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Impact of Meteorological Conditions on Overhead Transmission Line Outages in Lithuania

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Abstract: This study investigates the impact of meteorological conditions on unplanned outages of overhead transmission lines (OHTL) in Lithuania's 0.4–35 kV power grid from January 2013 to March 2023. Data from the Lithuanian electricity distribution network operator and the Lithuanian Hydrometeorological Service were integrated to attribute outage events with weather conditions. A Bayesian change point analysis identified thresholds for these meteorological factors, indicating points at which the probability of outages increases sharply. The analysis reveals that wind gust speeds, particularly those exceeding 21 m/s, are significant predictors of increased outage rates. Precipitation also plays a critical role, with a 15-fold increase in the relative number of outages observed when 3 h accumulated rainfall exceeds 32 mm, and a more than 50-fold increase for 12 h snowfall exceeding 22 mm. This study underscores the substantial contribution of lightning discharges to the number of outages. In forested areas, the influence of meteorological conditions is more significant. Furthermore, the research emphasizes that combined meteorological factors, such as strong winds accompanied by rain or snow, significantly increase the risk of outages, particularly in these forested regions. These findings emphasize the need for enhanced infrastructure resilience and targeted preventive measures to mitigate the impact of extreme weather events on Lithuania's power grid.

Keywords: overhead transmission lines outages; wind speed; precipitation amount; lightning discharges

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1. Introduction

A large part of overhead transmission lines (OHTL) outages is caused by their extended length and vulnerability to various factors, including constant ones like manufacturing and operation, as well as variable factors such as climatic conditions and human activity. Seasonal variations also play a role, with more outages occurring in spring and summer due to thunderstorms and high temperatures, while winter poses increased risks from stronger winds and solid precipitation. The growing influence of global climate change and the increased occurrence of extreme weather events have led to a rise in emergencies and outages within electrical grid companies. As climate change intensifies, the aging power grid, combined with increasing energy demands due to population growth, is expected to result in a higher likelihood of power outages [1–3] and raises concerns about the resilience of the electric grid to future climate and weather hazards. The impacts of power outages are heterogenous among different countries and larger impacts occur in countries of lower-income, larger land area, and lower electrification rates [4]. Additionally, increased social impacts are expected as the likelihood of outages increases [5].

In 2022, the Intergovernmental Panel on Climate Change (IPCC) released its sixth report, highlighting that human-induced climate change is already having a more extensive and profound impact on both nature and human populations than previously expected [6]. This report underscores that certain consequences of climate change are now inevitable, manifesting with greater intensity and frequency across broader geographic regions. As climate change progresses, there is a significant increase in the likelihood and severity of extreme meteorological conditions. Heatwaves are becoming more prolonged and intense [7], heavy rainfall events are occurring more frequently, leading to increased flooding [8], and both the frequency of storms and associated wind speed are rising simultaneously [9,10]. It is also known that thunderstorm activities are shifting towards the north, making summertime lightning density much higher in the northern regions, including Lithuania [11]. Additionally, increased intraseasonal variability in winter temperatures [12] contributes to an elevated risk of icing or wet snow load events in some parts of the European continent [13]. The increasing frequency of these phenomena collectively leads to higher losses and costs for the society, business, and the electricity sector.

Extratropical storms, with their strong winds, are among the foremost natural hazards in Europe, causing extensive damage to forests and society [14,15] and acting as a primary cause of OHTL outages worldwide [16]. Between 1980 and 2020, climate-related disasters accounted for approximately 80% of the total economic damage caused by natural hazards in the EU [17]. According to the EMDAT database, storms and floods each comprised about 35% of the total reported disasters, collectively making up nearly 70%. Notably, storms have been the most significant disaster type, impacting almost 60% of the entire EU [18]. In highly forested countries, power distribution companies face substantial challenges due to such storms, with falling trees leading to power outages affecting hundreds of thousands of customers annually [19]. Analysis shows that a 20% increase in the average values of extreme wind speed and ice thickness can decrease the reliability of the power line by 30% and 17%, respectively [20].

Lightning poses another significant risk to OHTLs. Lightning discharges can cause various forms of damage, including temporary disconnections or shutdowns following direct strikes. Additionally, nearby lightning strikes can lead to temporary disturbances in the operation of these lines. Historical outage data provided by the UK's NaFIRS indicate that lightning strikes were the primary direct cause of over 20,000 supply interruptions between 2010 and 2019 [21]. Studies have shown that these outages can result in substantial economic losses due to the need for repairs and maintenance and reduced service reliability, as well as the economic impact of power outages on consumers and businesses [22,23]. Lightning strikes also cause significant economic losses in the electricity sector by damaging infrastructure and reducing the reliability of power systems. For example, in China, lightning-related damages increased from $7.4 million in 1997 to $66 million in 2007 [24].

Icing on transmission lines can lead to increased mechanical load on the structures, causing line sagging, conductor galloping, and even tower collapses. This results in power outages and costly repairs. The phenomenon is particularly prevalent in regions with frequent snowfalls [25,26]. The accumulation of wet snow on power lines and ice storms poses significant challenges, leading to power supply failures during the cold season. In recent years, numerous widespread power outage incidents have been attributed to extreme atmospheric icing on electricity transmission and distribution networks caused by ice storms and wet snowstorms. These phenomena generate wet snow and ice, leading to extensive financial losses and prolonged power outages [27].

Ensuring the reliability and resilience of electricity infrastructure is a critical global concern, as modern society relies heavily on a consistent and adequate electricity supply. The significant interconnectedness between the electricity sector and other crucial infrastructure systems means that disruptions in this sector can have severe consequences for national security, societal and economic stability, and public health. Climate change, along with its associated extreme weather events, presents increasingly complex challenges that we must prepare for and overcome in the future.

Lithuania's power supply infrastructure, consisting of over 85,000 km of 0.4–35 kV overhead transmission lines and running through forested regions (forests cover one-third of the country's territory), is significantly vulnerable to disruption from windstorms, lightning, heavy snowfall events, and icing. The aim of this research is to determine the impact of meteorological conditions on the number of outages in the 0.4–35 kV power grid and to identify the threshold values of hazardous meteorological conditions or their combinations that lead to a significant increase in outages in Lithuania.

2. Materials and Methods

Unplanned OHTL outage data in the 0.4–35 kV power grid were obtained from the Lithuanian electricity distribution network operator "Energijos skirstymo operatorius AB" (ESO), covering the period from January 2013 to March 2023.

The data include information on the date, time, and duration of each outage event, as well as the line where the event was recorded. These data were integrated with the grid OHTL network data, including coordinates, to determine outage locations.

Meteorological and lightning data, provided by the Lithuanian Hydrometeorological Service, were used in this research. Hourly data from 25 meteorological stations were employed, covering air temperature (°C), precipitation amount (mm), and average and maximum wind speeds (m/s) (Figure 1).

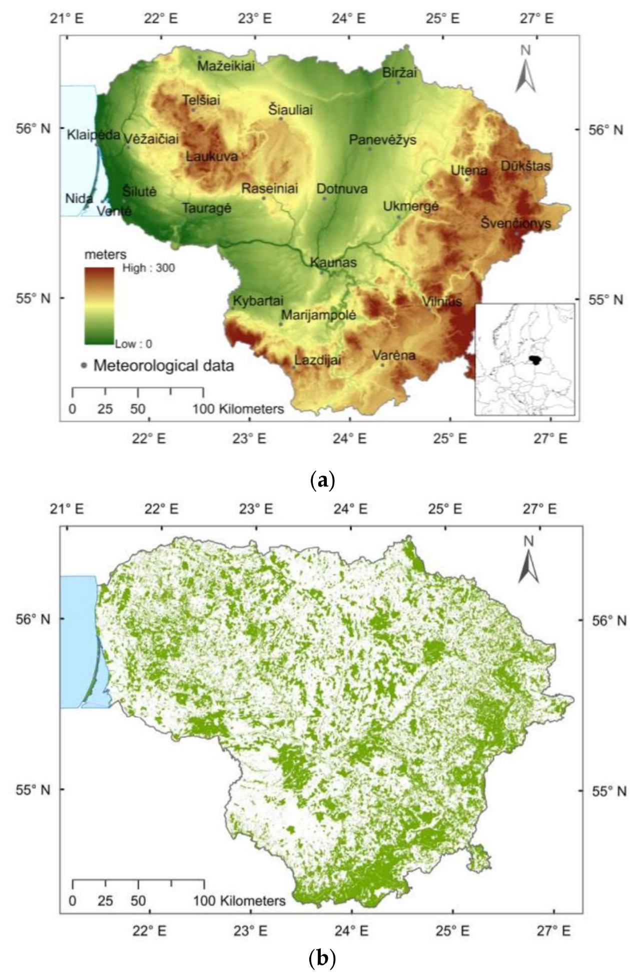

Figure 1. Topographic map of Lithuania with locations of the meteorological stations whose data were used in the study (**a**) and forest cover (**b**). Data obtained from georeferenced spatial dataset of the territory of Lithuania (GDR250LT).

Each OHTL outage was assigned to the nearest meteorological station. To determine the nearest station, 25 spatial polygons were created, one for each station. By intersecting the spatial information of the OHTL network with these polygons, the nearest meteorological station was assigned to each OHTL. The corresponding hourly meteorological information from the designated station was then linked to each outage event.

Using the state-georeferenced dataset, GDR50LT, we determined the percentage of each OHTL passing through forested areas. If any part of the line crossed a forest, it was considered as a line in a forested area. A total of 276,334 unplanned OHTL outages occurred in Lithuania from January 2013 to March 2023. Of these, 49.4% occurred in forests and 50.6% in non-forest areas. The average length of an overhead line is 0.41 km (1.28 km in forests and 0.21 km in non-forest areas), though in some cases, it exceeds several kilometers.

To determine the impact of lightning on the number of outages, 95,650 cloud-to-ground lightning strikes recorded in the territory of Lithuania from April 2018 to December 2022 were analyzed. This period was chosen due to data availability, as lightning in Lithuania has only been measured by their type (i.e., cloud-to-cloud, cloud-to-ground) since 2018. The territory of Lithuania was divided into a $0.25 \times 0.25^{\circ}$ grid, where the hourly sums of lightning strikes and the number of outages were calculated. These results were then recalculated for a 1000 km^2 area. Throughout the study period, 6037 OHTL outages were recorded during cloud-to-ground lightning events in certain areas.

Even in the absence of hazardous meteorological conditions, OHTL outages occur due to infrastructure faults, deliberate or accidental human impacts, and damage caused by wildlife and vegetation. On average, there were 3.1 overhead-line disconnections per hour in Lithuania or 0.036 disconnections per thousand kilometers of line. To assess the impact of meteorological conditions on the rate of OHTL outages, we calculated the relative number of outages (RNO) by dividing the number of outages associated with specific meteorological indicator values by the average number of outages observed over the entire study period. According to national regulations, an emergency situation arises in Lithuania when the number of disconnections exceeds 50 per hour, as this overwhelms repair teams availability and leads to an accumulation of outages. This scenario can be attributed to a more than 15-fold increase in disconnections compared to the average rate. This 15-fold increase criterion serves as a threshold in this research.

Not all meteorological variables are equally effective at describing the hazardous conditions leading to outages. To identify the most important variables, we evaluated how well each one correlates with the increase in the relative number of outages (Figure 2). OHTL outages are influenced not only by the meteorological conditions at the time of the outage but also by the conditions leading up to it. To evaluate these influences, we analyzed various variables, such as average wind and gust speed, snow and rain amounts, and mean air temperature over different time periods: 1, 3, 12, and 24 h. Minimum and maximum air temperatures were calculated for a 24 h period only. We divided each variable range into 20 bins and calculated the RNO for each bin. The last 20th bin represents maximum values and the most extreme conditions. Consequently, it has the smallest number of occurrences and thus the highest uncertainty. To minimize this uncertainty while comparing OHTL sensitivity, we used the RNO calculated with each variable values from the second largest bin (19th).

The most significant indicator of wind impact was the gust speed, either measured during the outage or over the 3 h preceding it. The mean wind speed had a much lower impact on OHTL outages compared to gusts.

Snow accumulation over the 12 h before an outage was a slightly better predictor of outages than 24 h accumulation and significantly better than shorter-term snow accumulation. The pattern for rain was different. Outages increased most significantly with rain accumulated over 1 and 3 h before the outage, while rain accumulated over longer periods had a weaker effect. Therefore, this study focused on analyzing the impact of 3 h and 12 h totals for rain and snow, respectively. Rain was distinguished from snow based on air temperature and relative humidity indicators, using a methodology developed by Finnish and Swedish scientists [28].

Unfavorable air temperature conditions led to a smaller increase in OHL outages. It is likely that the direct effect of air temperature is small and is more manifested in the fact that it characterizes the conditions for the formation of complex hazardous meteorological phenomena. For example, when the air temperature is close to 0 °C, icing or wet snow cover is likely, but the air temperature itself does not have a direct impact on the OHL outage increase. Among all air temperature indicators, the maximum temperature over the 24 h before the outage had the greatest impact on the relative number of outages (RNO) (Figure 2).

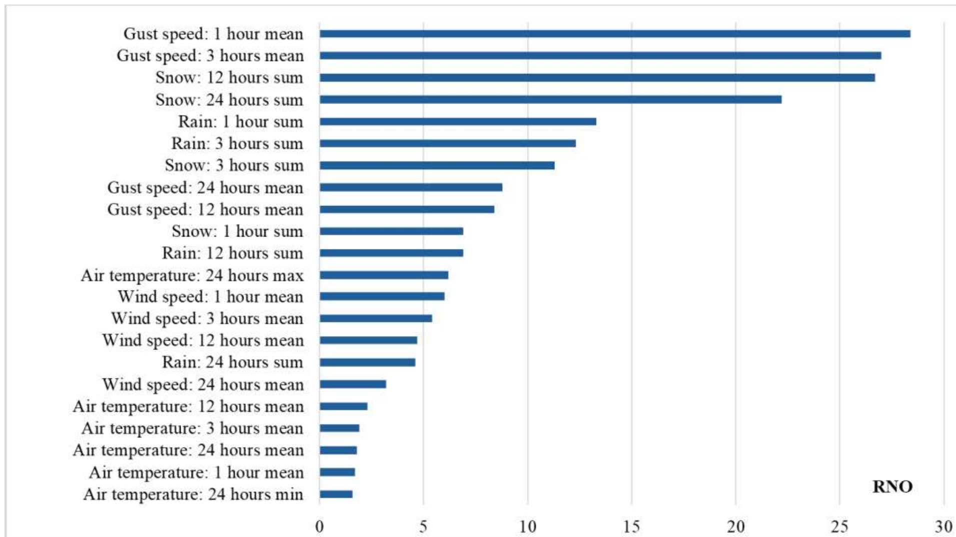

Figure 2. The impact of hydrometeorological elements on the increase in the number of 0.4–35 kV OL outages. The figures indicate how many times (RNO) the number of outages exceeds the average under very unfavorable conditions.

To identify sudden shifts in time series, indicating significant changes in mean or variance, various change point detection methods are employed. Change point detection methods are useful tools for identifying sudden shifts or structural breaks in time series data. They operate by identifying alterations in the underlying properties of a time series, like mean, variance, or trend, to indicate points where the series deviates from its prior behavior. These shifts are typically detected by comparing segments of the time series across different intervals and measuring statistical discrepancies between them. Such methods are especially valuable for identifying transitions in natural phenomena or system behaviors, enabling the detection of anomalies or adapting predictive models accordingly. One advanced method is Bayesian inference, which effectively identifies change points in complex and high-dimensional time series data. This approach aids in understanding system dynamics, detecting anomalies, and making future projections [29]. Bayesian analysis uses a probabilistic model to measure confidence in inferences based on specific assumptions. It treats unknown parameters or hypotheses as random variables rather than constants, making it particularly suitable for climate research [30]. In our study, we used the R version 4.4.1 bcp.package for Bayesian change point analysis, which returns the posterior probability of a change point occurring at each time index in the series. This package is designed to detect changes in the mean of independent Gaussian observations [31]. Interpreting a shift involves assessing the posterior probability at each point: a high posterior probability indicates a likely structural break. Structural breaks suggest that the process generating the data has undergone a change, making the patterns before the break potentially different from those after it. Structural breaks can highlight particular weather thresholds (e.g., wind speeds, precipitation levels) where transmission line reliability begins to decline. This can be useful for modeling the risk of outages under specific severe weather conditions and planning preventive maintenance or design reinforcements for resilience.

3. Results

3.1. The Impact of Meteorological Factors on the Number of Power Outages in OHTL

Meteorological conditions such as strong winds, snow load, or lightning can have a significant impact on OHTL and power supply. These factors can lead to both short-term and long-term disruptions in the power supply system.

3.1.1. Wind Speed

As the average wind speed increases, RNO starts to rise significantly after surpassing the 6 m/s threshold and continues to grow until it reaches 11 m/s, at which point the RNO exceeds five (Figure 3). After this threshold, the RNO remains relatively constant. The Bayesian analysis did not reveal any change points in this pattern.

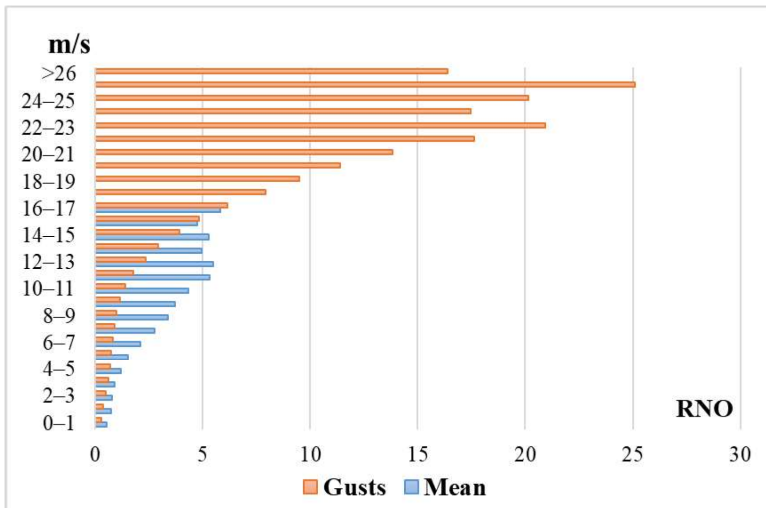

Figure 3. Dependence of RNO on wind speed. The last column of the mean wind speed displays all cases where the wind speed is >16 m/s.

Changes in maximum wind gust values have an exponential impact on the outage rate. When wind speeds increase to 21 m/s, the number of outages is 15 times higher than average. At 25 m/s, the number of outages increases 25 times. The Bayesian change point detection analysis indicates that these wind speeds have the highest probability ($p > 0.7$) of causing significant increase in outages. Upon reaching the 25 m/s threshold, the power outage rate per hour for 1000 km of OHTL reaches 0.95.

In forested areas, the RNO increases until the average wind speed reaches 11 m/s, at which point the number of outages is nine times higher than the average (compared to five times in non-forested areas). Beyond this threshold, the rate of increase stabilizes.

The relative increase in the number of outages due to rising wind gust speeds occurs slightly earlier in forested areas. On average, in the Lithuanian territory, a 10-fold increase in outages is observed at 18 m/s in forests, whereas this increase occurs at 19 m/s in non-forested areas. Similarly, a 15-fold increase is recorded at 20 m/s in forests, compared to 21 m/s in non-forested areas.

Extremely strong winds are rare in most of the country's territory and are significantly more frequent along the coastline (Figure 4a). In many regions of the country, wind speeds exceeding 21 m/s are not recorded annually, with several meteorological stations reporting no such occurrences during the study period. The average number of such days in the region closest to the Baltic Sea exceeds two days per year. However, since coastal overhead transmission lines (OHTLs) are designed to be more resistant to strong winds, the number of outages in coastal regions does not increase significantly under similar conditions as it does in other parts of the country. The strong design of coastal OHTLs helps them handle high winds with fewer disruptions. In contrast, in the eastern part of the country, where transmission lines may be less adapted, a greater impact under the same wind conditions is observed.

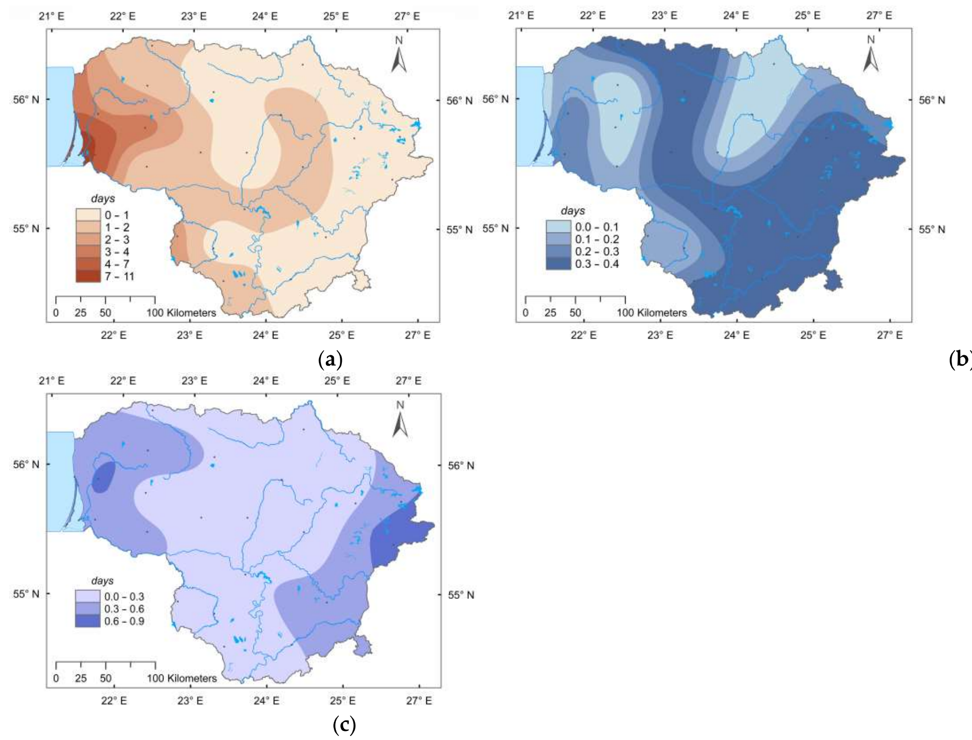

Figure 4. The average annual number of days when hourly wind gusts exceed 21 m/s (**a**), the rainfall amount exceeds 32 mm over 3 h (**b**), and the snowfall amount exceeds 16 mm over 12 h (**c**) in 2013–2022.

3.1.2. Precipitation

This study's results suggest that the RNO approaches 10 after 16 mm of rain accumulates over a 3 h period (Figure 5). Moreover, the threshold of 15 is exceeded, and a statistically significant breakpoint in RNO is reached (probability of change point 0.96) when the rainfall accumulation exceeds 32 mm over the same a three-hour period. Heavy rainfall is frequently associated with strong storms, complicating its attribution solely to the direct impact of rainfall; typically, it involves a combination of rain, wind, and, occasionally, lightning.

Similarly, analyzing snowfall, the RNO of 10 occurs when the snow accumulation over 12 h reaches 14 mm, increases to 15 times after 16 mm of snow, and surpasses 50 times after 22 mm of snowfall. However, the recurrence of such heavy snowfall was rare during the analysis period, suggesting that this estimation for extreme snowfall may lack reliability and could change significantly with additional occurrences of similar extreme events.

Extreme rain exceeding 32 mm in 3 h is rare. Such events are recorded on average no more than once every 3 years, and in some parts of the country, even less frequently than once a decade (Figure 4b). Days with extremely abundant snowfall (>16 mm) are also quite rare throughout Lithuania (Figure 4c). The southwest of the country records most of these events, while many meteorological stations have not recorded any such cases at all. This pattern broadly reflects the distribution of annual rainfall and heavy precipitation events in Lithuania. The main factors influencing this are moist air masses arriving from the west across the Baltic Sea and the country's varied topography. As these moist air masses reach the western slopes, they ascend, cooling adiabatically, which enhances convection and leads to increased precipitation. As the air masses descend on the leeward side, precipitation tends to decrease due to the downslope movement and drying effect.

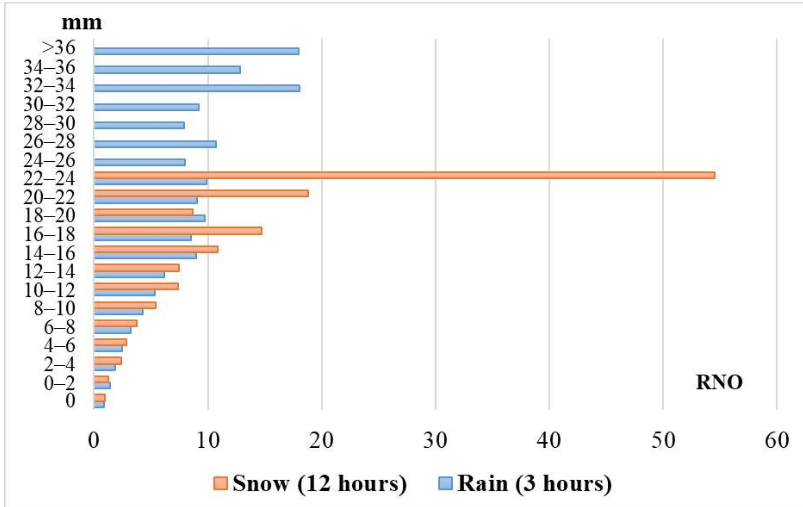

Figure 5. Dependence of RNO on accumulated rain (3 h) and snowfall (12 h) sums (mm). The last column of the accumulated snowfall displays all cases where the sum is >22 mm.

Although snowfall is expected to decrease as the climate warms, the probability of abundant snowfall will remain quite high, as extremely heavy snow tends to fall when the air temperature is close to 0 °C.

In both forested and non-forested areas, the number of outages increases with the amount of rainfall, but the increase is much faster in forested areas. In forested areas, the number of outages increases 5-fold with 8 mm of rainfall over 3 h, whereas in non-forested areas, it takes 14 mm of rainfall to see a similar increase. The 10-fold threshold is reached with 14 mm of rainfall in forested areas and 18 mm in non-forested areas.

In forested areas, when the 12 h snowfall amount approaches 10 mm, the number of outages increases 10-fold, and with 16 mm of snowfall, it increases 20 times. When the snowfall exceeds 22 mm, catastrophic consequences are observed, with the number of outages increasing more than 50-fold (probability of change point—0.98). In this case, the probability of outages per hour reaches 1.7 per 1000 km of power lines. However, it is important to note that such events are very rare, and this number is derived from only a few cases. In non-forested areas, the 10-fold threshold is nearly reached with 16 mm of snowfall, the 15-fold threshold with 20 mm, and, similar to forested areas, a sharp increase to more than 50-fold is observed when the snowfall exceeds 22 mm.

3.1.3. Air Temperature

The impact of air temperature on the number of outages is not very significant. With the air temperature rising to 19 °C, the RNO climbs to 1.5, and upon reaching 30 °C, it further increases to 1.8. (Figure 6). The increase in the number of outages can be explained by both the increased energy demand and the direct heat impact on power transmission lines. On the other hand, as the temperature rises, the intensity of economic activities in open areas also increases, which can lead to an increase in the number of unintentional damages to power lines.

At lower temperatures, the number of outages is slightly lower than average. Their number slightly increases at temperatures close to 0 °C. This is related to line damage occurring during frequent temperature transitions around 0 °C. Lines may freeze, or wet snow coating can form. The number of outages also increases slightly during extremely cold temperatures (below −20 °C). This can be attributed to both the rise in energy demand

and the direct impact of the cold weather on the infrastructure. No significant differences in the impact of air temperature were observed between forested and non-forested areas.

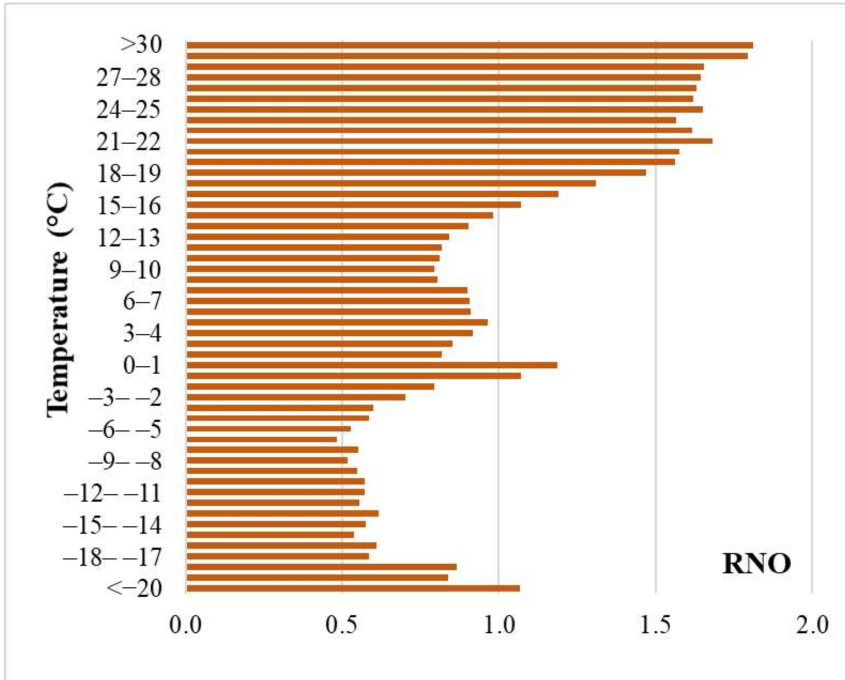

Figure 6. Dependence of RNO on air temperature.

3.1.4. Lightning

During the study period, 6037 power outages were recorded in OHTLs during cloud-to-ground lightning events. If all these outages were attributed to lightning strikes, it would mean that every 16th lightning strike caused an outage. However, some outages were likely influenced by wind or precipitation during storms, making it difficult to precisely identify the exact cause of each outage.

A linear relationship was observed between the number of OHTL outages and lightning discharges, as shown in Figure 7. As the number of lightning discharges increases, the number of outages also rises. On average, Lithuania experiences 0.05 outages per hour per 1000 km^2 (in 2018–2022). In total, 83% of lightning events range from 1 to 10 strikes per 1000 km^2 per hour, resulting in outages rates that are 4 to 12 times higher than on average (Table 1). However, when the hourly number of lightning discharges ranges from 11 to 20, the average outage rate increases significantly to 0.8 per 1000 km^2, marking a 17-fold increase compared to the baseline. With the increase in the number of cloud-to-ground lightning discharges per hour to 60, the number of outages increases by 50 times. However, such cases are extremely rare (Figure 7; Table 1).

Differences are noticeable when evaluating forested and non-forested territories. The data from the analyzed period indicate that thunderstorms led to more power outages in forested areas (4421 outages). This constitutes 73% of all outages during lightning. With 11–20 lightning discharges per 1000 km^2, the number of outages increases by 22 times compared to the average (Figure 7).

Significantly fewer outages, totaling 1616, were detected in non-forested areas. The number of outages increases linearly with up to 80 cloud-to-ground lightning strikes per 1000 km^2 per hour, after which it stabilizes. In non-forested areas, 11–20 lightning strikes per 1000 km^2 result in a 10-fold increase in outages, significantly lower than in forested areas. Statistically significant breakpoints based on the Bayesian analysis were not identified.

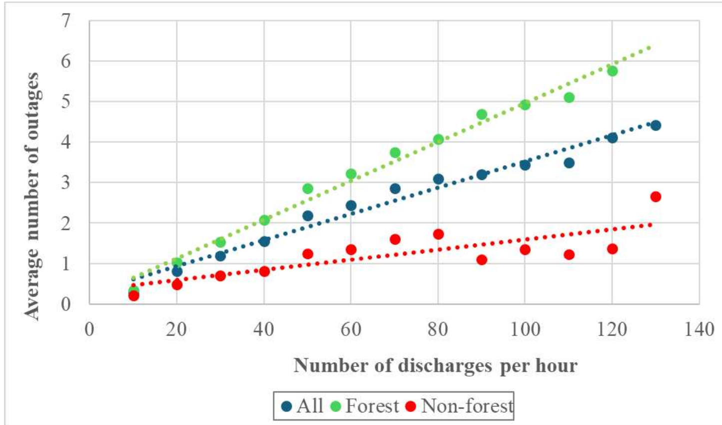

Figure 7. Dependence of the hourly mean number of OHTL outages on the number of cloud-to-ground lightning discharges in forested and non-forested areas.

Table 1. Recurrence of cloud-to-ground lightning discharges and the number of OTHL outages per 1000 km^2.

Hourly Number of Lightning Discharges (Recurrence, %)	Mean Number of Outages	Relative Number of Outages (RNO)
1–2 (46.10)	0.20	4
3–4 (1.00)	0.30	7
5–6 (8.70)	0.40	9
7–8 (9.50)	0.50	11
9–10 (3.00)	0.60	12
11–20 (8.69)	0.81	17
21–30 (3.43)	1.19	25
31–40 (1.97)	1.55	33
41–50 (0.81)	2.20	47
51–60 (0.54)	2.44	52
61–70 (0.40)	2.87	61
71–80 (0.23)	3.10	66
81–90 (0.16)	3.20	68
91–100 (0.09)	3.44	73
101–110 (0.10)	3.49	74
111–120 (0.07)	4.11	87
>120 (0.20)	4.42	94

3.2. Compound Meteorological Events

In previous sections, we analyzed the effect of individual meteorological elements. However, each element only reflects one dimension of the complex meteorological conditions. To better understand these compound effects, we analyzed the combined impact of two meteorological elements on OHTL outages.

This approach allows us to better identify and understand hazards, though the probability of combined extreme conditions is much lower than when analyzing individual elements. For example, strong wind gusts (>20 m/s) are infrequent, as is rain accumulation of more than 8 mm over 3 h. The likelihood of these conditions occurring simultaneously is even lower, resulting in few or no cases for some combinations (Figure 8). Combining more variables would further decrease the probability of such combinations and significantly increase the uncertainty of the results. Therefore, we limited our compound conditions research to combinations of two variables.

The data indicated that wind and prolonged accumulation of rain or snow had the greatest effect on increasing number of outages. The impact of rain during periods of strong wind becomes significant only when the amount of rain accumulated over 3 h exceeds

8 mm (Figure 8). However, even with high rainfall amounts, the RNO never reached 15 when wind gust speeds were lower than 10 m/s. The highest values occur when wind gust speeds exceed 20 m/s, similar to the threshold estimated in the individual wind speed analysis.

Figure 8. The combined effect of rain accumulated over 3 h before the outage and wind speed during the outage on the RNO in OHTL. The white areas represent conditions which did not occur during the analysis period.

The impact of rain combined with strong winds in forested areas was greater than in non-forested areas. Rain increases the vulnerability of trees to wind by saturating the soil, reducing root stability, adding weight to the tree canopy, and enhancing mechanical stress on branches. This makes trees more likely to experience uprooting or breaking branches during storms. The data analysis in our study reveals that even a relatively small amount of rain significantly increases the likelihood of outages. In forested areas, the RNO reached 15 when wind gusts reach or exceed 18 m/s and the rainfall over a 3 h period exceeds 3 mm. The probability of such meteorological conditions is quite high. Most often, such conditions are formed in western Lithuania (Figure 9).

Even small amounts of snow during strong wind events increase the number of outages by several times (Figure 10). The effect of snow becomes particularly evident when the wind speed in gusts is higher than 15 m/s. In such cases, even the 1–2 mm of snow accumulated over 12 h period could increase RNO by 15 times. Similar to the rain impact, snow accumulation does not make a significant impact when the wind speed in gusts was lower than 10 m/s.

The impact of snow combined with strong winds is significant in both forested and non-forested areas. Even a relatively small amount of snow (3 mm) accompanied by gusts of 14 m/s greatly increases the likelihood of outages, and such conditions are quite frequent (Figure 9). The most pronounced effect of snow occurs when the air temperature is close to 0 °C, likely due to wet snow accumulating on power lines or trees.

The combined effect of air temperature and precipitation is 2-fold. In the absence of precipitation, the probability of disconnections was only higher than the average when the air temperature was above 16 °C (Figure 11). With temperatures above this threshold, the number of OHTL outages increases even with small amount of rainfall (1–2 mm over 3 h) and grows with increasing rainfall, but the RNO reaches 15 only during few irregularly distributed high air temperature and high rainfall amount combinations and probably are also related to strong wind gusts during storms. The number of OHTL outages also increases when the temperature is close to freezing. In such temperatures, the probability of outages grows with the amount of precipitation, indicating that the outages are most likely caused by freezing rain, wet snowfall, or a similar phenomenon.

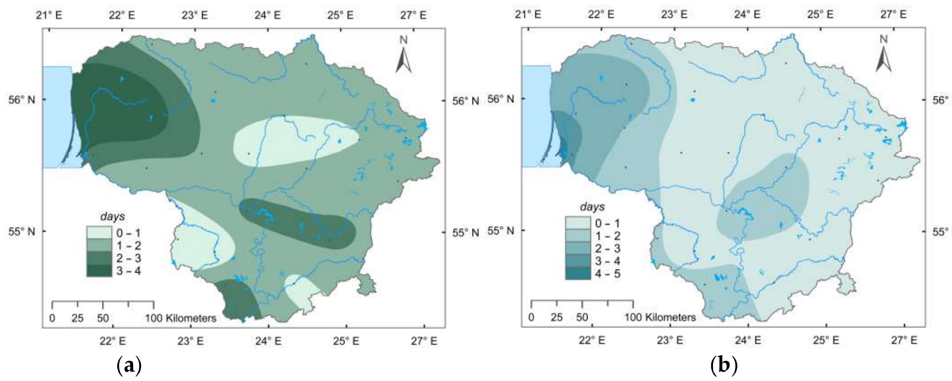

Figure 9. The average number of days per year with complex phenomena leading to a significant increase in the number of OHTL outages: (**a**) the wind speed exceeds 18 m/s, and the precipitation sum exceeds 3 mm in 3 h; (**b**) the wind speed exceeds 14 m/s, and the snowfall sum exceeds 3 mm in 12 h.

Figure 10. The combined effect of snow accumulated over 12 h before the outage and wind speed during the outage on RNO in OHTL. The white areas represent conditions which did not occur during the analysis period.

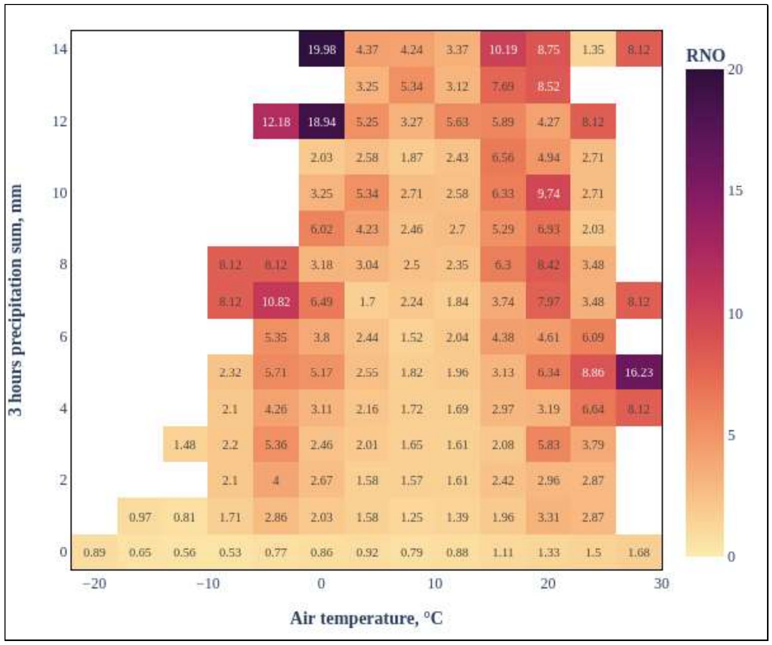

Figure 11. The combined effect of rain accumulated over 3 h before the outage and air temperature during the outage on the RNO in OHTL. The white areas represent conditions which did not occur during the analysis period.

4. Discussion and Conclusions

This study investigates the impact of various meteorological conditions on the frequency of unplanned outages of overhead transmission lines (OHTLs) in Lithuania's 0.4–35 kV power grid from January 2013 to March 2023. The investigation revealed that wind gust speeds, heavy precipitation, and lightning are the primary drivers of these outages, with compounded meteorological conditions significantly exacerbating the risk. Meanwhile, the direct impact of temperature is negligible.

A key factor is the significant rise in outage rates as wind gust speeds increase. When wind speeds reach 21 m/s, the number of outages increases 15-fold, and at 25 m/s, the outages rise 25-fold. This increase is more pronounced in forested areas where a 15-fold increase is observed at 20 m/s compared to 21 m/s in non-forested areas. This significant influence of wind gusts on outage rates aligns with findings from studies in other countries [19,32]. These findings are essential for power grid management, emphasizing the need for focused interventions in heavily forested areas frequently exposed to strong winds.

Precipitation, particularly heavy rainfall and snowfall, also plays a critical role. The analysis shows a significant increase in outages with accumulated rainfall and snowfall. A 15-fold increase in outages is observed when 3 h accumulated rainfall exceeds 32 mm. Similarly, when 12 h snowfall exceeds 16 mm, the relative number of outages increases 15-fold, highlighting the severe impact of heavy snowfall on the power grid. The substantial increase in outages during heavy precipitation events corresponds with the other research [13,33]. However, our study offers a more precise quantification of the impact thresholds specific to the Lithuanian conditions.

Lightning discharges are another significant factor contributing to substantial outages, especially in forested regions. The data indicate that during periods of high lightning activity, the number of outages can spike dramatically. For example, when the frequency of cloud-to-ground lightning strikes exceeds 50 per hour (per 1000 km^2), the number of outages increases by approximately 10-fold compared to periods with no lightning. In forested areas, the impact is even more pronounced, with the number of outages increasing up to 12-fold under similar lightning conditions. However, lightning often affects areas where wind or precipitation during storms likely played a role, making it challenging to pinpoint the exact cause of each outage.

This study's most critical insight lies in its analysis of the compound effect of meteorological factors. The combined impact of strong winds and heavy precipitation (rainfall or snowfall) significantly amplifies the outage risk. For example, even with a small amount of rainfall (8 mm in 3 h), the outage rate increases sharply when combined with wind gusts exceeding 20 m/s. Similarly, in forested areas, the relative number of outages reaches 15 when wind gusts are 18 m/s or more, coupled with 3 mm of rainfall over 3 h. For snowfall, the relative number of outages increases 15-fold with only 1–2 mm of snowfall when wind speeds in gusts are higher than 15 m/s. Such gusting wind speeds, along with rainfall and snowfall accumulation over 3 and 12 h periods, occur relatively frequently. Consequently, the hazard posed by these compound events is significant and represents a substantial risk to the power grid. Other studies have demonstrated that compound events, such as the combination of strong winds and precipitation, have a greater impact on overhead power line damage than wind alone [2]. This further underscores the importance of incorporating compound events into risk assessment and management strategies.

Such studies help to understand how different meteorological factors, both individually and in combination, determine the reliability of power grids. By identifying specific thresholds, such as wind speeds or precipitation values that lead to increases in power outages in Lithuania, targeted mitigation strategies can be developed. Emphasizing the compounded effects of multiple weather phenomena highlights the need for a holistic approach to infrastructure resilience. Such studies are essential for policy making, optimizing resource allocation and ultimately strengthening the resilience of power systems in the face of climate change and the increasing frequency of extreme weather events [16].

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