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Impact of Lightning-Induced Wildfires on Power System Based on Satellite Data and Climatological Projections

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Abstract. The Mediterranean is one of the most cyclogenetic regions in the world. One of the most significant cyclone characteristics that can influence power systems is lightning. Except in the Mediterranean basin, favorable conditions for convection development and lightning appearance can be developed in other warm and moist conditions and in the mountain area. Every season, heavy lightning appears in Croatia, a small Mediterranean country through which the Dinaric Alps stretch. Lightning can cause various damages to the power system network, but also cause wildfire that can lead to additional enormous damages. It is well known that lightning can be very well forecasted by combining different meteorological models and satellite data. Various satellite data can also be used in forest fire monitoring, analysis, and risk prediction. Among the others, fire spreading depends on the vegetation and soil moisture conditions that can also be obtained by satellite. Some climate projections indicate that in the future, it is possible to expect more extreme conditions, more thunderstorms on one side, and more droughts on the other side. Thunderstorms can cause fire development and spread, especially when there is not enough humidity for rain and showers. During the drought, due to soil moisture decrease and vegetation dryness, wildfire spreading becomes easier daily. This paper will present the analysis of lightning-induced wildfires, endangered power system components in Croatia, and a climatic review of wildfires. A method for wildfire protection, vegetation growth monitoring, and post-fire landscape recovery monitoring will be suggested. Conducted analysis and suggested methods can be applied in power system planning and everyday operation through N-k (N-1) analysis. In the analysis, various satellite, meteorological, climatological data, lightning location system, and power system data are used.

Keywords. Power system, lightning, wildfire, satellite data, meteorological conditions, climatological projection

1. Introduction

Typical meteorological conditions favorable for wildfire development and spreading are long, hot, and dry periods. Lightning appears when there are favorable conditions for convection, enough moisture in the air accompanied by strong vertical motions.

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Lightning-induced wildfire events develop and spread when there is a cloud-to-ground lightning strike, and when there is not enough moisture in the air for heavy showers development, that can extinguish the fire.

In literature, lightning-induced forest fires are analyzed in the case of the mountain region, Austrian Alps region [1], and continental area, e.g., Continental United States [2]. Also, the combination of lightning-induced forest fires and surface conditions' influence on the fire spreading is analyzed [3]. This paper researches the lightning-ignited fire events and their impact on the power transmission network in Croatia, a small country with various geographical and climatological conditions. There meets the Dinaric Alps, Adriatic Sea, and Pannonian Valley. In the climate context, according to Köppen's classification, there are four climatological classes [4]. In addition to lightning-ignited fire events and their influence on the power system analyses, the article also presents climatological projections of the fire danger index for the area of Croatia and methods for landscape monitoring.

2. Materials and Methods

This study investigated forest fire events in Croatia and accompanying thunderstorm activity from the beginning of 2017 till the end of 2022. It researched lightning data, information about forest fire events, landscape characteristics before and after the fire events, climate projections, and the power system topology. The primary data sources are the Copernicus Earth Observation Programme, LINET lightning location system data, and Croatian Transmission System Operator (TSO).

2.1. Lightning Data

Lightning data is provided by the Lightning Location System (LLS) as part of the LINET lightning detection network. The distance between sensors is 150 to 250 km, guaranteeing homogenous high-quality coverage of large areas. Data analysis shows satisfactory detection efficiency of down to 2 kA and location accuracy with an average statistical error of 75 m [5]. In Croatia, there were installed six sensors. Data recorded with sensors installed in Italy, Hungary, Serbia, Bosnia and Herzegovina, Hungary, and Austria are also used to generate overall lightning activity in Croatia [6].

The location of each lightning strike is provided as a latitude-longitude point, together with the statistical error in meters. Around each lightning stroke location, a buffer is created with the radius of statistical error. In this way obtained polygon is classified as lightning location. It is well known that lightning can be between cloud and ground and vice versa, inter-cloud, intra-cloud, and between cloud and surrounding air. This research investigated cloud-to-ground (CG) and inter-cloud (IC) lightning activity.

2.2. Fire Events Information

Fire events information important for this research are fire start and end time, fire location, and surface. This information is provided by the European Forest Fire Information System (EFFIS) [7]. EFFIS is part of the Copernicus Programme. It was established to support the services in charge of the protection of forests against fires. Today EFFIS provides historical data about forest fire events, fire danger assessment, rapid damage assessment, potential soil loss, vegetation regeneration, and air quality according to fire events, European Forest Fire Information System, official web page.

From the overall dataset, it was filtered lightning-induced fire events. The fire event is classified as lightning ignited if:

- Lightning location polygon and fire polygon intersect,
- Lightning appeared up to 5 days before the fire started or during the fire event.

The five days before the fire started were observed because firefighters experienced that the smoldering period can be even 14 days. The smoldering period is usually up to four days [1]. It is decided to consider the most likely smoldering period (up to four days) and one more day for safety's sake.

2.3. Landscape Characteristics

The landscape characteristics are obtained by calculating the Normalized Burn Ratio (NBR) and delta NBR (dNBR) [8]. The NBR calculation uses satellite data, spectral bands 8A and 12. Those bands represent near-infrared (NIR) wavelengths and short-wave infrared (SWIR) wavelengths (Equation 1) [9].

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} = \frac{(Band[8A] - Band[12])}{(Band[8A] + Band[12])} \tag{1}$$

Satellite data are obtained by the Copernicus SENTINEL-2 mission managed by the European Space Agency (ESA). The data of interest from the SENTINEL-2 mission is recorded by Multi-Spectral Instrument (MSI). The image's spatial resolution is 20 m, and the revisit time is approximately 4.5 days for Croatian latitudes. ESA preprocesses satellite data, and that grantee its reliability to use. Before the NBR and dNBR indices calculation, satellite images were filtered according to cloud coverage. Only images whose cloud coverage at the location of interest was less or equal to 10% were processed in further research [10]. The cloud recognition and the image filtration were done using a cloud mask provided together with other satellite data.

2.4. Landscape Characteristics

Forest fire danger projection till the end of the 2098 year is provided by Copernicus Climate Change Service (C3S). It is one of the six Copernicus programs for Earth monitoring. C3S provides consistent and authoritative information about climate change. A wide range of data is classified into several categories according to the product type, variable domain, spatial and temporal coverage, sector, and according to provider.

The product "*Fire danger indicators for Europe from 1907 to 2098 derived from climate projections*" is used in this research. It is based on the Canadian Fire Weather Index (FWI) under future climate conditions. The FWI model is incorporated in the Global ECMWF Fire Forecasting model (GEFF), ECMWF significates European Centre for Medium-Range Weather Forecast. The FWI is a meteorological fire danger index used worldwide. In Croatia, it has been in use for many years. Meteorological parameters used as input in the FWI model are air temperature, wind speed, relative humidity, and 24-hour accumulated precipitation. The output of the model is fuel moisture indices and fire danger index. The model's spatial resolution is 0.115 x 0.11°, and temporal resolution is daily, seasonal, and yearly [11]. The model was run according to three

Representative Concentration Pathway (RCP) scenarios. In the scenario RCP2.6 it is supposed that emissions started declining before 2020. In scenario RCP4.5 emissions declining is beyond 2040, and in the scenario RCP8.5. emissions continue to rise through the century, Fire danger indicators for Europe from 1970 to 2098 derived from climate projections [12]. This research analyses all RCP scenarios from 2006 till 2098. It was compared the same model in different scenarios, and different models in the same scenario.

2.5. The Power System Topology

Lightning-induced fire events were analyzed in the Croatian transmission network. Croatian TSO provides the type and location of each power system object. The power systems' objects were classified into three categories:

- Objects that can be directly endangered by fire such as transformer substations, power plants, switchyards, traction substations, etc.
- Objects that may be endangered in the process of extinguishing the fire such as transmission lines and poles (e.g., fire extinguishing using Canadair).
- Objects that may be endangered in both situations, directly by fire and in the process of extinguishing the fire such as transmission lines.

The influence of each fire event on the power systems' object was observed according to the distance from the object. That distance is classified in spatial intervals: 0-0.5, 0.5-1, 1-3, 3-5, 5-10, and 10-20 km. Analyzing the fire events and their ignition (e.g., lightning) fire events are essential for near real-time and day-ahead transmission line outage analysis and prediction. The transmission line outage analysis and prediction can be conducted for one line out of function (N-1 analysis) or several lines (N-k analysis).

3. Analyses

3.1. Lightning Ignited Fire Events Analyses

In the analyzed six-year period, 23 lightning-ignited fire events of 681 fire events were observed in Croatia. That is only 3.4%, but the average burnt area of lightning-ignited fire events is double that of all. Additionally, there were 11 IC lightning strokes that are related to the fire events. Lightning strokes/fire events were excluded from the overall statistics. Still, it is worth mentioning them because there is a possibility of LLS system error (CG lightning stroke may be misclassified as IC).

It can be concluded that lightning-ignited fire events do not appear often, but their consequences can be enormous even though the average lightning current is less than 20 kA. The most favorable year for lightning-ignited fire events was 2022, with 13 lightning-ignited fire events. The biggest fire event was developed in 2017. A year without any lightning-ignited fire event is 2019. In the year 2021 only one fire event related to lightning activity, but the lightning type is IC (see Chapter 2.1). Reasons for developing and spreading lightning-ignited fire events can be various, from favorable combustible materials, meteorological conditions, (not)disposable resources for firefighting, etc. A valid conclusion in that direction requires additional research that is planned.

3.2. Power Systems' Objects Endangered by Fire Events

A directly endangered power systems object by a lightning-induced fire event is an object whose location point is inside the fire polygon. The analyses showed that there were not any directly endangered power plants, substations, or similar objects, but there were fire events under the transmission lines. When the fire is under the transmission line, because of the high air temperature, the dynamic thermal rating can be disturbed, and losses on the transmission network increase, and insulators can also be damaged, etc. Mechanically, influenced by winds and convection, embers can approach the wires and damage them.

Using buffers around the power systems' objects, it is found that most fire events are in a 5-10 km buffer. The most dangerous fire events for the power system were near the town of Obrovac, 1823 ha, in a 0.5 km buffer in 2017 (Figure 1.), and near the town of Opuzen, 568 ha, in a 1-3 km buffer in 2018. Both fire events endangered important roads and made traffic communication difficult. The fire event near Opuzen also risked nearby settlements (Figure 1.). The number of cloud-to-ground lightning strokes per fire event is 7 to 21.

Figure 1. Fire in buffer 0.5 km around the transmission network object, Obrovac 2017 (left); fire in buffer 1-3 km around the transmission network object, Opuzen, 2018 (right)

3.3. Vegetation Monitoring

Vegetation growth and postfire landscape recovery monitoring are done by calculating NBR and dNBR indices using satellite data (see Chapter 2.3). The mechanism of NBR and dNBR indices interpretation is done using an example of an earlier-mentioned fire event near Opuzen, Croatia.

Healthy vegetation shows a very high reflectance in the NIR and low reflectance in the SWIR channel. Equation 1 calculates the pre-fire (Figure. 2. (left map)) and post-fire NBR index (Figure 2. (middle map)). Non-burnt areas are attributed to values close to zero. More positive values represent a higher percentage of green vegetation in a particular area.

The vegetation damage severity and landscape recovering monitoring are done using the dNBR index, i.e., the difference between the pre-fire and post-fire NBR indices. Positive dNBR values indicate severity level and negative vegetation growth. The dNBR values from the interval [-0.1, 0.99] represent the unburned area. Higher positive values, significate more severe damage, and lower negative values mean higher landscape recovery (Figure 2. (right map)) [9], [13].

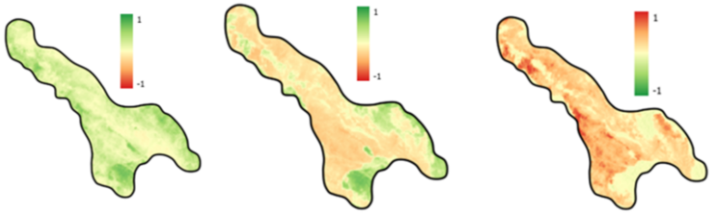

Figure 2. Landscape monitoring, fire in Opuzen, 2018: Pre-fire NBR index (left), post-fire NBR index (middle), dNBR index (right)

3.4. Climate Projection of Forest Fire Danger

The output of models presented in Chapter 2.4. is observed according to the climatological seasons (December-January-February (DJF), Marth-April-May (MAM), June-July-August (JJA), and September-October-November (SON)). Till the end of the century, during the high fire season (JJA), all scenarios give FWI mean values mostly in the very high or in the extreme class (Figure 3). Notably, FWI maximal values are mostly between 60 and 110 (Figure 4). That values are significantly higher than the minimum value of the extreme class according to the actual EFFIS FWI classification, European Forest Fire Information System, official web page. Models showed pretty similar results for both seasons, MAM, and SON, and it is expected because spring and autumn in Croatia have similar meteorological conditions. The winter season (DJF) constantly shows values that mostly correlate with today's FWI values.

Models EC-EARTH (ICHEC, Ireland) and MPI-ESM-LR (MPI, Germany) do not differ significantly. Observing model HadGEM2-ES (UK Met Office, UK), at the beginning and at the end of the century, values are like the previously mentioned models' values. In the middle of the century, a significant difference is obvious. Considering all seasons, during the JJA, the FWI values are the lowest. In the rest of the seasons, the mean FWI values are between 20 and 60 (Figure 5). Those values correlate to today's FWI values in the late spring, summer, and early autumn seasons. The reason for that significant disproportion requires wider consideration of the climatological situation and the models' physical background. It can be done in future papers.

According to the IPCC report from 2021, it is very likely to expect an increase in the intensity and frequency of hot extremes and a decrease in cold extremes. At the same time, it is possible to expect an increase in the intensity of severe storm activity [14].

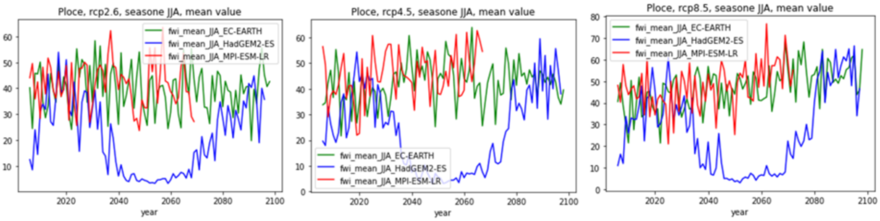

Figure 3. Mean value of FWI climatological projection, season JJA: RCP2.6 (left), RCP 4.5 (middle), RCP8.5 (right)

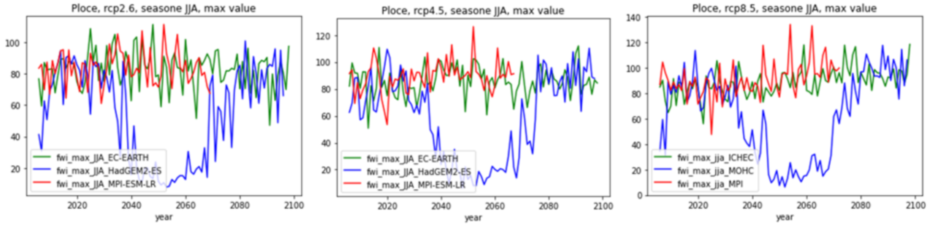

Figure 4. Maximal value of FWI climatological projection, season JJA: RCP2.6 (left), RCP 4.5 (middle), RCP8.5 (right)

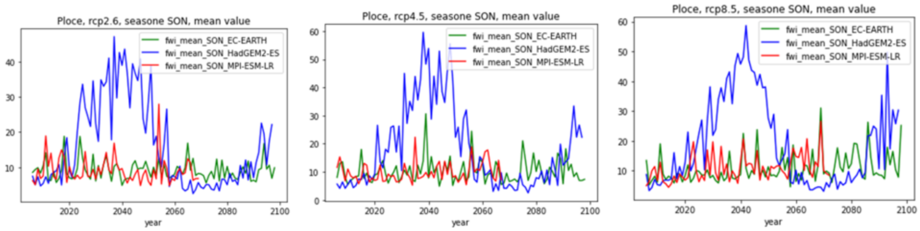

Figure 5. Mean value of FWI climatological projection, season SON: RCP2.6 (left), RCP 4.5 (middle), RCP8.5 (right)

4. Conclusion and Future Work

The paper presents the lightning-induced wildfire impact on the transmission network in Croatia. It is possible to conclude that lightning-induced wildfires do not appear often in the observed area, but their consequences are enormous. These events can be classified as rare but with high and expensive impacts. Observing the fire danger risk index climatological projection, it was possible to notice that extreme values of the FWI rise significantly in most cases. At the same time, it is possible to expect a higher number of developed thunderstorms. So, the expectation that lightning-induced fire events will appear more often and cause more damage than already analysed fire events is justified. Extremely dangerous can be the JJA season, but in the MAM and SON seasons, FWI values can be like today's summer values.

Short-term protection is possible by monitoring landscape and vegetation growth around the transmission network objects using NBR and dNBR indices. For long-term protection, the creation of a fire impact risk model that incorporates climatological conditions, landscape, and transmission system objects' conditions and significance to the customers is necessary. The next step in creating the fire impact risk model is to research the climatological projection of other parameters significant for the lightning appearance and fire spreading such as air temperature, precipitation, indices of convection, vegetation, etc. To minimize unwanted wildfire consequences, the new model is possible to incorporate in a transmission line outage analysis (N-1, …, N-k analysis) model. Implementing the N-k analysis can significantly increase the network reliability and decrease the losses, and customer dissatisfaction caused by the network outages. The development of the hybrid model that incorporates the fire impact risk model and N-k analysis is planned for future research.

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