The Increasingly Critical Role of Communication Networks in Enhancing Power Grid Resilience Under Climate Change

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Abstract: The increasing frequency and severity of extreme weather events, driven by climate change, pose significant challenges to the resilience of power grids worldwide. As critical infrastructure, power grids must adapt to these disruptions while meeting the growing demands of renewable energy integration, distributed energy resources (DERs), and energy system electrification. This position paper highlights the important role of communication networks in enhancing power grid resilience and the integration of renewable energy resources. Advanced communication technologies, such as 5G, IoT, and AI-driven analytics, enable real-time monitoring, fault detection, demand forecasting, and resource optimization, all of which are crucial for grid reliability under dynamic and extreme conditions. The paper analyses the vulnerability of electricity grids to climate-related disruptions, examines technical solutions to these challenges and provides strategic recommendations for the design of robust communication infrastructures. With a focus on redundancy, supporting technologies such as 5G and AI-powered analytics and decision support, this paper makes the argument for prioritising investment in resilient communication systems to future-proof power grids. By presenting communication networks as an essential part of grid modernisation, this paper underlines their crucial role in ensuring reliable, efficient and adaptable energy systems in the face of climate change.

1 INTRODUCTION

As climate change progresses, the frequency and intensity of extreme weather events such as storms, floods and heatwaves are increasing, putting pressure on electricity grid infrastructure like never before. A reliable electricity supply is essential for modern society, but these climate-related disruptions are increasingly threatening the stability, reliability and resilience of the grids. Overcoming these challenges requires new concepts for the design, operation and maintenance of electricity grids.

Central to this shift is the role of communication networks. These networks provide the infrastructure needed for real-time monitoring, control, and coordination of grid operations, enabling utilities to detect faults, respond to disruptions, and manage distributed energy resources (DERs). With the increasing use of renewable energy sources, the electrification of key sectors and the decentralisation of power grids, communication networks have evolved from secondary components to indispensable building blocks for grid stability.

This position paper argues that communication networks are key to increasing the resilience of electricity grids to the effects of climate change. It explores the growing vulnerabilities posed by climate-driven disruptions and examines how advanced communication technologies—such as 5G networks, IoT-enabled devices, and AI-driven analytics—can help overcome these challenges. Furthermore, it outlines key principles for designing robust, multi-layered communication infrastructures that ensure the grid's reliability under both normal and extreme conditions. Section 2 outlines the motivation and background to this paper by examining the impact of climate change on electricity grids and the overall role of communication networks in managing electricity grids. Section 3 analyses how communication networks contribute to overcoming the challenges in electricity grids caused by climate change. Section 4 gives recommendations on how to tackle the issue before section 5 summarizes and concludes.

By framing communication networks as a corner-

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stone of modern power grids, this paper aims to provide actionable insights and strategic recommendations to strengthen grid resilience in the face of an increasingly volatile climate.

2 BACKGROUND AND CONTEXT

The number of extreme weather events is increasing world wide. The frequency of events like floods, droughts, heat waves, storms and heavy rainfall is growing and effecting also critical infrastructures like power grids and communication networks. Figure 1 shows the increasing number of weather-related outages in the United States in between the years 2000 and 2021 (Carvallo and Casey, 2024). To adapt to these environmental changes and mitigate their impact, infrastructure operators must explore innovative strategies to enhance their systems. In order to keep outage times low and speed up asset management processes, they have to reconsider and upgrade their infrastructure. This growing challenge highlights the importance of resilient communication systems, driving the need for investments in upgrading and strengthening these networks.

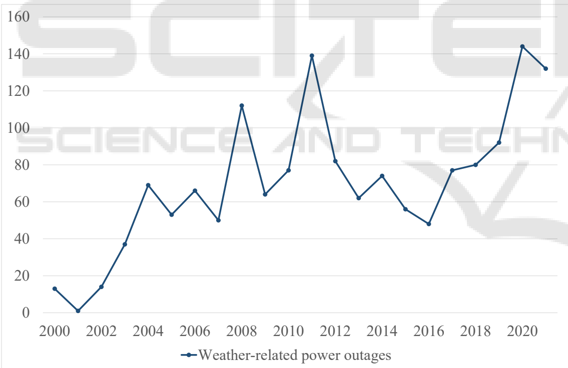

Figure 1: Number of weather related power outages.

Power and communication networks are not only the most important critical infrastructures for society, but also play an important role when it comes to dealing with climate change. However, when considering the resilience of both systems, the interdependence of communication networks and power grids is a critical issue that needs to be carefully considered, particularly as the number of severe weather events that can potentially cause disruption to both systems is increasing. The main issue is that failures in one infrastructure may cascade to the other infrastructure and vice versa. The power grid equipment is managed and controlled via telecommunication systems, which in turn depend on the power grid for their power supply.

2.1 Climate Change and Power Grids

The electricity grid is affected by climate change in many ways. Various types of severe weather events can cause disruptions to the electricity grid infrastructure, some examples of which are addressed below.

Heatwaves and rising temperatures are directly affecting the efficiency of transmission and distribution systems since the equipment's power rating and the induced energy losses depend on temperature (Ward, 2013). At the same time energy consumption is increasing because of increased needs for cooling. In general, energy consumption for heating and cooling is heavily influenced by temperature fluctuations. With climate change, we expect not only a change in overall consumption, but also a change in seasonal consumption patterns (Gonçalves et al., 2024).

Strong winds can cause faults and damage to overhead lines, e.g. if trees fall on the lines or power poles collapse in extremely strong winds. The experience from storms in Europe shows that the majority of customer disconnections are due to trees damaging distribution networks, and only the most severe storms cause damage to the transmission grid. However, it is not expected that there will be a significant change in extreme wind-related events in most European regions (European Commission. Joint Research Centre., 2020).

Heavy rain is usually accompanied by strong winds or lightning, which pose a greater risk of disruption than the rain itself. The consequences of long periods of heavy rain can have a more serious impact on the electricity grids, as they can trigger flooding or landslides. While floods threaten power grid equipment such as switchgear, transformers and control cabinets in substations, landslides pose a major threat to overhead lines, but can also damage underground cables.

While increasingly exposed to severe weather events, electricity grids are at the same time undergoing a massive transformation in their structure because of the need for carbon-free energy generation and the increasing integration of renewable energy sources into power grids. Grids are shifting from a hierarchical infrastructure dominated by a few large power plants to a decentralized system comprising numerous smaller entities like rooftop PV systems, or small wind and hydro power. While controlling large power plants was relatively straightforward for plant operators - sometimes even achievable through simple phone calls to plant personnel - managing decentralized systems requires more sophisticated and also automated control mechanisms that require secure and reliable communication networks.

New challenges are also arising on the demand side due to the ongoing electrification of energy systems, e.g. through heat pumps and the spread of electric vehicles. The resulting increased demand and the volatility of electricity generated from natural resources such as wind and solar require advanced control mechanisms to balance demand and consumption. This means that there are even more components in the electricity grid that need to be communicated with. With demand-side management, it will be possible to leverage the flexibility of these loads to consume electricity during periods of availability or when there is a surplus in production.

Wired and wireless communication technologies are thus playing a crucial role in optimizing power consumption and enabling more intelligent grids within the evolving digital landscape. They are an enabler for reliable control of decentralised generation and controllable consumption and they have to support communication with a large number of digital devices - PV installations, heat pumps, charging stations.

Table 1 shows the extreme weather conditions and how they effect the power grid and the communication networks.

2.2 Communication Networks in Power Grids

Communication networks are the backbone of modern power grids as they enable many applications that are already indispensable today and will become even more important in the future. While functions such as real-time monitoring, fault detection and grid automation are already commonplace in transmission grids, the distribution grid is currently developing into a more intelligent grid, partly due to the requirements resulting from upgrading the grid to accommodate more electricity from renewable energy sources. Communication networks must ensure that data can be exchanged in between various components of the grid, from power generation facilities to transmission systems, distribution networks, and end-users in an efficient and reliable manner.

The different smart grid applications come however with different requirements concerning delay, bandwidth and connected number of devices. While fault detection and grid protection require allow only for minor delays in the order of milliseconds, applications like smart metering have relieved timing requirements, as data is often only exchanged only once per day. When considering grid reconfiguration and load curtailment this is usually in the order of minutes, or even days with forward planning.

Depending on the segment of the power grid and the communication network, various technologies are employed, each with distinct characteristics and varying levels of risk during extreme weather events. Many distribution system operators manage their own communication networks, with network nodes typically co-located at primary or secondary substations.

The wide-area network connecting primary substations spreads over a larger area can be implemented as a fully meshed fiber-optic network, where each substation is directly interconnected with others. This topology provides a high level of reliability and resilience by providing multiple redundant paths for data exchange also if a single link is failing. Due to the structure the network can reroute data through alternative paths. Fully meshed support high data rates, low latency, and robust fault tolerance, all essential for real-time grid monitoring and control.

Secondary substations can be connected further on to primary substations using a star topology based on fiber-optic or copper cables. If cabling is to cumbersome also wireless communication technologies are being used. Thus, secondary substations can also be connected using radio links or mobile radio such as LTE 450, which brings benefits e.g. concerning coverage (Caldeira et al., 2017) or 5G mobile networks (Bhat, 2024).

Customer premises can finally connected to the secondary substation via power line communication (PLC) (Abrahamsen et al., 2021) or mobile radio like 5G. Controllable devices in the customer domain include home PV installations, heat pumps or electric vehicle charge stations.

Just as power grids communication networks are affected by climate change in many different ways (Horrocks et al., 2010). Rising temperatures can increase the risk of overheating in data centres, exchanges and base stations. Heavy and extensive precipitation can cause flooding of equipment and reduce the quality of wireless services. Strong wind can cause damage to all overground transmission infrastructure. Table 1 provides and overview of how communication networks are prone to disruptions due to extreme weather events.

However, integrating grid components into communication networks also introduces cyber security risks, including unauthorized access, data manipulation, and cyberattacks (e.g., malware, DDoS, or ransomware). A compromised network can disrupt grid operations, potentially causing blackouts, equipment damage, and safety hazards. Safeguarding power grids requires robust encryption, advanced intrusion detection, system redundancy, and regular security updates.

Table 1: Impact of severe weather conditions.

Weather conditions	Effects on the Power Grid	Impact on Communication Networks
Heat waves	Increased electricity demand due to cooling systems (air conditioning).	Overheating of data centers and communication equipment, leading to reduced efficiency or failures.
	Reduced efficiency and capacity of power plants (especially thermal and nuclear).	Signal degradation in wireless networks due to thermal effects on electronic components.
	Overheating of grid infrastructure, such as transformers and cables, leading to outages.	Increased energy demands for cooling communication equipment, risking network downtime.
Heavy Rainfall	Reduced water availability for hydropower plants, lowering electricity production.	Soil shrinkage affecting underground communication lines, leading to increased vulnerability to damage.
	Flooding of substations, transformers, and other critical infrastructure.	Damage to underground cables and communication hubs.
	Risk of landslides damaging transmission and distribution lines.	Interruption of fibre optic cables and underground lines due to ground movement.
	Interruption in fuel supply chains for power generation plants	Increased risk of connectivity loss due to damaged network infrastructure.
Heavy Snowfall	Damage to transmission and distribution lines caused by snow load on power lines or falling trees.	Snow can weigh down antennas and cables, leading to breakages or collapses.
Flooding	Permanent damage to low-lying grid infrastructure, causing prolonged outages.	Submersion of communication towers, fiber-optic cables, and critical nodes, leading to widespread outages.
	Increased maintenance costs to repair water-damaged equipment.	Corrosion of equipment exposed to floodwaters, shortening its lifespan.
Stronger Storms	Damage to transmission and distribution lines due to high winds or falling trees.	Physical damage to communication towers and antennas.
	Increased frequency of power outages and repair costs.	Disruptions in wireless networks due to alignment issues caused by strong winds.
	Disruptions in renewable energy sources, such as wind turbines, due to extreme wind speeds.	Loss of connectivity due to damaged infrastructure and power outages at network hubs.

3 THE ROLE OF COMMUNICATION NETWORKS IN ADDRESSING CLIMATE CHALLENGES

Communication networks in electricity grids play a crucial role in grid monitoring and control. They also pave the way for the integration of technological innovations that enable utilities to efficiently manage decentralised energy resources. The following section provides an overview of the functions and technologies employed in these communication networks.

3.1 Real-Time Monitoring and Data Collection

Communication networks support Supervisory Control and Data Acquisition (SCADA) systems, allowing operators to monitor and control grid operations remotely (Kamwa and Johnson, 2023). This was one of the key drivers for utilities to deploy communication network technology. SCADA systems allow grid operators to remotely monitor and control electricity transmission and distribution and to interact with substation equipment from the control room. Thus SCADA systems contribute significantly to enhanced efficiency of the power grid experience nowadays.

One of the challenges that electricity grids are increasingly facing is the uncertainty caused by inverter-based generation (Crivellaro et al., 2020). Inverter-based sources such as photovoltaic systems and wind turbines do not have the natural inertia of synchronous generators, which makes grid stability, frequency regulation and voltage control more difficult, especially in the event of sudden fluctuations in generation or demand. One way to deal with the uncertainties of modern renewable energy grids is to use decision support tools with real-time capabilities that require continuous, up-to-date measurements. More comprehensive data in real time are a critical enabler for artificial intelligence (AI) with proven capabilities in decision support complex scenarios.

Communication networks enable the seamless transmission of real-time data from sensors and monitoring systems to control centers, facilitating rapid decision-making and coordination. Reliable communication support the integration of advanced technologies like artificial intelligence (AI) and IoT devices, which rely on robust data exchange to optimize responses in complex scenarios. In essence, the availability of robust communication is the backbone for grid monitoring and control.

3.2 Fault Detection and System Recovery

Communication networks are essential for the ability of modern power grids to maintain reliability and resilience in case of faults. They are an enabler for dealing with different kinds of faults in the grid by gathering grid status information required for fault localization, fault prediction, and fault isolation in order to prevent cascading failures. Faults in energy systems lead to dangerous overvoltages, device failures and power outages, which impair the reliability of the system and result in financial losses for the operator. To move from the reactive and inefficient maintenance approaches to a more proactive maintenance strategy, fault prediction plays an important role.

They also help in reducing grid recovery times through remote control and real-time coordination (Purushottam Kumar Maurya, 2024). AI-driven self-healing grids can significantly reduce downtime, improve grid resilience, and enhance the reliability of power supply. By analyzing grid measurement data these algorithms can identify patterns indicating faults or anomalies. Thus it is possible to detect or even predict potential disruptions in real-time and to enable automated responses such as fault isolation and rerouting power. This approach ensures faster recovery and minimizes the impact of outages on consumers and critical infrastructure.

Intra and inter substation communication networks are also important for teleprotection where circuit breakers automatically disconnect lines e.g. in case of earth faults.

3.3 Renewable Energy Integration

Communication networks play a crucial role in managing intermittent renewable energy sources through smart grid technologies. These networks facilitate real-time data exchange, enhance energy distribution efficiency, and improve grid stability, which are essential for integrating renewable energy into existing power systems.

Communication networks enable the transmission of real-time monitoring data from the grid, including renewable energy generation facilities such as solar parks or wind turbines, to grid operators. This data includes, for example, information on power generation, weather conditions and the status of the plants, allowing operators to predict variations and adjust grid operations accordingly. Renewable energy sources are often smaller, distributed and decentralized entities. Communication networks link these Distributed Energy Resources (DERs) with centralized and decentralized grid management systems, enabling coordinated control. This ensures that energy generated from multiple small-scale entities is effectively integrated and distributed.

The growing share of volatile renewable energy generation from wind turbines and photovoltaic (PV) installations presents significant challenges for both distribution and transmission systems. Distribution system operators (DSOs) must handle increased generation capacities, which can cause over-voltage issues, especially during periods of high solar generation and low local demand. These challenges can be mitigated through grid expansion, the adoption of advanced grid technologies, or by controlling feed-in power using measures such as curtailment or flexible grid management. Transmission system operators (TSOs), on the other hand, are typically responsible for maintaining the balance between electricity supply and demand across the grid. During periods of high renewable energy production, excessive supply may arise, requiring regulation through curtailment or other grid management strategies to ensure system stability. While there will be slight increase of solar photovoltaic (PV) energy across in European (Hou et al., 2021) there is a risk that also weak wind phases will increase (European Commission. Joint Research Centre., 2020). For curtailment measures on both the demand side and the supply side, reliable communication networks are required that can reach a large number of installations.

4 STRATEGIC RECOMMENDATIONS

To ensure the resilience of the power grid in the face of emerging climate change challenges, the reliability and functionality of the communication networks within the power grids are critical. Many factors need to be considered when modernising utility communication networks in order to be prepared for the challenges of climate change - extreme weather events, decentralised energy generation and electrification of the energy system. The communications failures that occurred during severe storms such as Hurricane Katrina in the US highlight the importance of the key principle of resilience in the design and evaluation of a utility's telecommunications network (Khalid et al., 2023).

In addition to the purely technical measures discussed below, operator training is also crucial for minimising the impact of storms on electricity and communication networks. Well-trained personnel can quickly assess risks, implement emergency protocols, and restore services efficiently during events like heavy rain, storms, or heat waves.

4.1 Network Availability and Redundancy

Many utilities rely, at least in part, on commercial communications infrastructure, which is more susceptible to disruption during severe weather events. Commercial providers are usually not able to provide redundant communication paths to equipment and do not have backup generators to power communications equipment such as base stations in the event of a power outage. Thus, grid operators often also run their own private communication network that connects important primary substations in an redundant manner by e.g. using a fully meshed network. Private networks for grid operators perform better than commercial providers as more stringent requirements are applied that commercial providers do not follow. However, secondary substations are often linked to the primary substation using a simple star topology. The star topology is cost-effective and straightforward but can create vulnerabilities because a link failure can disrupt communication with the connected substation. However, commercial providers are used when it is not cost effective to deploy a dedicated utility-owned networks. Apart from the issue of back-up power supply in general, this dependency can lead to problems such as a lack of control.

As the control of customer equipment becomes increasingly important, these systems will also be connected through commercial network operators or Power Line Communication (PLC), with the data concentrator typically located in the secondary substation. This makes robust connections to secondary substations critically important. To enhance reliability, operators should support redundant communication paths further downstream, e.g. extending to secondary substations.

To implement such redundancy and diversity in communication, multi-layered communication pathways—such as fiber optics, wireless, and satellite—can be utilized. These pathways ensure continuous operation even during extreme weather events or infrastructure failures, improving the overall resilience of the grid.

4.2 5G Networks

A wireless communication technology that is for several reasons ideally suited to support communication for power grids are 5G networks. Private 5G networks can offer low latency (down to 1 millisecond), high reliability and bandwidth and are thus well suited for power grid applications that require real-time data transmission and decision making. Several European countries have allocated frequency spectrum dedicated to private networks to enable critical infrastructure sectors, such as power grids, to deploy their own 5G networks (European 5G Observatory, 2024). 5G networks also introduce a technology called slicing. A single 5G network can be divided into multiple virtual slices tailored to specific performance requirements. Different slices can thus be establishes to support different kinds of power applications. One slice could be dedicated to real-time grid monitoring, ensuring reliable, low-latency communication.

A 5G networks are also capable to support ad hoc networking, a decentralized type of wireless network within the 5G framework where devices communicate directly with each other without depending on centralized infrastructure, such as a base station or core network. The feature of Device-to-Device (D2D) communication was originally introduced by the so called Proximity Services (ProSe) in LTE networks in order to allow direct communication between User Equipments (UEs) without using the network infrastructure the Sidelink (SL) interface was defined. In 5G the SL and ProSe features were adapted to support direct discovery, direct communication, and UE-to-Network

(U2N) relays. With U2N relays UE without coverage can used an network connected UE as a hop to connect to 5G networks.The U2N relay feature also supports single-hop UE-to-UE (U2U) relays, allowing direct communication between UEs via a single intermediate relay (Gamboa et al., 2023).

The feature of D2D communication was primarily developed for first responders to communicate in scenarios where no network connection is available due to a lack of or malfunctioning infrastructure. This function could also be used by network operators if lines are interrupted or cell towers collapsed during natural disasters. Deploying 5G networks for last mile communication in power grids is thus providing significant benefits concerning resilience and performance.

Utilizing 5G communication for real-time information flow and control among power grid devices is essential. 5G can be seen as a key technology to address current and future challenges in the energy sector because it provides flexibility, reliability, coverage, throughput, low latency and massive device support. Smart grid technologies, such as distribution automation and network reconfiguration, also contribute to system reliability.

4.3 AI for Grid Resilience

Artificial Intelligence (AI) can play an important role in enhancing the resilience of power grids by leveraging its ability to process and analyze vast amounts of real-time data. Areas of AI applications include:

- AI-driven tools use machine learning algorithms to monitor grid infrastructure in real-time. They can detect anomalies, such as device failures or line faults before they develop into major outages. Predictive maintenance models based on AI can forecast potential failures, enabling utilities to address issues proactively.
- AI-based methods can help in optimizing the use of existing grid capacities while ensuring fairness. By analysing real-time data on electricity demand and supply AI can predict fluctuations and optimize load distribution across the grid. In cases of grid congestion, AI can establish dynamic, customer-specific energy quotas based on historical usage patterns, contractual agreements, and available grid capacities.
- AI algorithms based on artificial neural network are used for solar forecasting is used and the resulting PV power generation (Pedro and Coimbra, 2012) in order to enable a more reliable and cost-effective integration into the grid.

Governments and utilities should fund and adopt AI systems to enable predictive maintenance, detect vulnerabilities, and optimize grid performance during extreme weather events.

4.4 Decentralized Decision-Making

A key aspect of increasing this resilience is decentralised decision-making, which enables local units to make decisions autonomously without having to rely on central control. Decentralised systems can continue to operate autonomously in the event of a central control centre failure. This increases the reliability of the network and ensures that the power supply is not interrupted. Decentralised decision-making is a key aspect of self-healing networks that are able to automatically detect, isolate and correct faults in order to maintain network operation. The use of AI techniques can play an essential role here (Purushottam Kumar Maurya, 2024). Decentralised decision-making enables faster response times and better adaptation to dynamic conditions, which is essential for coping with the effects of climate change.

5 CONCLUSIONS

As climate change increases the frequency and intensity of extreme weather events, reliable communication networks have become indispensable for ensuring the continuous operation and resilience of power grids. They enable real-time monitoring, control, and recovery processes critical for modern energy systems.

The integration of advanced communication technologies, such as 5G, IoT, and edge computing, allows utilities to enhance grid operations by improving data collection, low-latency communication, and decentralized decision-making. These technologies provide the adaptability needed to respond swiftly to dynamic and unpredictable climate conditions.

Deploying redundant and multi-layered communication pathways (fiber optics, wireless, satellite) is essential to ensure connectivity during extreme weather or infrastructure failures. Resilient communication networks minimize the impact of disruptions, supporting both grid operations and disaster recovery efforts.

AI and machine learning play a critical role in predicting failures, optimizing energy distribution, and enabling predictive maintenance. These tools leverage communication networks to gather and process vast amounts of real-time data, ensuring proactive rather than reactive responses to potential grid challenges.

Communication networks facilitate the integration of decentralized energy resources (DERs), microgrids, and renewable energy sources, which are increasingly essential in the transition to a more sustainable and resilient energy system. Reliable connectivity ensures that these distributed assets can operate harmoniously within the larger grid.

Strengthening grid communication infrastructure must be prioritized in energy policies and investment strategies. Governments, utilities, and stakeholders need to collaborate on standardizing communication technologies and ensuring interoperability to enhance resilience on a global scale.

Enabling intelligent decision-making at the edges of the power grid, instead of relying solely on control centers, is important, especially during extreme weather events were the connection to the control center can fail.

Addressing grid resilience in the context of climate change requires a holistic approach, combining robust communication networks with smart grid technologies, predictive analytics, and sustainable energy integration. This approach will ensure power grids remain reliable, efficient, and adaptive in the face of evolving climate challenges.

Communication networks are no longer a secondary consideration but a cornerstone of modern, climate-resilient power grids. Investing in advanced, secure, and resilient communication technologies is essential to meeting the dual challenges of climate adaptation and energy transition.

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REFERENCES

Abrahamsen, F. E., Ai, Y., and Cheffena, M. (2021). Communication Technologies for Smart Grid: A Comprehensive Survey. *Sensors*, 21(23):8087.

Bhat, S. (2024). Leveraging 5G Network Capabilities for Smart Grid Communication. *Journal of Electrical Systems*, 20(2):2272–2283.

Caldeira, R. T., Melgarejo, D. C., and Coutinho, R. (2017). Application of LTE 450 MHz in the electric energy sector. In *2017 European Conference on Networks and Communications (EuCNC)*, pages 1–5, Oulu, Finland. IEEE.

Carvallo, J. P. C. and Casey, J. (2024). Surging Power Outages and Climate Change. Technical report, Climate Central.

Crivellaro, A., Tayyebi, A., Gavriluta, C., Gross, D., Anta, A., Kupzog, F., and Dorfler, F. (2020). Beyond low-inertia systems: Massive integration of grid-forming power converters in transmission grids. In *2020 IEEE Power & Energy Society General Meeting (PESGM)*, pages 1–5, Montreal, QC, Canada. IEEE.

European 5G Observatory (2024). 5G Private networks – 5G Observatory. https://5gobservatory.eu/5g-private-networks/.

European Commission. Joint Research Centre. (2020). *Climate change impacts and adaptation in Europe: JRC PESETA IV final report.* Publications Office, LU.

Gamboa, S., Ben Mosbah, A., Garey, W., Liu, C., and Rouil, R. (2023). System-Level Evaluation of 5G NR UE-Based Relays. In *MILCOM 2023 - 2023 IEEE Military Communications Conference (MILCOM)*, pages 807–814, Boston, MA, USA. IEEE.

Gonçalves, A. C. R., Costoya, X., Nieto, R., and Liberato, M. L. R. (2024). Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures. *Sustainable Energy Research*, 11(1):4.

Horrocks, L., Beckford, J., Hodgson, N., Downing, C., Davey, R., and O'Sullivan, A. (2010). Adapting the ICT Sector to the Impacts of Climate Change – Final Report. Technical report, AEA group.

Hou, X., Wild, M., Folini, D., Kazadzis, S., and Wohland, J. (2021). Climate change impacts on solar power generation and its spatial variability in europe based on cmip6. *Earth System Dynamics*, 12(4):1099–1113.

Kamwa, I. and Johnson, B. K. (2023). Grid communications: The wide-area control and situational awareness [Editors' Voice]. *IEEE Power and Energy Magazine*, 21(5):4–13.

Khalid, S., Hotovec, S., and Clancy, J. (2023). Utilities' Need for Advanced Telecommunications. *Climate and Energy*, 39(6):1–10.

Pedro, H. T. and Coimbra, C. F. (2012). Assessment of forecasting techniques for solar power production with no exogenous inputs. *Solar Energy*, 86(7):2017–2028.

Purushottam Kumar Maurya (2024). Self-Healing Grids: AI Techniques for Automatic Restoration after Outages. *Power System Technology*, 48(1):494–510.

Ward, D. M. (2013). The effect of weather on grid systems and the reliability of electricity supply. *Climatic Change*, 121(1):103–113.