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Vegetation: a risk influencing factor for Natech scenarios

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Ensuring the availability of critical infrastructure systems, such as power grids, is of utmost importance for industrial risk management. Studies have shown that vegetation is among the major hazards power grids are exposed to. Typically, the consequences of vegetation-induced power disruptions are limited to inconveniencing end-users, yet their severity may escalate considering technological accidents caused by natural hazards involving the release of hazardous chemical substances—known as Natech. Recent Natech events in the United States involving extended power blackouts triggered by extreme hydro-meteorological phenomena emphasized the need for robust and reliable power grids. In this study, we bring attention to an underlying risk factor that can potentially jeopardize the reliability of power grids during Natech scenarios: vegetation. From a systemic risk standpoint, we frame vegetation as a Natech risk influencing factor with respect to power grids, which is further amplified by Climate Change. We then examine the interaction between vegetation and power grids considering the case of Norway. Finally, we propose a risk-based decision support framework aimed at enhancing decision-making for vegetation management along power lines and discuss its implications in the Natech risk management context.

Keywords: Critical Lifelines, Hazardous Material Release, Natech Risk Management, Power Grid, Risk Influencing Factor, Vegetation.

1. Introduction

With soaring demand for electricity for human activities, the need for safe, reliable, and continuously operating energy infrastructure is more relevant than ever nowadays. Power grids are the backbone of electricity distribution, providing a critical service through connecting electricity generation with utilization. As critical infrastructures, they are designed to function as defenses against extreme events: to sustain the supply of essential services that different parts of our societal systems rely upon (UNDRR 2022). Due to their enormous size that consequently exposes their physical components to various natural hazards (Bian *et al.* 2021; Petrova 2022), and because they fulfil the abovementioned important role for our societies, power grids consist of a major vulnerability for the overall energy infrastructure system.

It becomes apparent that failures to power grids entail significant consequences for a great number of beneficiaries. For instance, households may be deprived of vital access to energy, *inter alia*, with potential consequences ranging from a mild inconvenience in everyday routines to several fatalities due inability to meet basic human needs (*e.g.*, house heating, cooking) over extended periods (see "The Great Texas Freeze" of 2021; 2023). Furthermore, the industrial sector relies heavily on power grids to ensure both an uninterrupted operation of their processes and—more often than not—the reliability of certain safety measures during emergencies (Krausmann and Necci 2021). Such safety measures are particularly important for industrial facilities that handle hazardous substances, where preventing and mitigating the impact of accidental releases is the primary concern (Suarez-Paba *et al.* 2020). Thus, apart from incurring significant costs to households and businesses, long-term power disruptions subject communities living nearby industrial facilities to life-threatening scenarios.

Scenarios like the above, which involve the release of hazardous substances due to a technological accident caused by a natural hazard, are known as *"Natech"* (UNDRR-APSTAAG 2020). Natech accidents are multi-hazard, cascading events that are systemic by nature (Krausmann and Necci 2021). There is a multitude of factors delineating the characteristics of the triggering natural hazard, the chemical release, and their subsequent consequences. Various triggering mechanisms have been studied so far, from geological hazards (*e.g.*, earthquake, tsunami, landslide, and volcanic eruption) to hydro-meteorological hazards (*e.g.*, flood, lightning, extreme temperature, and weather-related) and multi-hazard scenarios analyzing various contributing risk factors (Suarez-Paba *et al.* 2019). Recent studies underscored the increasing trend in severity and frequency of hydro-meteorological Natech events (Luo *et al.* 2020; 2021), while international organizations brought to the forefront potential vulnerabilities of our critical infrastructures to extreme weather events (UNDRR 2022), with potentially detrimental effects for the resiliency of industrial facilities, as noted by Suarez-Paba *et al.* (2020).

In this context, this study emphasizes the need for robust and reliable power grids in the pursuit of minimizing Natech accident risk from—increasingly frequent and severe—extreme hydro-meteorological phenomena. We bring attention to an underlying risk factor that can potentially jeopardize the reliability of power grids during Natech accidents: vegetation. To our knowledge, this study is the first attempt in conceptualizing vegetation as a Risk Influencing Factor (RIF) for Natech accidents. Our main scientific contribution is framing vegetation as a Natech RIF with respect to power grids, particularly considering hydro-meteorological hazards. In this vein, we wish to introduce to the academic discussion certain systemic interdependencies concerning the interface between vegetation and power grids from the perspective of Natech risk management. With a view toward risk reduction, we also present a rudimentary risk-based decision-support framework for managing vegetation-related hazards to power grids and discuss its implications in the context of Natech accident risk.

The rest of this article is structured as follows. Section 2 discusses Natech accident risk considering the specificities and systemic interdependencies of power grids. Section 3 introduces the risk landscape of power grids, while the following section draws upon the previous discussion to conceptualize vegetation as a risk influencing factor and looks into the case of the Norwegian power grid. Section 5 presents a risk-based decision framework for vegetation hazards to power grids. The last section offers a brief discussion of challenges and concludes with future research directions.

2. Natech Scenarios as a Systemic Risk

Systemic risks lurk in scenarios where the impact of a hazard not only affects a part of the system, but has the potential to cause failures to the overall system or damage other functionally connected systems (Okada *et al.* 2018). Considering the increasingly interconnected systems of our societies today (UNDRR 2022), it is imperative to adopt a systemic approach to effectively address risk management for assets that materialize these sub-system interlinkages and provide critical services, such as power grids. For Natech scenarios, this is particularly relevant, since they are a gateway to the systemic risk landscape, cutting across sectors, territorial scales, and conceptual boundaries. Unfortunately, due to their complex and rare nature, Natech events have been erroneously considered as “Black Swans”, *i.e.*, unforeseeable and unpredictable technological accidents. Nonetheless, as Krausmann and Necci (2021) conclude, chemical process safety studies reject this notion arguing that the vast majority could have been addressed through mindful risk assessment and conventional risk management processes.

Indeed, ensuring the safety and availability of critical infrastructure under natural hazard scenarios is of utmost importance for industrial risk management (Suarez-Paba *et al.* 2020; Krausmann and Necci 2021). Industries rely heavily on external power supply systems and thus, power grids are a crucial component in the Natech risk landscape. Often, the efficiency and operability of critical industrial process safety equipment, for instance pumps, sensors, and temperature control systems, depend on off-site power in order to prevent and/or mitigate a hazardous substance release (Krausmann and Necci 2021; Suarez-Paba *et al.* 2020). Moreover, safe and reliable access to electric power during and immediately after the crisis is a key enabling factor for the effective deployment of first responder teams trying to take control of the situation to mitigate damages. Thus, the systemic interdependencies introduced by power grids play a key role in the propagation of Natech accident scenarios.

We refer to two relevant, recent extreme weather-related events to better illustrate the fundamental aspect of power grids in Natech accidents. In the first example, Hurricane Harvey (2017) caused extensive floods in the area of Texas (United States – US), which led to chemical releases from the Arkema chemical processing facility (eNatech 2023). After external power supply to the chemical processing facility was disrupted and emergency backup power sources failed due to flooding, the operation of critical cooling equipment was abruptly shutdown. Facility operators then moved temperature-sensitive chemicals (150 tons of organic peroxides) into refrigerated trucks to ensure the safe storage and removal of self-decomposing, explosive substances from the site. However, the trucks were stranded and unapproachable by emergency response teams due to the high floodwater level at the site. The result was the degradation, release, and ignition of flammable chemicals, leading to fires, explosions, and noxious gas clouds. According to reports, 18 on-site responders were injured from inhaling noxious gases, while around 300 people in total were at risk during that incident (eNatech 2023).

The second example is the multiple chemical releases from equipment failures and process disruptions due to the “Great Texas Freeze” of 2021. A lack of adequate preparedness measures from industrial operators for the winterization of power infrastructure, compounded with an extreme cold spell that affected the greater area, left the isolated power grid of Texas vulnerable to cascading failures (Petrova 2022; Bridger 2022). As the ice and strong winds snapped power lines and caused multiple industrial equipment and emergency system breakdowns, numerous petrochemical processing industries reported sudden disruptions to their operations, leading to massive, unplanned emissions of hazardous substances (*e.g.*, almost 130.000 pounds of sulfur dioxide and 263,000 pounds of methane) (Uteuova 2021). That is notwithstanding the increased pollution associated with idling and restarting petrochemical facilities (Roston *et al.* 2021). An estimated 4.5 million households and businesses were without electricity for heating and cooking—some of which for several days—during the cold spell, leading to at least 264 deaths from the cold and 300 billion USD in economic damages (Petrova 2022; Bridger 2022). Furthermore, communities near petrochemical facilities were exposed to hazardous substances several times over the permitted levels (Uteuova 2021).

In both cases, Natech accidents are attributed to sudden disruptions of the normal operating conditions brought by hydro-meteorological phenomena. Additionally, these events highlighted the cascading effects of prolonged and wide-area power blackouts in conjunction with poor accident preparedness measures and the subsequent inoperability of redundancy systems.

3. The Risk Landscape of Power Grids

Although certain vulnerabilities and the importance of power infrastructure from a systemic perspective were mentioned in the previous section, it is worth elaborating here on the risk characteristics of power grids with respect to natural hazards. In fact, several researchers have labeled the electric power sector as a high-risk industry (Tervo *et al.* 2021; Petrova 2022; Bian *et al.* 2021; Pacevicius *et al.* 2020). Electricity transmission is still carried out using copper and aluminum cables at its core. Electric power lines are the connectors between power-generating infrastructure, substations, and the energy-users. Considering that energy is rarely consumed at the system nodes where it is produced, electricity grids need to extend for thousands of kilometers to deliver power. In order to efficiently build and maintain such a vast power infrastructure system, installing overhead power lines seems to be the most cost-effective and straightforward option, given the size of the network, the variety of terrains it has to cross, and minimizing disturbances to natural and human activities.

The above factors comprise a unique risk profile for power grids. On the one hand, their extensive coverage physically exposes overhead power lines, the pylons, and the substations to an array of natural hazards. Previous studies found that wind, ice, lightning, wildfires, and falling trees are among the most severe hazards to power grids (Bian *et al.* 2021; Petrova 2022). For instance, Tervo *et al*. (2021) investigated the impact of extratropical storms on power grids. They concluded that wind gusts constitute a significant hazard to overhead power lines due to both direct damages to the infrastructure and falling trees on cables. On the other hand, transmission power lines often traverse remote areas, such as woodlands or mountainous regions. This makes it particularly costly for operators to perform maintenance inspections—and thus there is a tendency to carry out checks infrequently—while response times from technical crews in case of system failures are severely hampered due to poor location accessibility (Pacevicius *et al.* 2020).

These features describe an infrastructure inevitably exposed to a high level of natural hazard risk. Compounded with the fact that power grids provide a critical service for numerous and diverse beneficiaries namely households, industries and public utilities, interruptions can have severe and costly consequences for societal systems (UNDRR 2022), which can even escalate to national crises (see the Great Texas Freeze). From a technological accident perspective, even if there is no direct impact from the natural hazard on *in situ* industrial equipment, sudden disruptions to the industrial processes due to power outages coupled with insufficient accident preparedness measures can lead to releases of hazardous chemicals (Suarez-Paba *et al.* 2020; Krausmann and Necci 2021).

It becomes apparent that power grids are a critical lifeline at high risk. Therefore, effective risk management of power grids is a top priority not only for the electricity grid operators themselves, but also for communities, governments, and businesses that depend on such a critical, but vulnerable, lifeline. In addition, researchers noted that the significance of monitoring and managing natural hazard risks to power lines is becoming increasingly relevant in the context of Climate Change, as extreme hydro-meteorological events are becoming progressively more frequent and severe *(Tervo et al.* 2021).

4. Vegetation as a Risk Influencing Factor

Following the reasoning so far, we argue that inadequate vegetation management along power grids can be a Natech Risk Influencing Factor. According to Øien (2001), a Risk Influencing Factor (RIF) is defined as "an aspect (event/condition) of a system or an activity that affects the risk level of this system/activity". RIFs have the potential to generally influence risk scenarios and inhibit the effective operation of barrier systems; they can be understood as "error-producing conditions" that facilitate errors and create dangerous, latent conditions if left unchecked as Sonnemans *et al.* (2010) noticed. This is exactly what we observed in both Natech accidents we presented earlier. Finally, it is worth noting that RIFs and safety indicators were studied initially mainly from a technical and quantifiable perspective (Sonnemans *et al.* 2010). However, scholars and practitioners have recently recognized the need for more socio-technical approaches, which incorporate technical, human, and organizational aspects (Sonnemans *et al.* 2010). Our argument aligns with this direction because we are not reductively suggesting that vegetation is the root of this problem—in which case widening and clear-cutting the power lines' right-of-way would suffice—but rather we acknowledge the challenges of managing the vegetation around such an extensive and critical infrastructure and underscore the importance of a risk-based maintenance approach in the context of Natech accident scenarios.

Several studies have shown that vegetation is in fact among the major natural environment threats our electricity grids are exposed to (Bian *et al.* 2021; Petrova 2022; Tervo *et al.* 2021). International organizations also recently stressed the need to increase critical infrastructure resilience against natural hazards "such as trees falling on power lines" (UNDRR 2022, 38). But how exactly can vegetation affect a power grid?

There are two main mechanisms through which vegetation in proximity to power lines can pose a threat to electricity grids. The first way is when an entire tree (or a tree branch) breaks or is uprooted and falls directly onto the infrastructure. Coupled with strong winds, such heavy objects can potentially sever power lines, damage substations, and cause pylons to deform or even collapse. The second way involves plants gradually encroaching on the power line's right-of-way. If left unattended, vegetation that grows underneath, overhead, or alongside the power grid may move due to a light breeze or precipitation, potentially coming in contact with the high-voltage cables or other sensitive equipment at substations, short-circuiting the network as a result.

The consequences of these incidents are usually limited to minor disturbances or power outages that inconvenience downstream users from a few minutes to a few hours. Nonetheless, as discussed in Section 2, power disruptions compounded with the impact of wide-area natural hazards may lead to or considerably escalate Natech accident scenarios. Apart from that, damaged power lines and short-circuits due to vegetation may also trigger wildfires during prolonged drought periods (Bian *et al.* 2021). Such scenarios may put nearby people, property, and other critical infrastructure at risk, thus further exacerbating an emergency situation by overwhelming the response mechanisms with multiple fire fronts. In fact, extreme drought combined with other factors caused more frequent and severe wildfire incidents in the past years (Pishahang *et al.* 2022). Of course, wildfires at Wildland-Urban Interfaces (WUI) are particularly concerning, as they can threaten nearby facilities handling hazardous substances, and thus pose in turn a new Natech accident risk.

4.1. *The Norwegian case*

We examine the interaction between vegetation and power grids considering the case of Norway, where vegetation was the primary cause of power outages in 2018 (Norwegian Water Resources and Energy Directorate 2019). In order to frame vegetation as a Natech RIF, it is important to also take into account the impact of extreme hydro-meteorological events in our analysis. In fact, falling trees on power lines due to gales and storms are a major concern for the northern European region (Tervo *et al.* 2021).

The high-voltage electricity network of Norway consists of about 11,000 km of transmission grid lines, 19,000 km of regional grid lines, and 100,000 km of distribution grid lines (Ministry of Petroleum and Energy 2019). This expansive power network commonly traverses remote woodland areas throughout the country (Pacevicius *et al.* 2020). Thus, apart from the natural hazards presented earlier, a significant part of the Norwegian power grid is subject to risks stemming from the country's dense vegetation in conjunction with severe weather phenomena, as discussed next.

Studies have shown that trees of the species *Picea abies* (commonly known as *Norway spruce*) exhibit a significantly high probability of breaking in strong winds. Researchers categorize them as the most susceptible tree species to wind damage in boreal and hemi-boreal forests (Snepsts *et al.* 2020). As its name suggests, this species is native to central, southern, and eastern regions of Norway, but it can also be found in central and eastern European forests.

Moreover, recent evidence suggests that extreme hydro-meteorological events in northern Europe are becoming progressively more frequent and severe due to Climate Change (Tervo *et al.* 2021). In detail, future extratropical storms in the area are estimated to have increased precipitation, higher wind speeds, and an expanded area of effect. Notably, according to Owen *et al.* (2021) precipitation extremes for Norway seem to precede wind gust extremes by 6 to 24 h. In other words, future extratropical storm systems are even more likely to cause floods due to heavy rainfall a few hours before the region is exposed to extreme winds.

Combining all the above aspects, it is not impossible to imagine the following multi-hazard scenario unfolding. A severe extratropical storm brings record levels of rainfall, putting critical infrastructure, such as stormwater sewerage systems, to their limit. After a few hours, the subsequent strong winds cause an extensive storm surge, flooding coastal regions over a wide area and overwhelming the capacity of normal-operation safety measures (*e.g.*, sewerage systems). With unavailable stormwater sewerage systems, several industrial facilities impacted by the heavy rainfall activate backup pumps to protect critical processing equipment from inundation. Meanwhile, the strong winds also cause a Norway spruce elsewhere in the region to snap and fall onto the nearby transmission grid, severing the power line and triggering a prolonged blackout. Suddenly, the backup power generators are insufficient for the continuous and effective operation of said emergency safety systems (*e.g.*, pumps and temperature control apparatus). As a result, a flammable and/or toxic substance is released. The already-overwhelmed first response teams now face yet another hazard, significantly complicating field operations.

5. Risk-Based Decision Support Framework for Vegetation Management

We acknowledge that Natech accident scenarios are multi-faceted and depend upon numerous risk factors. Yet, we turn our attention to addressing vegetation: a seemingly minor and relatively common RIF for power grids, but one that can have significant consequences in Natech scenarios, as discussed above. Mindful of the important challenges involved in the maintenance of expansive power grids, we outline the components of a risk-based decision support framework grid drawing on the work of Pacevicius *et al.* (2020).

Nowadays, technology advancements (*e.g.*, Big Data, Internet-of-Things, and Machine Learning) have enabled data-driven approaches, which are driving innovations in risk assessment and becoming commonly employed in risk analysis methodologies (Pacevicius *et al.* 2020). It should be noted that an efficient and meaningful data-driven framework for power grids does not imply simply processing available grid data. Instead, a risk-oriented perspective is rather suited. This begins with adopting a workflow that prioritizes defining grid operators' needs concerning information on vegetation-related risk. It is followed by delineating the content of said information, which ultimately dictates the design of an appropriate framework to collect and analyze the necessary data.

The generalized framework would consist of the following steps. First, relevant data from various sources are collected. Remote sensing data (*e.g.*, satellite images and point clouds) along the power lines and terrain geomorphology and grid topology maps are needed to establish the context (Pacevicius *et al.* 2020). Also, historical reports of past power disruptions and their causes are crucial for estimating future grid failure. Additionally, a comprehensive forest inventory can be compiled by valorizing flora growth models, vegetation health analysis, clear-cutting reports, and field measurements. The dataset may consist of estimates about the forest age, dominant tree species, mean and total tree volumes, and overall biomass (Tervo *et al.* 2021). Furthermore, meteorological data and weather forecast models covering the whole span of the electricity grid are required to estimate the risk of falling trees. Finally, land use maps, information about the geographic distribution of end-users and a high-level description of their activities is needed to estimate consequences from a potential power blackout more accurately.

The second step of the framework involves data processing and risk analysis. Based on the aforementioned data, risk managers and/or grid operators can obtain estimates about the proximity of vegetation to power lines and determine the probability of trees breaking due to gale. With that, a probability of vegetation-related power grid failures can be obtained, and potentially vulnerable areas along the network can thus be identified. The consequence analysis entails not only the anticipated economic and productivity losses of end-users, but also the cascading hazard scenarios. In detail, areas prone to wildfires from a vegetation-power grid interaction can be defined at this step. Notably, a preliminary assessment of critical infrastructure and potentially hazardous industrial facilities dependent on the power grid can be performed in order to estimate the broader consequences of power disruptions and identify systemic risks, such as Natech accident scenarios.

In the final step, the overall vegetation-related risk is evaluated based on the generated information, and risk-informed decisions about appropriate treatment actions can be taken. Through detecting potentially vulnerable areas and performing a high-level risk assessment for vegetation-related hazards on a regular basis, grid operators could dynamically prioritize and carry out necessary vegetation management tasks (*e.g.*, sending inspection teams and clear-cutting) well before the risk reaches a critical threshold. Apart from gaining precious time for restoring power grid operation during emergencies by optimizing human resource allocation, identifying network bottlenecks, anticipating developments, and quickly pinpointing susceptible locations, the framework's output can serve as valuable input to support Natech risk management overall. From a long-term disaster preparedness planning perspective, it would allow grid operators and risk managers to identify potential crucial network "hotspots" prone to vegetation-related outages and account for the subsequent consequences in possible conjoint hazard scenarios.

6. Discussion and Conclusion

Even though multi-hazard, cascading accident scenarios—such as the one presented in this article—involve multiple conditionalities and thus seem highly improbable, their eventual occurrence has severe consequences. Adopting a system engineering perspective and focusing on resilience is crucial for Natech risk management (Suarez-Paba *et al.* 2020; Krausmann and Necci 2021). It is important to expand the scope of risk assessment concerning high impact/low probability events by including risks to critical lifelines (*e.g.*, power grids) through an all-hazards approach for conjoint disaster scenarios. Hence, paying attention to minor and commonly negligible RIFs, such as vegetation for power grids, can considerably benefit the resilience of the overall infrastructure system against Natech scenarios. However, to realize any data-driven approach, data is *sine qua non*. For the purposes of collecting data on and managing power grids, remote sensors and "smart grid" components can be retrofit into existing systems (Bridger 2022; Pacevicius *et al.* 2020), while refining weather models, establishing early-warning indicators of future changes in local hydro-meteorological regimes are equally important (Krausmann and Necci 2021).

This study framed vegetation as a Natech RIF for power grids with respect to hydro-meteorological hazards. We presented the potential impact of vegetation considering the systemic linkages in the context of Natech risk management. Finally, we proposed a preliminary risk-based decision support framework for risk managers and grid operators aimed at enhancing decision-making for vegetation management along power lines. Nonetheless, this study represents only a first step towards better understanding vegetation risk for power grids in the context of Natech accident scenarios. Future studies may consider elaborating and specifying the necessary data input. Going forward, the research direction would greatly benefit from an application of this conceptual framework to a risk assessment case study for the purposes of examining in depth the influence of vegetation on potential Natech risk scenarios.

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References

Bian, Haifeng, Jun Zhang, Ruixue Li, Huanhuan Zhao, Xuexue Wang, and Yiping Bai. 2021. Risk Analysis of Tripping Accidents of Power Grid Caused by Typical Natural Hazards Based on FTA-BN Model. *Natural Hazards* 106 (3): 1771–95.

Bridger, Jessica. 2022. The Texas Coldwave Disaster – How Cascading Risks Took out an Entire Power Grid. *United Nations Office for Disaster Risk Reduction (blog)*. June 28, 2022. www.undrr.org/news/texas-coldwave-disaster-how-cascading-risks-took-out-entire-power-grid. Accessed 20 April 2023.

eNatech. 2023. eNatech: Natural Hazard-Triggered Technological Accidents Database. *Natech Accident Database*. Ispra, Italy: European Commission, Joint Research Centre. enatech.jrc.ec.europa.eu.

Krausmann, Elisabeth, and Amos Necci. 2021. Thinking the Unthinkable: A Perspective on Natech Risks and Black Swans. *Safety Science* 139 (July): 105255.

Luo, Xiaolong, Ana Maria Cruz, and Dimitrios Tzioutzios. 2020. Extracting Natech Reports from Large Databases: Development of a Semi-Intelligent Natech Identification Framework. *International Journal of Disaster Risk Science* 11 (6): 735–50.

Luo, Xiaolong, Ana Maria Cruz, and Dimitrios Tzioutzios. 2021. Climate Change and Temporal-Spatial Variation of Tropical Storm-Related Natechs in the United States from 1990 to 2017: Is There a Link? *International Journal of Disaster Risk Reduction* 62 (August): 102366.

Ministry of Petroleum and Energy (MPE). 2019. Energy Facts Norway: The Electricity Grid. Olje- og energidepartementets (OED).

Norwegian Water Resources and Energy Directorate (NVE). 2019. Avbrotsstatistikk 2018. Rapport No. 29–2019. Oslo, Norway: Norwegian Water Resources and Energy Directorate.

Øien, K. 2001. Risk Indicators as a Tool for Risk Control. *Reliability Engineering & System Safety* 74 (2): 129–45.

Okada, Norio, Ilan Chabay, and Ortwin Renn. 2018. Participatory Risk Governance for Reducing Disaster and Societal Risks: Collaborative Knowledge Production and Implementation. *International Journal of Disaster Risk Science* 9 (4): 429–33.

Owen, Laura E., Jennifer L. Catto, David B. Stephenson, and Nick J. Dunstone. 2021. Compound Precipitation and Wind Extremes over Europe and Their Relationship to Extratropical Cyclones. *Weather and Climate Extremes* 33 (September): 100342.

Pacevicius, Michael, Marilia Ramos, and Nicola Paltrinieri. 2020. Optimizing Technology-Based Decision-Support for Management of Infrastructures under Risk: The Case of Power Grids. In Piero Baraldi, Francesco Di Maio, and Enrico Zio (Eds.), *Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference*, pp. 4508–15. Venice, Italy: Research Publishing, Singapore.

Petrova, Elena G. 2022. "Natural Factors of Accidents at Power Transmission Line." IDRiM Journal 12 (1): 39–55.

Pishahang, Mohammad, Andres Ruiz-Tagle, Enrique Droguett, Marilia Ramos, and Ali Mosleh. 2022. WISE: A Probabilistic Wildfire Safe Egress Planning Framework and Software Platform. In *Proceedings of the Probabilistic Safety Assessment and Management Conference PSAM 16*, pp. 1–10. Honolulu, Hawaii, US: IAPSAM & ESRA.

Roston, Eric, Sergio Chapa, and Barbara J Powell. 2021. Restarting Texas's Frozen Energy Heartland Will Be a Climate Mess. *Bloomberg*, February 22, 2021. www.bloomberg.com/news/articles/2021-02-21/texas-deep-freeze-restarting-oil-and-gas-will-be-an-emissions-mess. Accessed 20 April 2023.

Snepsts, Guntars, Mara Kitenberga, Didzis Elferts, Janis Donis, and Aris Jansons. 2020. Stem Damage Modifies the Impact of Wind on Norway Spruces. Forests 11 (4): 463.

Sonnemans, P. J. M., P. M. W. Körvers, and H. J. Pasman. 2010. Accidents in 'Normal' Operation – Can You See Them Coming? *Journal of Loss Prevention in the Process Industries* 23 (2): 351–66.

Suarez-Paba, Maria Camila, Mathis Perreur, Felipe Muñoz, and Ana Maria Cruz. 2019. Systematic Literature Review and Qualitative Meta-Analysis of Natech Research in the Past Four Decades. *Safety Science* 116 (July): 58–77.

Suarez-Paba, Maria Camila, Dimitrios Tzioutzios, Ana Maria Cruz, and Elisabeth Krausmann. 2020. Toward Natech Resilient Industries. In Muneta Yokomatsu and Stefan Hochrainer-Stigler (Eds.) *Disaster Risk Reduction and Resilience*, 45–64. Disaster and Risk Research: GADRI Book Series. Singapore: Springer.

Tervo, Roope, Ilona Láng, Alexander Jung, and Antti Mäkelä. 2021. Predicting Power Outages Caused by Extratropical Storms. *Natural Hazards and Earth System Sciences* 21 (2): 607–27.

The Great Texas Freeze: February 11-20, 2021. 2023. National Centers for Environmental Information (NCEI). www.ncei.noaa.gov/news/great-texas-freeze-february-2021. Accessed 20 April 2023.

UNDRR. 2022. Principles for Resilient Infrastructure. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction.

UNDRR-APSTAAG. 2020. Asia-Pacific Regional Framework for NATECH Risk Management. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction – Asia-Pacific Science, Technology and Academia Advisory Group.

Uteuova, Aliya. 2021. Texas Facilities Released 3.5m Pounds of Extra Pollutants during Winter Storm. *The Guardian*, February 26, 2021, sec. US news. www.theguardian.com/us-news/2021/feb/26/texas-emissions-pollutants-winter-storm. Accessed 20 April 2023.