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Regular Article

Climate change increased risk of forest fire, winter storm and technical failure risks related to power transmission lines – a spatial GIS risk assessment at Cologne district, Germany

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ABSTRACT

In Central Europe, climate change is increasing the frequency and intensity of extreme events and weather variability. We need to better understand the interrelations between natural hazards and related extreme events and their impacts on gray, blue, and green infrastructures. According to literature research, a broad spectrum of hazard impacts can lead to transmission line and tower failures in Germany. A spatial assessment in a case study area in western Germany, using a geographic information system reveals the spatial exposure of forests, settlements, roads, rail, and waterways to transmission line failure. The main purpose of this study is to map this spatial exposure risk. In some districts, there is a higher risk of forest fires ignited by dropping transmission lines and impacts of winter storms or earthquakes.

The result indicates that better integration of climate change and other natural, technical, and man-made hazards is required and needs to be researched. We also need to better understand the linkages with critical infrastructure, such as emergency management, and the different cascades of impact on primary, secondary, and tertiary infrastructure.

The findings can inform fellow scientists, planners, and practitioners on better capturing and applying interconnected risks through spatial assessments. Moreover, the results can also inform operators and emergency managers on preparing for rare and unexpected risks.

1. Introduction

The topic of critical infrastructure is gaining attention in international frameworks on disaster risks [56]. However, interconnections such as forest fires or other natural hazards that can potentially trigger infrastructure failure have not yet been analyzed. The lack of analyses contributes to a lack of data and information that would be useful for emergency response managers and other decision-makers Enabling better preparation for future natural hazard events in combination with additional cascading effects such as electricity failures or traffic interruptions. Cascading effects and related impact chains are a line of increasing research interest about interconnected risks, and climate change has the potential to accercerbate such cascading failure and impact chains [12,27,43]. Forest fires are a good starting point, but other natural hazards such as winter storms or earthquakes may also have similar outcomes and will also be studied in this paper.

Transmission lines trigger forest fires, as have occurred in California, which tend to be larger than fires triggered by other sources [33]. Forest fires greatly risk settlements, flora and fauna, and critical infrastructure such as power transmission. In 2018, 87 people died in forest fires in California, and two billion acres of land were burnt [13]. The role of transmission lines in triggering wildfires has also been discussed for the Maui 2023 fire, the deadliest in modern US history [11]. Forest fires are now occurring more frequently in Germany, as of yet no connection with transmission lines has been reported. Nevertheless, it is important to analyze these risks, as the likelihood of heat and drought will increase due to climate change impacts [53] and the risk of forest fires [14]. In this context, Golub et al. [18] highlight the high vulnerability of the German energy sector to heat and drought, and Niggli et al. [37] emphasize cascading and interconnected risks due to simultaneously

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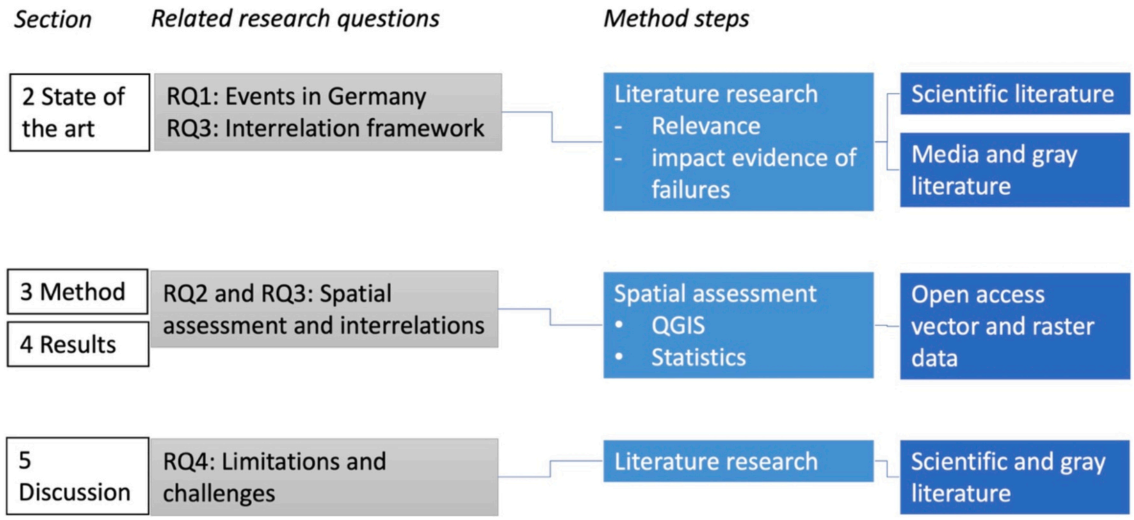

Fig. 1. General methodological steps in this study.

occurring weather extremes.

There are many other reasons for transmission line failures worldwide as well. Heat and drought increase the risk of such failures since they increase the likelihood and spread of forest fires. Wind speed, duration, and air temperature vary according to geographical region and season. For example, some recent fires in California had been driven by foehn winds [33]. Wind speed loadings of transmission lines are designed for up to 50 mph, but the foehn gusts in Santa Ana exceeded this value, averaging 59 mph (26 m/s) [33]. In Germany, winter storms are a hazard that has already led to major blackouts. Climate change is also a driving force here, as more storms and wet snow accompany the projected warmer and wetter winters. The 2005 event in Münsterland received attention when 80 transmission towers collapsed due to wet snow and ice loads on the transmission lines [23]. This event is often referred to in national critical infrastructure protection studies and strategies [5,44]. Wet snow load is also a major risk in European countries such as Italy, where forecast models and precautionary measures have also been analyzed [6]. Winter storms are a major concern in many more countries and have a long history of scientific research [4].

In addition to climate-induced risks, other types of natural hazards must be considered regarding transmission line failure risk. Earthquakes are an example of natural hazards that cause power poles, towers, or transmission lines to collapse [9]. As a secondary hazard, they often trigger large urban or forest fires [51].

In addition to risks from natural hazards, anthropogenic risks include fires set by humans [15] and sabotage. Technical failure is also a potential risk, but due to the high standards and building codes in countries such as Germany, it is less common than accidents caused, for example, by collisions between agricultural machinery and power towers.

The spectrum of hazards already indicates that the topic of risk assessment in relation to power transmission lines is an overarching one and is not limited to a few hazard types. Power generation and transmission are the backbone of society and critical infrastructure [57]. Energy is one of the most significant critical infrastructures, the failure of which can cause cascading effects on all other infrastructures and human electricity consumption in various forms [49]. Power distribution can severely impact households, industry, and many other sectors. Especially in disaster situations, additional failure of critical infrastructure, such as power supply, can severely exacerbate damages and impair many other services, such as emergency services, communication, and heating. It is, therefore, crucial to analyze the overall picture of hazards, drivers, and impact chains of power distribution with other sectors.

This study investigates the extent to which failures in electricity distribution are relevant. Taking stock of what has already happened to set a benchmark for future developments is important in the face of climate change. The future likelihood of power failures caused by the collapse of transmission lines or towers is still uncertain. However, the impacts of climate change are already evident in many countries through an increasing frequency and intensity of droughts, heat waves, and associated forest fires.

Germany is a country with high industrial safety standards, and the power grid structure itself is regarded as highly reliable. Power outages are rare in comparison and only last around 10 to 15 min annually [44]. However, based on a media and gray literature analysis, this study reveals that many failures can be attributed to accidents, sabotage, natural hazards, or technical causes. In addition, the preceding eight years have been the warmest and very dry for Germany, increasing the risk of forest fires. It is therefore necessary to scientifically analyze the causes and extent to which forest fires and other hazards could lead to massive power failures in Germany. This is especially important in countries such as Germany, where the vulnerability paradox comes into play, according to which highly developed countries are increasingly vulnerable to disruptions of basic infrastructure services because society has become accustomed to their daily functioning [38].

The aim of this paper is to contribute a method and case study application of how to analyze natural hazards in combination with critical infrastructure failure risks. Using a geo-information system, we show how such a method can be generally conducted for larger geographical regions, and for different types of natural hazards, expanding it more detailed at the example of forest fires. The analysis focuses on exposure assessment, which can be an important component for future risk assessments that include potential vulnerabilities or consequences. To better illustrate the possible application range, we also have included hazard scenarios for winter storms and earthquake. The administrative district of Cologne (Regierungsbezirk Köln) in western Germany was selected as a case study because it contains a variety of large and middle-sized urban centers and large agricultural and forest areas. According to the regional climate change preparedness strategy [48], the district is vulnerable to heatwaves in urban areas and droughts and forest fires in suburban and rural areas. It is an area with heterogeneity that enables comparisons to be made. A literature review is conducted to establish baseline parameters for failure types and spatial extents. A spatial assessment is conducted as this allows for larger regional overviews and is based on a comparable data source that can also be applied in any other region in Germany and most countries worldwide. Open access data can be retrieved from public geo-information portals or, in other countries, could be extracted from

Table 1
Detailed methodological steps of the spatial assessment.

Methodological step	Description	Data and software
Download data	Download data for Cologne district–specific items, such as transmission towers per search term in QGIS, using the Quick OSM extension. And land use from the Federal Office for Cartography, earthquake zones from the Geoportal.nrw - all data are open data	Open Street Map (OSM), BKG.bund.de, Geoportal.nrw
Analyze features	Measuring transmission tower cross arm with and forest clearance widths under transmission lines using the ruler feature and satellite imagery from different sources (Google, Bing, Sentinel-2)	QGIS; WMS
Save data and reproject	Export and save all layers as shape files, fitting them to the UTM WGS84, Zone 32 N projection	QGIS; shape-files
Clean and check	Deselect and delete items such as transformer station lines, busbars, bays, or earth cables not along the transmission lines to be analyzed. Generate a spatial index to boost computation times	QGIS; shape-files
Select	Create individual layers for high voltage transmission lines using the attribute table: 110 kV, 220 kV, etc.	QGIS; shape-files
Clip	Clip all individual and aggregated sets of transmission lines with other line elements such as roads, rail, or waterways.	QGIS; shape-files
Calculate amounts	Calculate the number of points (NUMPOINTS) of line features crossing line features. Calculate line lengths of line features (LINELENGTH) crossing polygons (forest, settlement area)	QGIS; shape-files, export as excel-files
Calculate sums and ratios	Calculate sums of total line lengths and ratios per county area	Excel
Create buffers	Create buffers of 40 m and 60 m as bands along the transmission line features and dissolve them to create one single-area polygon. Create buffers of 50 m (tower length) and 150 m (transmission line length) as circles around transmission towers and dissolve them. Join all buffers to create a single hazard zonation file	QGIS; shape-files
Analyze features	Clip the buffer file with point data such as hospitals, petrol, or fire stations that are critical infrastructure Calculate the number of points exposed	QGIS; shape-files
Analyze features	Clip the earthquake zones with the transmission tower point data Use NUMPOINTS to calculate the number of towers per earthquake zone	QGIS; shape-files
Create a scenario	Build a 10 × 10 km2 grid in the GIS. Select three example areas with an area similar in size to a historical event in Münsterland 2005	QGIS; shape-files
Create maps	Layouts including legend, etc.	QGIS; export as .jpg

satellite imagery if such spatial platforms do not exist.

Limitations and challenges in using such a spatial information system will be discussed after the presentation of the results.

To summarize the tasks of this study, the following research questions are formulated:

RQ:

1. Which electricity tower and transmission line failure events have occurred in Germany so far?
2. How can spatial exposure risk assessments be carried out for larger regions such as districts?
3. Which spatial interrelationships can be identified between blue (water bodies), green (forests), gray infrastructure (roads, rail), and transmission lines?
4. What are the limitations and challenges for spatial exposure risk assessments?

2. Method and model

The general methodological steps are outlined in Fig. 1. The state of the art and literature are from international and national research (Section 2). Scientific platforms used include Scopus, Web of Science, and Google Scholar. An exploratory literature review is conducted, documenting the time of search and search terms used. The reason is to generate sufficient evidence of the topic's relevance and indicate heterogeneity of events and effects.

The next step describes the method and model in Section 3. The literature research on specific impact evidence of failures related to transmission lines in Germany is conducted using scientific search engines and standard browser-based search engines. Due to the few findings from scientific studies for the study area of Germany, the evidence of hazard events and damage records was mainly collected from online media and gray literature. The findings are summarized in tables, distinguishing between events, causes, and damages. Another important outcome is parameters for spatial and technical details to be used in the subsequent spatial assessment. As another form of summarizing these preliminary results, a conceptual framework is created outlining the dimensions of hazards, drivers of the hazard, and impact chains on primary, secondary, and tertiary infrastructure sectors. This working framework helps identify the research streams in this study and indicates relations and feedback loops that deserve further research and follow-up studies.

In Section 4, the results are described and visualized. The spatial assessment method using a geographic information system (GIS) enables the research questions and tasks outlined in the conceptual working framework in Section 3 to be addressed. Quantum GIS is an open-access software that can be shared on multiple platforms and thus also by fellow researchers without additional costs. We use open access vector and raster data and document in a detailed spatial assessment methodology (Table 1). The results section demonstrates how spatial assessments can be carried out on this topic and also focuses on spatial interrelations outlined in the conceptual framework. This is conducted by a detailed description of the GIS-assessment at the example of forest fires, and in addition it is illustrated for other natural hazards using scenarios.

Section 5 is followed by a discussion based on a literature review to back up findings and enable comparisons with other studies. Limitations and challenges, such as research question 4, are especially addressed, reflecting on the lesson learned by conducting the study.

2.1. Conceptual framework

A conceptual framework is developed to guide the assessment concerning conceptual components of risk and impact. Fig. 2 illustrates the interactions of hazards in a power grid with primary, secondary, and tertiary impacts on green, blue, and gray infrastructure. It further separates the hazard into drivers and actual hazards observed. It differentiates the impact side by primary infrastructure impacts on the power grid and its elements and the secondary and tertiary infrastructure impacts.

The organization of the conceptual framework is informed by the

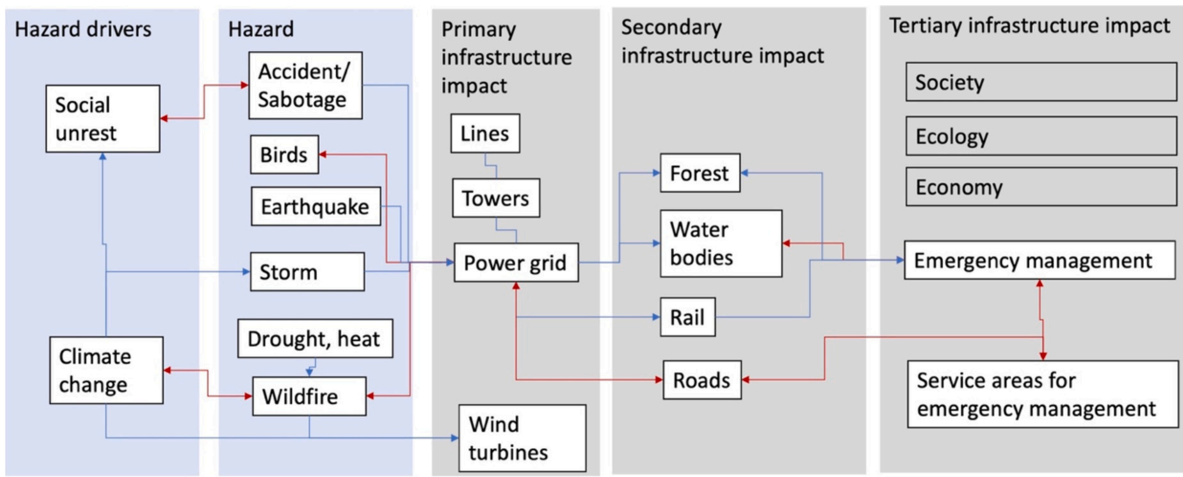

Fig. 2. Interactions of hazards with a power grid with first impacts on green, blue, and gray infrastructure and secondary interdependencies with the emergency management. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

separation of primary and secondary cascading effects typical for critical infrastructure systems, as published by an interdisciplinary group of researchers in 2001 [49]. There are also similarities and relationships to the Pressure and Release Model (PAR) used in risk assessments regarding natural hazards, distinguishing drivers, processes, and resulting interactions of hazard and vulnerability factors [58]. Overall, the symbology used in the framework relates to system theory representations of elements or nodes, depicted by topic boxes [10]. The boxes representing society, ecology and economy are grayed out because they are important, but not analyzed further in this paper due to limitations of scope and space to analyze them thoroughly. The arrows between the boxes represent vectors, and interdependencies are symbolized by arrows pointing in both directions. For better visualization, the interdependencies are marked in red. The background boxes indicate subsystems that are used in system theory to capture complex phenomena in more detail by trying to increase the knowledge about such black boxes by further detailing their content of elements and interrelations between the elements in the subsystem and between other subsystems [10]. The conceptual framework must be expanded to include many more elements and aspects. Still, it should primarily direct this study and the reader toward the selected interrelations addressed in this paper.

2.2. GIS-assessment

The spatial assessments consist of several detailed steps explained in Table 1. It uses terminologies of assessment steps as well as data types that should enable fellow researchers to repeat the same approach or perform it in other areas.

Spatial assessment as a methodology is selected because it can be applied in many world regions. Using open-source data allows for a wider regional overview based on the same pool and data type. Spatial assessments are also useful for planners and decision-makers regarding novel risks when getting a first oversight of the problem.

The limitations pertaining to spatial assessments include data dependency and accuracy, accessibility, and data updating, among other aspects. For example, Open Street Map (OSM) vector data has comprehensive data on public infrastructure, but the data is collected by volunteers and could benefit from improved coverage. However, an advantage of the geographic information system (GIS) was that vector data of transmission lines and towers could be compared with satellite imagery. Using various sources, it was, for instance, possible to confirm the location and length of transmission line cross-arms. On the other hand, the availability of satellite imagery is also limited in temporal resolution, so some recent changes or additions in the power grid could not be ruled out.

The OSM data only captures the middle line of transmission lines, not the entire breadth of all transmission lines on each tower. Therefore, the lateral extent of several transmission lines installed on one transmission tower had to be estimated using literature documentation of operators, which was confirmed by satellite imagery analysis. The findings revealed different types and sizes of transmission towers. The spatial resolution hampered the identification of minor power poles, so these had to be excluded when generating buffer analysis of exposure zones.

We then had to identify buffer distances between forest fires and forests or settlement that could be ignited. We took this from international literature, since local data or experimental data was not available. Bush or grassland fires can be triggered by winds that cause transmission lines to sway and thereby enable collisions with trees. Three physical reasons for transmission line-triggered forest fires are “tree contact, line slap, and metal fatigue” [33]. Wind distributes metal sparks or burning embers [55]. Specifically, arcing copper transmission lines can produce hot particles, arcing aluminum transmission lines can produce burning sparks, and the collision of transmission lines with trees can produce burning embers [55]. At a 48.3 km/h wind speed, copper particles can reach a trajectory distance of about 13–14 m, aluminum particles of over 17 m, and burning embers of up to 38 m under laboratory conditions [55]. Line aging is another physical effect impacting fire risk based on flame characteristics, wind, and load ratio [19]. Transmission line temperature and line extension or sagging are also influenced by forest fires [13].

The risk interface between transmission lines and vegetation consists of a) the height risk of transmission lines above vegetation, b) the lateral distance risk of transmission lines to vegetation, and c) the fall risk of trees toward the transmission lines on a transmission tower [20]. Safety distances between conductors vary between 0.9 and 4 m for transmission lines, 0.46 m for distribution lines, and up to 0.95 m for 300 kV transmission lines in California [33]. Safety measures for line slap include a maximum of 0.9 m of sag at a 100 m length of a transmission line [33]. Seasonality of vegetation growth is another variable to be observed and used in fire risk indices related to transmission line risks [15].

Creating hazard exposure zones has been another challenge. While the location of the transmission lines is easy to access, the lateral extent is more difficult to estimate. Different types of hazards lead to different types of potential collapse scenarios and, thus, to different spatial coverage of the potential hazard exposures. Transmission towers are also built to different heights, which means that there are multiple possibilities for length and exposure zones. Because there are thousands of towers in the research area, it was impossible to conduct individual

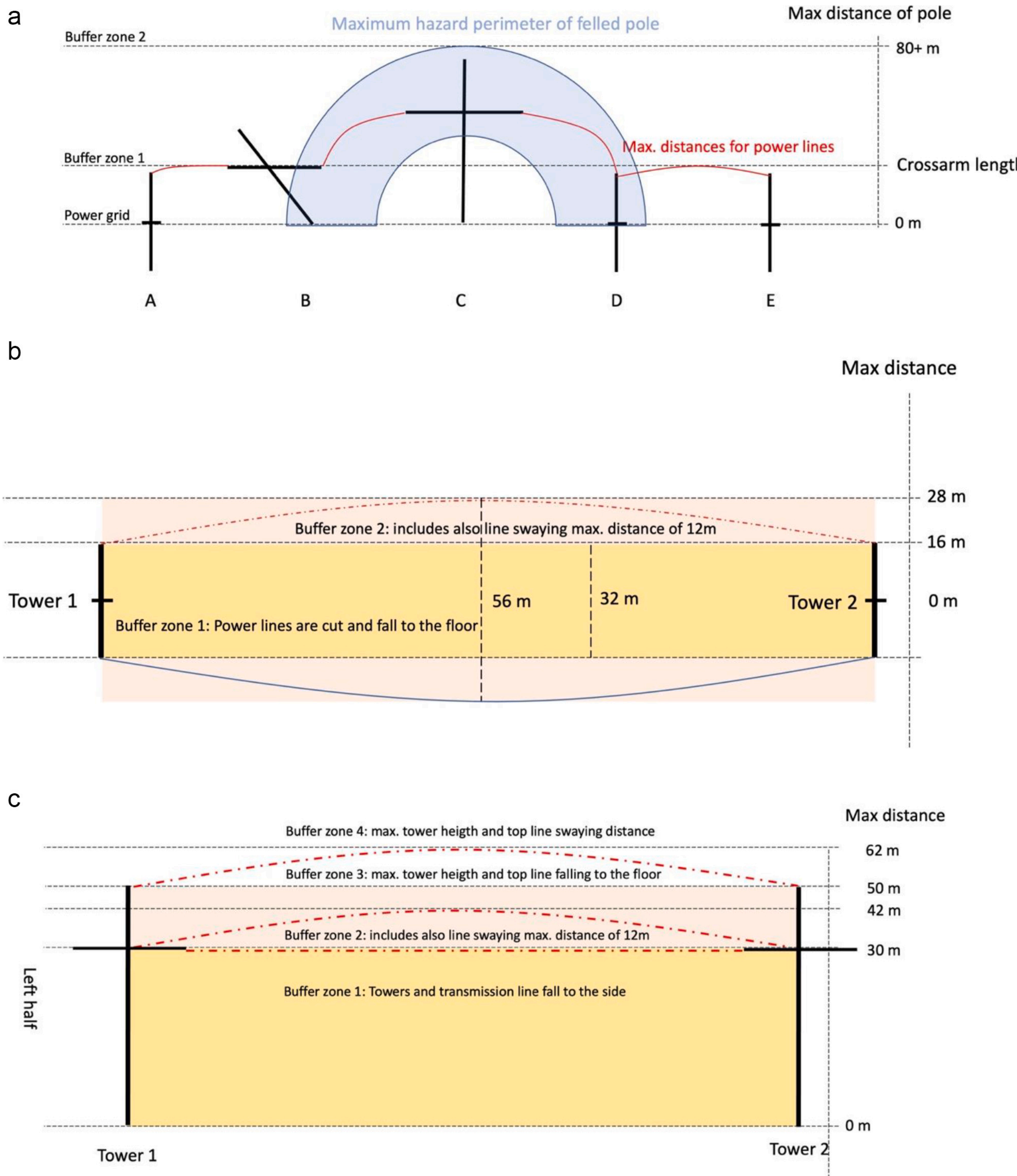

Fig. 3. a. Hazard zones general explanation for transmission towers and lines.
b. 380 kV Transmission tower and line collapse exposure buffers selected for the analysis. *Scenario 1:* ***Towers remain standing****, power line trips - scene observed from above.*
c. 380 kV Transmission tower and line collapse exposure buffers selected for the analysis. *Scenario 2:* ***Towers collapse to the side****, power line trips - scene observed from above.*
d. 380 kV Transmission tower and line collapse exposure buffers selected for the analysis. *Scenario 3a:* ***Power line severed*** (left), *Scenario 3b: Power line severed,* ***and tower falls*** (right).
e. 380 kV Transmission tower and line collapse exposure buffers selected for the analysis. *Scenarios combined.*

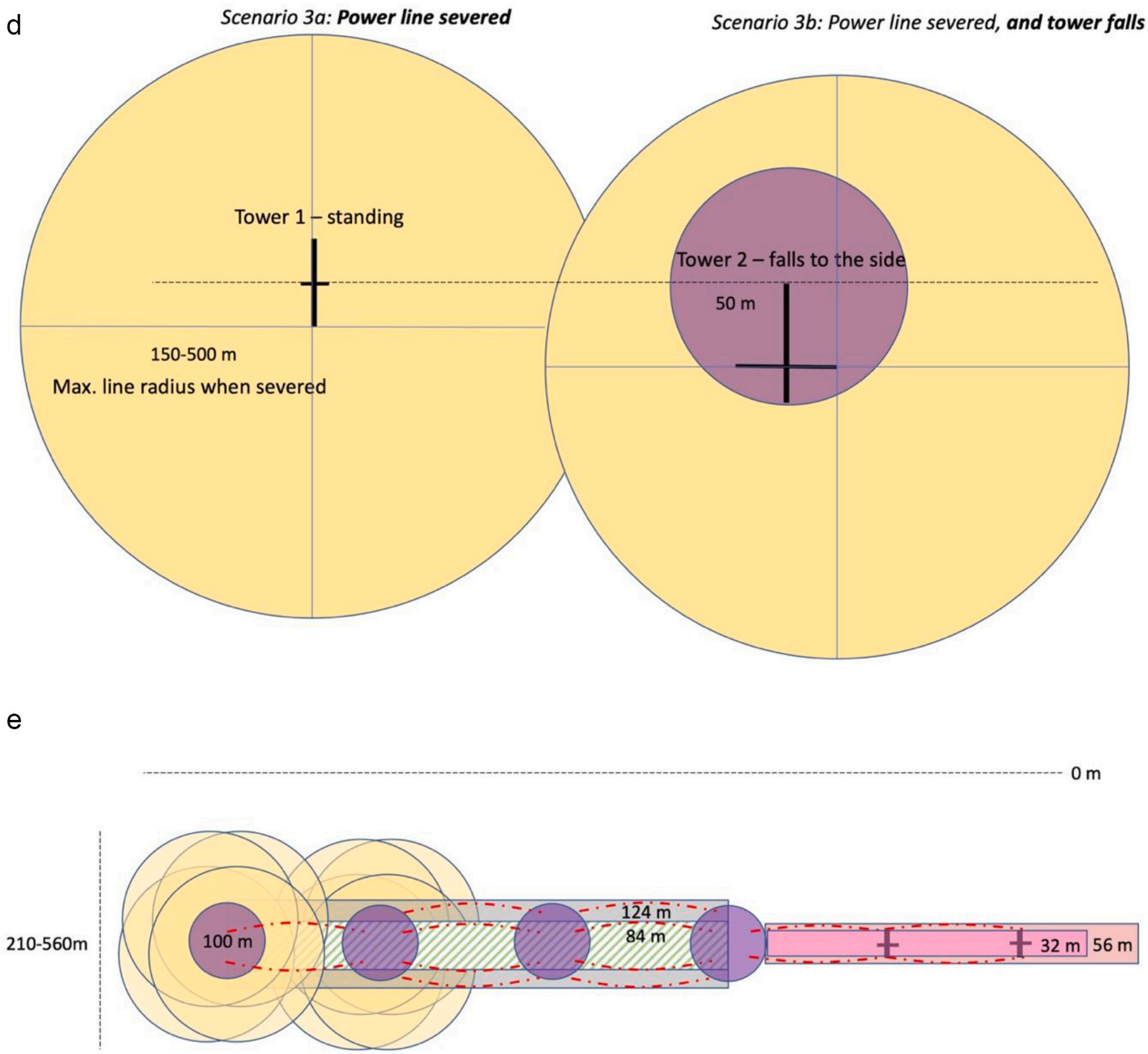

Fig. 3. (*continued*).

mapping as the height information in the OSM data is not available for each tower. A visual evaluation was conducted through site visits for some exemplary transmission line sections. The result revealed a large heterogeneity even within one transmission line. Therefore, the decision had to be made to select the most typical distances in the region.

For example, as Fig. 3a shows, a transmission tower can fall completely perpendicular to the transmission line at a 90° angle and cover the largest possible area. However, it can also fall to only 45° or another degree to the side so that the buffer corridor of potential exposure would be smaller. In addition, towers have different heights even for the same high voltage system, such as 380 kV. By the field visits, it could be confirmed that they varied in height. Selecting the smallest height could be regarded as the most cautious and, therefore, extrapolated in the GIS and the assessment for all towers of this type. This introduces an error in those locations where towers over 50 m are installed. It is, however, sufficient to demonstrate how to conduct the GIS approach in general so it can be replicated for different heights.

Additional variations are related to the construction type of transmission towers. The line lengths differ and, therefore, also the potential swing distance. An operator handbook indicates that line operators plan with a swing distance of 12 m to the side of the 380 kV transmission lines [1]. In addition, they add a 5 m safety range. The operator's description also shows that the powerlines are installed at a height of around 30 m. Technical sources reveal that the heights should range from 18 m for 110 kV towers, over 21.7 m for 220 kV towers, to 25.8 m for 380 kV towers [41]. A safety clearance height is 6 m above ground from roads [41]. In the operator handbook used, the height is given at 12 m. Then we also made observations based on the photos of press releases about real events that collapsing structures will not maintain their full height when collapsing. On the other hand, real cases have shown that sabotage often results in towers being cut at the base, allowing the maximum height to be reached. As a result, the full height is used when combining all sabotage and accident scenarios.

While Fig. 3a shows the general considerations for developing buffer zones, further explanation is necessary to explain the range of possible buffer zones. A buffer zone is a polygon created in the GIS that represents a potential hazard exposure area due to a falling transmission tower or the whole transmission line falling to one side.

Fig. 3b shows a buffer zone of the area potentially exposed under the transmission line between two towers. Several power lines are typically

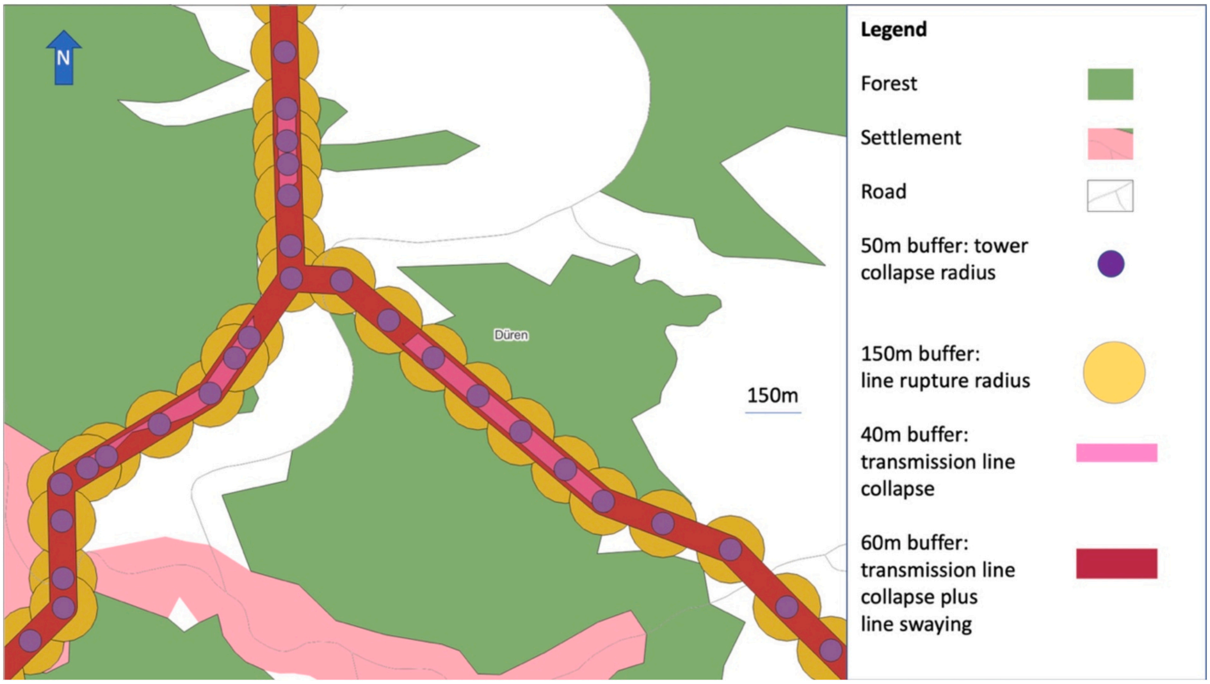

Fig. 4. Types of buffers applied in an example area.

fixed to the crossbars. Therefore, any severed line could reach the area between the two towers. This buffer zone can reach a width of up to 32 m for the largest towers carrying the 380 kV lines. Buffer zone 1 is the most conservative of the alternatives, while buffer zone 2 includes the 12 m swaying distance the operators provide in their brochure [1]. The swaying distance is where the transmission lines can swing to the side in windy conditions and potentially touch nearby vegetation. The operator recommends an additional 5 m safety buffer in the brochure figure, however, this is excluded here to remain conservative. In a heat wave, however, powerline lengths may extend due to the heat, so an additional 5 m should be considered during these times.

Fig. 3c shows a scenario where two transmission towers would collapse and fall to the side. Typically, and as derived from the literature and media survey, the transmission towers would fall to only one side of the transmission grid. Therefore, the figure only shows the distance on one side.

It must be considered, however, that the transmission line could also fall to the other side, so double the amount must be added for the full buffer distance of the GIS assessment. Some exceptions exist, such as corner transmission towers where the transmission line changes direction. These are quite rare, and in this case, the transmission towers would only fall to the inward side.

Four different buffers are displayed. The first is the range of about 30 m, where the distance is taken from the height of the powerlines installed above ground before the tower collapses. When the towers fall to the side, these 30 m can be potentially exposed.

The next buffer zone includes the 12 m swaying distance, making 42 m in total. The next buffer includes the full height of the transmission towers. We use 50 m, the minimum height observed in technical descriptions of 380 kV towers installed in the region. However, such towers can reach up to 76 or even 80 m.

The fourth and final buffer again adds the 12 m swing distance of the top lines. While these do not carry high voltage, they still pose a risk to any human, animal, or structure below.

There are also several uncertainties included in this scenario. For example, the transmission line may not fall exactly to the side but could be tilted and, therefore, does not reach the full buffer distance. In this case, the towers would not fall at 90° but at an angle of 45°, for example (see Fig. 3a).

Another uncertainty is the full maximum distance of 62 m at a swing distance of the powerlines. As shown in Fig. 3c, the maximum swing distance of 12 m will not be reached directly around the towers, where the cables could still be fixed to the transmission towers. This uncertainty also affects the previous Fig. 3b.

Fig. 3d shows examples of the radius of transmission towers that could collapse. The purple circle indicates the distance of 50 m from the full height of the transmission towers. As they could potentially fall to all sides, a circle of 100 m in diameter is a further buffer for the spatial assessment. There are several uncertainties in this scenario. For example, the tower could crumble and not fully collapse. For example, when a tractor or caterpillar crashes into the tower, the height could be reduced by approximately 4 to 5 m. However, certain simplifications are also selected for the assessment here.

The next scenario in this figure contains the transmission lines that could be severed. Due to technical accidents or a falling tree, the powerline could be cut at any place between two towers.

For convenience and simplicity, the maximum distance is assumed. This maximum distance is difficult to generalize. From operators' brochures, typical distances between 380 kV towers in the region range between 150 and 500 m. A technical book mentions 280–300 m as an optimal and cost-efficient distance [41]. The figure shows a scenario where the maximum distance could be reached. This would be the powerline installed at the outer end of the cross arms. From there, the powerline could reach the ground anywhere in the area in a circle of 150 to 500 m around the tower. In another case, when the tower still stands, the installation height of 30 m at the highest cross arm would have to be subtracted.

Fig. 3e combines all scenarios and buffer distances around transmission towers and collapsing transmission lines. It includes the collapse of transmission lines to both sides and therefore, the corridor or band ranges are double the size as in Figs. 3b and 3c.

The circular buffer of 100 m is also integrated along the transmission towers. And the scenario of severed power lines is added as well.

In addition, Fig. 3d indicates that the transmission tower could fall to all sides. Therefore, the starting point of the maximum length of transmission lines hitting the ground could also start on either side of the

Table 2
Specific GIS procedure.

GIS procedure	Data set description
Input	Display A. 60 m and 150 m combined transmission line exposure buffer over OSM
Clip	A. with forest = B.
Buffer	B. with 1500 m buffer, not dissolved (round styles, default) = C.
Difference	C. difference to settlements = D.
Correct	Manually removing wrong buffer areas of D. with feature tool – to preserve only continuous forest areas. = E.
Result	E. Risk map of forest ignition over 1500 m from each side of 110–380 kV transmission line
Buffer	E. with 400 m wildland urban interface (WUI) buffer = F.
Clip	Clip F. with settlement areas = G.
Result	G. Risk map of forest ignition over 1500 m from each side of 110–380 kV transmission line triggering flyover up to 400 m WUI with settlements exposed (in yellow color).
Comparison	Add *H. WUI* 400 m of other forest settlements outside of transmission lines for comparison (in red color)
Calculate areas	$area for G. and H.

falling tower and at the end of the cross arms. This means that in addition to Fig. 3d, the 30-m height of the powerline installation at the cross arm has to be added. This results in another buffer circle around transmission towers of between 210 and 560 m.

Fig. 3e also shows that the combination of buffers eliminates some of the uncertainties. For example, the 12 m maximum distance of swaying lines would be incorrect if they were closer to the transmission towers. Therefore, only 56 m is used for the buffer bands to remain cautious. However, since the (yellow) buffer circles fill this area, the buffer bands are already included within the exposure area of the circles.

Alternatives to deriving buffer distances are danger and barrier distances used by fire brigades. These include 20 m to the electric lines, 50 m to the hazard, and 100 m to create a barrier [3].

Hazard zones can also be derived from technical knowledge about the voltage. However, it is difficult for first responders and non-technical experts to know whether a dropped transmission line voltage still exists.

Analyzing the risk of forest fires and tower failures due to storms and other natural hazards requires estimating the potentially affected area. For this purpose, we created buffer zone polygons in addition to the previous line feature assessment (Fig. 4). This was challenging, not only to derive the buffer distances from the literature but because similar studies are rare. The resulting hazard exposure zonation layer looks quite unusual. It combines the circle polygons-related exposure of single towers with band buffer polygons composed of transmission lines.

It should be noted that this is just a first step for further risk assessments, which would include potential damage, vulnerability or impact data. To better illustrate the wide applicability of this spatial assessment approach, we first apply the methodology at a detailed example of forest fires (Table 2, Fig. 5). In addition, we use scenarios of winter storms and earthquakes to visualize the broader applicability for other natural hazard types as well.

Fig. 5 shows an example where manual editing was necessary to remove unrealistic areas. This is done because the buffers are created on both sides along the transmission line. However, only fire ignition and propagation along individual forest areas should be observed in this scenario. Settlements need to be excluded and have been removed by clipping. Additional smaller polygons had to be removed manually, as indicated in Fig. 4.

3. Results of the spatial assessment

In the following, we describe the results of the spatial assessment conducted in the case study. We present maps and resulting calculations that fit the research questions and the conceptual framework. We have performed a selection of visual results and calculations to show a variety of applications that can also be conducted by other researchers.

3.1. Evidence of transmission line failures

There are many causes of power or transmission line cuts in Germany. Outages are often caused by fallen trees in storm events and snow loads on tree branches [50], but snow loads on the lines themselves have also led to cross-regional failures, in 2005 for example [23].

The first result of a media search (Nov 2023) in German online media

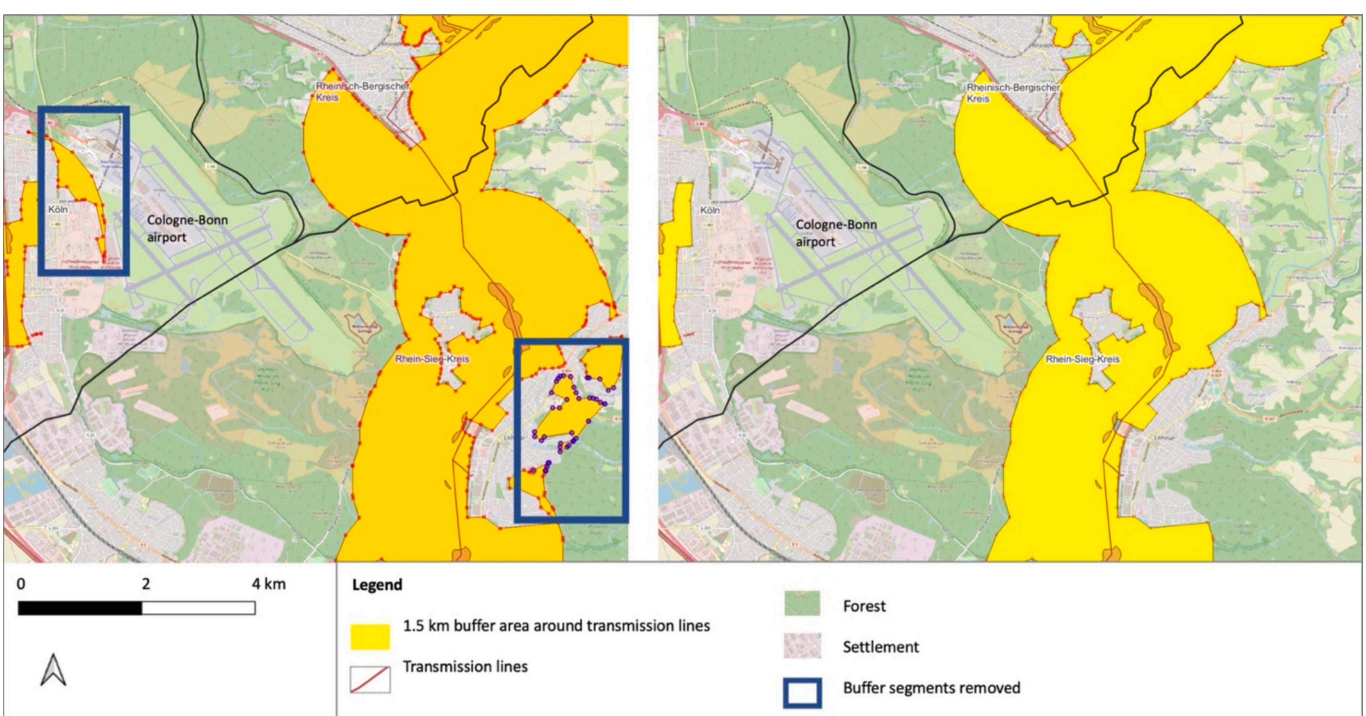

Fig. 5. Risk map of forest ignition over 1500 m from each side of 110–380 kV transmission line – removal of incorrect areas.

Table 3
Transmission line and tower failures in Germany, from media search Nov 2023. Search terms used: "Strommast geknickt" (= transmission tower bent).

Event	Cause	Affected structure and damage	Information for GIS assessment	Source
2016 brown coal mining area Inden, NRW	Sabotage	Transmission tower	Transmission tower 80 m	Rp-online.de 2023
9. July 2022, Otterberg in county Kaiserslautern, RLP	Farm machinery	Tower, high voltage. Blackout, damage in 5-digit numbers in €	The tower was bent at basis; the full length was approximately 15 m minus the car's height. 90° to the side	Agrarheute.com 2022
4. Aug. 2022, Weilerswist, Horchheimer Straße, NRW	Farm tractor	Tower, high voltage 110 kV. Blackout of 65.000 people without power in Euskirchen, Düren, Rhein-Erft- and Rhein-Sieg-counties for 4 h, highway A1 and a parallel power line cut off, a fire ignited, one person was hurt	Tower bent at base; full length minus the height of the tractor	Merkur.de 2022, general-anzeiger.de 2022, westnetz.de 2022, aachener-zeitung.de 2022
12. March 2023, Grevenbroich, at Gustorfer Höhe, NRW	Sabotage assumed, strong wind	Tower	Tower cut at basis; full length of 80 m	Rp-online.de 2023

Table 4
Transmission line failures in Germany, from media search Nov 2023. Search terms used: "Stromleitung OR Hochspannungsleitung gerissen" (= transmission line OR high voltage line cut).

Event	Cause	Affected structure and damage	Information for GIS assessment	Source
9 Jan 2014, Wiesmoor, Aurich County, LS	Unknown	High voltage line 110 kV severed between Wiesmoor and Conneforde, in the settlement area	Settlement area	nwzonline.de, uvp-verbund.de 2014
26 Jan. 2019, Mörlenbach, Bergstraße county, Rhine-Main, H	Unknown	Medium voltage 20 kV, soil burnt at 20 m width and several hundred m long	20 m by >200 m	Fr.de 2019
10 Feb 2020, Krefeld, Rine river, NRW	Unknown	A cable (lightning rod, no power) fell into the river, and ship traffic interrupted	River crossings	Sz.de 2020
21 April 2023, Laatzen und Hildesheim-Drispenstedt, highway A7, near Hannover, LS	Failure, repair works	A cable (lightning rod, no power) fell onto the highway, four cars collided, and two persons were hurt.	Highway crossing	NDR.de 2023

sources show a surprising number of events and occasions in which power towers and lines were damaged (Table 3). This is surprising since such events often do not appear on the evening news or in the headlines of newspapers. Perhaps this is why a lack of public awareness of this hazard exists. It is not exactly underreported but is mainly reported at the regional and local levels.

These are just examples, but they are sufficient to show that such transmission line damages occur, and information can be derived for the following exposure risk assessment. The hazard spectrum ranges from accidents to deliberate sabotage and natural factors, such as strong wind (Tables 4–6). The maximum magnitude can only be estimated by looking at photos of the damaged towers.

Other worries are expressed in towns where high-voltage lines are very close to the settlement area, such as in Mengenich, near Cologne. Local citizen organizations have formed to protest against such transmission lines or transmission of electric fields and the suspected cancer risk of the "electrosmog" [25].

As a preliminary summary, the search results are documented in Tables 4 to 6, shows that a wide range of recent power line failures can be documented in Germany. These examples, extracted from media and gray literature, require further validation but already reveal important and credible information about the type of hazard, type of transmission line, and damages. The results, such as the heights of transmission line towers and collapsed structures, can be used for a spatial assessment. What is not visible are press photos, which provide more information about real accidents, e.g., collisions of farmers' tractors with transmission line towers. The height of the cars that damaged the towers must be subtracted from the total height of the towers. Such photos are useful to estimate the height of collapsing structures better. However, such photos are not included in this paper for copyright reasons.

3.2. Linear Intersections of Transmission Lines with Roads, Rail, and Rivers

Due to the densely populated areas, many roads and highways cross the district. The following maps (Fig. 6) show points where transmission lines intersect with roads or highways, railway lines, or waterways, such as rivers. Spatially differentiated patterns are visible with concentrations of road crossings, potentially exposed to sagging or dropping powerlines (Map A. in Fig. 6). For example, such concentrations are in the region's center along the large urbanized areas and are also concentrated in the other regions around Aachen in the west.

When analyzing the highway crossings, a different pattern emerges: only a few 380 kV transmission lines cross highways compared to 110 or

Table 5
Examples of winter storms triggering high-line transmission tower and line failures in Germany.

Event	Cause	Affected area and damage	Information for GIS assessment	Source
25–26. Nov. 2005, Münsterland, NRW	Snow load on transmission lines, wind	83 towers, up to 250.000 people, and 20 communities were affected by blackouts over several (>5) days, with three deaths	Area approx.. 40 × 15 km	Bundesnetzagentur 2006
13 April 1994, Kaufbeuren, Ostallgäu, BW	Snow load on transmission lines, wind	69–172 transmission towers, several hours		Bundesnetzagentur 2006, all-in.de 2004
24 April 1980, Fürstenfeldbruck, BY	Snow load on transmission lines	150 towers, blackouts for several days		Bundesnetzagentur 2006, merkur.de 2009

Table 6
Transmission line failures in Germany, from media search Nov 2023. Search terms used: "Waldbrand AND Stromausfall" (= forest fire AND power failure).

Event	Cause	Affected structure and damage	Information for GIS assessment	Source
Mücheln (Saalekreis), Sachsen-Anhalt, 16 July 2023	Agricultural fire damaged a transmission line, technical defects of farming machines, drought and heat	220–240 ha acre burned (Raps, wheat, barley, and potatoes), Parts of Mücheln without power for 1 h, 8500 people. 150 firefighters active.	240 ha	Bild.de 2023, mdr.de 2023
Zörbig (Anhalt-Bitterfeld), 16 July 2023	Agricultural fire, harvesting activities, drought and heat	Close to highway A9 and B183. Wind turbine saved by fire fighting. 100 firefighters active	200 ha	Bild.de 2023, mdr.de 2023
Zilly im Landkreis Harz, 16 July 2023	Farming activities, drought, and heat	Federal roads were closed for 2 h		mdr.de 2023
Stegelitz, Möckern, Jerichower Land, 16 July 2023	Farming activities, drought, and heat	Acer and forest. 140 firefighters were active	120 ha	mdr.de 2023
Hohenseeden and Schattberge, Jerichower Land, 13. July 2023	Transmission line cut due to tree falling, sparking a wildfire	Hohenseeden, Güsen, Zerben, and Schattberge were without power for a short time	2000 m2 forest burned	Meetingpoint-jl. de 2023
Rietz-Neuendorf (Oder-Spree), between Görzig and Pfaffendorf, 13. May 2023	Wind, tree falling on transmission lines, cable falling to the floor, forest fire	Power failure for a short time, 100 firefighters active	10,000 m2	Tagesschau.de 2023

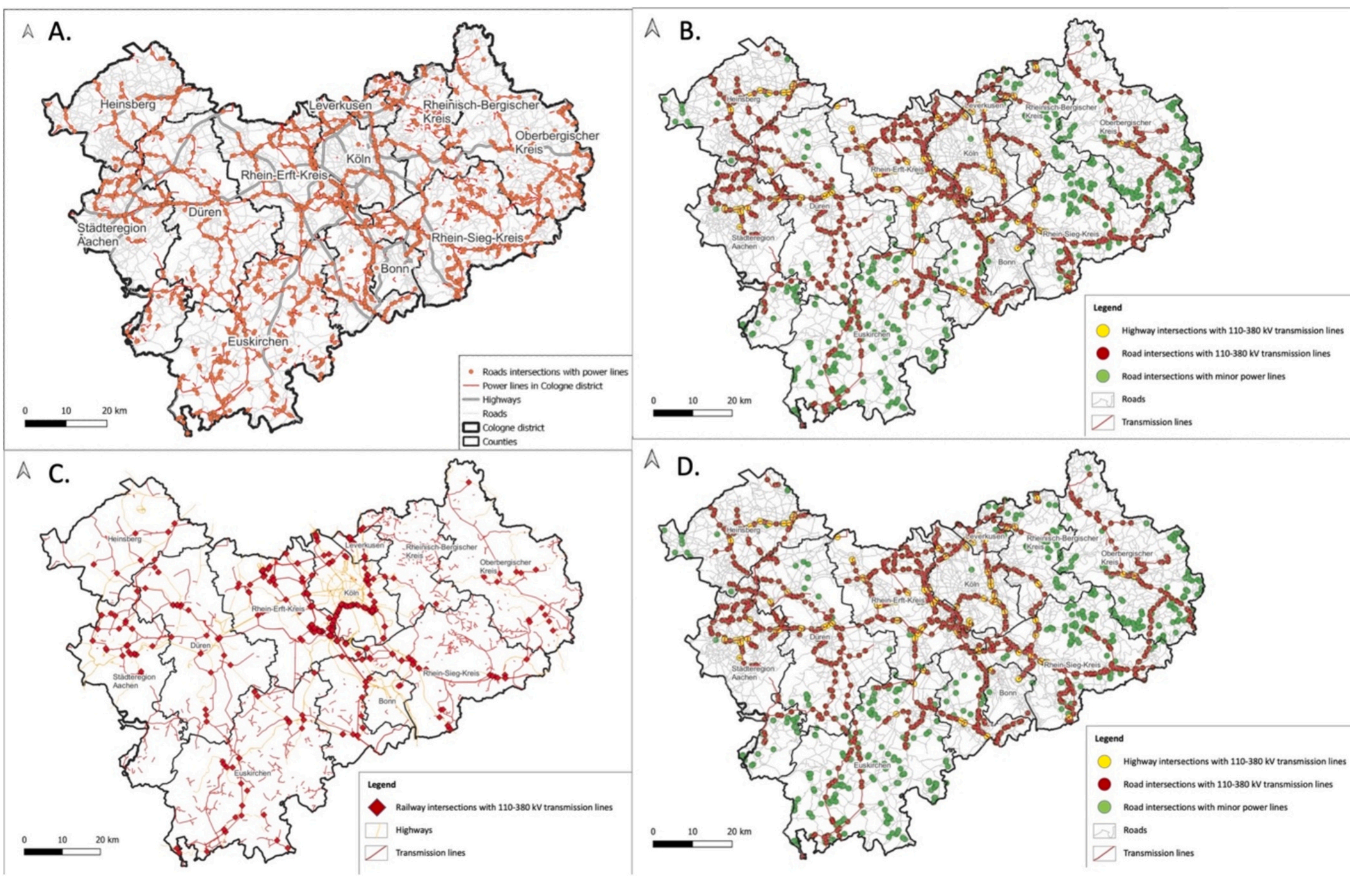

Fig. 6. A. Road crossing transmission lines in the Cologne district. B. Highways crossing transmission lines in the Cologne district. C. Rail crossing transmission lines in the Cologne district. D. Waterways crossing transmission lines in the Cologne district.

220 kV transmission lines. Again, the red dots in Fig. 6, Map B., show that numerous potential hazard zones along the major highways cross the area from north to south due to crossings with transmission lines. The transmission lines also cross railways, and there is a very high concentration in the south of Cologne city and generally in the zone between Cologne and Bonn (Fig. 6, Map C.).

Water bodies are largely affected outside densely populated areas (Fig. 6, Map D.). This shows that crossing transmission lines also heavily affects the blue infrastructure. This is significant for larger waterways, where important shipping traffic occurs, along the river Rhine. But smaller rivers are also relevant since power lines that fall into open waters are not only a problem for firefighters and operators to repair but also negatively impact aquatic and riparian ecology.

Analyzing the number of towers and transmission line crossings with roads and waterways reveals that three counties are most affected (Tables 7a and 7b). Here, the Rhein-Sieg-Kreis is also most affected by all crossings with roads, railways, or waterways. It is followed by the Rhein-Erft-Kreis, a more rural county. In third place is the city of Cologne, which shows that larger settlement areas have relatively large numbers of transmission towers and lines and, therefore, are also heavily affected.

Interestingly, the relative numbers of transmission line crossings calculated per area size of the county show a slightly different picture (Table 7b). Again, Cologne is among the top three but topped by the city of Leverkusen in all five categories and the Rhein-Erft-Kreis. This shows

Table 7a
Number of towers and transmission line crossings with roads and waterways.

	Transmission towers (number)	Transmission lines (TL) crossing roads (cases)	110–380 kV TL crossing roads (cases)	TL crossing railways (cases)	TL crossing waterways (cases)
Bonn	36	22	10	5	2
Köln (Cologne)	598	224	214	253	20
Leverkusen	170	54	50	68	20
Städteregion Aachen	623	213	177	48	83
Düren	682	151	122	44	104
Rhein-Erft-Kreis	1216	339	315	336	81
Euskirchen	503	236	85	44	186
Heinsberg	333	106	92	11	42
Oberbergischer Kreis	400	225	95	14	88
Rheinisch-Bergischer Kreis	226	102	45	9	79
Rhein-Sieg-Kreis	1140	469	359	110	277

Table 7b
Relative number of towers and transmission line crossings with roads and waterways per area size.

	Towers per km^2	Transmission line crossings with roads per km^2	110–380 kV Transmission line crossings with roads per km^2	Transmission line crossings with railways per km^2	Transmission line crossings with waterways per km^2
Bonn	0.26	0.16	0.07	0.04	0.01
Köln (Cologne)	1.48	0.55	0.53	0.62	0.05
Leverkusen	2.16	0.68	0.63	0.86	0.25
Städteregion Aachen	0.88	0.30	0.25	0.07	0.12
Düren	0.72	0.16	0.13	0.05	0.11
Rhein-Erft-Kreis	1.73	0.48	0.45	0.48	0.11
Euskirchen	0.40	0.19	0.07	0.04	0.15
Heinsberg	0.53	0.17	0.15	0.02	0.07
Oberbergischer Kreis	0.44	0.24	0.10	0.02	0.10
Rheinisch-Bergischer Kreis	0.52	0.23	0.10	0.02	0.18
Rhein-Sieg-Kreis	0.99	0.41	0.31	0.10	0.24

Table 8
Total line length in the Cologne district.

Feature	Length in km
Forest crossing roads	1467
Forest crossing highways	163
Forest crossing all transmission lines	211
Forest crossing 110–380 kV	131
Forest crossing 110 kV	96
Forest crossing 220 kV	6
Forest crossing 380 kV	28
Forest crossing minor transmission lines	80
Settlements crossing all transmission lines	335
Water bodies crossing all transmission lines	10
Transmission towers with a 150 m circle buffer crossing roads	705
110-380 kV lines with a 56 m band buffer crossing roads	264

that it is important to analyze total and relative numbers. This could, for example, indicate the number of towers to be repaired for the operators and emergency management.

3.3. Buffer Zone Exposure

The results of the total lengths in the Cologne district reveal that roads-crossing forests have a length of over 1000 km (Table 8). This points to a general risk that is not directly related to transmission line failure. However, roads are found to be places for human-induced forest fire ignitions when cigarettes or barbeques are involved [32].

By comparison, a 200 km exposure zone is identified for all transmission lines combined when they cross forests. In these zones, either summer heat and sagging lines or power lines swinging in storms can potentially ignite forest fires or trigger line failures. The risk, in terms of exposure, is highest for high-voltage transmission lines. It is the lowest for the 220 kV lines because they are less common in this area. Nevertheless, over 80 km of minor transmission lines are also exposed.

Not only forests but also settlements are exposed, which intersect with transmission lines over 335 km. Line failures could potentially expose the houses to forest fire. Moreover, 10 km of water bodies are exposed, which is relatively low compared to other exposure risks.

The risk increases when applying the buffer created. For example, we have investigated whether the transmission towers within the 150 m circle buffers could reach roads. 705 km of roads could be affected, which poses a high risk for traffic and emergency management, which would need to take care of such sites and incidents. 264 km are also exposed along a 56 m wide band of roads crossing the high transmission lines between 110 and 380 kV.

3.3.1. Critical infrastructure

An assessment of the location of selected critical infrastructure within the risk zone buffer identified along the transmission lines reveals that only a few would be potentially exposed. Thirty-six petrol stations would have to be taken out of service by applying preventive measures. In addition, there is also a risk of ignition. Eighty-five bridges must also be taken into account, as one failed transmission line would affect various traffic routes at the same time.

Within the 60 m band buffer zone and in the 150 m radius buffer zones:

- Fire stations exposed: 2
- Hospitals: 0
- Airports: 0
- Schools: 9
- Petrol stations: 36
- Bridges: 85

3.4. Exposure scenarios

The paper’s main objective was to indicate how spatial assessments

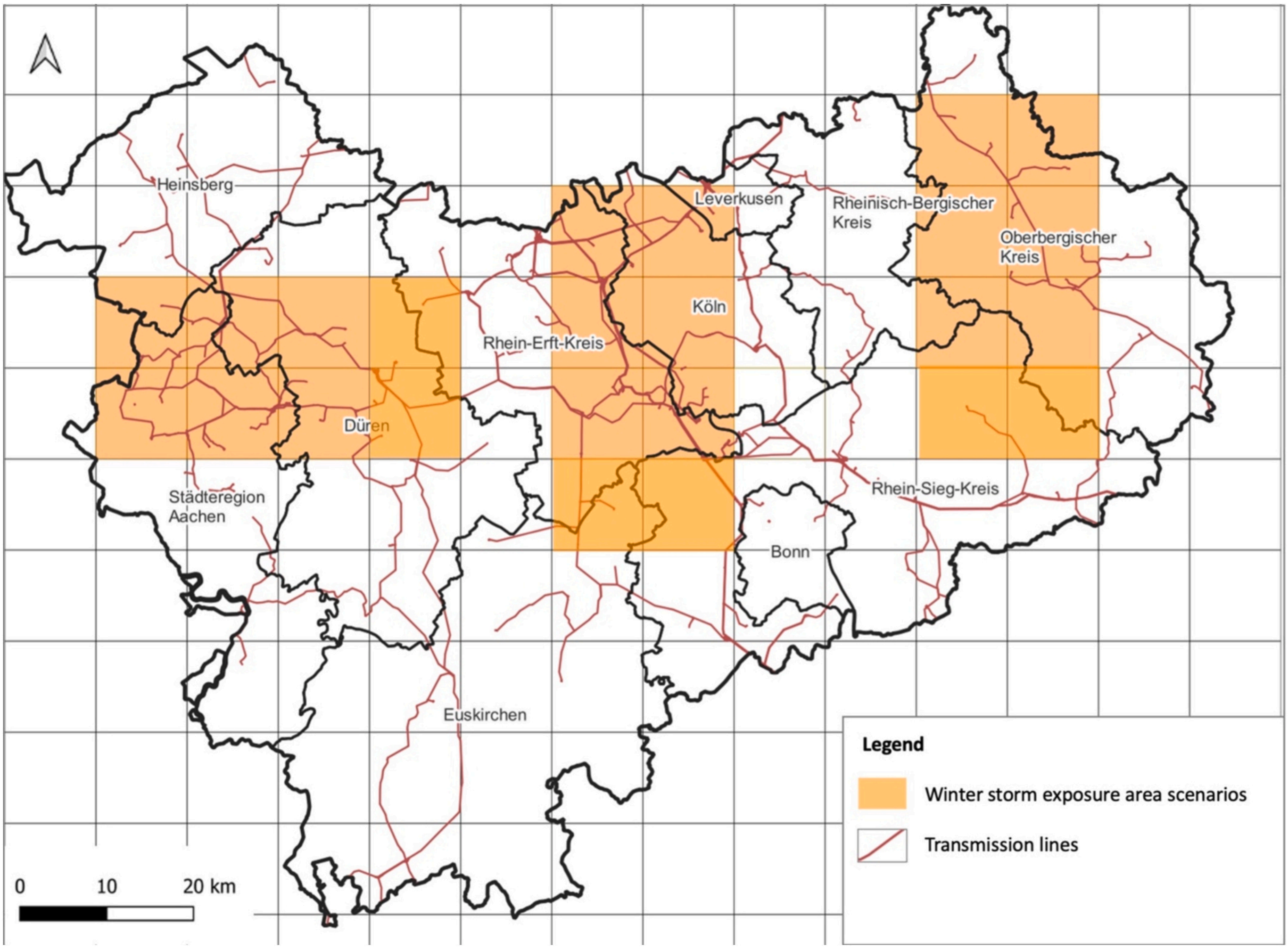

Fig. 7. Three examples of areas with a winter storm exposure similar to the 2005 event.

can be conducted and help to analyze interrelationships between transmission lines and other features. Although this has been covered in the previous sections, we want to provide at least an indication of how this information could be used further. Within the definition of risk assessments, the previous steps have mainly shown the identification of important elements and spatial exposure potential. Risk, however, needs a combination of exposure with probabilities of events or severity of damages. Therefore, the following three examples illustrate how to utilize scenarios derived from previous events, which could help future emergency management or disaster preparedness planning.

3.4.1. *Winter storms*

The first scenario covers a winter storm scenario (Fig. 7). Winter storms are a notable hazard in Germany, leading to a significant power outage in 2005, for example [23]. Houses, agricultural sites, and other sectors sometimes lacked power for up to seven days. This is a serious event and scenario for civil protection and other planning.

The spatial extent of the 2005 event was extracted from a report showing a map of the location of 80 tower transmission towers that collapsed due to heavy loads of wet snow and ice [23]. That report displays that roughly an area of around 40 × 20 km was affected. The following map shows three examples of 40 × 20 km areas in our case study area. This is entirely hypothetical and only shows how such assessments could be combined. Such scenarios could be used in mock-up training programs or national exercises. This would show that an event similar to 2005 could also be transferred to highly populated areas or areas with high densities of transmission lines. Two areas highlighted in the figure in the west and center show areas with high densities. The third area, in the east, which is not densely populated and has fewer transmission lines could also be highly significant because there are fewer redundancies of alternative transmission lines, and a single interruption of one transmission line could result in heavily affected rural areas with no alternative power supply.

3.4.2. *Earthquake scenario*

The next example is an earthquake scenario (Fig. 8). This is important to consider, even though Germany has not yet experienced severe earthquakes. However, smaller and sometimes stronger earthquakes occur more frequently in the Lower Rhine Graben, where the study area is situated. This was last the case in the 1992 Roermond earthquake (Netherlands), which reached a magnitude of 5.4 on the Mercalli scale and caused 30 injuries and considerable damage to buildings in North Rhine-Westphalia [17]. Three zones of earthquake risks are differentiated and shown on the map. It should be noted that the earthquake risk could be much higher than recent records indicate as archaeological excavations suggest even stronger earthquakes have occurred during the last 500 years [21].

The three earthquake zones show that the densely populated areas in the center, such as Cologne, Leverkusen, and Bonn, are in earthquake zone 1. Table 9 shows that most transmission lines and towers would be affected in earthquake zone 2, characterized by medium-sized towns and rural areas. The city of Aachen in the west would also be affected, as it is located in earthquake zones 2 and 3.

The scenario shows that non-climate-related hazards are also

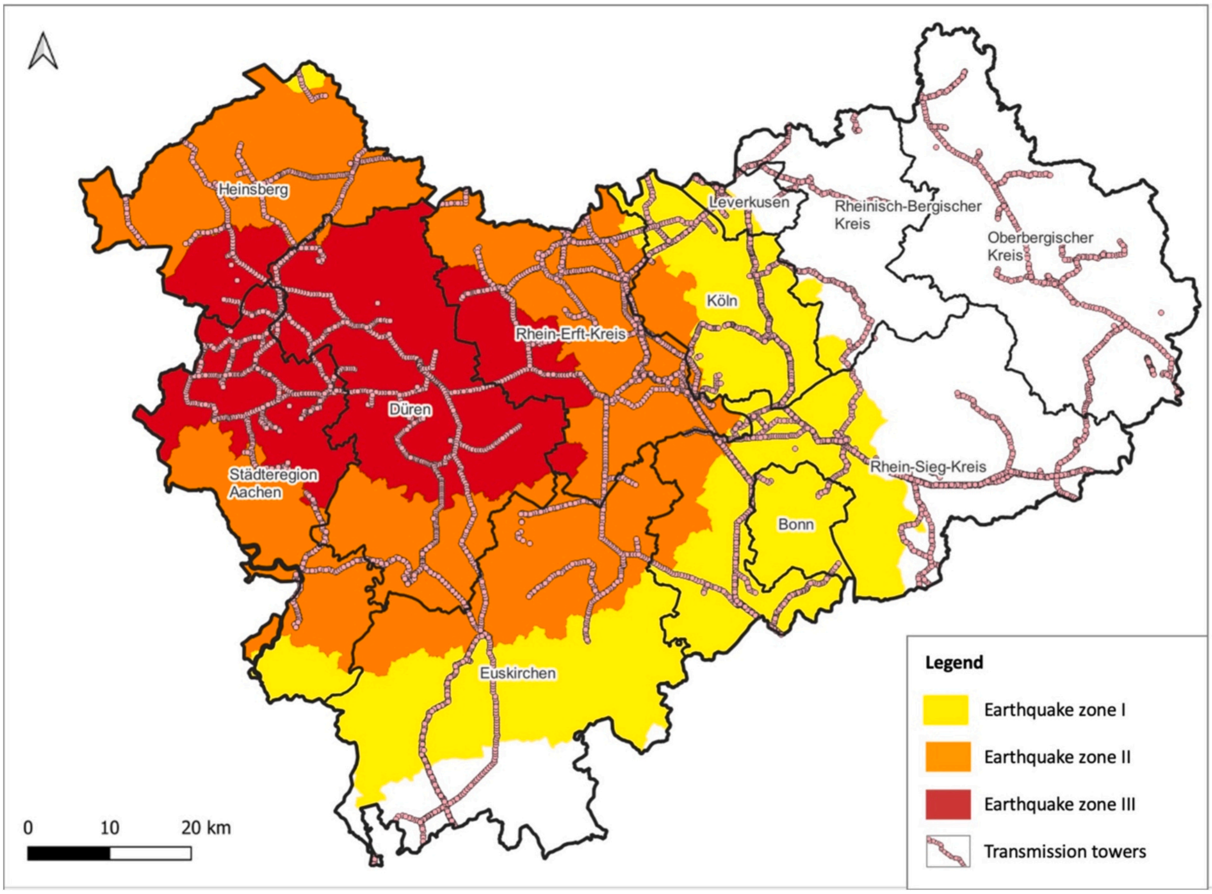

Fig. 8. Earthquake zones and exposure of transmission lines in the Cologne district.

Table 9
Number of transmission towers per earthquake zone.

Zone	Transmission towers
Earthquake zone 1	1492
Earthquake zone 2	1965
Earthquake zone 3	1220

relevant and can be analyzed using this approach.

3.4.3. *Forest fire scenario and exposure assessment*

In 2018, significant wildfires occurred in forest and heathland ecosystems in the counties of Meppen and Lübtheen. Using the NASA website documenting fires and thermal radiation events (FIRMS), we identified roughly 3 × 6 km areas. These areas could also be applied similarly, as shown for the winter storm scenario. However, even larger wildfires are possible. In Mediterranean countries such as Portugal, large wildfires have burnt across areas up to 60 km × 30 km. Because temperatures and summer droughts are increasing across Central Europe, there is still a great deal of uncertainty and a need for further research to estimate the potential extent of forest fires in Germany and what this means for disaster risk assessment and emergency management. In the GIS examples above, we have only covered forest fires, but this approach could also map other types of vegetation fires.

In addition to the previous assessment, we conducted an exposure analysis for a forest fire scenario. The fires in 2018 affected an area of around 3 × 6 km. We have applied a 3 km potential fire risk zone around the transmission line to remain cautious. The detailed procedure is described in the methods section.

The resulting risk map and Fig. 9 show orange bands, which are fires sparked by a transmission line collapse that could potentially burn an area of 3 km in diameter. The so-called wildland urban interface (WUI) bordering settlement areas could be affected along the edges of these burning areas. The 400-m distances resembling potential fire spark flying distances have been derived in a previous study from an international literature study [14].

The map shows that areas with large forest coverage in the south west and eastern part are potentially exposed to ignition triggered by failing transmission lines. In addition, the yellow areas indicate that settlements in more densely populated areas are even more affected by forest fire ignitions of this type. Calculating the total areas exposed per county shows this risk is not evenly distributed (Table 10). Some highly populated cities, such as Bonn or Leverkusen, are less affected than certain rural counties. However, it is interesting that other highly populated areas, such as Cologne, have large areas affected. Only the total area figures are used here, not the relative figures for the different sizes of the districts. The map also shows the WUI for all forest areas bordering settlement areas. Comparing these red zones with the yellow areas, which are only triggered by transmission line failures, shows that transmission line failures of this scenario type could trigger most WUI in the area.

4. Discussion

The study shows that electricity tower and transmission line failures occur in Germany.

The first research question was addressed through an online media search to source documented events. To answer the second research question, we presented a risk mapping method that allows us to detect potential future exposure corridors along transmission lines with an ignition risk or overlapping exposure with roads, railways, and other

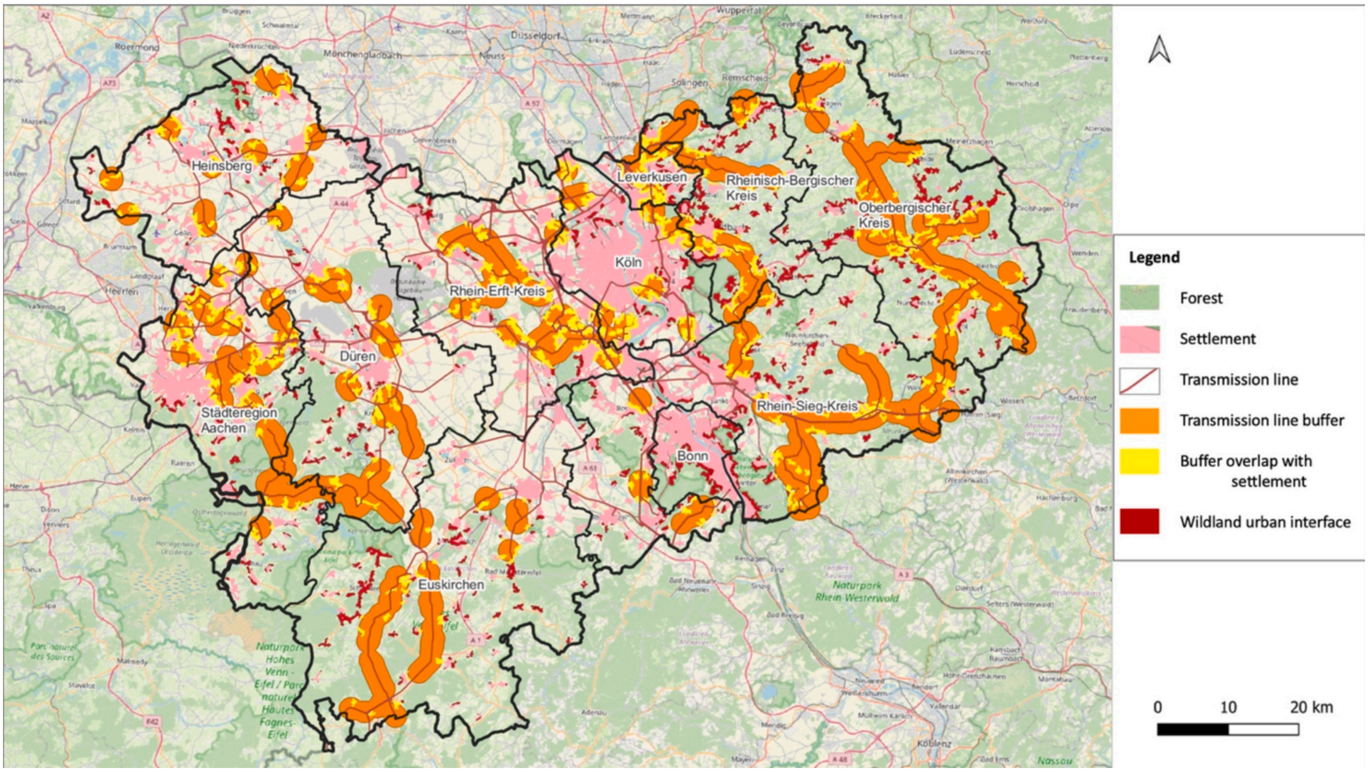

Fig. 9. Risk map of forest ignition over 1500 m from each side of 110–380 kV transmission line triggering flyover up to 400 m WUI with settlements exposed (in yellow color). And WUI 400 m of other forest settlements outside of transmission lines for comparison (in red color). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 10
Areas of 400 m overlaps of transmission line buffer zones with settlement areas per city or county.

City/ County	WUI area in km^2
Bonn	4.668
Euskirchen	13.617
Leverkusen	15.720
Heinsberg	23.926
Düren	29.277
Rheinisch-Bergischer Kreis	29.431
Köln	37.152
Rhein-Sieg-Kreis	41.263
Oberbergischer Kreis	46.536
Städteregion Aachen	53.467
Rhein-Erft-Kreis	55.932

infrastructures. We have examined in detail the spatial relationships between blue, green, and gray infrastructure, for the third research question. The findings can serve as a basis for future interdisciplinary approaches to better link sustainable development, climate change adaptation, and disaster risk reduction with critical infrastructure. Regarding the fourth research question, certain limitations and challenges for spatial exposure risk assessments of this type remain, which are further detailed below.

4.1. Limitations and Challenges for Spatial Exposure Assessments

Visual analysis of the satellite imagery and field visits revealed that many larger trees and shrubs are located under the transmission lines or in their direct vicinity, e.g., at the edge of highways, along rivers, and between agricultural fields. In future studies, it would be important to map these, but this was not possible in this study due to the large area. Discussions with experts also revealed that this is a sensitive topic since forest managers are not allowed or responsible for ensuring that the trees under the transmission lines are felled or pruned. This is because the operators are responsible for this maintenance work. This could indicate a future study on how various actors can cooperate to avoid future forest fires in Germany. In some of the recent forest fires, it was also observed that the clearance of forest access roads was hampered by the failure of forest managers to clear trees after the storms that preceded the forest fire. This is a controversial and important field to improve future risk management by better actor cooperation.

It is also interesting to read extensive technical books on construction types and safety distances of towers [41]. It is recommended to differentiate between newly felled and longer existing corridors in the safety buffer zones through forests. The argument is that a newly felled corridor with trees at its edge could still collapse. However, storm damage has shown that trees can fall within mature forests and at the forest edges. Therefore, tree growth and safety corridor widths should be considered in further developments of the spatial assessment.

4.2. Challenges for Emergency Management

Transmission line failure is a problem for the population when power blackouts occur [39]. It is also a major concern for the industrial and service sectors that rely on electricity [49]. It is also a problem for the service maintenance, repair, and delivery operators [7]. Furthermore, the tertiary impacts on emergency management should not be neglected. For example, firefighters have to handle such events, extinguish fires sparked by such accidents, and ensure that safety is guaranteed and hazard zones are cordoned off. At the same time, these emergency services depend on functioning roads [40] and sometimes even waterways for fire boats, which, as the analysis shows, can also be affected during such events.

This information is important for logistics planning for emergency management planning, It is crucial for emergency service providers,

Table 11
Transmission line failures in Germany, from media search Nov 2023. Search terms used: "Vogelschlag AND Stromausfall" (= bird damage AND power failure).

Event	Cause	Affected structure and damage	Information for GIS assessment	Source
Parts of Altenstadt, Ortenberg and Glauburg in the Wetteraukreis, 27. Sept 2021	Maintenance works and larger bird	Blackout for about 50 min; 7000 people affected	20 kV line	Fnp.de 2021
Sigmaringen, 4. Nov. 2021	Swan at a transmission line at Diefurt Mühle	650 households for 20 min without power	20 kV line	Stadtwerke.sigmaringen.de 2021
Verbandsgemeinde Nieder-Olm, 14 June 2018	Bird damage in the transformer station Ober-Olm	36,400 people for 11 min without power		SZ 2018, rheinhessen-news.de 2018

such as firefighters, to have a better understanding of which counties have a higher exposure risk to transmission line incidents and those that are also facing additional exposure risk due to the affected infrastructure, such as roads.

4.3. Expanding the Assessment to Other Hazards, for Example of Bird Damage

One problem of critical infrastructure research is that it is often limited to technical aspects and the field of security research. Recent developments try to better integrate these so-called gray infrastructures with blue and green infrastructure approaches to better connect security and disaster risk research with environmental research. This is also highlighted at the international level by the attempt of international strategy or agenda alignments [22,36]. Along this line, we want to indicate one example of how to better connect the topic of natural hazards not only for humans but also for other environmental aspects. Our aim is to highlight that birds cause power failure as well, but at the same time to encourage better design of power supply structures and urban planning so birds are not killed.

After natural hazards, animals, particularly birds, are a leading cause of transmission line failure and wildfires across different transmission lines, from 230 kV to distribution lines in California [33]. In recent years, numerous publications have investigated the danger of bird nests on transmission lines [24,29]. The danger of bird droppings has also been addressed [28,30]. Several papers are dedicated to the reduction of these hazards through management [31,34], technical solutions, such as remote sensing [16] and UAV inspection [45,60] and the application of artificial intelligence [26,46,59]. On the other hand, several papers discuss and model the negative impact on specific bird species [8,52] or larger bird populations [42,47] and in some cases propose solutions to reduce the conflicts [35,54] [35,54].

There is a risk of electrocution for birds due to the large wingspan of birds of prey touching two conductive wires or the connecting mass between a wire and mast [54]. The type of power tower strongly influences electrocution risk for birds of prey, as shown in a study in Catalonia, Spain [54]. Birds of prey, such as waterfowl, are prone to such risk, and transmission lines next to power plants should not be planned over water bodies to reduce this risk [2]. Also in Germany, transmission line failures are documented (Table 11).

5. Conclusion

In Central Europe, climate change is increasing the frequency and intensity of extreme events and associated natural hazards, such as heatwaves, droughts, and forest fires. As a result, critical infrastructures such as transmission lines are exposed to an increased risk of failure. In the administrative district of Cologne, Germany, the combined effects of climate change have increased the risk of forest fires, winter storms, and technical failures of power transmission lines. This study uses a spatial geographic information system (GIS) to assess the interplay of these hazards and suggest improvements to preparedness and resilience strategies.

The results here demonstrate that a spatial exposure assessment of interlinking transmission line and forest fire exposure risk can be conducted using open-source information. Furthermore, it is shown that the general methodology can also be applied to other natural hazards, using spatial scenarios. The results show areas within the Cologne district with increased risk of power line failure due to exposure to forest fires and winter storms. Earthquake exposure areas are also shown. In addition, the study identifies areas of overlap where multiple hazards come together and amplify the overall risk profile. Concrete findings are that about 1400 km of roads in the area are exposed to forest fire risk, and over 160 km of national highways. Over 30 petrol stations and over 80 bridges add to the exposure potential in the Cologne district. More than 1000 transmission towers are located in the highest earthquake zone of the country. These findings provide valuable insights for policymakers, emergency responders, and urban planners to prioritize mitigation efforts, effectively allocate resources, and improve community resilience.

This GIS exposure risk assessment highlights the urgent need for proactive measures to address the multi-layered challenges posed by climate change-related hazards in the Cologne district. By integrating spatial data analysis with exposure risk assessment methods, this study provides a comprehensive framework for understanding and mitigating the complex interplay of wildfires, winter storms and power line outages in a changing climate landscape.

Usage of AI

No AI tools were used in this manuscript.

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CRediT authorship contribution statement

Alexander Fekete: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Udo Nehren:** Writing – review & editing, Writing – original draft, Investigation.

Declaration of competing interest

The authors have no competing interests to declare. Declarations of interest: none.

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Data availability

Data will be made available on request.

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