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Research Report

Causes and effects of historical transmission grid collapses and implications for the German power system

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Causes and effects of historical transmission grid collapses and implications for the German power system

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Abstract

Against the background of the energy transition accompanied by a rising penetration of renewable energy (REN) sources and a stepwise phase out of conventional power plants in order to fulfill climate protection targets, the requirements for a reliable transmission grid infrastructure increased in the last years. High coordination and communication efforts among market and system operators as well as weather extremes that occur more frequently enhance the probability of critical network states.

In this paper, causes and impacts of 250 prominent transmission grid collapses in the period from 1965 to 2012 were analyzed. Based on historical events, blackout data sets were clustered inter alia by their date, affected continent as well as the duration of interrupted supply, respectively. We find an ascending number of outages along with a longer averaged duration over time. It is studied how different categories of causes evoking large-scale power blackouts are distributed regionally and temporally. Furthermore, challenges to prevent grid malfunctions, both from a technical and societal perspective, are elaborated focusing on the German power system.

Keywords

transmission grid stability · power network blackouts · cascading outages · critical infrastructures

1 Introduction

A high share of volatile decentralized REN feed-in and notably the restructuring process of the European electricity market demand additional capacities from the role-changing stakeholders and power grids to obviate stress in energy supply systems. A large-scale blackout is characterized by Terzija et al. as “the loss of supply to the load in the entire power system, or parts of the system” [26, 12]. In case of a large-scale blackout, a lacking power supply leads to frequency drops or even power plant outages decoupling cities and parts of countries from electricity supply areas. Power outages typically occur in cascades, where instabilities of generating units, exceeded voltage bands as well as overstressed protective devices interact. From a systemic perspective, cascading failures are specified by “a sequence of dependent outages of individual components that successively weakens the power system” [12]. For instance, a short circuit due to insulation damages augments the threats for further line overloads in energy systems with long transmission distances and equipment failures.

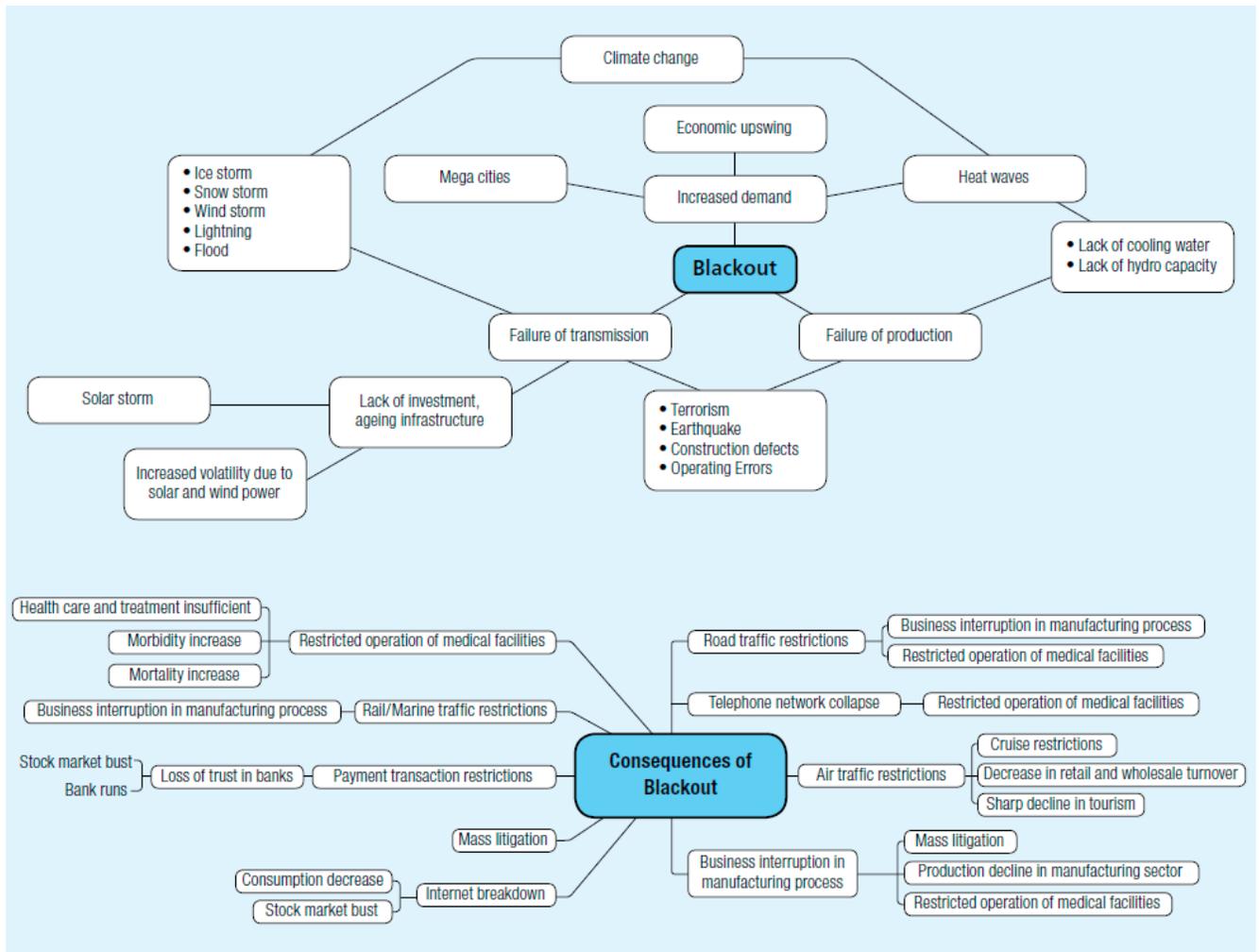


Figure 1: Reasons and consequences of large-scale power blackouts that might last for several minutes or hours [9].

Figure (1) displays how blackouts significantly influence other vital infrastructures, social and economic activities such that the concept of critical infrastructures (CRITIS) applies to electric power systems, since

“the impact of a failure, loss or unavailability is high in scope (potentially international), magnitude (major) and effects of time (immediate)” [17]. More precisely, CRITIS are defined as “a network of independent, large-scale, man-made systems [...] that function collaboratively and synergistically to produce a continuous flow of essential goods and services” [17]. CRITIS are interdependent subject to multiple threats carrying technical, intentional or human, physical, natural and cyber attributes that might evoke serious supply bottlenecks. Figure (2) exhibits that electric power supply is a cornerstone for a functioning society, since it is joint to other infrastructure services such as drinking water supply, sewage disposal or emergency services [4, 5, 17].

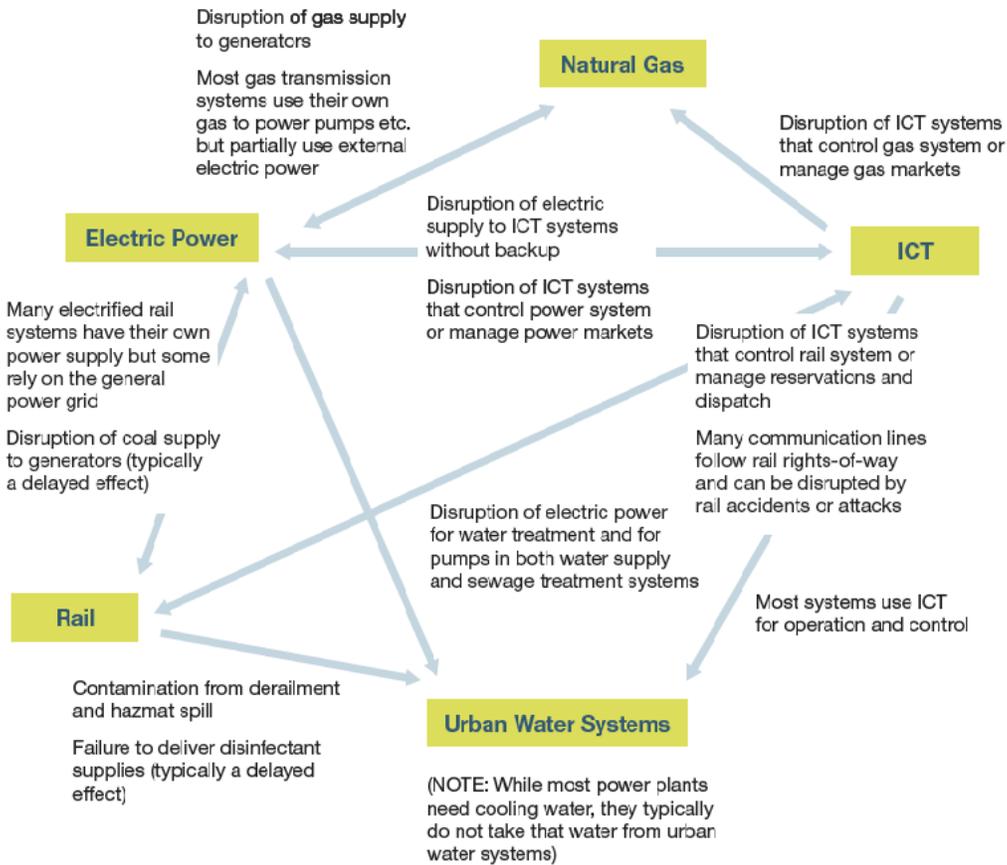


Figure 2: Cross-linked interactions of threats among five CRITIS related to power grid malfunctions [17].

Our study is devoted to the following research issues.

- Which impact do weather extremes have on power grid outages?
- How are blackout cause categories distributed regionally and with respect to their duration?
- Which measures are available to prevent supply outages and to intervene in critical network states?

The remainder of this paper is organized as follows. In section 2, the emergence and prevention of blackouts from a technical perspective is discussed. Corrective redispatch measures (RM) and technical challenges to preserve grid stability are presented focusing on the German power system. Section 3 comprises a review on literature surveys which portray and categorize prominent transmission power network outages that

happened in the last decades. Therein, the courses of two historical power outages are considered more closely. We proceed with an empirical analysis of 250 temporally and regionally clustered transmission grid outage events including the percentage distribution of their cause categories. The paper closes with the main conclusions drawn and a suggestion of further research topics in section 4.

2 Origins of blackouts and challenges for reliable power grids

This section addresses the interplay between technical, human-related and economic factors contributing to maintain grid stability as well as to short-term emergency preparedness in situations of critical network states. Table (3) in the appendix and figure (3) depict prerequisites for system security in transmission grids against the background of a stepwise integration of a high share of spatio-temporally fluctuating REN and innovative flexibility options along the path of the energy system transition.

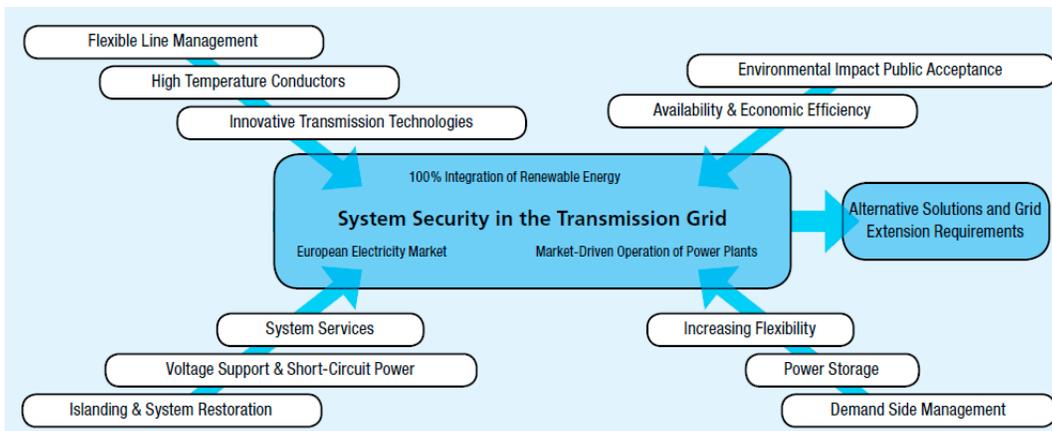


Figure 3: Challenges towards a sustainable transmission grid design (adapted version of [9]).

Emergence of large-scale cascading power outages

In general, power system stability can be classified according to rotor angle short-term stability as well as frequency¹ and voltage stability. Thus, blackouts are associated to stability related, interdependent events evoking a loss of supply such as protection failures, power flow (PF) changes after outages implying the risk of cascade overloads or a proximity to line security limits [12].

For instance, certain overloaded long transmission lines accompanied by small amounts of systemic reactive power² reserves involve an ascending risk of an outage of a specific power line and a significant drop of its nodal voltages. Accordingly, the loads on other lines grow complemented by an augmented reactive power provision of the generators until reaching their technical limits. Further stress on the lines as well as an increased number of power plants that are to be shut down induce reversed PFs and uncontrolled voltage drops in the power system. Finally, voltage instabilities lead to serious cascading large-scale outages, where affected parts of the wide area synchronous grid³ are isolated via interconnectors.

¹In a normal state, alternating current transmission systems operate at a nominal frequency of $f = 50$ Hertz (Hz) with a maximum permissible deviation of $\Delta f = \pm 0.2$ Hz [13].

²Reactive power lacks are to be compensated in the energy system. Reactive power is required for voltage control in transmission grids and it has to be provided with an equal distribution.

³Technically and economically independent control areas operate at a synchronous frequency. They are linked via inter-

This results in synchronously operating network segments and remaining parts that are out of operation induced by the blackout.

In case the generators cannot balance power supply deficits within decoupled network areas due to malfunctioning lines or protective switch offs, the frequency drops. As described in the next section, load shedding is initiated to ensure frequency stability in a power grid that is operating in a vulnerable state⁴. Since also the reactive power is modified and the voltage changes, the power generators loose their static stability and are shut down. Attributable to this active power depression, the frequency drops again. Below a threshold of $f = 47.5$ Hz, generating units are switched off in order to avoid damaged turbines elicited by oscillations. With this purpose, strategic reserves beware the power system of declined grid frequencies.

To relieve the power grid, an operation in compliance with sufficient security margins is appropriate. In addition, adequate local reactive power reserves at critical network nodes and the provision of the four ancillary services (ANS) – i.e. voltage and frequency control as well as system control and restoration – are relevant building blocks for system stability [2, 24].

Technical measures for power system stability

The TSO remove transmission congestion on a specific line by redispatch measures, where the generator power output levels are changed. Therefore, down-regulation of units located in front (negative RM) and up-regulation behind (positive RM) a bottleneck is performed, respectively. The resulting PF rebalances the network congestion [25]. Figure (4) shows the temporal development of RM since 2010 for Germany. Analogously to the annual duration and regulation volume, the yearly redispatch costs increased drastically from 13 million € in the year 2010 to 220 million € in 2016 to keep up system security [3].

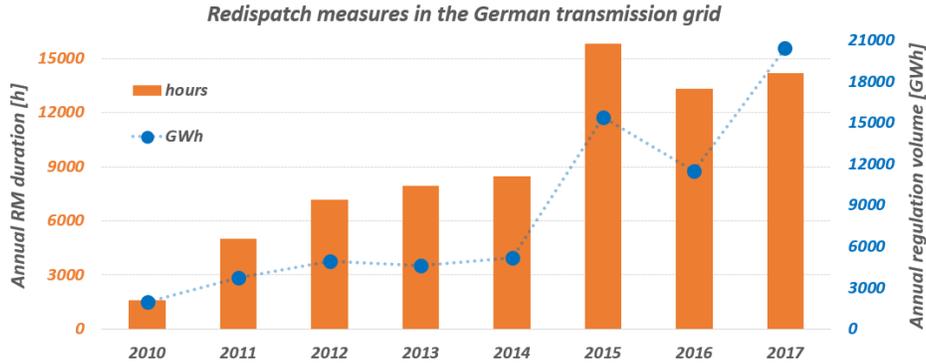


Figure 4: RM in Germany from 2010 to 2017 showing the total volume of down- and up feed-in regulations (*right*) [GWh] and duration of redispatch measures originating from bottlenecks (*left*) [h] (own illustration, datapoints taken from [7, 6, 19, 25]).

In general, the power network operation efficiency is extendable by optimization, before reinforcements connectors to other power systems with the aim of a stable electricity supply and to prevent grid malfunctions by exchanging power. In Germany, there are four transmission system operators (TSO) operating at the 220/380-kV voltage level within their control areas. The ENTSO-E (European Network of Transmission System Operators for Electricity) was created representing the European TSO to establish a uniform liberalized European market area.

⁴Vulnerability denotes the “flaw or weakness (characteristic) in the design, implementation, operation and/or management of an infrastructure or its elements that renders it susceptible to destruction or incapacitation by a threat” [17].

in advance of grid extension adhering to the NOVA⁵ principle are initiated. In the recent years, preventive technical measures were developed to protect the energy system from serious grid collapses.

Flexible phase-shifting transformers (PST) control load flows over high-voltage lines either via voltage amplitude modulation, by phase angle regulation to adjust the shift of the three alternating current phases to 120°, or by an implementation of both coupled options. PST that consist of a wired magnetic core controlled via mechanic tap changers, are bounded by 100 daily switching operations. They are technically mature and implemented in transmission grids for years in many European countries for congestion management. To master highly dynamic behavior, unified PF controllers are used [11]. Recently, at the German-Czech and German-Polish interconnectors, PST were installed to control unplanned PFs that might endanger the grid stability [16].

Fault ride through (FRT) denotes the ability of a generator to remain switched on and to operate synchronously by communicating with turbine controllers despite the occurrence critical network states like short circuits. Since synchronous machines serve as stabilizing devices, they are directly involved to network faults. FRT allows the detection of grid malfunctions in a millisecond range hampering a drastical boosting of the generator’s rotational speed in case of a voltage collapse [18].

Power electronic components (FACTS) control the transmitted active PFs or compensate reactive load flows in alternating current networks with the purpose of an optimal use of available security capacity reserves to overcome temporary bottlenecks. In case of required short reaction times or frequent power gradients, FACTS are advantageous to conventional devices like series condensators – in particular, if they are linked to coordinated protective and control systems of the grid via ICT (information and communications technology) components based on wide area monitoring systems (WAMS). Worldwide, hundreds of FACTS control elements are installed, whereby an augmented use of FACTS is supported via governmental incentives of ANS provision in Germany [11].

WAMS are used to trace and control fast changes within the power grid in real-time with the aim to record and stabilize critical states and to avoid blackouts. For large-scale area monitoring, voltages, currents and phase angles are detected via Global Positioning System (GPS) up to 60 measurements per second synchronized in time and distributed geographically. The data can be collected and evaluated in control centres to perform switching operations. A value-added of WAMS is the possible data exchange between different TSO on an international level [11, 26]. In conjunction with a fast evaluation, control and switching, WAMS can be successively extended to automatized wide area control or protection systems. Combined to FACTS, WAMS contribute to key technologies that realize the concept of selfhealing power grids. An automatic identification and isolation of critical operational states is facilitated before cascading outages emerge.

The principle of overhead line monitoring systems (LMS), i.e. the real-time determination of the line ampacity, is explained in the next section.

Overall, in the event of large-scale grid collapses, a coordinated crisis management entailing the provision of emergency power aggregates is essential. Since the consequences and extent of hazards like force majeure or adverse weather conditions on vulnerable power systems are difficult to predict, the affected

⁵German abbreviation for “Netzoptimierung vor -verstärkung vor -ausbau”

stakeholders should be prepared in advance by means of integrating early-warning systems, by extending the skills of the involved personnel and by raising the public awareness on coping with outages.

3 Data analysis of large-scale power network blackouts

In this section, we examine 250 historical blackout events each affecting more than 70'000 people between 1965 and 2012. The data set was clustered by the date and cause category of each power outage, the geographical region, the maximum number of affected people and the duration of the unplanned supply interruption.

3.1 Exemplary prominent historical blackout events

Several surveys addressing severe historical power outage events serve as a basis for our meta study.

Bompard et al. classify natural, accidental and malicious threats, events and consequences of historical outages [8]. The report comprises a comprehensive list starting with the Northeast blackout in 1965 covering the USA/Canada. Therein, the authors document the chain of events encompassing their date, geographical coverage, origin, population affected, duration or economic cost. Papic et al. present contingency analysis tools for risk assessment of cascading outages [20]. In their IEEE survey, a collection of continent-major blackouts sorted by date, duration and collapse time as well as the MW lost is found. Styczynski et al. list chronologically severe blackouts including their scope. The authors consider aspects to ensure reliably operating transmission grids from a purely technical perspective [26]. Besides characterizing interdependent dimensions of vulnerable CRITIS in detail, an overview on selected European power grid outages between the years 2003 and 2008 is given in [4]. The authors describe exemplarily how natural hazards or human errors lead to adverse impacts on the power supply. What is more, Bruch et al. estimate blackout risks from an economic and societal point of view influenced by the electricity market liberalization [9]. Their study focuses on blackout risk management that contains trends affecting the business interruption risk landscape and the power dependency for industrial production processes as well as mitigation strategies. Finally, Quester et al. report extensively on power grid malfunctions [22]. Particularly, emergency situations in nuclear power plants from 2003 to 2012 were taken into account. Beyond discussing technical reasons responsible for network failures, that is voltage deviations or collapses, frequency fluctuations and the loss of transient stability, the course of power outages as well as their international experiences are elaborated.

Table 1 shows how 250 transnational blackouts since 1965 were categorized with respect to their origin sorted by percentage in a descending order. It depicts typical events belonging to each class and prominent historical examples. Obviously, extreme weather events (30 %) and defect electrical equipments (27 %) are the two most leading causes of power outages, whereas blackouts due to human errors or violence and short circuits were less responsible for damages. If interdependent causes of a blackout event were registered, the major reason was identified to exclude double counting in the data interpretation.

Subsequently, we portray the course of two prominent blackouts that happened in Germany.

Categorized power outage causes [%]	Malicious threats	Exemplary prominent blackout events <i>Geographical region – date – persons affected (p.)</i> Background
Weather events** [30 %]	thunderstorms, strong winds, ice formation, hurricane or tornado, snow storm, arcing and flashovers between power lines and trees	<i>Germany (Münsterland) – 11/2005 – 250'000 p.</i> Extreme snowfall and ice formation: snow loads led to line destruction and damaged the pylons.
Electrical equipment [27 %]	technical faults in transformer stations or protective relays, outages of gas turbines, power plants, disconnectors, switchgears or lines	<i>Turkey (Istanbul and surroundings) – 01/2012 – 20 million p.</i> A failure in a gas-fired power plant caused a power cut.
Faulty network operation [12 %]	incorrectly adjusted protective relays, power plants in poor condition, planned shutdowns, inadequate maintenance, switching faults	<i>Europe (Germany, France) – 11/2006 – 15 million p.</i> Planned line switch-off: communication and coordination deficits among the grid operators induced a split of the UCTE (Union for the Coordination of Transmission of Electricity) region into three areas of over- and underfrequency followed by load shedding.
Temperature [8 %] ** considered as a separate category	very high or extremely low	<i>India – 01/2010 – 70 million p.</i> Fog and cold temperatures elicited transmission grid defects. A disruption of the Northern grid was accompanied by a disconnection of power plant capacities. <i>Great Britain (London) – 07/2006 – 7.6 million p.</i> A higher electricity demand than generation due to a heatwave resulted in load shedding (rolling blackouts).
Force majeure [8 %]	earthquake, tsunami, forest fire or bush fire	<i>Venezuela – 04/2008 – 10 million p.</i> Forest fires near a hydroelectric power plant gave rise to a short circuit in the transmission lines. <i>Chile – 02/2010 – 13 million p.</i> Strong earthquake.
Network congestion and overload [5 %]	less power generation than demand, load shedding, excess of electricity imports	<i>India – 07/2012 – 1.04 billion p.</i> Power demand exceeded generation: transmission grid defects were followed by cascading outages of lines and power plants. After the Northern grid collapsed, the (North-)Eastern grids were out of operation.
Human violence [4 %]	sabotage, manipulations, cyber attacks, vandalism	<i>Cameroon (Jaunde) – 08/2011 – several million p.</i> Sabotage of pylons as protests against the government led to power outages in several regions.
Human errors [3 %]	construction crane or helicopter damages transmission line and electrical equipment	<i>Peru (Lima) – 10/2006 – 2.5 million p.</i> A hot air balloon collided with a high-voltage pylon followed by a short circuit, an electric arc and the deactivation of several lines. <i>Japan (Tokyo) – 08/2006 – 1.4 million p.</i> A floating crane damaged a transmission line over the Edo river.
Short circuit [3 %]	–	<i>Canada (Ontario) – 01/2003 – 150'000 p.</i> The gritting salt deposits on the insulators in a power plant evoked a short circuit with an electric arc and a high-voltage power supply outage.

Table 1: Classes of origin and selected examples of 250 historical transmission grid outages since 1965 with the percentage distribution [< 5 | < 10 | < 20 | < 30 | 30] % based on [2, 22].

Power outage in the Münsterland and Osnabrück region, Germany

In the night of November 25 in 2005, there was a heavy snowfall in the Münsterland region due to adverse weather conditions, see figure (5) below. The interaction of coincident threats – strong winds reaching hurricane force, temperatures about 0° C, heavy snow load on the lines and rain – gave rise to torn power lines and over 80 ruptured pylons such that seven 100-kV transmission lines failed within a short time period. This led to a blackout affecting 250'000 people who had to cope with electricity supply interruptions for nearly five days. Apart from that, a temporal power outage in Osnabrück affected 600'000 people [15]. Moreover, the highway A31 near Gronau had to be completely closed due to torn high-voltage power lines that fell down cutting off of further lines for safety reasons. Subsequently, emergency power generators were flown in to cool down perishable goods or to operate milking parlors on the farms. Simultaneously, the grid and supply restoration by a repair crew of 400 employees from the RWE power supply company took place until December 1, 2005. The costs thereby incurred were estimated at about 130 million €. Expert reports investigating the network conditions did not identify safety deficiencies, material defects or poor maintenance. The conclusion was that the weather-related weight overload of snow on the power lines was tremendously exceeded according to valid technical regulations. The German Federal Network Agency (BNetzA) recommended a closer coordination with the meteorological service and intensified preventive measures [22, 15].

A substantial challenge was to coordinate the supply and care of the population as well as the operation of emergency power generators in hospitals, rest homes or at farms, since many households were poorly provided with food supplies. This historical blackout event highlights the special relevance of an increasing dependence on other CRITIS. Therefore, Birkmann et al. examine to which extent energy supply underlies the vulnerability paradox⁶ [4].

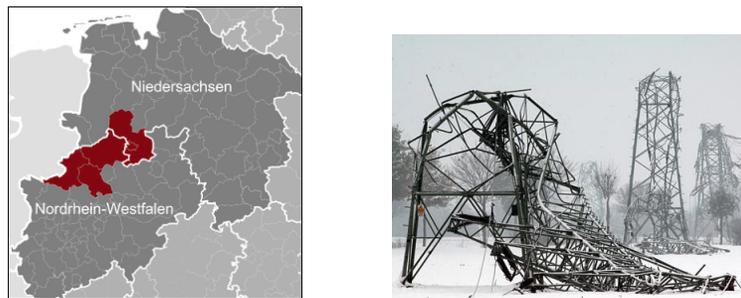


Figure 5: Affected areas located in North Rhine-Westphalia/Lower Saxony and kinked power line pylons in the Münsterland region in November 2005 due to a large-scale power blackout in Germany [22, 4].

Cascading blackout in the European transmission grid (UCTE) region

On November 4 in 2006, human errors caused a failure in the European transmission grid system leading to power outages in several parts of Europe. This severe blackout affected 15 million people during one night. As planned, a 380-kV transmission line had to be switched off to let a ship of tall height pass underneath between the Ems river and the North Sea. Coincidentally, an amount of 10 GW wind electricity

⁶In correspondance to the vulnerability paradox, the use of electricity for efficient processes in economic and everyday life in industrialized and highly developed countries enhances steadily, whereas the vulnerability of the society raises tremendously in case of malfunctions of this CRITIS, e.g. the outage of a specific electrical equipment [4, 5].

was fed into the European grid. Insufficient communication and a lack of coordination between the system operators, especially checks of compliance with the (N-1)⁷ criterion and load flow calculations about the switch-off led to grid frequency instabilities and overloaded lines [9, 22]. Within several seconds, the European electricity transmission network was split, since the power balancing between generation and load could not be fulfilled in the three zones, as figure (6) indicates. In the Western part ①, the frequency declined to 49 Hz and over 9 GW of generation capacity were lacking resulting in automatic load shedding and power outages. In addition, several German and Swiss nuclear power plants showed active power deviations [22]. Moreover, the transportation infrastructure was effected: the subway had to be evacuated complemented by long delays in rail transport mainly in Germany [9]. An excess power of approximately 10 GW in the North-Eastern part ② rapidly increased the frequency to 51.4 Hz that was balanced by feed-in power reductions. In the regions of lower frequency, controlled shut downs of industrial and household customers were performed to avert uncontrolled blackouts. Since several German conventional power plants were already operating at a minimum level, a manual shut down of Polish power plant blocks had to compensate the excess energy. Additionally, the lack to control early automatic restarts of some wind turbines and a missing access to real-time data about the state of various generation units connected to the distribution grid hampered an immediate network stabilization and resynchronization [4].

Restoration measures were initiated directly after the split of the European grid. After the frequencies of the Western and North-Eastern parts were synchronized, the South-Eastern region ③ with a frequency of 49.7 Hz followed. About 37 minutes later, the three regions were operating uniformly again. Within a time interval of two hours, grid restoration was completed in all European countries. To guarantee a secure network, the BNetzA stated to extend the grid [4].

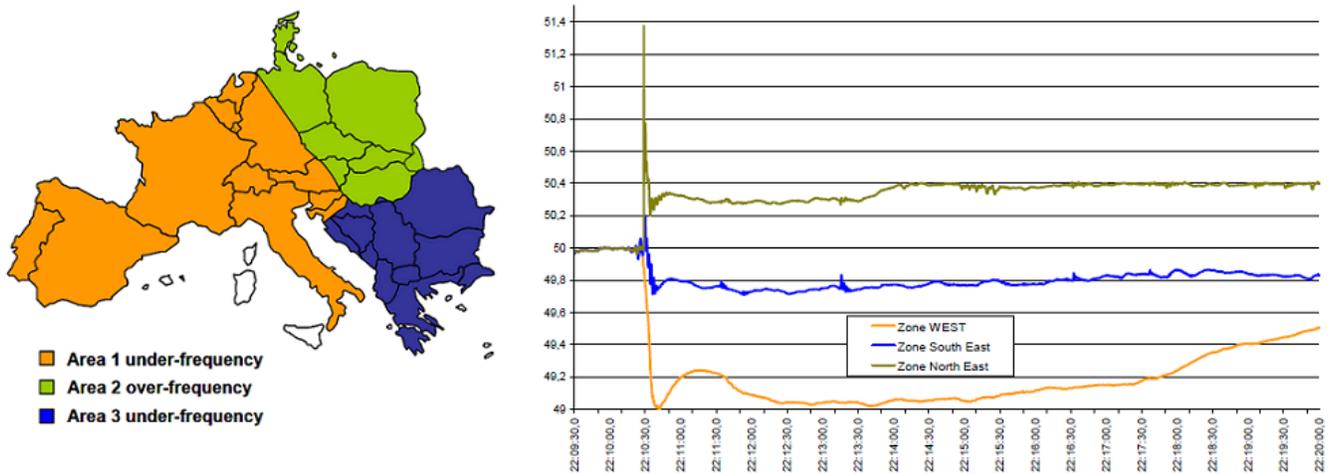


Figure 6: Frequency behavior within the minutes after the split of the UCTE transmission grid into three zones due to a cascading blackout in November 2006 [22, 14].

⁷The (N-1) criterion specifies that “any probable single event leading to a loss of a power system element should not endanger the security of the interconnected operation, that is, trigger a cascade of trippings or the loss of a significant amount of consumption. The remaining network elements, which are still in operation, should be able to accommodate the additional load or change of generation, voltage deviation or transient stability regime caused by the initial failure” [17].

3.2 Data clustering of power outages

Figure (7) displays a risen number of large-scale blackouts over time. On the one hand, more frequent adverse weather conditions entailed by the global climate change enhance the probability of network collapses [1]. Figure (7, dashed) and section 3.1 reveal that heavy rains, storms, black ice and snowfalls might induce technical power line and pylon defects, short circuits or damaged electrical equipment.

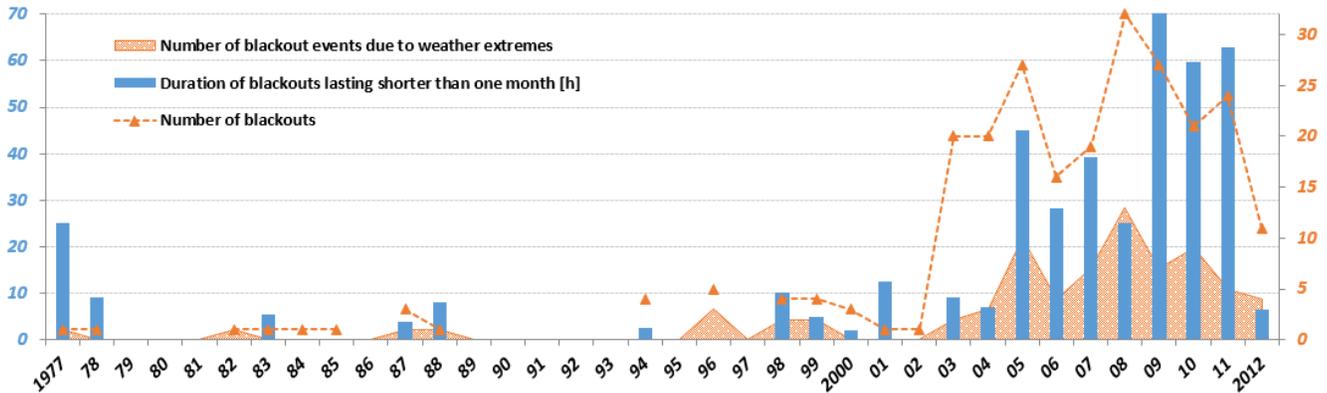


Figure 7: Number (dashed line, $n = 249$) and average duration in hours (bar chart, $n = 151$) of large-scale blackout events between 1977 and 2012 (own illustration according to [2]).

To attune to extreme events such as strong wind and ice and to intervene in case of damages – besides the integration of weather forecast into network operation – line loads are measurable via overhead transmission line monitoring systems (LMS). By using LMS, the sag or line tension and conductor temperature allowing the detection of unused current-carrying capacity reserves are determined under normal conditions in real time [10, 11].

Despite a secure and reliable power supply in Germany, critical grid states can be provoked by certain circumstances. First, an ascending number of stakeholders in the course of the energy sector deregulation complicated the coordination and communication processes among market participants – especially concerning the network control stations of different countries, as the blackout in November 2006 affecting large parts of Europe impressively demonstrates. The formation of large transmission grid systems like the ENTSO-E raised the risk of heavily loaded interconnectors if a decoupling into subsystems triggered by power oscillations becomes necessary. What is more, the number of outages was effected by the electricity sector liberalization, where PFs initiated by the market forced up some transmission line loads. On the other hand, corrective redispatch measures and REN generation capacity expansion were augmented.

For this reason, figure (7, bar chart) shows that blackouts were lasting for longer time periods, notably between the years 2005 and 2011.

As figure (8) depicts, power outages registered in Europe arose primarily due to technical defects or damaged protective relays. Therefore, investments in grid maintenance, extension and modernization are required for a reliable and efficient power supply. In contrast to deficient electrical equipment mainly causing grid collapses in Europe, Africa and Asia, extreme weather events are a major threat for blackouts occurring in North and Central America.

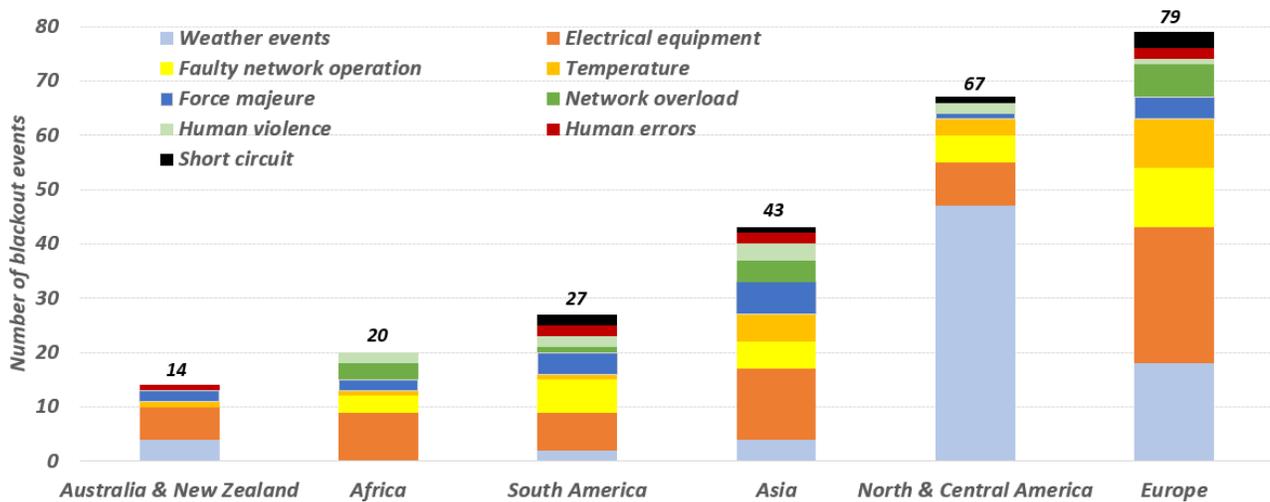


Figure 8: Distribution of power outage causes for 250 events grouped by continents (own illustration).

Figure (9) demonstrates a wide spread of duration depending on the origin of the blackouts. Particularly, weather events and force majeure strongly influence their time periods. In case of earthquakes, tsunamis or bush fires, a complete grid restoration might last for days or persist up to weeks. On the contrary, it took approximately ten to 13 hours, until failures stemming from network overloads or faulty network operation were remedied.

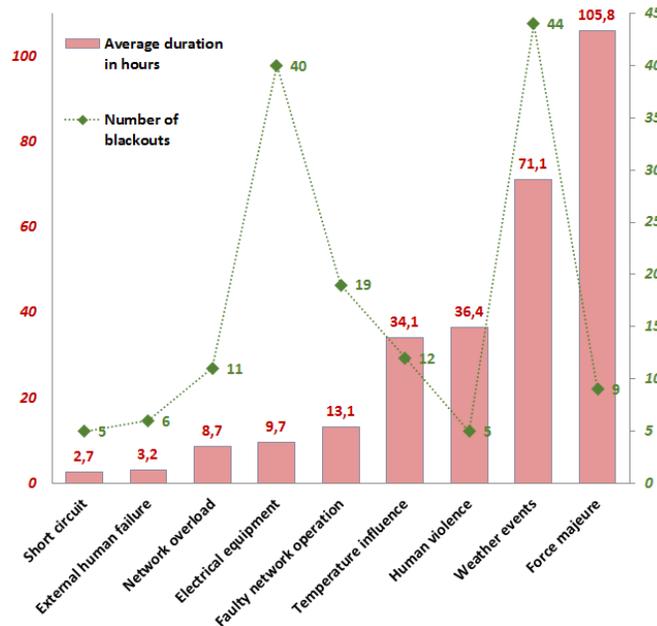


Figure 9: Average duration (bar chart) and allocation (dashed line) of 151 categorized power grid collapses from 1977 to 2012 lasting shorter than one month (own illustration based on [2]).

Figure (10) unveils that about 8.8 % of all considered 250 blackout events were at least attributed to two different causes introduced in table 1. Especially, 6.8 % of the power outages induced by faulty network operation were combined with other events such as extreme temperatures or a violation of the (N-1) criterion followed by a share of 4.4 % by reason of malfunctioning electrical equipment supplemented

by a second power blackout cause category. This implies that the operational personnel has to be trained more intensively with the purpose to better cope with rising requirements in stress situations.

total (*, **) 17	F. network operation	Electrical equipment	total (hor.)
Faulty network operation*	x	6 **	6
Short circuit	1	2	3
Network overload	2	1	3
Temperature	2	1	3
Weather events	0	1	1
(N-1) criterion violation	6	0	6
total (vert.)	11 *	11	22

Figure 10: Distribution of 22 historical blackouts which happened between 1994 and 2011 caused by two reasons. The origin categories are introduced in table 1 (own illustration).

Date	Continent	Affected country	Type of human violence
Jan, 2000	North and Central America	USA	manipulation
Mar, 2000	North and Central America	USA	/
Sept, 2003	Asia	Georgia	sabotage
Jan, 2005	South America	Brazil	cyber attack
Aug, 2005	Asia	Iraq	sabotage
July, 2009	Europe	United Kingdom	vandalism
Sept, 2007	South America	Brazil	cyber attack
April, 2008	Asia	Malaysia	sabotage
Aug, 2011	Africa	Kenya	vandalism
Aug, 2011	Africa	Cameroon	sabotage

Figure 11: Power outages attributable to human violence sorted by region and type (own illustration).

4 Conclusion and outlook

This paper emphasizes the relevance of preventive measures – both with respect to societal and technical dimensions – to ensure a flexible and secure electricity supply by regarding historical power network outage events and their relation to other CRITIS. Therefore, we performed an empirical analysis of causes and effects of 250 transmission grid collapses each affecting more than 70'000 people between the years 1965 and 2012. Above all, the impact of weather extremes – amounting to 30 % in our data set – was identified as a major reason for serious power blackouts in North and Central America. A prominent example for

this category is the blackout that happened in 2005 in the German Münsterland region due to an extreme snowfall and ice formation lasting for almost five days. Moreover, the data reveal that power network malfunctions occur more frequently with an increasing duration in time. In case of weather events or force majeure like earthquakes, tsunamis and bush fires, a complete grid restoration might last up to weeks. Contrarily, it takes approximately ten hours, until failures originating from network overloads or faulty network operation are repaired. In addition, we examined how historical blackouts are distributed regionally and temporally within the nine cause classes weather events, electrical equipment, faulty network operation, temperature, force majeure, network overload, human violence, human errors and short circuit, respectively. Besides adverse weather conditions, we identified that 27 % of the large-scale power outages in our data set were provoked by electrical equipment failures. Accordingly, investments in grid extension and modernization are required for a reliable power supply. By clustering the data set by continents, we conclude that power outages in Europe primarily arose as a result of technical defects, as damaged protective relays. On the other hand, blackouts originating from human errors, human violence or short circuits were less causal to damages with a share below 5 %. Concerning interlinked categories, 6.8 % of our registered grid malfunctions induced by faulty network operation were combined with other blackout causes such as extreme temperatures or a violation of the (N-1) criterion. This implies that the operational personnel has to be better prepared and trained more intensively with the aim to cope with more stress situations. Within this scope, preventive measures are worthwhile to sensitize the population and to avoid panic situations.

To detect critical network states, dynamical grid monitoring by means of synchronized measuring devices (WAMS) is a useful option. Complementarily, power electronics intended for load flow management comprising active power control or reactive power compensation (FACTS) and the installation of real-time overhead LMS are recommendable. Apart from smart grids and innovative storage technologies aiding to smooth load peaks and generation profiles, transmission loss reduction is achievable by implementing high-temperature superconducting components. Thereby, sophisticated technical measures contribute substantially to an optimal network operation [11, 2].

In general, a coordinated crisis management is essential by means of focusing on emergency power provision. To intervene efficiently in supply outages, sufficient, locally available fuel resources and regularly supplied emergency power aggregates preserved at service stations is appropriate. Another possibility are stand-alone electrical networks, where connected regions are supplied via distributed generation systems during a period of grid disruption [21].

Further research should address the interdependence among different power outage cause classes more deeply from a technical perspective. As a critical appraisal, the data set is to be completed by a documentation of more severe historical events, particularly before the deregulation of the energy sector was initiated in the 1990s. The examination of power outages grouped by voltage levels is an inspiring topic, since this sheds light on the influence of decentralization processes and the enhanced penetration of fluctuating REN in the energy mix. Recently, power network malfunctions with regards to human violence like cyber attacks, manipulations or sabotage and their linkage to ICT gain special attention.

From an economic point of view, to assess the costs and their different types associated to blackout cause categories is a valuable research contribution. Firstly, it reveals concrete investments into transmission

technology components. Secondly, an estimation of power outage costs taking into account n^{th} -order CRITIS coupling effects as discussed by Rinaldi et al. in [23] is a crucial aspect. They can be assigned to infrastructure restoration or financial expenses elicited by animal death or crop losses.

Appendix

<i>acronym</i>	<i>term</i>
ANS	ancillary services
BNetzA	Federal Network Agency (German: Bundesnetzagentur)
CRITIS	critical infrastructures
ENTSO-E	European Network of Transmission System Operators for Electricity
FACTS	flexible alternating current transmission systems
FRT	fault ride through
ICT	information and communications technology
LMS	line monitoring systems
PF	power flow
PST	phase shifting transformers
REN	renewable energy
RM	(corrective) redispatch measures
TSO	transmission system operators
UCTE	Union for the Coordination of Transmission of Electricity
WAMS	wide area monitoring systems
Hz	Hertz $[\frac{1}{s}]$, frequency unit

Table 2: Nomenclature of terms introduced in this paper.

<i>term</i>	<i>definition</i>
threat	“Any event or circumstance that has the <i>potential</i> to adversely impact on an infrastructure, or any element thereof, through accidents, natural hazards, unauthorized access, capacity overloads as well as deliberate attacks (cyber, terrorism) ...”
reliability	“... <i>ability</i> (probability) of satisfactory operation (design function) over the long run (within a given time interval under specified operational conditions). It denotes the ability to supply adequate (correct) service on a nearly continuous basis, with only a <i>few interruptions</i> over an extended time period. While reliability denotes the <i>continuity of correct service</i> , availability refers to the readiness of correct service.”
power system stability	“... refers to the continuance of intact operation following a disturbance. It depends on the operating condition and the nature of the physical disturbance [...]. To be <i>reliable</i> the system itself must be <i>secure</i> most of the time. To be <i>secure</i> the system must be <i>stable</i> but also be secure against other contingencies that would not be classified as stability problems.”
security	“... of an infrastructure refers to the degree of <i>risk</i> in its ability to survive imminent disturbances <i>without interruption</i> of customer service. It relates to robustness of the system and, hence, depends on the system operation condition as well as the contingent probability of disturbances.”
security of supply	“... is assured when at <i>any time</i> the required service, e.g. amount of electricity of satisfactory quality, is <i>available</i> at an <i>affordable</i> price within the <i>whole</i> network.”

Table 3: Definitions used in the framework of CRITIS and power system reliability quoted from [17].

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