmission area OS with significant damage to towers and other equipment.

In the transmission area ZG, a total of 20 towers were damaged, 13 of which were broken, that is, the damage to the structure is such that it is not possible to correct the damage only with locksmith interventions. Looking at the km of the route, a little more than 5 km of the transmission line route was damaged in total. For the needs of temporary transmission line operation, 10 modular emergency towers were used.

In the transmission area OS, a total of 31 towers were damaged. Of these, 27 were completely demolished and 4 towers were damaged. Looking at the kilometers of the route,a total of about 12 km of the transmission line route was damaged. For the needs of the temporary operation of the transmission line, 12 modular emergency towers were installed. On the 110 kV voltage level transmission lines, modular towers were installed by HOPS, and on the interconnection (HR-RS) OHL 400 kV Ernestinovo - Sremska Mitrovica, two emergency towers were installed by the contractor.

Overview of consequences of OHLs outages, obtained from the Network Manager SCADA system (based on [16]), are shown in Table 1. The exact causes of the OHLs outages were determined subsequently by inspecting the routes according to the locations obtained from the inputs from the relay protection department.

Table I.

Overview of the Consequences after Storms and total Impact on Transmission Network

	110 kV	220 kV	400 kV
Total No. of disconnected OHLs	51	7	1
Total No.ofdisconnected OHLs due to lightning strikes	10	3	0
Total No. of damaged OHLs	14	5	3
Total No. of damaged OHL towers	40	5	6

Figures 10 and 11 shows some of damaged towers on location of transmission area ZG, while Figures 12 and 13 some of damaged towers on transmission area OS.

Fig. 10. Damages on OHL 110 kV Međurić – Daruvar located in transmission area ZG (tower no. 3) due to storm on July, 2023

Fig. 11. Damages on OHL 220 kV Međurić – TPP Sisak located in transmission area ZG (tower no. 99) due to storm on July, 2023

Apart fromthe unavailability of a large number of OHLs, asa consequenceofthetwostorms,therewasnomajorlossof consumption (EnS from 19th–21st July 2023 was <50 MWh), except during the moments of the storm in certain localities, which is significantly less than a comparable event caused by ice conditions in 2014 (in the transmission area RI, when EnS through 5 days was ≈ 100 MWh).

Fig. 12. Damage on OHL 400 kV Ernestinovo – Sremska Mitrovica located in transmission area OS (tower no. 120) due to storm on July, 2023

Fig.13. Damage of 110 kV OHL near substation

In the event of a OHL emergency, it is necessary to act immediately and to start with recovery measures, which require organized work and clearly defined procedures withthe aim of establishing the normal operating state as soon as possible.

After the accident, the most important thing was to find possible network power supplies and to perform urgent temporary or permanent recovery of the damaged OHLs, based on the realistic possibilities in the network considering the significance of their damage.

For that reason, modular towers are used. Emergency modular towers enable the establishment of temporary operation of a damaged overhead line in such a way that interruption of operation is minimal. The same is achieved in such a way that, after their installation, conductors and grounding wires are transferred to them. This enabled uninterrupted operation of the transmission line until the construction of new steel lattice towers, and the interruption of operation was limited only to the time needed to disconnect the conductors and grounding wires from the existing pole and hang them on temporary modular towers. An example of their implementation is shown in Figures 14 And 15 and previously used and elaborated [13].

Fig.14. Modular tower installation

Fig. 15. View on consoles and conductors of one installed modular tower

HOPS owns modules and equipment for the formation of 110 kV, 220 kV, and/or 400 kV towers [13,16], but it is important to mention that without support from neighboring TSOs and loans of their modular towers, there wouldn't be enough of them, and the normal operation of the transmission network would not be established.

In the transmission area ZG, the next day after the storm on July 19th, preparation for damaged OHL recovery has started, and priorities for repair have been agreed upon. The priorities implied the establishment of temporary powersupply for OHL 110 kV Međurić–Daruvar (which was put back in temporary operation on 28th July), OHL 220 kV Međurić–TPP Sisak, due to the importance of the line for the 220 kV network (which was put back in temporary operation in the middle of August), and other 110 kV OHLs.

On the transmission area OS, priorities for repair implied OHLs 220 kV Đakovo–Gradačac and Đakovo–Tuzla (where temporary repair was not possible considering the major damage on the BA side), interconnection OHLs 400 kV Ernestinovo–Sremska Mitrovica (which was put back in temporary operation in the middle of August), and other 110 kV OHLs.

Final repair of the damaged OHLs lasted until the first half of 2024, due to the procurement procedure of replacement equipment etc.

IV. Recommendations and Lessons Learned

This paper shows an example of direct impact of climate change on essential TSO assets, such as power system OHLs or substations. It is shown that in areas with basic expected wind speed in the range of 20-25 m/s, a wind with strength above 50 m/s can occur and consequently, cause significant damage in a wider area, and therefore endanger the safe operation of the entire power system. From this, we can conclude that TSOs should be prepared to act immediately,and therefore:

- to consider establishment of internal resilience mechanisms (methodology and plan) based on a probabilistic risk-based method including different climate models,
- to establish a database of emergency events at the TSO level,
- to ensure availability of weather data & measurements from different platforms & tools (particularly for wind, ice, snow, wildfire, floods, lightings, saline pollution, dust, sand, and other possible weather impacts),
- to prepare risk maps based on the above-mentioned data, update them on a yearly basis, and correlate them with the most critical overhead lines from the system operation state of view,
- to prepare the "action plan for unpredictable weather phenomena" with neighboring TSOs/DSOsand other relevant institutions in the country, including determination of the OHL priority list for the returnto operation in case of emergency events,
- to ensure enough replacement equipment for unpredictable weather phenomena (i.e., modular towers, insulators, etc.),
- to ensure enough technical staff (together with machinery/vehicles) that will be in a state ofreadiness for emergency events and to educate them on how to design and mount such equipment,
- to establish an internal working group that will recognize and recommend stricter requirements according to valid standards and communicate them to the transmission line designers (i.e., NNA in Croatia).

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In general, grid resilience refers to the ability of an electrical power grid to anticipate, prepare for, respond to,and recover from disruptions, whether caused by natural disasters, cyberattacks, equipment failures, or other unexpected events.It involves the grid's capacity to maintain and quickly restore reliable electricity supply in the face of such challenges.

It is obvious that the causes of OHL outages can be from different factors and that it is impossible to predict them, especially if they are being triggered by unpredictable weather events. So, it is important for TSOs, especially located in our Mediterranean region to consider establishing of Resilience mechanisms, in terms of "Resilience Methodologies and Plans", that are already implemented in other TSOs.

For instance, TERNA (IT) has integrated climate adaptation measures into its operations.Key initiatives include climate impact assessments, resilient design standards, methodology and plan, and digitalization [17-18].

IPTO (GR) has a resilience strategy [19] that emphasizes the importance of network modernization to manageincreasing renewable energy penetration and extreme weather resilience by strengthening inter-island and mainland connections to reduce dependency on vulnerable systems, deploying advanced automation and monitoring systems to anticipate and mitigate risks from climate-related disruptions, etc.

Tennet (NE & DE) integrates resilience [20] into its operations by deploying innovative offshore grid solutions. One of its key strategies includes the development of multi- purpose interconnectors, which combine the functions of connecting offshore wind farms and enabling cross-border electricity trade. This reduces the need for extensive infrastructure while ensuring reliability and adaptability to extreme weather events.

National Grid (UK) has a detailed climate change adaptation plan [21] that includes investments in flood defenses, upgradings ustations,and using predictive analytics to assess risks from extreme weather. The company allocated over £150 million to mitigate flooding risks at high-priority sites and has embedded resilience measures into its asset management strategies.

Elia (BE) focuses on grid reinforcement and the deployment of digital technologies to enhance operational resilience [22]. They conduct regular assessments of infrastructurevulnerabilityto extreme weatherandcollaborate with other European TSOs to optimize grid stability during regional crises.

Such resilience measures not only protect infrastructure, but also ensure continuous operation amidst increasing climate-related disruptions. Construction of new infrastructure is definitely the best preventive measure for increasing grid resilience, but not always possible. So, the establishment of monitoring & observability measures is also very important, and requires the implementation of smart grids, new technological solutions, digitalization etc.

V. Conclusion

In recent years, the effects of climate change have led to increasingly frequent extreme weather events. For TSOs, it means greater exposure of their infrastructure to levels of stress that could endanger service continuity. Understanding these potential impacts is crucial for designing resilient,robust, and adaptive energy infrastructure.

Due to strong storms that occurred on July 19th and 21st, 2023, and direct impact of strong wind and lightning strikes,in total, 59 OHLs were disconnected from the network.Almost half of these OHLs were significantly damaged. In total, 51 transmission towers were damaged, which is equal to approximately 17 km of transmission route. In order to immediately restore the damaged part of the transmission network, in total, 22 modular emergency restoration towersare used. Other damages require more time for repair.

This fact led us to the conclusion that detailed planning and preparation in advance are necessary, together with the determination of critical OHLs that will likely remain undamaged and, as such, help in restoring the network as soon as possible.

Also, based on example from this paper, it would be beneficial for TSOs to ensure enough modular emergency restoration towers and other equipment, in order to cover at least a 25-30 km route of transmission line corridor.

Taking into account all the events of the last few years, it is evident that the impact of climate change is gaining momentum. Although the number of OHL outages and damages cannot be immediately visible in the statistics of operating events, TSOs should consider stricter OHL design requirements in order to adapt to the newly created circumstances. It can be beneficial for the design of new OHLs, especially if they are located in areas sensitive to some of the above-mentioned climate factors.

At the end, as climate change continues to present new challenges, the resilience of power networks is playing an increasingly vital role in ensuring reliable and sustainable energy supplies. So, in the new circumstances, TSOs should consider the establishment of resilience mechanisms. By adopting a holistic approach that includes technological innovation, infrastructure upgrades, policy support, and community engagement, power networks can be better prepared to face the impacts of climate change and maintain continuity of service in the face of growing uncertainties.

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