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# Regulatory Considerations for Resilient Power Networks against Wildfires

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**SUMMARY**

In January 2017, large geographical regions of Chile were significantly exposed to an array of extreme wildfire events that devastated more than 500 thousand hectares, destroying public and private infrastructure. Such extreme wildfires have never been experienced before in Chile. As a result, the critical electricity transmission system infrastructure of Chile has been significantly affected, suffering severe damage in transmission assets leading to prolonged outages, which left customers without electricity supply for extended periods. Transmission systems have been traditionally designed and operated under reliability criteria, which establish network planning and operation standards to withstand normal or expected abnormal conditions. However, the resilience of transmission systems against high impact low probability events, such as extreme wildfires, has not been adequately considered and captured in regulatory frameworks. Additionally, the frequency and severity of wildfires may increase in the future as a direct impact of climate change (e.g., increased temperatures and prolonged drought periods). In this context, it is essential to have an adequate regulatory framework that enables the consideration and planning against wildfires to both minimise their impact and improve the system response to wildfires. Driven by the 2017 wildfire in Chile, this paper first critically reviews the applicability of the concept of resilience on wildfires and discusses potential mitigation measures that can be taken against wildfires. It then provides an overview of the 2017 wildfire in Chile, along with an advanced spatio-temporal assessment tool for reflecting and quantifying the impacts of wildfires. The current Chilean regulatory transmission planning framework is then reviewed and potential recommendations are finally provided to enable the systematic enhancement of the Chilean transmission system against wildfires, contributing to the social and economic well-being of the country.

**KEYWORDS**

Wildfires - Bushfire - Natural Hazard - Resilience - Reliability - Transmission Planning - Regulatory Framework.

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## 1. Introduction

In recent years, a series of catastrophic wildfire have devastated millions of hectares worldwide, causing significant environmental damage, as well as economic and human losses [1], [2]. The exposure of countries and critical infrastructures around the world to such catastrophic wildfires may get significantly worse, taking into consideration the direct impacts of climate change that generate favourable conditions for the ignition and rapid development of extreme wildfire event occurrence [3]. Extreme wildfire events can reach rapid speed of spreading (more than 3 km/h), intensities over 10,000 kW/m, and have chaotic and unforeseeable spreading over large geographical areas [3]. These characteristics make extreme wildfires extremely difficult to predict, control and mitigate. Unlike other natural disasters, wildfires may last long periods (i.e. several days or even months), devastating enormous geographical zones due to their rapid spread, resulting in a prolonged threat to the power system affected. A very recent example is the bushfires that lasted for several months in Australia in 2019-2020, leaving behind disastrous consequences on critical infrastructures and human lives.

Unfortunately, Chile is another country that suffers greatly and frequently from catastrophic wildfires. During the summer of 2017, the country witnessed the largest wildfires recorded in recent years in the country. This extreme event, denominated as the “firestorm”, devastated more than 500 thousand hectares (ha) along seven regions of Chile, destroying both rural and urban areas, and burning 2,383 houses [4]. Outages caused by the firestorm, left several customers for extended period without energy supply. Such intense and catastrophic wildfires have also devastated the Municipality of Pedrógão Grande in Portugal in June 2017, burning 45,328 ha and causing 65 deaths [3]; Attica in Greece in July 2018, killing about 100 people [1]; and, California in the United States during fire season 2017-2018, destroying 1.2 million ha, and causing 151 deaths [5].

The enormous impacts of wildfires on power systems makes it urgent to improve the resilience against these natural disasters. Transmission systems play a crucial role in the resilience response of power systems. This crucial role has been recently recognized by the Chilean authority, who has incorporated the concept of resilience in the new regulatory framework for transmission networks. In fact, this new regulation has incorporated the *minimisation of electricity supply risk due to natural disasters* as one of the criteria to determine new network investments [6]. Thus, resilience against natural disasters became an important part of the transmission planning process, driving a critical and radical change in the traditional power network planning standards. Yet, tools and models usually utilized by network planners do not incorporate resilience as an explicit objective or criteria. Building on this new paradigm and recognizing the growing need for providing a hedge against the catastrophic impacts of wildfires, this paper aims to provide insights and suggestions to be included in the transmission planning process that allows improving the resilience of electrical sector against wildfires, contributing both to the security of supply and the social and economic well-being of a country exposed to such catastrophic events.

This paper is structured as follows. Section 2 presents a conceptual framework for the resilience response against wildfires. Section 3 studies effects of the firestorm in the power system of Concepción. Section 4 analyses the regulatory framework for transmission planning. Section 5 proposes modifications to the regulatory framework. Finally, Section 6 presents conclusions.

## 2. Resilience response against wildfires

### 2.1. Definition of resilience

The CIGRE Working Group C4.47 “Power System Resilience” has recently defined the resilience of power systems as "the ability to limit the extent, severity and duration of system degradation following an extreme event” [7]. According to this definition, for achieving resilience it is necessary to take the measures of "*anticipation, preparation, absorption, sustainment of critical system operations, rapid recovery; and adaptation, including the application of lessons learnt”.*

## 2.2. Resilience performance against wildfires

The resilience performance of power systems can be analysed as a time dependent function as proposed in [8], where the authors introduce a quantification framework called the resilience trapezoid (Figure 1). This framework describes the evolution of the event in the following five states: Pre-disturbance resilience state, disturbance progress, post-disturbance degraded state, post-disturbance degraded state, and restorative state. This quantification framework set a five time-dependent metrics that measure the performance system through the disturbance progress (Phase I), post-disturbance degraded state (Phase II), and restorative state (Phase III). Along with the resilience levels, Figure 1 also shows the time sequence of the event and the restoration process (in green) together with the type of actions to be carried out to minimise the impacts of the hazard on power supply (in red). Here, various mitigation and adaptation measures in the form of preventive and corrective actions can be undertaken to reduce demand curtailments due to hazards.

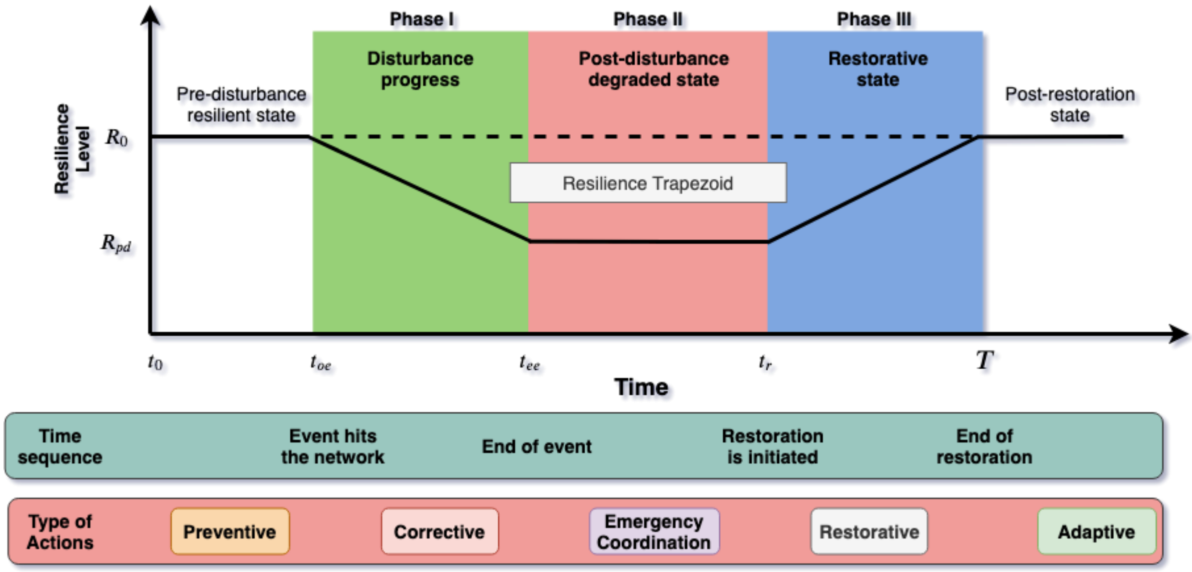


*Figure 1. Resilience trapezoid.*

In the particular case of wildfires, these can affect transmission systems by excessive heat transfer and/or smoke. In the former case, the tensile strength can be affected, producing an excessive conductor sag. Also, in the most extreme cases, infrastructure can be burnt. In the latter case, ashes and particular matter transferred by smoke reduces insulation capacity, producing flashovers between conductors or between conductors and towers [9]. Additionally, the extended duration of wildfires may leave power systems in Phase II for a significant time. Next, we discuss some exemplary actions that can be taken before and during the occurrence of a wildfire.

a) Pre-disturbance actions: the rapid spread propagation that extreme wildfires can reach in a short-time makes critical to carry out measures such as:

   i. Preventive measures: these are crucial for providing the first protection mechanisms to the power system assets. There are operational measures that need a short time to be implemented, such as disconnecting facilities preventively to minimize the risk of generating a new wildfire under adverse weather conditions. This measure has been already applied by the Pacific Gas and Electric Company (PG&E) in the state of California [10]. However, its application is still controversial due to the possible large effects on customers [11]. Additionally, there are other measures such as building compartmentation for critical infrastructure such as substations; and establishing a fire safety distance between the vegetation and power system facilities in order to protect facilities from heat radiation and minimise the risk of wildfires reaching critical facilities. These measures are considered long-term planning.

ii. Detection measures: These focus on early detection of wildfire. The technology selected depends on the area and/or facility supervised. For instance, transmission systems can be equipped with distributed temperature sensors and optical or visual flame detection technology to monitor the forest surrounding the transmission infrastructure. This technology is being applied currently by the company PG&I in California [12].

b) Disturbance progress: there are early suppression measures taken to combat the wildfire itself and operational measures taken to minimise wildfire impacts on power systems.

i. Coordinated suppression measures: Performing coordinated actions between different sectors is essential for ensuring effective firefighting, especially when wildfires are in the vicinity to transmission lines and may represent a high risk for firefighter safety. In this case, it is recommendable to disconnect transmission lines in order to avoid damage to firefighter. In this context, it is advisable to establish coordination protocols among institutions from different sectors. Currently, in Chile there is a protocol in place to carry out coordinated actions among the Ministry of Energy, the electrical companies and the National Forest Corporation of Chile (Corporación Nacional Forestal, CONAF is the Spanish acronym) [13]. This protocol is established to avoid conflicting actions and take advantage of potential synergistic ones that can be carried out by several participants in a coordinated fashion.

ii. Forecast wildfires tools: another key measure for improving the early system response against wildfires consists in predicting wildfires trajectories. This serves, for instance, to improve operational measures. In effect, an accurate propagation prediction model of the fire evolution allows optimizing the coordination and allocation of resources, as well as identifying which the most vulnerable point in the power system are. Propagation prediction models have been explored in [14] and [15].

iii. Operational measures: re-dispatching as a response to wildfire evolution and forecasts in order to maintain security of supply levels in case that transmission lines are (or may be) affected by wildfires. That way, the power system is prepared to face transmission line outages, minimizing the impact on the electricity supply due to potential outages. Another operational measure consist in disabling automatic recloser when wildfires approach transmission lines. This measure may be taken because some failures may occur if conductors are touching burning material when automatic reclosers operate [11]. Finally, another measure explored in [16] is using distributed generation to minimize the energy not supplied during and after the event.

c) Post-disturbance degraded state: in this state, transmission companies plan the strategy to start restoration of the damaged infrastructure and the reconnection of customers. Environmental conditions could affect the time that the system remains in this state due to smoke or wildfires that surround facilities.

d) Restoration state: Transmission companies verify that facilities do not present damage and environmental conditions are adequate to reconnect those facilities; and communicate this information to the National Independent System Operator. In some situations, it is necessary to carry out additional activities such as washing and cleaning conductors and insulators in order to avoid futures outages due to residues.

e) Post-restoration state: in this state, adaptation measures such as new investments can be studied. In addition, analysis of the current maintenance and operational practices could be carried out in order to identify possible improvements.

### 2.3. Metrics

As resilience is a multifaceted concept, defining metrics for it is not an easy task [17]. Furthermore, currently there is no consensus in the power system community regarding the appropriate set of metrics to measure system resilience. In [18], authors propose a unique time dependent metric system called the resilience triangle. In the same line, reference [8] proposes a more comprehensive set of five time-dependent metrics called the resilience trapezoid (previously introduces in Figure 1). In [19], authors propose the Energy Not Supply (ENS) as metric. In [20], the "conditional expectation" of the ENS (CEENS) under high impact low probability scenarios is proposed. In a similar vein, reference [21] has also proposed the use of risk metrics such as the conditional value at risk (CVaR) to improve and optimize decisions incorporating resilience as a decision-making criterion.

## 3. The 2017 Firestorm in Chile.

### 3.1. Context

In Chile, the frequency and intensity of wildfires have increased significantly in the last years [22]. In fact, the area burnt during the fire seasons 2013-2014 and 2014-2015 exceeded twice the historical average registered since the mid of 70s of 54,000ha/year. Moreover, the area burnt during the fire season 2016-2017 exceeded in more than ten times the historical average [22]. The extension of fire seasons also had a notably increase, having the period 2010-2018 64 days more than period 1985-2009 [22].

The 2017 firestorm devastated parts of seven regions of Chile, registering 681 wildfires, 120 of those were occurring simultaneously on January 26$^{th}$. The most affected regions by this extreme wildfire event were Libertador General Bernardo O'Higgins, Maule, and Bio-Bío, where 417 wildfires razed around 467 thousand hectares [23]. Wildfires reached an intensity of 60,000 kW/m, and a maximum speed above 6 km/h, starting the "sixth-generation" wildfires [23]. The classification according to "generations" was initially proposed by [24] in 2009. In this research, the authors classify wildfires according to the decade when wildfires occurred and resources available to deal with them, differentiating five generations until that moment. Hence, the first generation was developed between the fifties and sixties, including wildfires that burnt between 1,000 ha and 5,000 ha. The fifth generation started in 2000, involving several simultaneous ignition points and affecting urban areas.

The city of Concepción, located in Bio-Bío's Region, was analysed in detailed due to its relevance and the number of fires occurred (around 353). Figure 2 illustrates the topology of the transmission system around Concepción and the active wildfires on January 26$^{th}$ at 14:52 hrs [25]. As shown by Figure 2, Concepción is connected to the SEN (Sistema Electrico Nacional in Spanish) in Charrúa substation through three main transmission corridors. One of these corridors also connects Santa María power plant to the SEN. Importantly, although this power plant is located in Concepción, it is not connected to the city network. Evidently, this plays a major role in the levels of resilience of the electricity supply in Concepción.

### 3.2. Spatio-temporal system response analysis

A spatio-temporal, stochastic impact assessment tool has been developed at the University of Chile, aiming to replicate the performance and response of the Chilean transmission network to the 2017 wildfires. In the assessment tool, the ENS was modelled by replicating failures occurred in the transmission lines shown in Figure 2. Furthermore, the system operation of that day was replicated considering the unavailability of the largest generators in the area due to its previous failures. Finally, the dynamics of the restoration process was also modelled by calculating reconnections of loads throughout time.

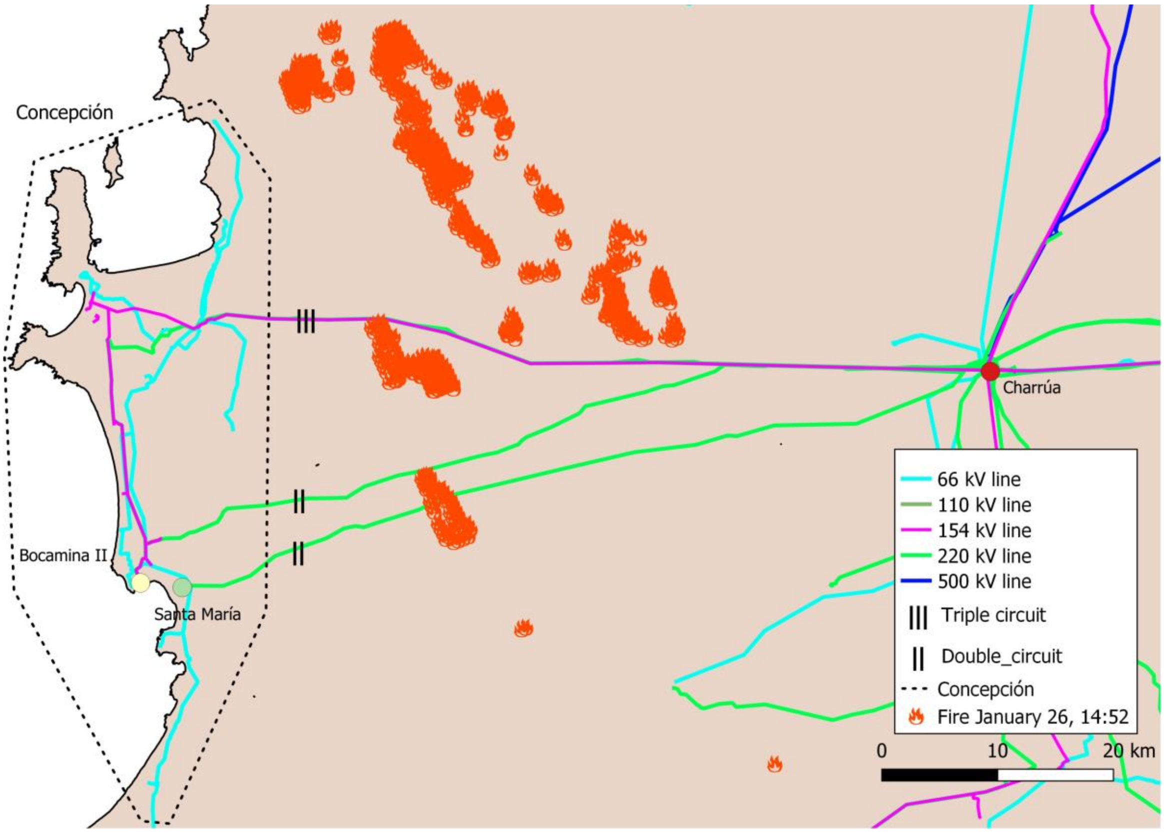


Figure 2: Electricity network and active wildfires around Concepción on 26 January at 14:52.

With the abovementioned mathematical model, we determine the ENS in the period between January 23rd and January 29th 2017. For this purpose, three demand levels were studied: the actual or "real" demand (that corresponds to the aggregated, actual consumption of Concepcion while the fire unfolded), the base case (that corresponds to an hypothetical case, assuming that the fire did not occur, which was determined through interpolations) and the simulated demand (that shows the results of our simulation). These three demand profiles are shown in Figure 3. At a glance, Figure 3 shows that the assessment tool developed at the University of Chile is capable of reflecting the real system behaviour during and after the 2017 wildfire in Chile. According to analysis carried out, the firestorm had the most significant impact on January 26th, resulting in a drop of power equal to 200 MW right after the fire affected the power network (see Figure 3).

The significant impact of the firestorm on Concepción electricity supply can be explained due to the simultaneous line failures due to multiple fires, the lack of alternative routes to connect Concepción and the SEN, and the failure of local generation within the affected area. The geographical proximity of the various transmission lines that supply Concepción originated simultaneous outages in the transmission network. Additionally, at the time when the wildfires hit transmission lines, one of the main power plants (Bocamina II) in the area of Concepcion was outaged, leaving the system more vulnerable. This particular situation suggests that appropriate risk assessment should consider both faults due to exogenous and endogenous events. Also, although a major power plant (Santa María) is located within the city, this is not directly connected to it, which plays an important role in the lack of resilience in the electricity supply of the city. This highlights the need to identify and assess adaptation measures that can be implemented in a straightforward fashion.

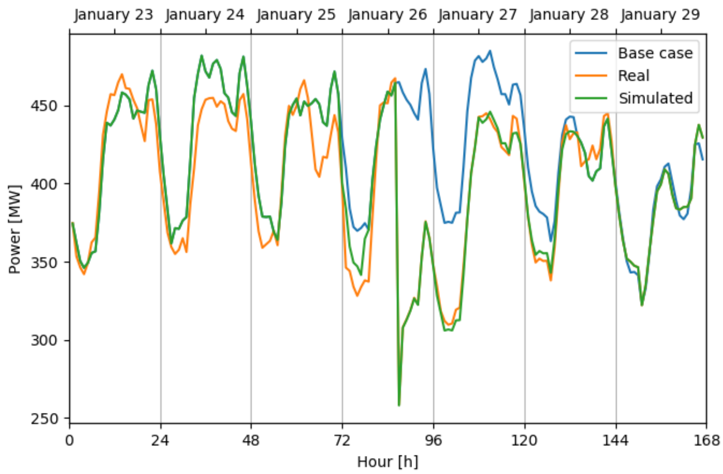


Figure 3 : Simulation of ENS in 2017 wildfire, Chile

## 4. Resilience in the new regulatory framework for transmission networks in Chile

In 2016, the Chilean Electrical Law (Law) established a new regulatory framework for transmission systems [6]. Under this new regulatory framework, it was defined that the ISO's first priority should be to preserve the security of supply, displacing the economic operation of the Chilean power system to a second place.

Considering the critical role of transmission networks in the economic and security performance of the entire power system, the Law established that the National Energy Commission (Comisión Nacional de Energía, CNE is the Spanish acronym) must carry out the annual transmission planning process in a centralised fashion. Remarkably, one of the new features of the recently published regulatory arrangements dictates that supply risks due to the occurrence of unexpected events such as natural disasters must be minimised within the transmission planning process. Hence, albeit implicitly, the new framework refers to the concept of resilience by clearly indicating that a hedge against natural disasters must be incorporated as a criterion to ensure security and quality of supply.

The details regarding the implementation of the abovementioned criterion within the transmission planning process have been established in another, subsequent normative body, elaborated by the CNE in 2017 [26]. Following the fundamental concepts contained in the legal modification made in 2016, the CNE explicitly incorporated the concept of resilience as a criterion in the transmission expansion process in the following normative body. For practicality, thought, the normative body limits the assessment to a few disasters and shocks, namely, tsunamis, fuel price spikes, deferrals in the commissioning of hydropower plants, and extreme hydrological conditions and inflows for hydropower (i.e., droughts). Hence, in the first version of the abovementioned normative body, wildfires are not considered.

One particular characteristic of the planning process established in the normative body is that it proposes a sequential, two-part methodology to identify new network investments. The first process is aimed to identify investments to provide security of supply, meaning compliance with the N-1 criterion (among other security criteria). The second process focuses on resilience, providing a hedge against a number of potential exogenous, catastrophic events that may occur.

Another important aspect introduced by the new Law in 2016 is the consideration of control, information and communication (ICT) technologies to defer asset-heavy network investments. This modification is critical for opening up opportunities to new non-wires, smart grid technologies in the provision of security of supply and resilience. Indeed, this approach has the potential to unlock innovative solutions based on advanced special protection schemes, microgrids, storage and demand response, among others, to provide security of supply and resilience at the transmission level, in a similar way as that indicated in [27].

## 5. Recommendations to improve resilience against wildfires

In the context of the new regulatory framework for transmission networks in Chile and in light of the latest experiences with devastating wildfires, we recommend the following measures:

- Differentiate hazards by zone: Currently, there is a single list of natural hazards at a national level against which transmission plans have to remain resilient. However, given the diversity of natural hazards that may occur along the country, we recommend adapting the list by zone. Certainly, there are areas with higher exposure to wildfire risk due to weather conditions such as temperature, humidity and wind speed. For this purpose, risk maps elaborated by CONAF [28], indicating zones with a higher probability of ignition, can be utilised.
- Plan not only investments but also operational measures to be resilient against wildfires: Resiliency against natural hazards has been mainly discussed in Chile in the context of investment planning and addressing other natural hazards such as tsunamis and extreme droughts. Despite this, there is a body of work that has already investigated the impacts on planning decisions of other hazards such as earthquakes [20]. Expanding on this, there are opportunities to increase resiliency levels, particularly against wildfires, by improving operational measures too, taking advantage of the current infrastructure. This will require a more optimal use and dispatch of current resources, including distributed energy resources, repair crews, line switching (i.e. topology configuration) at both transmission and distribution levels and the utilization of potential microgrids that can be formed at lower voltage levels [16]. Although this may require new investments in monitoring, communication, control and protection systems, we anticipate that a number of these investments are marginal in comparison with the installation of primary network assets such as new lines and transformers. In this vein, it is also advisable that network owners, in coordination with other institutions out of the power sector, evaluate new sensing and monitoring technologies for an early detection of wildfires.
- Use of advanced mathematical tools in network planning and operations: As improving the resilience performance of the power system depends primarily on appropriate risk assessment, quantitative analyses will be needed to identify and justify optimal decisions in planning and operation [20] . Such mathematical tools should solve the problem of network investment in a multi-objective fashion considering that new network investment must comply with economic, reliability and resilience criteria. This problem should identify, in one optimization problem, the optimal portfolio of network investments. This differs from the current sequential process used today by the Chilean authority, in which different criteria are used, sequentially, to identify different portfolio of network investments that comply with each criterion at the time.

  Remarkably, as wildfires are a slower phenomenon that allows operators to respond while the catastrophic event unfolds, forecast tools will be necessary to predict potential areas of the power network affected and hence respond in real-time.
- Increase coordination among institutions within and beyond power systems: Clearly, the occurrence of severe wildfire events affects multiple parties within and beyond the power sector. In this context, there are a number of institutions whose interactions, responsibilities and hierarchies are unclear, even within the power sector, among them: the ISO (i.e. transmission system operator), other transmission and distribution network operators and companies, generators, institutions in the forestry sector, firefighters, policemen and array of

regulatory and governmental authorities. In this vein, synergies and conflicts will need to be properly addressed. For instance, we may need to consider the support from distribution systems to the main transmission system [27], conflicts between ISO instructions and companies' policies regarding operation and safety of their facilities and personnel, and conflicts between instructions by firefighters and policemen and the energy sector.

- Charge according to beneficiaries-pay: Network charges used to remunerate network investments should be, ideally, cost reflective[29] . In this context, the advanced mathematical models used to determine resilient investments (and described above) can also be used to identify those who benefit from the new investments. Hence, resilient investments can be remunerated via network charges to those who perceive an improvement in the resilience performance of their supply. An appropriate charging scheme is key to unlock future investments to make the power system more resilience. In other words, if new network investments are charged inappropriately, there may be a risk of opposition to new investments since who pays for new assets does not perceive the benefits from them.

## 6. Conclusions

Due to the catastrophic impacts of extreme weather events and natural hazards on critical infrastructures, including power systems, and in turn on the economic and social well-being and growth of modern societies, it is becoming increasingly important to explicitly consider the resilience of electrical power systems against such events in the network planning and operation standards. This has been widely recognized by regulatory, policy and decision-making bodies around the world. However, in contrast to other extreme weather events and natural hazards, such as windstorms, floods and earthquakes, it is still not clear among the decision-making bodies how to enhance the resilience of power systems against wildfires, mainly because their stochastic nature and impact is still to be well understood and modelled as it is a complex, multi-dimensional extreme event.

In this context, this paper provides unique insights on the relevance and applicability of the power system resilience concept to wildfires and discusses measures to be taken to provide hedge against such catastrophic events, recognizing the contribution of both operational actions and infrastructure investments. Importantly, an overview of a spatio-temporal, stochastic impact assessment tool that has been developed at the University of Chile is provided, which is capable of reflecting the performance and response of the Chilean transmission network to the 2017 wildfire. Such a tool provides unique capabilities of not only quantifying the performance of a power system during and after a wildfire, but also to systematically evaluate and quantify the effect of different actions and investments on the transmission network resilience to extreme wildfires.

The implementation of such resilience enhancement strategies requires though a regulatory framework that will enable and encourage the application of these strategies and the transition towards a more resilience-oriented network planning and operation of power systems. In Chile, given the exposure of the country to a number of extreme weather events and natural hazards, including for example wildfires and earthquakes, there have been initiatives to amend current practices to explicitly consider resilience against such events. A critical review of the current regulatory framework in Chile is provided in this paper, along with recommendations to further amend this framework towards supporting the resilience of the Chilean transmission network. These recommendations critically recognize the importance of both infrastructure investments and operational measures in the provision of resilience, including the role of non-network or non-wire solutions, as well as the importance of advanced models for decision making and efficient forecast, the need for further coordination among a number of institutions within and beyond power systems, and the need to appropriately charge for new investments aimed to improve resilience. These recommendations are relevant and applicable not only to the context of the Chilean transmission system, but also to countries around the globe that are exposed to extreme wildfires.

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