Fighting Against Wildfires in Power Systems

SEVERAL EXTREME WILDFIRES HAVE RECENTLY affected many countries worldwide, causing enormous economic and human losses and vastly damaging ecosystems. For example, in January 2017, a highly destructive series of wildfires destroyed more than 500,000 hectares in Chile, burned 3,000 houses, and left 11 dead. The intensity and impact of these wildfires had never been experienced before in the country.

In June 2020, the Brazilian National Institute for Space Research detected 103,000 wildfires in the Brazilian Amazon with an annual increase of 16%. The systematic increase of wildfires in Brazil has led to a significant concern internationally as the Amazon rainforest represents the largest carbon dioxide sink in the world with important mitigating impacts on global warming. In 2019, the economic damage of wildfires was estimated at circa US$3.5 trillion for the Brazilian economy.

These events have also highlighted the exposure and vulnerability of critical infrastructures to wildfires, including power systems. For example, transmission lines are threatened by excessive heat transfer and smoke during wildfires, resulting in temporary and permanent faults. In particular, wildfires can damage towers and poles, conductors, insulators, and other components of transmission lines, causing, in some cases, a collapse of the network corridor.

Also, high temperatures can reduce the capacity of transmission lines near wildfires. The combined effects of heat and smoke (dust and soot) generated by the fires can lead to short circuits. For instance, changes in the physical properties of the air gap can reduce the dielectric strength between conductors and between conductors and ground, causing phase-to-phase and phase-to-ground faults and making reclosing impossible. In a similar vein, distribution networks can be destroyed by

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Lessons and Resilient Practices From the Chilean and Brazilian Experiences

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wildfires, with supply relying on mobile and temporary solutions for restoring the electricity supply. In several cases, the situation awareness of system operators is also limited due to the fast and widespread impacts of wildfires, reducing their ability to effectively and timely react to the evolving system conditions.

These impacts have placed the resilience of critical infrastructures and services against catastrophic wildfires, including power systems and uninterrupted electricity supply, in the spotlight and high on the agendas of infrastructure planners, operators, and decision-making bodies in Chile, Brazil, and around the globe. Moreover, it is expected that global temperatures will continue to rise as a direct impact of climate change, further affecting the frequency and intensity of catastrophic wildfires and creating a new "norm" that system operators and planners will need to consider.

The prevention of cascading impacts of wildfires on power systems will require suitable mitigation measures. The proactive operational and investment planning against such disastrous and highly uncertain events will require supporting and enabling policy and regulatory frameworks to incentivize the operational and investment planning toward resilient power grids.

In this context, this article will first share experiences with wildfires from Chile and Brazil to shed light on the

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actual impacts of these events and the system's performance under such stressed conditions. Driven by these real-world events, we will then describe the responses of key actors, such as network operators, planners, regulators, and policy makers, in terms of the implementation of prevention, mitigation, and adaptation measures aimed to hedge the risks of wildfires in several timescales. Lessons and recommendations are summarized at the end of this article.

The Chilean Experience

Chile is witnessing a significant risk associated with wildfires. Figure 1 shows the number of wildfires and the total surface/area affected from 1964 to 2020, clearly reflecting this increasing trend in risks. For instance, the number of wildfires from 2011 to 2020 was 42% higher than the historical average (1964–2020). In the future, the prospects are not better. Currently, Chile is ranked 25th among the countries most affected by climate change with a Global Climate Risk Index of 33. Chile is expected to experience significant changes in the temperature and rainfall patterns by the end of the century with an expected temperature increase of 2–6 °C and a decrease in winter precipitation by up to 40%.

Wildfire risks have also severely affected power systems. The entire set of transmission failures (forced outages) in the Chilean power systems from January 2017 to June 2020 was analyzed. Of the approximately 3,000 transmission failures, around 200 correspond to outages caused by wildfires.

Our analysis identified 16% of failures caused by smoke and 84% of failures caused by a mixture of heat and smoke. We also determined that 10% of the failures were due to broken conductors and 90% due to short circuits cleared by protection systems. Since large volumes of smoke can fly far from the fire source, wildfires can cause failures even when they are distant from the electrical infrastructure. An approaching wildfire can also cause the lowering of line capacities. All of these issues need to be considered by network owners, operators, regulators, and policy makers to mitigate the risk of outages due to wildfires.

Next, we present the recent developments in terms of wildfire effects and mitigation actions in Chile, touching upon network impacts, operation, planning, and regulation.

The 2017 Firestorm

The 2017 "firestorm" is considered the most destructive wildfire event experienced in Chile. This natural disaster lasted 19 days, from 18 January to 5 February 2017, registered 681 ignition points, and razed more than 500,000 hectares along seven regions in the central-south zone of Chile. O'Higgins, Maule, and Bío-Bío were the most affected regions. The spatiotemporal progression of the event and the total area affected are illustrated in Figure 2. The sequence of images shows the relevance of the geographical wildfire spread in terms of speed and area affected.

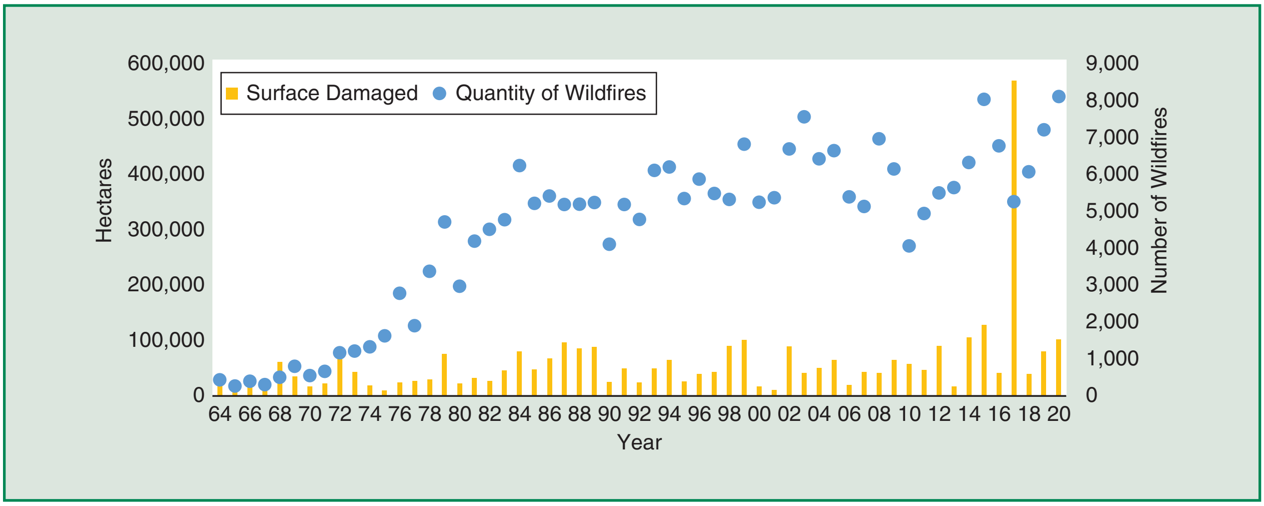


figure 1. The frequency and intensity of wildfires in Chile.

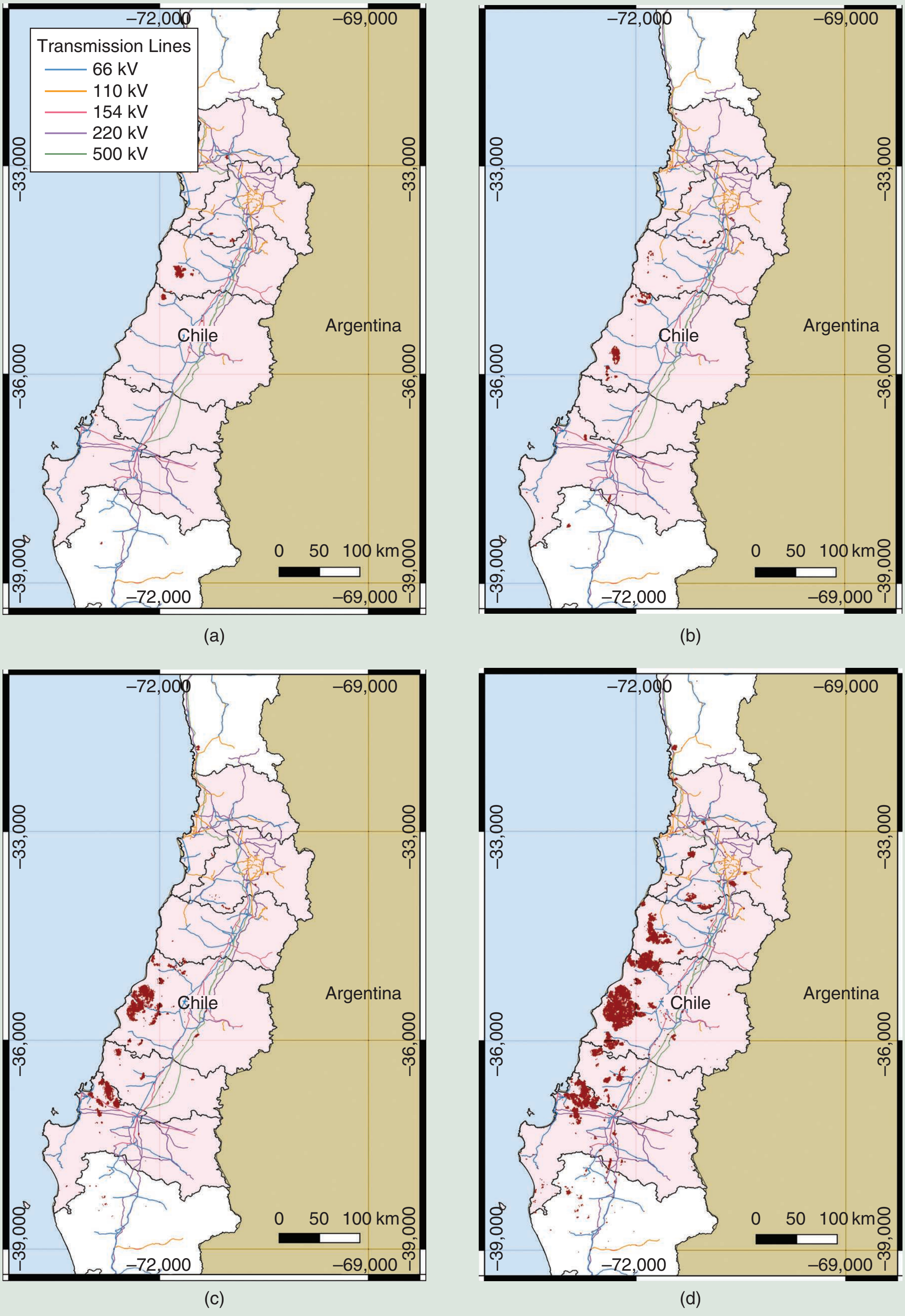


figure 2. The spatiotemporal progression of the Chile firestorm in 2017. The data were obtained from NASA satellites *VIIRS* and *MODIS*. (a) 18 January 2017, (b) 22 January 2017, (c) 26 January 2017, and (d) total surface damaged.

The wildfires affected 24 transmission lines with more than 50 failures. Table 1 shows the main events. The city of Concepción was one of the most affected areas. It was surrounded by 353 fires that triggered simultaneous failures in several transmission lines. Among the most affected lines, we found Charrúa–Ancoa 500 kV (around 20 h out of service because of three outages), Charrúa–Concepción 154 kV (3.3 h out of service because of four outages), Charrúa–Concepción 220 kV (12 h out of service because of eight outages), Charrúa–Hualpén 220 kV (8.2 out of service because of eight outages), and Concepción–Mahns 66 kV (209 h out of service because of one outage). The consequences on system operation and the responses by the authorities are presented next.

Reduced Power Transfers

Table 1 shows the impact of wildfires on major network infrastructure, i.e., 220–500 kV. To efficiently deal with these impacts, the Chilean Independent System Operator had to redispatch the system postcontingency, increasing the generation from more costly units in importing areas to avoid demand curtailments. Because of the increased risks, preventive measures were also undertaken by the Chilean Independent System Operator. An interesting example corresponds to the incident in the Charrúa–Ancoa 500-kV corridor. After this corridor was affected by a wildfire in one of their circuits (the corridor is composed of two single circuits on separate routes), one circuit had to be disconnected and the other operated at a reduced rate as a

table 1. Transmission lines affected per day, time, and region during January 2017. Local-generation-provided frequency control services are also pointed out.

Day	O'Higgins	Maule	Bío-Bío
19		**19:30** Line San Javier–Constitución 66 kV	
20			
21			
22		**20:35** Line Cauquenes–La Vega 66 kV	
23		**14:28** Line Itahue–Talca 66 kV **15:30** Line Charrúa–Itahue 154 kV	
24	**16:10** Line Candelaria–Maipo 220 kV **16:50** Line Santa Rosa–Alhué 66 kV	**10:20** Line San Javier–Constitución 66 kV **15:12** Line Hualañé–Ranguilí 66 kV **17:37** Line San Javier–Constitución 66 kV **19:51** Celco and Viñales plants at Constitución **20:05** Substation Nirivilo 66 kV	
25	**18:12** Line Ancoa–Alto Jahuel 4,500 kV	**00:00** Celco plant with frequency control at Constitución **13:50** Line Hualañé–Ranguilí 66 kV **17:39** Line Charrúa–Ancoa 2,500 kV	**09:30** Line Coronel–Horcones 66 kV **15:50** Line Charrúa–Concepción 220 kV **17:27** Line Charrúa–Hualpén 220 kV **17:41** Line Alonso de Ribera–Penco 66 kV
26		**00:00** Celco plant with frequency control at Constitución **14:09** Line Charrúa–Ancoa 2,500 kV **18:31** Line Parral–Cauquenes 66 kV	**00:47** Line Concepción–Penco 66 kV **09:49** Line Charrúa–Concepción 220 kV **15:06** Line Charrúa–Hualpén 220 kV **15:11** Line Charrúa–Concepción 220 kV **15:11** Line Charrúa–Lagunillas 220 kV **16:17** Line Santa María–Charrúa 220 kV
27		**00:00** Celco plant with frequency control at Constitución **17:45** Line Ancoa–Itahue 220 kV	
28		**00:00** Celco plant with frequency control at Constitución **14:54** Line San Javier–Constitución 66 kV	**14:25** Lines Charrúa–Concepción 220 kV and 154 kV
29		**00:00** Celco plant with frequency control at Constitución	
30	**16:28** Line Ancoa–Alto Jahuel 4,500 kV	**00:00** Celco plant with frequency control at Constitución	**19:51** Lines Charrúa–Concepción 220 kV and 154 kV
31		**00:00** Celco plant with frequency control at Constitución **21:53** Line San Javier–Constitución 66 kV back to service	

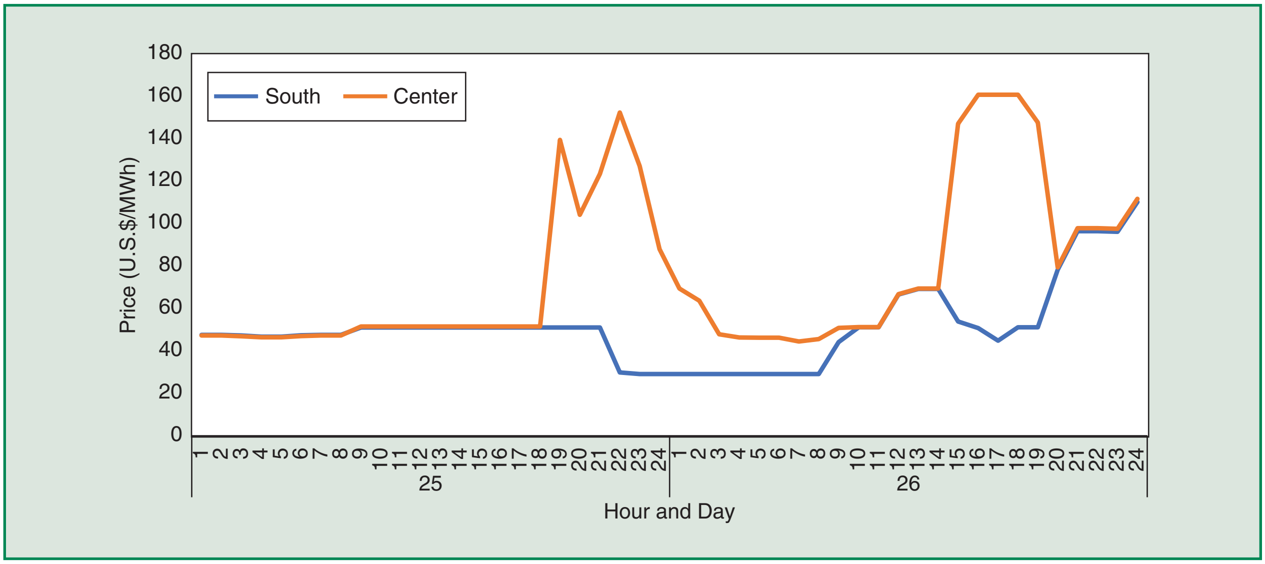


figure 3. Energy prices in the spot market on 25–26 January 2017.

preventive measure. Before the fault, the two circuits were transferring about 1,000 MW, which was reduced to 300 MW after the incident.

As a consequence of the limited transfers, a large price differential across the network arose (Figure 3), increasing congestion costs. In turn, this price differential can be explained by the increased dispatch of more costly (diesel-fueled) units in importing areas, in this case, the center of the country. Although a fault caused part of the cost increase, another portion of was caused by preventive actions undertaken by the system operator. In this case, the system operator preferred to face a congestion cost increase caused by the preventive measures targeted to hedge risks (derived from another potential line failure) rather than increase power transfers (reducing congestions costs). This approach by the system operator reflects, in our opinion, a risk-averse mentality when facing high-impact events.

Support From Distributed Generation

Wildfires can also affect local subtransmission systems and entry points to distribution systems. In such cases, distributed energy resources (DERs) can be a powerful support to supply the loss of infeed. For example, the series of wildfires in January 2017 affected the line San Javier–Constitución 66 kV (single circuit), leaving the city of Constitución operating as an island. This island was supplied by local generation between 25 and 31 January, with the Celco power plant providing the needed frequency control. Hence, residential and industrial (pulp and paper production) consumers continued to be supplied through local thermal generation using biomass and diesel (Figure 4). Although the justification to install these distributed generating units was not their capability to provide reliability and resilience services, this may change going forward. Increasing risks bring awareness to policy makers and promote DER-based solutions to resilience concerns.

Authority's Response

Situation Awareness Developments

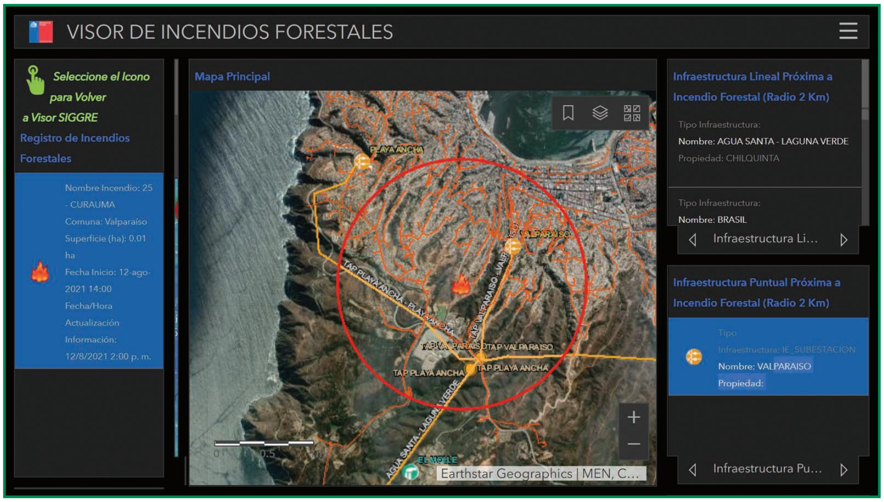
Since 2017, the Ministry of Energy (MoE) has taken a key role in alerting key stakeholders about natural hazards,

figure 4. Constitución and its supply transmission system on 26 January 2017. Areas affected by wildfires are marked with a red flame symbol.

such as wildfires near critical energy infrastructure. To this end, the MoE has developed advanced situation awareness tools (a territorial viewer that allows permanent monitoring of the main threats affecting the energy sector) called *#EnergíaAlerta*. The graphical interface contains georeferenced data of the energy facilities (location of electricity, liquid fuels, and gas infrastructure), their criticality levels, and the location of informed natural hazards. The viewer also contains climate variables, such as wind speed and direction, humidity, and temperature, which allow users to anticipate potential trajectories of natural hazards (wildfires). This powerful tool is managed by the MoE and accessible by the regulatory authority, system operator, network companies, and different market participants. Figure 5 shows a snapshot of the tool's main screen.

Regarding wildfires, the MoE signed a collaboration agreement with the National Forestry Corporation so that databases and platforms from both institutions can interact. This allows viewers to have real-time information on the location and status of wildfires, study the exposure of relevant energy infrastructure to wildfire threats, and promptly warn network owners and operators. The system automatically informs the system operator, network owners, regulatory office, and the MoE (among other authorities) when a wildfire gets too close to the energy infrastructure (2 km).

In addition to wildfires, the viewer features information about volcanic risks, earthquakes, tsunamis, and flooding areas, among other hazards. This tool also features information about the location of critical consumers (in particular, hospitals, prisons, and police stations), rural drinking water, telecommunication antennas, and so on, with information related to backup systems of generation and energy storage. Lately, the viewer also displays information regarding areas in the country that are locked down because of COVID-19.


VISOR DE INCENDIOS FORESTALES

Seleccione el Icono para Volver a Visor SIGGRE

Registro de Incendios Forestales

Nombre Incendio: 25 - CURAUMA
Comuna: Valparaíso
Superficie (ha): 0.01 ha
Fecha Inicio: 12-ago-2021 14:00
Fecha/Hora Actualización Información: 12/8/2021 2:00 p. m.

Mapa Principal

Infraestructura Lineal Próxima a Incendio Forestal (Radio 2 Km)

Tipo Infraestructura:
Nombre: AGUA SANTA - LAGUNA VERDE
Propiedad: CHILQUINTA

Tipo Infraestructura:
Nombre: BRASIL

Infraestructura Puntual Próxima a Incendio Forestal (Radio 2 Km)

Tipo Infraestructura: IE_SUBESTACION
Nombre: VALPARAISO
Propiedad:

figure 5. The situation awareness tool managed by the MoE is called *#EnergíaAlerta*.

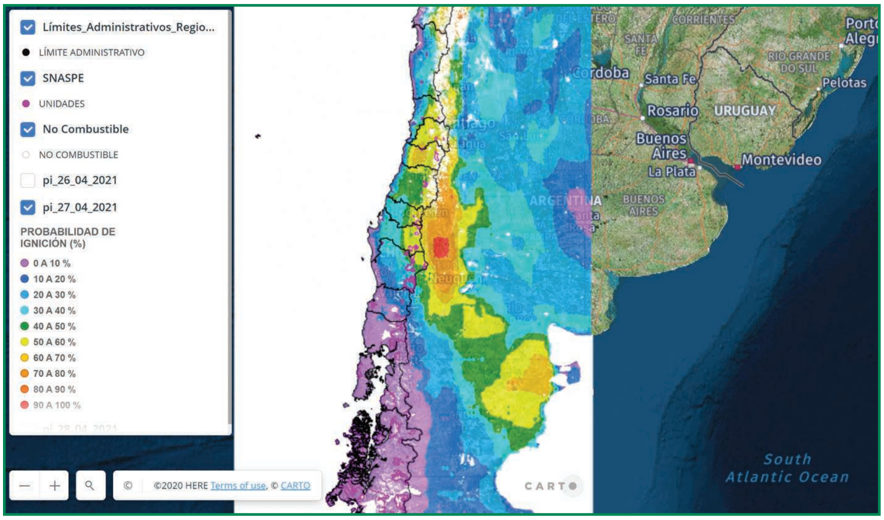


figure 6. Forest Fire Ignition Probability Map (27 April 2021). (Source: https://geprif.carto.com/; used with permission.)

New Security Standards for Transmission Network Planning

In 2021 May, new planning standards were issued by the MoE to expand and harden transmission networks. The regulating body (Reglamento de los Sistemas de Transmisión y de Planificación de la Transmisión) instructs the regulatory authority, the National Energy Commission, on new methodologies to plan transmission networks. One of the main innovations is to include resilience as a specific stage of the network planning problem. This regulation mentions explicitly that:

> … The National Energy Commission, in the Resilience Analysis stage, shall determine the transmission expansion projects that will provide security of supply to end-customers under high impact and low probability events such as increased costs or unavailability of fuels, delay or unavailability of energy infrastructure, natural disasters or extreme hydrological conditions …

Notably, and following the new planning process introduced in this regulation, the new Resilience Analysis stage complements the more classical Adequacy Analysis stage, Security and Quality of Supply Analysis stage, and Economic Analysis stage of the network planning process. According to the Chilean regulation, each stage can identify projects that enhance a given characteristic of transmission networks.

In this vein, the system operator has been developing new concepts to incorporate the risk of wildfires in future network reinforcement/expansion plans. Hence, the Forest Fire Ignition Probability Map (Figure 6), developed by the National Forestry Corporation, has been studied as a data source to identify areas of the transmission network exposed to wildfire risks. This probability is computed daily based on solar radiation, temperature, and dead fine-fuel moisture. Lately, there have been new methodologies emerging to plan system investments using these maps.

The Brazilian Experience

In Brazil, wildfires rank high among the most common causes of forced outages of overhead transmission lines (Figure 7). The figure indicates that adverse weather and wildfires stand out significantly from the other causes. Figure 8 shows the seasonal pattern of outages caused by these two events (where adverse weather causes are largely attributable to atmospheric discharges), comparing the aggregated number of events per month of the year and considering all outages in overhead transmission lines between 2012 and 2020.

Figure 8 also shows that wildfires correspond to the main causes of outages in certain months and seasons. The frequency of events since 2012 indicates a seasonal

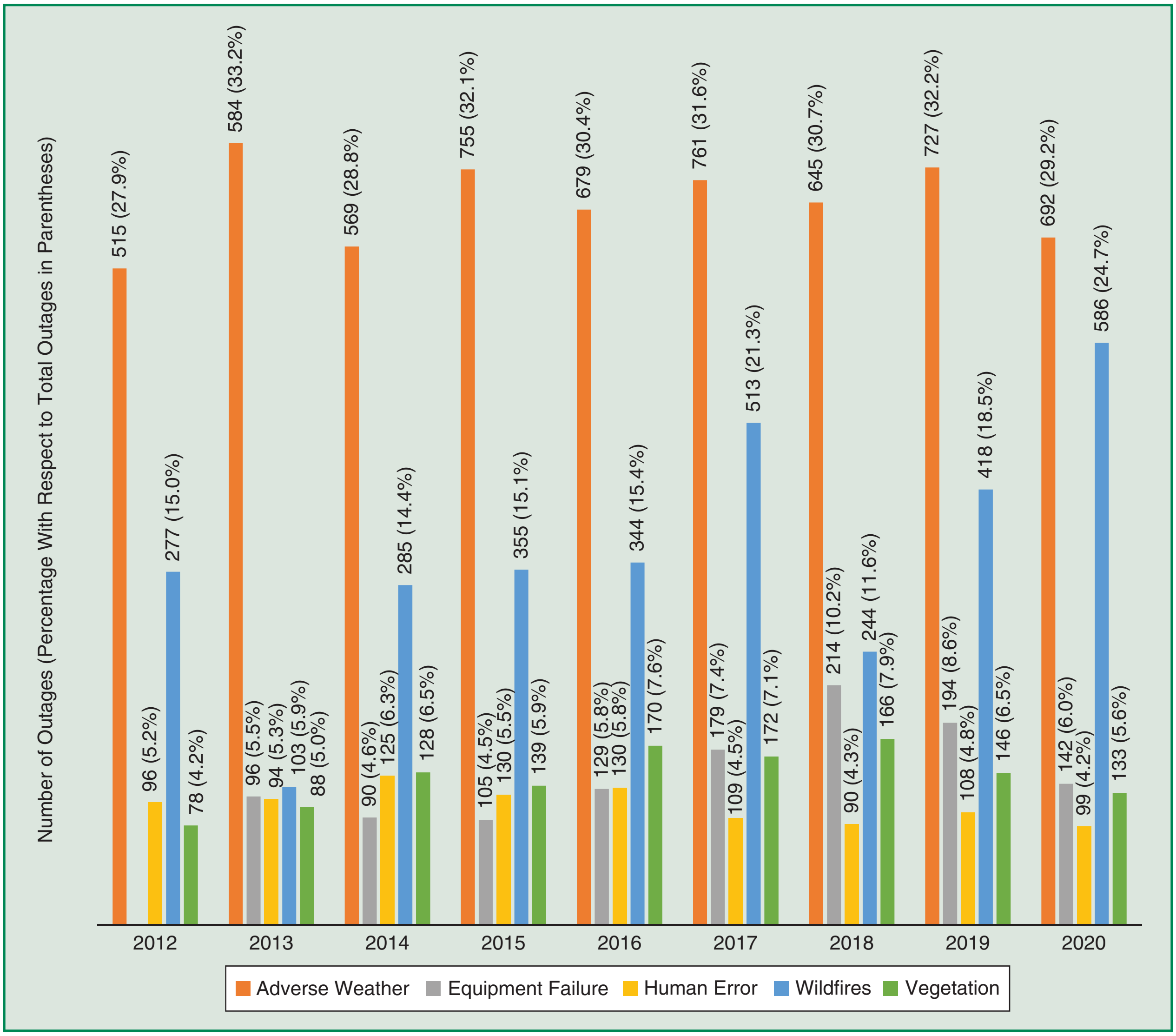


figure 7. The evolution of outages in transmission lines of the basic grid (voltages of 230 kV and above) per cause.

complementarity. While atmospheric discharges are more likely to occur in months of significant rainfall in the southeast (December–April), outages related to wildfires are concentrated in the dry season (May–November) in those regions that account for the largest part of the load in Brazil. Notably, the peak of outages due to wildfires tends to occur in September. This is consistent with the weather patterns. The stronger winds and scarce rain between July and November make several regions of Brazil, including those in the *cerrado* (a tropical savannah) and *caatinga* (xeric shrubland) biomes, more vulnerable to fire outbreaks. In the same vein, Figure 9 shows the dispersion of thermal hotspots (active fires captured by meteorological systems) in Brazil and Latin American countries for all months during 2020.

From the point of view of system operation, the dry season is typically defined by significant power flows from the northeastern and northern regions of Brazil to the southeast region, largely via overhead transmission lines that run through the *cerrado* and *caatinga* biomes. This is due to the typically lower output of hydropower plants (HPPs) in the southeast region and the higher outputs of the generation fleet in the north. Notably, the HPPs of this region are located in basins whose hydrological regime differs from those in the southeast. Also, the northeast region features significant participation of wind generation, whose output is higher in the drier months.

The seasonal combination of wildfires and relevant latitudinal flows, caused by typical availability patterns of renewable resources, presents a challenge for power system planning and operation in Brazil. However, the increasing frequency of outages caused by wildfires is not leading to a deterioration of the robustness index of the system (Figure 10). The robustness index is the ratio between outages that do not lead to load shedding and the total outages in a year. This is due to proper system expansion practices, which consider the reliability criterion $N-1$, which results in alternative flowpaths to be used when there is a circuit disconnection.

The network expansion also aims to increase the connectivity of different areas in the network to have redundant supply routes. For operation planning, the system operator uses limits to

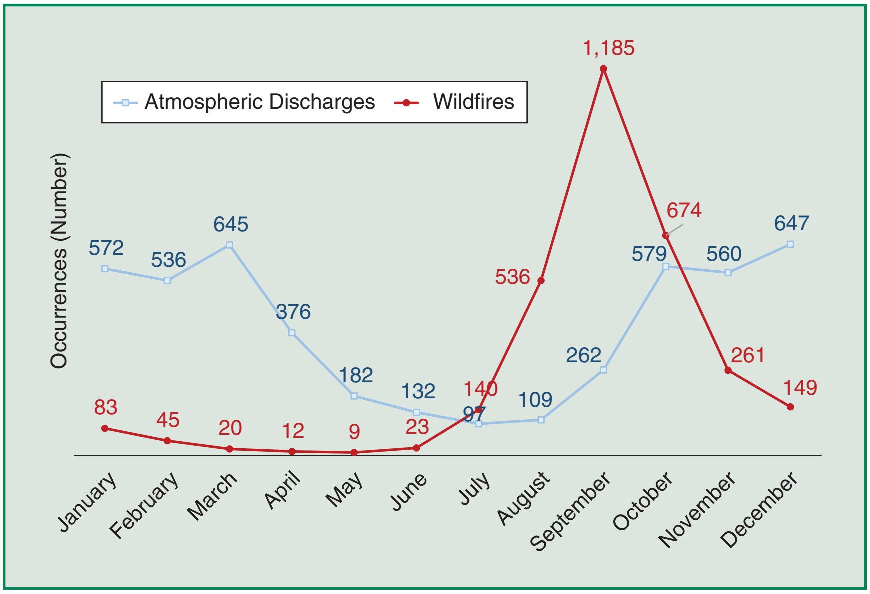


figure 8. The seasonal pattern of outages in the basic grid for outages caused by adverse weather and wildfires.

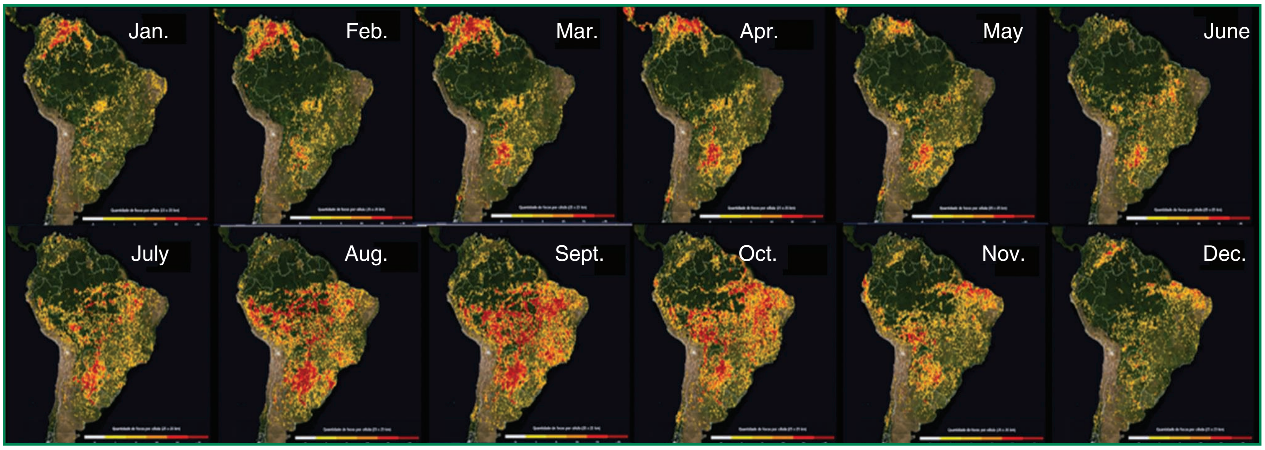


figure 9. Dispersion of thermal hotspots, 2020. (Source: Instituto de Pesquisa Econômica Aplicada; used with permission.)

restrict power exchanges between the north/northeast and the southeast systems in case there is a loss of any circuit. Exchange limits used for hydrothermal scheduling are frequently updated, and a real-time security assessment is used to update limits dynamically during real-time operations. The export capacity limits between the areas consider the $N - 1$ security criteria, and, importantly, this includes the preparation for possible wildfires along the path/route of the interconnections.

Relevant Events

Next, we enumerate a few relevant events that demonstrate the impact of wildfires on the Brazilian power system.

- ✔ In August 2020, wildfires in the state of Rio de Janeiro caused outages in four transmission lines of the concessionaire FURNAS. There were, nonetheless, no electricity supply interruptions to the final consumer.
- ✔ CTEEP, another transmission concessionaire, announced that it recorded approximately 133 wildfires in the neighborhood of its transmission lines from January to December 2020. This represented an increase of about 400% compared to the previous year. Among the cities more impacted were those in the interior of the state of São Paulo (Figure 11). Yet, CTEEP is one of the transmission utilities with the best asset availability levels in Brazil.
- ✔ In May 2019, wildfires affected the distribution lines in the Brazilian state of Mato Grosso do Sul. According to the local distribution utility, wildfires resulted in more than 160 h of supply interruption in 75 of the 77 municipalities in the state. Firefighters explained that the most frequent cause of fire outbreaks was inefficient vegetation management, including garbage and wood in hot, dry weather, and people who used fire to clear lands and pastures.
- ✔ The year 2017 featured a severe dry season in several regions of the country. On 10 September, there were 21 occurrences of transmission line outages due to wildfires, none of these leading to load shedding. The most critical outages affected the north–northeast intertie: the 500-kV transmission lines Imperatriz–Presidente Dutra C2, Imperatriz–Presidente Dutra C1, and Tucuruí–Marabá. The performance of the system without load shedding was only possible because the system operator took several preventive measures, such as reducing loading on the possibly affected transmission lines through redispatching of generating units.
- ✔ On 30 August 2016, an outage in a 500-kV transmission line in the Tocantins region (northern Brazil) caused frequency oscillations and deeply affected the supply of electricity in the north and northeast regions of the country. According to the system operator, the problem was caused by wildfires near the transmission line in question (Figure 12). Load shedding exceeded 3 GW and affected 13 states of Brazil, impacting 15 distribution companies and four deregulated large consumers. The system was entirely restored in approximately 2 h.
- ✔ On 28 August 2013, wildfires resulted in a blackout in Brazil with two successive transmission line outages. At the time of the outages, there was a substantial transfer of power from the southeast to the northeast

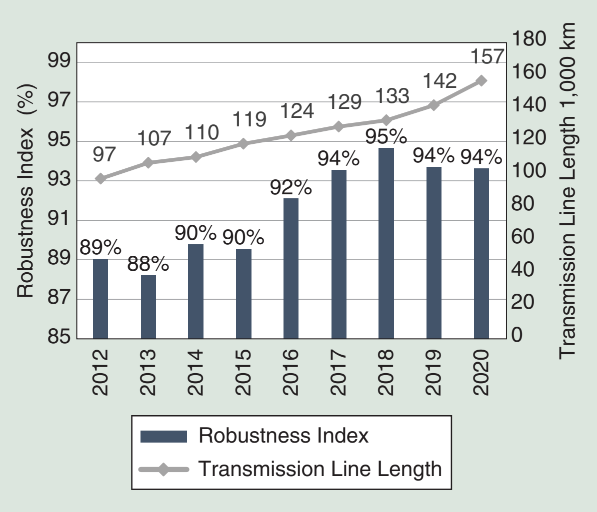


figure 10. The evolution of the robustness index of the Brazilian basic grid.


(a)

(b)

figure 11. (a) A wildfire under a transmission line in the Ribeirão Preto region (São Paulo state). (b) A fire near a transmission line in Bauru (São Paulo state). (Source: CTEEP; used with permission.)

region, and the outages of these two lines caused a loss of synchronism between the electrical subsystems in different regions of the National Interconnected System, leading to the separation of the northeast region from the rest of the system and interruption of about 11 GW of load.


(a)
(b)

figure 12. Wildfires close to the transmission line in Tocantins, (a) under and (b) near a transmission line. (Source: National Electric System Operator; used with permission.)

The sequence of events occurred as follows. At 2:58 p.m., one circuit of a 500-kV double-circuit transmission line was disconnected because of a wildfire. At 3:04 p.m., the circuit was manually reconnected, but there was a new outage for the same reason 2 min later. At 3:08 p.m., also because of a wildfire, the other circuit of the same 500-kV transmission line was disconnected, which led to the loss of synchronism and isolation of the northeast region from the rest of the National Interconnected System. In addition, other 500-kV lines connecting northeast and southeast Brazil were disconnected, resulting in load shedding in all nine states of the northeast region. Figure 13 illustrates the loss of synchronism among the electrical subsystems. Load restoration started at 3:35 p.m. and concluded at 7:15 p.m., resulting in a blackout of more than 4 h.

Prevention

Given the previous experience of Brazil dealing with wildfires affecting the power infrastructure, there is a series of regulations aimed to prevent wildfires. A significant part of wildfires near transmission lines originates from fires caused by human activity, such as farming-related activities, disposal of waste (cigarette stubs), and

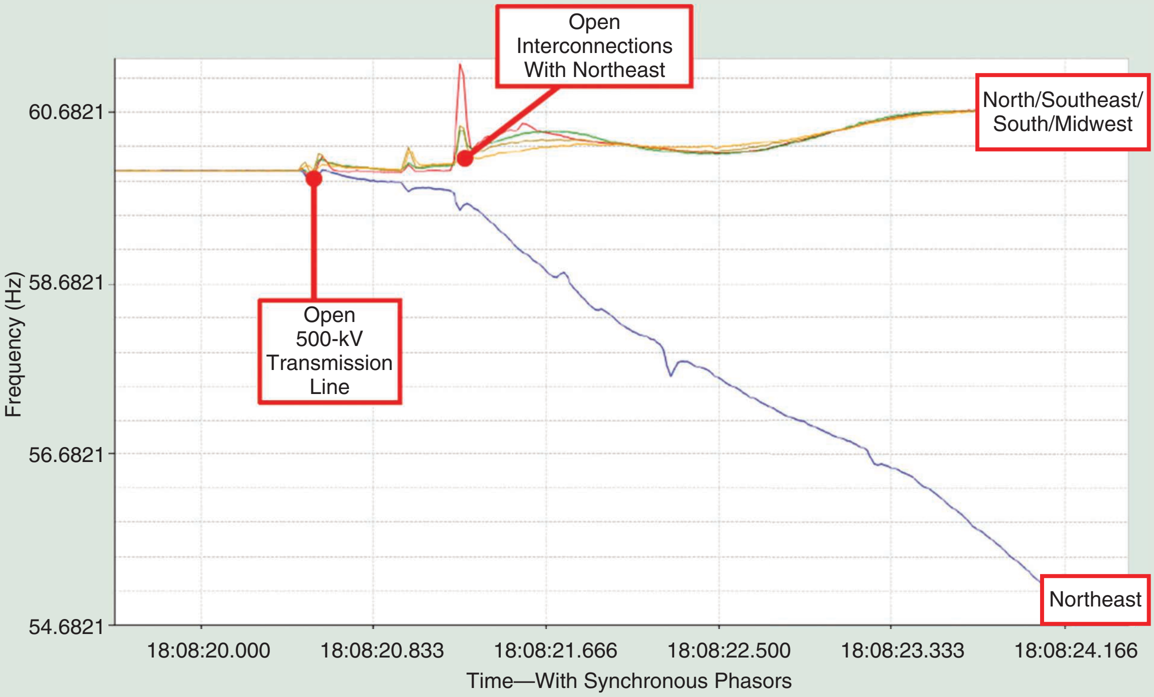


figure 13. The loss of synchronism among electrical subsystems. (Source: National Electric System Operator; used with permission.)

Given the previous experience of Brazil dealing with wildfires affecting the power infrastructure, there is a series of regulations aimed to prevent wildfires.

the use of small hot-air balloons (sky lanterns) in festivities. Lighting fires in the neighborhood of transmission facilities—within 15 m of the right of way of transmission lines and 100 m of substations—is a crime punishable by Brazilian law. However, the extension and remoteness of the transmission system is a hurdle for strictly monitoring and enforcing this rule.

To cope with the problem of wildfires, many Brazilian transmission concessionaires carry out public information campaigns to prevent dangerous practices involving fire lighting. Some of these campaigns target rural populations, particularly landowners. These are naturally combined with other measures, such as the periodic cleaning of rights of way and the mobilization of telephone lines to allow the population to report fires readily.

In 2015, ANEEL, the Brazilian Electricity Regulatory Agency, issued a regulation obliging transmission companies to perform annual clearing and vegetation control in the rights of way of transmission lines. Since 2017, ANEEL has monitored and managed the vegetation control for transmission assets that are part of large interties within Brazil, inspecting the rights of way until 31 May, and if necessary, issuing commands obliging the concessionaires to clear vegetation until 31 July. These dates are defined taking the seasonal pattern of wildfires into account. In October 2018, ANEEL also started a communication campaign to raise awareness about the risks of fires close to the transmission assets. This campaign targeted the east and southeast/midwest populations living in agricultural areas in the *cerrado* biome, which account for a large part of the outages due to wildfires.

Mitigation Through Operational Measures: The Case of Amapá

A recently forced outage drastically affected the electricity supply to the state of Amapá in northern Brazil. The event was not caused by wildfires but rather by the islanding of the state's power system due to the unavailability of substation equipment, including the explosion of one of the transformers, which led to a large fire. The event represents an interesting case study of the actions taken by the system operator in critical situations caused by forced outages over a long period. In terms of the postcontingency actions described next, this event will not differ significantly from one caused by a wildfire damaging substation equipment or the transmission lines that supply the substation.

On 3 November 2020, the event began with a disturbance in the Amapá supply system via a double contingency (N-2). Two 230/69-kV transformers of the Macapá substation became unavailable (Macapá is the name of the substation as well as the capital city of Amapá). This ultimately led to the shutdown of the embedded HPP Coaracy Nunes due to frequency instability. This plant is connected to the 230-kV grid within Amapá. Hence, the Macapá substation became entirely unavailable, resulting in the interruption of supply to the entire downstream system, including the state capital city.

In coordination with the local distribution utility, the system operator made important mitigating decisions to partially restore service as quickly as possible. These included 1) partial service restoration via existing generation resources in the local system, including the Coaracy Nunes HPP; 2) contracting of emergency thermal plants; and 3) rolling blackouts. Note that these actions require an important coordination effort in the interface between the transmission and distribution networks, i.e., transmission system operator–distribution network operator coordination, to orchestrate and sort various delicate measures to reconnect infrastructure and restore supply.

Restoration via Local Generation

The restoration process took place gradually with the utilization of local generation. The graduality aimed to avoid frequency or voltage oscillations in the area to be restored, which could cause more disturbances and the tripping of equipment already synchronized. Unfortunately, the initial attempts to restore supply to the Amapá system, from 3 to 7 November, were not successful. The first attempt to reestablish the supply of the Macapá area was initiated through the Coaracy Nunes HPP. It started with the black start of a single generating unit, but because of underfrequency problems, the process was not successful. Finally, on 11 November, the supply was partially restored to about 25% of the local load.

Reconnection of the Islanded System to the Main System

Other efforts took place in parallel to the restoration with local generators. On 7 November, a transformer was brought from another substation to the Macapá substation. Its capacity was 150 MVA, the same as that of the damaged transformers. This allowed restoration of the supply to about 60–70% of Amapá's demand.

Rolling Blackouts

Until full restoration, rolling blackouts were implemented. The Companhia de Eletricidade do Amapá, the local distribution utility, determined the schedule of the rotation. The rolling blackouts were initiated on 8 November.

Contracting Emergency Thermal Plants

To increase the availability of local generation, thermal plants were contracted on an emergency and temporary basis. The plants were connected to the local distribution network. The costs of this emergency solution were socialized among all electricity consumers in Brazil via an off-market payment called *system service charges*. The costs were monitored and audited by the regulator.

Policy Lessons

Brazilian institutions have adjusted their planning, operation, and monitoring practices in response to recent events regarding wildfires. Next, we focus on 1) procedures to inspect transmission companies and monitor the impacts of long-term outages and 2) methodological adjustments in system planning and line routing.

Monitoring and Inspection

Because of the outages caused by wildfires, ANEEL started to act in an increasingly preventive manner. It reinforced its work with transmission companies to diligently carry out the cleaning and vegetation-control programs for rights of way, mitigating the risk of fires, and, consequently, transmission line outages. In this context, in 2017, a set of prioritized transmission lines was selected to be monitored with greater intensity as they are responsible for the largest exchanges of power flows among the north, northeast, and midwest regions. These lines are also more susceptible to disconnections due to wildfires.

The Electric System Monitoring Committee adjusted its procedures by monitoring indicators of the severity of transmission system outages leading to supply interruptions. The system operator was also invited to regularly present to the committee a list of the countermeasures identified in postdisturbance analyses that were implemented to improve reliability. As this is a high-level committee with the managers of the main power sectors institutions, this facilitates communication at the managerial level and the engagement of resources of the institutions in a coordinated way.

Power System Planning

Still related to wildfires, the Brazilian Energy Planning Agency (EPE) is studying the possibility of adjusting methodologies to define the routes of transmission lines to reduce exposure to outages caused by lightning and by wildfires. The EPE is also considering the exposure to risks of outages caused by lightning and wildfires in the evaluation of 1) the tradeoffs among single-circuit, double-circuit, and two-single-circuit arrangements for overhead transmission lines and 2) spacing between circuits in the same right of way. The EPE currently recommends that, for areas exposed to significant risks of wildfire outbreaks, two single circuits should be considered with a distance between them of at least 200 m. The EPE highlighted that this recommendation was based partially on the assessment of the historical performance of the Brazilian transmission system.

The tradeoff among single-circuit, double-circuit, and two-single-circuit arrangements naturally goes beyond the exposure to outages caused by lightning and wildfires. It also concerns 1) the impacts on reliability and resilience of outages with a wider range of causes and 2) socioenvironmental awareness in the regions where the transmission asset will be installed.

The planning agency and the system operator also carried out a joint assessment of reliability criteria for remote, large load centers supplied by radial transmission systems, such as the system of Macapá. A possibility considered is that of a different—and stricter—planning criterion for these centers. For the specific case of Macapá, a recent planning study specified that reliability should be increased by implementing an additional connection with the rest of the bulk transmission system, including a new substation at 230 kV.

Final Remarks

This article presents two case studies, based on Chile and Brazil, demonstrating the severe impacts of wildfires on power systems. Along with the physical impacts on network infrastructure, we also described a set of prevention, mitigation, and adaptation measures aimed to hedge the risks of wildfires in several timescales. We focused on the impacts on network infrastructure and the responses from network operators, planners, regulators, and policy makers.

Apart from the typical practices that go beyond power systems to prevent wildfires (e.g., vegetation control), particular measures can be carried out within power systems that can be of particular interest to network operators, planners, regulators, and policy makers. These are:

- ✔ *Situation awareness and forecast tools*: Appropriate anticipation and risk assessments are key to operating power systems facing wildfire outbreaks. Chilean authorities have used a Forest Fire Ignition Probability Map to anticipate fire ignitions, but other metrics can be used, such as the Keetch–Byram drought index, the Fire Potential Index, and the Large Fire Probability. These metrics have been widely used in the United States. Apart from forecasting ignitions, it is extremely relevant to forecast the trajectories of wildfires after the outbreak occurs and the probability of such outbreaks reaching power infrastructure.
- ✔ *Preventive and corrective control in system operation*: The previous information regarding situational

awareness and risk assessment can be used to determine, in a dynamic fashion, a set of preventive and corrective measures, such as

- ✔ line disconnections and de-energization
- ✔ network topology control
- ✔ power transfer reductions
- ✔ redispatch of generating and energy storage units using various types of generation reserves to minimize the loss of supply in critical areas
- ✔ deployment of mobile units (backup generation, energy storage, transformers, and so on) if supply in a particular area does not suffice
- ✔ exercise of demand curtailment and response in various forms, including rolling blackouts
- ✔ transmission system operator–distribution network operator coordination, optimally operating DERs downstream (including topology control of distribution networks) in a coordinated fashion with the preventive measures undertaken in the main grid
- ✔ organizing repairing crews across network companies, sharing human resources and equipment.

Importantly, this complex set of decisions can be made through emerging optimization tools:

- ✔ *Adapting system infrastructure in the long term*: This includes hardening measures (such as splitting double circuits, undergrounding lines, covering bare conductors, and hardening, anchoring, and increasing the number of poles/towers), network expansions to increase redundancy and connectivity (having multiple and optimal routes to supply/connect key points of the system), and deployment of DERs and microgrids that can be, in several cases, more cost-effective and resilient than enhancing the main grid. In the case of network enhancements, these can be carried out through new security/planning standards like those in Chile and Brazil.
- ✔ *Stakeholder engagement*: Companies, network operators, and regulators work together in critical activities, such as vegetation control and management, identification of critical assets, and implementation of a set of prevention, mitigation, and adaptation measures to protect power systems. The Electric System Monitoring Committee in Brazil is an exemplary case.

In the context of climate change that suggests that wildfires and other natural disasters will become more intense and frequent, a broader resilience framework will be needed to operate and plan system infrastructure and thus hedge against an array of natural hazards. This resilience framework can take advantage of the future digitalization of the energy systems, opening up opportunities to use new nonwires technologies, information and communication technologies, distributed control, microgrids, and the electrification of other energy vectors (using distributed energy storage devices) to maximize the chances to ride through and keep the lights on during high-impact events.

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For Further Reading

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