Electricity distribution and wildfires: Survey of events, challenges, and mitigation

Sähkönjakelu ja metsäpalot: Tutkimus tapauksista, haasteista ja metsäpalojen ehkäisystä

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Bachelor's thesis
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ABSTRACT

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Key words: Climate change; Electricity distribution; Wildfires; Wildfire mitigation; Smart Grids; Microgrids

Increasingly frequent climate change-related phenomena are aggravating wildfire intensity and frequency across the globe, which is particularly evident in warmer regions of North America, Europe, and Oceania. This troubling context poses new challenges to fire containment programs and operations, as it does to various public and governmental stakeholders, but it also calls for a reassessment of the relation between electricity distribution activities and wildfires. This Bachelor's thesis utilizes desk research supported on recent literature to investigate and reflect on that renewed relation. It does so by depicting two relevant case studies, one being California's Kincade Fire, of 2019, and the other one being Portugal's wildfires of 2017.

Collectively, the case studies suggest that vulnerable or poorly maintained power grids pose substantial wildfire risks to surrounding communities and regions. On the other hand, hot and dry weather, especially when combined with extreme, unpredictable winds, can greatly exacerbate such risks. These circumstances put existing fire containment programs and operations under great pressure, leading to unprepared action and lack of coordination between competent public authorities. Electricity grid innovations that can help mitigate wildfires include the deployment of microgrids and smart grid technologies. The former are valuable for their ability to provide clean and reliable electric supply, while the latter can enhance the monitoring, control, and intelligence capabilities of the grid.

However, first and foremost, effective wildfire mitigation requires more concerted action at both the preventive and operational levels, including investing in scientific research addressing the behaviour and mitigation of wildfires under the new climate change reality, significant advancements at the policy level, to successfully transform research findings and technical recommendations into concrete actions, and revised protocols for handling public authority branches during wildfire emergencies.

TIIVISTELMÄ

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Metsäpalo tapaturmien yleisyys on kasvanut ympäri maailmaa ilmastonmuutos nimisen ilmiön seurauksena. Ilmiön jättämät vaikutukset ovat selvästi huomattavissa Pohjois-Amerikan, Euroopan ja Oseanian alueilla, joissa lämpötila on yleisempää lämpimämpi. Tämä on tuonut esille tuoreita ei-toivottuja haasteita metsäpalontorjuntaohjelmalle, tämän toiminnoille sekä hallituksen kuten julkisten sidosryhmille. Syntyneiden haasteiden vuoksi olisi tärkeää uusiksi tutkia sähkönjakeluverkon sekä metsäpalojen välistä suhdetta. Kandidaattityö suoritettiin kirjallisuustutkimuksena ja tutkiakseen kahden edellä mainitun tekijän välistä suhdetta, tutkittiin lähivuosien aikana tehtyjä tutkijoiden havaintoja aiheesta.

Kaksi tapaustutkimusta suoritettiin, joista ensimmäinen on Kalifornian Kincade Fire vuodelta 2019 ja tämän jälkeen analysoitiin vuoden 2017 Portugalin metsäpaloja. Tapaustutkimuksista käy ilmi että huonosti huolletut sähkönjakeluverkot ja ne jotka ovat alttiita vahingoille, toimivat isoina metsäpalon aiheuttajana ja täten ovat vaarallisia lähialueella asuville ihmisille kuin myös eläimille. Metsäpalojen todennäköisyyttä kasvattavat muut tekijät myös kuten lämmin ja kuiva sää yhdessä arvaamattomien ja äärimmäisien tuulien kanssa. Microgridiä sekä älykästä sähköverkkoa on sanottu olevan innovaatioita, joiden käytön avulla voi ennaltaehkäistä mahdollisesti metsäpaloja. Microgrid tarjoaa luotettavaa ympäristöystävällistä sähköä ja älykkään sähköverkon käytön tarkoituksena on parantaa sähköverkon hallintaa ja tämän valvontaa.

Tärkeämpää on kuitenkin uusiin tiedetutkimuksiin investoiminen, joissa käsiteltäisiin metsäpalojen käyttäytymistä nykyajan ilmastonmuutoksen aikana ja näiden ehkäisemistä. Muita toimintoja joita täytyy operatiivisella ja ennaltaehkäisevällä tasolla suorittaa hätätilanteissa metsäpalojen käsittelemiseksi ovat teknisten suosituksien sekä tutkimuksien tuloksien muuntamista konkreettisiksi toimiksi. Myös protokollat täytyy olla päivitettynä metsäpalotilanteissa käsitelläkseen viranomaishaaroja.

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
AC	Alternating Current
CPUC	California Public Utility Commission
DC	Direct Current
DER	Distributed Energy Resources
ETF	Enhanced Transparency Framework
IPCC	Intergovernmental Panel on Climate Change
kW	kilowatt
PG&E	Pacific Gas and Electric Company
PSPS	Public Safety Power Shutoff
UN	United Nations
UNEP	United Nations Environment Programme
US	United States
WMO	World Meteorological Organization
WWF	World Wide Fund for Nature

1. INTRODUCTION

The aftermath of the Industrial revolution has seen great amount of human progress as a result from technology innovation. However, this has happened at the expense of planet Earth. Anthropogenic emissions of carbon dioxide, having a strong hold on the atmosphere, impacted the normal course of nature, by increasing average temperatures and consequently the frequency of wildfire events globally. Australia and the US state of California are among the most affected regions, having fallen prey to devastating consequences of climate change. Estimated costs of recent wildfires in Australia from 2019-2020 reach four billion dollars, with over 17 million hectares of land burned [1]-[2]. In 2020, at over four million acres of land burned, California experienced its worst wildfire season in modern history, breaking the previous record by over 200 percent [3]. The average cost of annual fire suppression is also rising, as wildfires are becoming more and more extreme. Among the 20 largest wildfires ever recorded in California, six took place only in 2020 [3] (Figure 1).

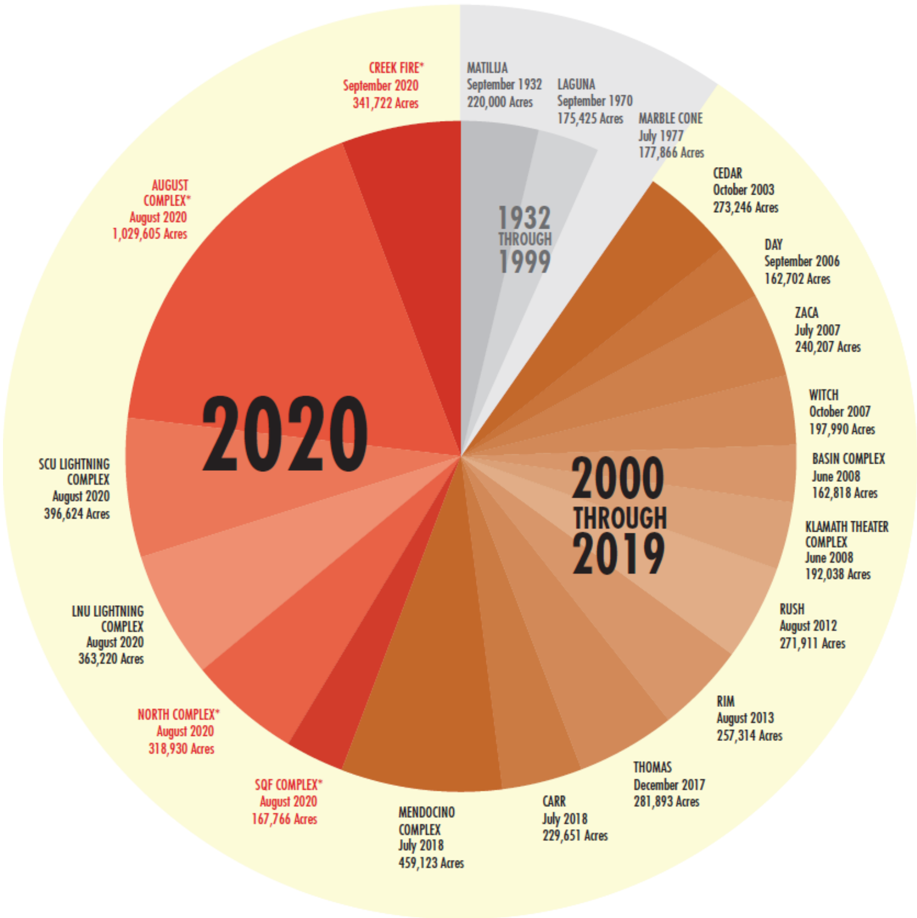

Figure 1. California's 20 largest recorded wildfires by amount of burned land, in acres [3].

This thesis investigates the above troubling trends, exploring further the potential existence of a relation between increasingly frequent wildfires and electricity distribution activities, amidst the contemporary context of aggravating climate change phenomena.

The thesis is divided into five chapters: The present and first chapter offers brief insights into the main problems addressed and specifies the goals of the research. The second chapter overviews the electricity distribution system as a whole, highlighting its key operational processes, modern-day problems it faces, and emerging solutions and paradigms. The third chapter is allotted to explaining the concept and perceptions over climate change, and its impact in the increasing frequency and magnitude of wildfires. In that section, the reader is introduced to the much touted Paris Agreement of 2015 and the IPCC, which has been appointed by the UN to check if progress is according to its various binding clauses. The fourth chapter focuses on depicting recent sequences of wildfire, offering a timeline of events, real-world consequences, and actions taken to mitigate them. These have taken place in different dates and case study locations: One in California, during the summer of 2019, and the other in Portugal during the summer and late fall of 2017. The fifth chapter, looks briefly into technology and policy innovations being driven by increasingly concerning wildfires and their relation with the electrical distribution.

2. ELECTRICITY DISTRIBUTION SYSTEM

This chapter will be introducing a larger picture of an electricity distribution system along with its basic operation and the components contributing to it with their own specified features. The figure (Figure.2) below explains figuratively how electricity distribution systems operate, all the way from electricity generation until the electricity is supplied to the industry or houses. In the second sub-chapter, problems occurring in the modern day power grid are to be explored with the potential solutions, for these problems, being told in the ultimate sub-chapter.

2.1 Essential components and operations

A power distribution system has all the necessary components and facilities which connect the customer's different equipment with a transmission system and the generation equipment (Figure 2) [49]. The components which feature in the power distribution system substations are supply lines, transformers, busbars, switch gear, outcoming feeders, switching equipment, a protective mechanism and power system – and an equipment grounding [4].

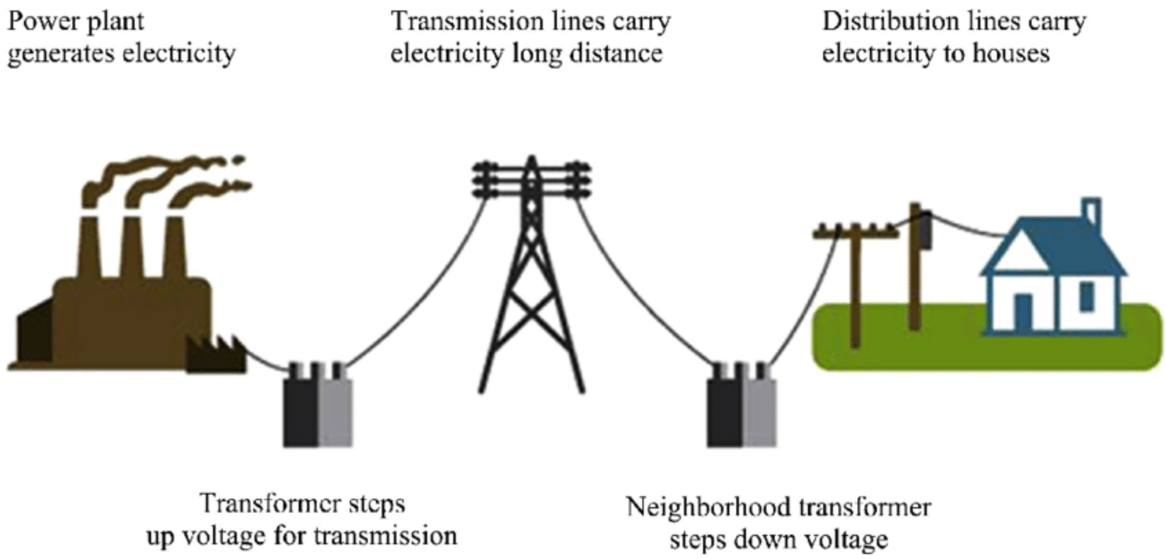

Figure 2. Example representation of a power distribution system [49].

From the electrical substation, energy in the form of electricity is distributed to industrial and residential consumers. Through multiple supply lines, which are also called primary feeders, the substation is connected to a sub-transmission system. Utilization of multiple primary feeders is necessary in order to increase the reliability of power being supplied as there are chances once in a while that some primary feeder might get disconnected. Between the primary feeders and substation, there is a disconnecting switch. This high voltage switch is used when there is need for maintenance or repair work. On the sides of the distribution substation, there are shield wires which work as a safety mechanism. It diverts the lighting coming from the sky inside the ground [4]. After this, come the transformers which work as "voltage modifiers" as they drop the voltage to a correct distributable level.

Transformers are arranged according to six significant elements, namely power rating, insulation, rating of voltage, cooling, regulating voltage and connections. The power rating tells about the amount of power that is possible to transfer through the transformer and its unit is expressed as either megavolts-amperes or kilovolts-amperes. The power rating of transformers in the distribution substation ranges in between of three kilovolts-amperes and 25 megavolts-amperes. Second factor is the insulation and there are two types of insulation. Liquid insulation, which can be mineral oil, non-flammable or low-flammable liquids. The second type of insulation is dry insulation and it includes the cast coil, enclosed non-ventilated and ventilated types among other types. The voltage rating is ruled by the distribution and sub-transmission voltage levels. It’s marked by the manufacturer on the transformer. Standards also govern nominal voltage levels and these voltage ratings affect the insulation needed for the transformer and the construction of it as it should be able to endure the amount of voltage going through it when the system is at work. The maximum temperature during peak demand and power rating of the transformer affect the cooling temperature. Transformers include a self-cooling rating which activates when the temperature hits a specific number. Transformer windings have two types in which they are connected; delta or star connection. In the delta connection a triangle is formed while in the star connection the windings are forming a star-like shape. The transformer in the distribution system is often having its windings connected with a delta connection at the side with higher voltage and star-connection at the low-voltage side. Voltage regulation is the transformer’s capability of maintaining nominal voltage at the customer service points by modifying voltage at the low voltage side. As a direct effect of primary system voltage fluctuation or extreme drop in voltage, customer service point’s voltage is volatile. Voltage tap regulators are installed on the transformers, through which the voltage is regulated by a single tap.

The third component of the distribution substation are busbars. They are utilized to carry and divide the current among many circuits present in the switchgear or equipment. Busbars are used at high and low voltage-sides for transferring power to outcoming feeders from the power supply. The conductors and parts which carry current on busbars can be either copper or aluminium [4].

Switchgear is a collection of circuit breakers, fuses and switches used to cut the connection or connect it from the components of the power system to other parts of the system. Their utilization is extensive throughout the power distribution system. Switches have been utilized for transferring service among various supplying sources, isolation, and load interruption. Isolating switches aid with the possibility of having safe access to the component which is isolated [4]. Fuses are devices used as protection against overcurrent. When the overcurrent goes through it, the fusible link of the fuse gets heated and severed. Fuses are made for various voltages, currents, interrupting ratings and for both outdoor and indoor functions [4]. The devices that are invented to open and close a circuit either manually or automatically, are called circuit breakers. An automatic circuit is programmed so that it should be capable of, on a fixed overload of current without harming neighbouring elements or itself, opening a circuit automatically [4].

For transporting power to points of service from the substation, multiple outcoming feeders are connected to the substation bus. When an error happens on the feeder, a breaker will open as a reaction of the protection detecting an error. The feeder will be tried to reenergize and the breaker will be closed if the error is short-term, but if the error is permanent then some operators will be brought on-site to fix the part of the feeder which is faulted [4]. Overvoltages are a product of lightning and/or volatile changes in conditions of the system such as load rejection and switching operations. As a result of natural and built-in characteristics of power systems, volatility in overvoltage can be detected. Damage on a great level to the parts of the power system, that are insulated, can happen if overvoltage is not contained rapidly. To reduce the magnitude of overvoltage, surge-protective devices should be applied [4].

Grounding of the power system means that at some point of the system there are calculated electric connections between the electric system phase conductors and earth, which is also called the ground. Three ways of grounding the power system are solidly grounding system, ungrounded grounded system or resistance grounded system. Each of these options bring various benefits and disadvantages and engineers have the last say as to which type of grounding system is necessary. Solidly grounded systems are formed so that protective devices of the circuit are able to catch an error in the circuit and then isolate it from the rest of the system regardless of the error type. In case of having any personnel working in the area, it's mandatory to have equipment grounded. This is achieved by having all the metallic components, which don't carry current, inside the industrial plant premises interconnected and grounded [4].

2.2 Modern power grid challenges

As humans take a firm stand against climate change by looking at alternative means of producing energy, they appear to overlook the amount of energy being wasted through the power grid. The transmission of electricity from generation sites to distant consumption points, for example, incurs significant inefficiencies, effectively translating into substantial energy losses. The lost amount of energy needs to be compensated by additional "not-nature-friendly" generation i.e. by burning fossil fuels. For this reason, if the power grid's losses could be minimized, this would work in favour of the fight against climate change. A study conducted by The National Interest brought out differences in power grid losses between developing, emerging, and developed economy countries. Power distribution losses in India and Brazil were 19 percent and 16%, respectively. In Haiti, Iraq and the Republic of Congo a staggering half or more of the electricity is lost during the electric transmission phase. In the US, losses are reported at six percent, while in Germany and Singapore at five percent and two percent, respectively [5].

These statistics pinpoint the fact that producing and distributing electricity to populations living within shorter distances – distributed generation – may result in significantly less grid losses.

Other issues faced by the ever-evolving electrical grid are the integration of renewable energy resources, the volatility and unpredictability of new load curves (for example from electric heating or mobility electrification) and voltage regulation under this new distributed generation paradigm.

The power grids were originally designed to be dependent on large, controllable resources for achieving the needed balance between supply and demand. However, renewable electricity generation is challenging this paradigm, by posing intermittency problems for these grids. Peter Lundberg, Global Product Manager at Hitachi ABB Power Grids, commented this situation with "*You might get new bottlenecks in the grid that cause strains. You have new power flows, and renewable generation is a lot more fluctuating than the conventional. So you need a much smarter and faster controller for your transmission grid*" [6]. As a result, electric powerhouses such as as Hitachi ABB Power Grids, Siemens, Schneider Electric, and others are developing new electric machinery that support these new smarter and faster grid operations [6].

Keeping the voltage steady is another important power distribution task that must be served to the paying electric customer. The three most problematic power quality effects of shifting from fossil and nuclear to renewable generation are reductions in reactive power, short-circuit current, and frequency stability, as rotating generators are being excluded from the power grid. Bernd Niemann, a business development manager at Siemens Energy, stated that the "*lack of reactive power means that we have voltage fluctuations"* [6]. As conventional power plants are not there to produce reactive power, new solutions and approaches for reactive power compensation need to be designed. In order to prevent blackouts, the volatility of frequency must be kept within the 50 Hz or 60 Hz frame, depending on the country. The addition of inertia into the system is seen as a solution for this dilemma. The problem of short-circuit current descending amount is said to be as a result of traditional power plants being disconnected. One envisioned solution for this obstacle is adding short-circuit current by introducing synchronous condensers to the grid [6].

Another problem with the grid is the increasing number of disasters brought upon natural causes, and its burden on the shoulders of the aging infrastructure. Storms are the most common causes of power grid disruption, globally, but other natural disasters, such as hurricanes, also take a toll. Nevertheless, natural disasters are not responsible for power grid problems alone, as failing infrastructure increases the chances of power grid problems. Power outages are common when components are in need of replacements or restoration [7].

2.3 Emerging paradigms and technologies

Many disruptive technologies have been poised as the future of the power grid. Among these, three in particular have captured great attention, namely smart grids, microgrids and distributed energy resources – DER.

By merging the digital world with the physical energy infrastructure, the smart grid may be among the most significant technological advancements to the conventional electrical system. The smart grid is becoming a large multidirectional network connecting devices, flexible distributed energy resources and back-up generation. A broad range of new technologies, such as energy management systems, electric vehicles, electricity storage, and microgrids, are being driven by the smart grid, aiding consumers in more efficiently managing their energy utilization. Recently, New York power utility ConEd called for aggressive investments on the smart grid, arguing that the societal value of smart grid technology is very substantial [8]. The smart grid is said to "give us tools that make the grid more flexible and responsive during extreme weather, which allows us to minimize power outages."[8] ConEd experts also stated that "*smart grid measures, such as sectionalizing switches allow system operators to identify and isolate problem areas and rapidly bring power back to the surrounding areas, keeping more customers in service*" [8].

A topic holding at least as much interest as the smart grid is the adoption of renewable energy. A change towards more renewables is rapidly happening in the industry, as the interest in DER grows. DER is a term used for the growing panoply of local power generation assets that operates in parallel and somewhat interlinked to the centralized power generation system (within which renewable generators are included). Public pressure, political requirements, and subsidies for the utilization of low to no-carbon alternative energies have had an immense effect in the power industry. To take this energy revolution even further, extensive growth is expected to happen in renewable energy capacity, since emerging electrical technologies are presently supporting the use of distributed energy resources [9]. The total amount of DER technologies is on a rise, examples of which are wind turbines, microturbines, photovoltaic arrays, energy storage devices (e.g. lithium-ion batteries), and small-scale heat and power systems [10]. Critics have also had their say on the heavy approach for DER, because it challenges the working model of selling centrally generated energy. One benefit which paying customers reap from utilizing DERs is that they can zero their electricity bill throughout the year, hence becoming a 'net-zero' household [10]. Point to be noted is that this is possible only when sufficient amount of solar panels are deployed so that enough electricity gets stored, in the form of credits, on the grid. This is called "net metering". It's a fresh invoice system that gives solar energy system owners credits for the electricity they add to the grid [50].

The third new technological invention pushing for change is the microgrid. As the name implies, it is a miniature version of the conventional grid system, being focused on local power generation supplied to small communities or campuses [10]. Even if the microgrid is connected to the primary power grid, it still has enough capacity to disconnect and operate "islanded" in a completely coordinated manner, if and when a disruption occurs. This makes microgrid systems uniquely resilient. Microgrids could be described as a reorganized application of DER, but alongside localized generation, they include localized distribution also [10].

One argument behind the adoption of microgrids is the ability of these systems to work as self-reliant power systems amidst major disruptions, which brings operational surety to both customers and operators during moments of stress.

3. CLIMATE CHANGE

Climate change is the transformation of weather patterns is different regions of the globe. When talking about this phenomena, people tend to refer to the change in global temperatures over the last century. The changes caused by these oscillations in the weather patterns have shown to have worldwide impacts and multifaceted societal implications. This section sheds some light over these phenomena, introducing both the history behind it and the scientific records that give evidence of its widespread effects.

3.1 Evidences and causes

Human activity has been singled out as the primary reason for the global warming trend found in modern days. Satellites, operating on Earth's orbit, have aided scientists with data that offers valuable information as to how the climate has been changing. Carbon dioxide and other greenhouse gases are causing the Earth to warm. While other gases, such as water vapour, nitrous oxide and methane, also contribute to the greenhouse effect, the importance of carbon dioxide is unparalleled, due to the massive amounts of its anthropogenic emissions [15]. The graph in Figure 3 highlights the spike in carbon dioxide concentrations in the atmosphere registered in modern days, when compared to recent times and the times Before the Common Era (BCE).

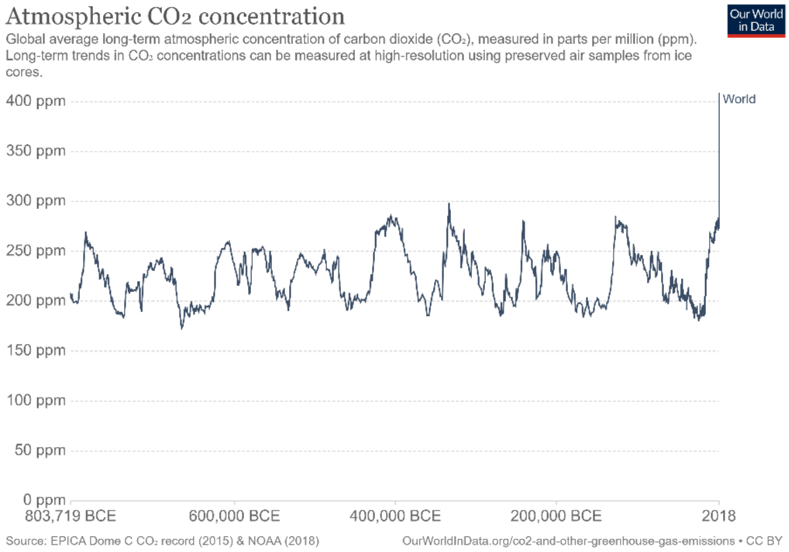

Figure 3. Historic evolution of the global concentrations of carbon dioxide [51].

Since the last Ice Age, carbon dioxide concentrations grew 250 times faster than what would be expected, if exclusively from natural reasons [13]. This has led to international scientific consensus as to human activity being the main cause of global warming. Great levels of carbon dioxide in the atmosphere led to global temperature rising, with most growth happening during the 21st century. As Figure 4 shows, global temperatures grew intensely during both the last century and the 21st century, due to technology progress and highly carbon leveraged-industrial revolutions. Figure 5 indicates which regions emit the most carbon dioxide, which helps devise the footprint of certain human activities.

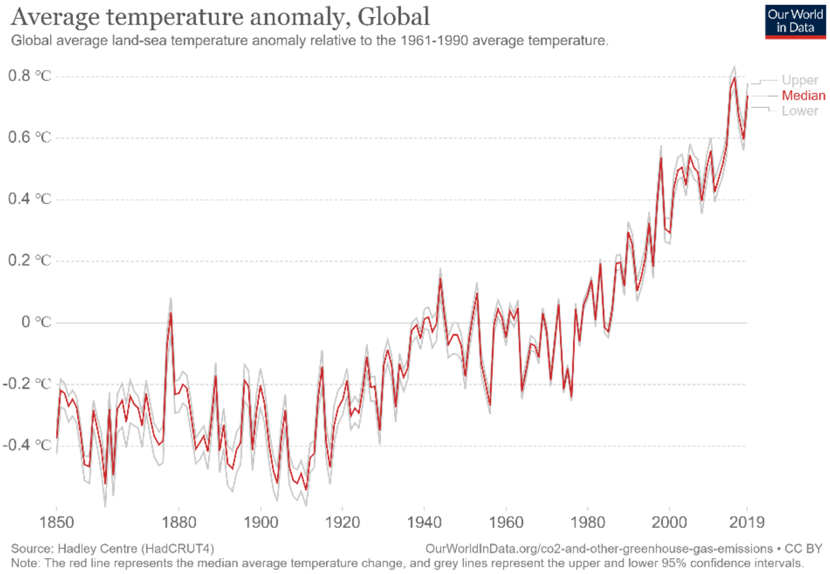

Figure 4. Historic evolution of global average land-sea temperature anomaly [53].

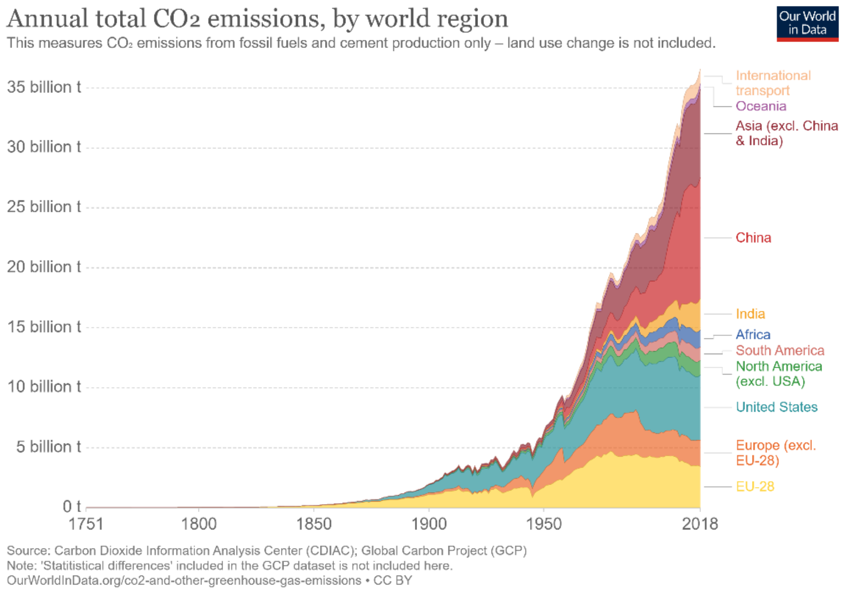

Figure 5. Historic evolution of annual carbon dioxide emissions in different regions of the world [52].

The majority of Earth's trapped heat gets saved in the oceans. For related reasons, the ice sheets of Antarctica have been slowly deteriorating. During the last one hundred years, the sea level has risen about 20 cm, but during the last two decades, it has risen by almost double that amount [14]. In a separate but parallel process, carbon emissions are also being absorbed by oceans at a large scale, and the increment in acidity levels of the surface ocean is an important example manifestation of how human activity may be jeopardizing its own and other living being's subsistence [12,13].

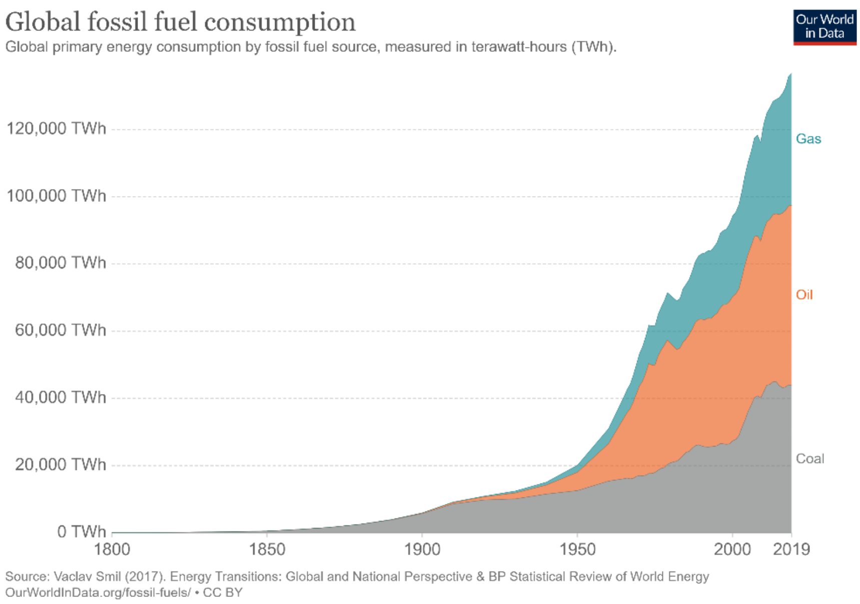

Figure 6. Historic evolution of global fossil fuel consumption, by fuel type [54].

Figure 6 shows the historic accumulated evolution of different types of fossil fuels, globally, and the resemblance with the graph from Figure 5 is striking. The figure shows a massive increase in the global consumption of fossil fuels, which is likely to have greatly contributed to climate change. Fossil fuels are the factor that needs to be fought against smartly, if the concentration of carbon dioxide in the atmosphere is to be minimized within useful time.

3.2 Effects of a changing climate

The effects of climate change are majorly seen in the form of more and more intense heat waves, rise in sea level, and increasingly frequent wildfires, among other devastating phenomena. The Intergovernmental Panel on Climate Change (IPCC), has estimated that global average temperatures will suffer dangerous increments, greatly affecting nature and life on Earth from every potential angle [16]. As weather patterns become more unpredictable, seasons are becoming either longer or shorter. This has significant general effects on the natural ecosystem, and particularly on the agricultural sector. Winter seasons have begun starting later, and ice has begun melting earlier. As climate change takes a strong hold of Earth, natural disasters are becoming more intense and frequent. These include hurricanes and massive wildfires [16]. Figure 4 and Figure 6 also display a concerning correlating story, as to why wildfires are becoming devastatingly frequent. The intensity and frequency behind modern-day wildfires are primarily a result of human-induced elements. Similarly to other natural disasters when in context of climate change, wildfires have lost their seasonality, and can now happen year-round in most regions. Flexing of the financial muscle is aggressively required when combatting with wildfire like natural disasters.

3.3 Brief history and developments

In 1988, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) inaugurated the Intergovernmental Panel on Climate Change (IPCC), with support from the UN General Assembly. Its initial task was to assemble a comprehensive analysis of the social and economic impacts of climate change for the policymakers, including possible response strategies and elements for inclusion in a potential future international convention on climate change [17].

The IPCC brings representatives from different governments together so that they can analyse expert reports, after which they pass verdicts as to if they will be accepting or rejecting them. The IPCC Bureau supervises the Panel's scientific and technical aspects on a regular basis, and when needed offers direction on these fronts. The reports and assessments of IPCC are provided by three different working groups, each reflecting a different viewpoint on the science behind climate change. The first working group targets the assessment of the physical basis of the climate system and of climate changes [18]. The second working group assesses the vulnerability of socio-economic and natural systems to climate change, as well as other negative and positive impacts at different scales, while searching for human adaptation pathways. In a rephrased manner, it examines effects of climate change on the ecosystem and biodiversity, from a local and regional view, all the way to a global view [19]. The third working group looks at mitigating climate change and ways in which anthropogenic greenhouse gas emissions could be minimized and its atmosphere concentrations reduced [20].

On the 12th of December 2015, 197 countries came together for the COP21 conference, in Paris, to significantly reduce the risks and impacts of climate change, taking up the joint initiative of endorsing the Paris Agreement [21]. This international treaty on climate change, which came into power on the 4th of November 2016, has the target of restricting global warming to 1.5 degrees Celsius well within the century [22]. According to the IPCC, the difference between 1.5 and 2 degrees increase could mean substantially more poverty, extreme heat, sea level rise, habitat loss, and drought. By 2050, participating parties aim to achieve a climate neutral world, by reaching a global peak of greenhouse gas emissions.

Many countries coming under the same roof and fighting for a common cause makes of the Paris accord all the more momentous, as such an agreement has not occurred previously in the last 200,000 years of mankind history. Implementing the treaty is important if humans are to reach the Sustainable Development Goals. The agreement acts as a guide for reducing emissions and building climate resilience [22]. An Enhanced Transparency Framework (ETF) was established by the agreement, under which countries are to report transparently on progress in climate change mitigation, adaptation measures and whether the country has received or given financial aid. Even though there are many steps that still need to be taken for the goals of the Paris Agreement to be achieved, low carbon solutions and new markets have been sparked and gained traction globally [22]. Carbon neutrality targets are being set day after day in many countries, both publicly and in the corporate world.

Zero-carbon solutions are most noticeable in the power and transport sectors, while they are becoming competitive also in other economic sectors [22].

4. CASE STUDIES

This chapter investigates two real-world cases that raised attention to the potential relation of wildfires with electricity distribution. The cases put under a magnifying glass are the California 2019 wildfire events and the Central Portugal's 2017 series of wildfires. Each case study report is divided into three parts: 1) The course of events, which briefly reviews the timeline of the fires and takes into account statements from various involved parties; 2) Disaster-induced consequences, which deals with both the physical and socio-economic effects of the events; and 3) Mitigation plans adopted by respective authorities post-events, as a means to reduce the severity of future wildfires.

4.1 The Kincade Fire, California 2019

In 2019, California faced some of the most gruesome wildfires in its history. Based on the experience from previous years, a wildfire season was highly anticipated, but mostly centered between early June and September. Unfortunately, that year, wildfires started igniting much earlier than initially thought. The first wildfire was known as the Pilot Fire, happening on New Year's Day [45]. The wildfire analysed in this chapter is the Kincade Fire, deemed the most havoc-wreaking in the season.

4.1.1 The course of events

On the evening of the 23rd of October 2019 at 21:27, the largest wildfire of the 2019 California wildfire season was ignited [46]. The so-called Kincade Fire burned in Sonoma County consecutively for 20 days, until it was contained on the 6th of November 2019 by 19:00. The California Department of Forestry and Fire Protection (CAL FIRE) stated that the unsolicited spark for this wildfire was given by the transmission lines of Pacific Gas and Electric Co.(PG&E), a utility company providing natural gas and electric service in the western US [47, 48]. Three days into the initiation of the wildfire, near Santa Rosa, north of San Francisco, on the 26th of October, PG&E had cut off power supply to 179 thousand customers in 17 counties, situated in north and central California, as a strategy to decrease further chances of wildfire activity. Ironically, the following events were not in the favour of the utility company, as the Kincade Fire spread with a terrorizing nature [27, 29]. As the wildfire, fuelled by dry conditions and strong winds, started to hack through Sonoma County, many residents from the region were forced to evacuate their homes [28, 29]. It is estimated that the number of evacuated residents amounts to circa 2000. In Southern California, 26 thousand paying customers were on the receiving end of a blackout [29]. Despite having distribution lines powered down in the proximity, because of its public safety power shut-off (PSPS) policy, PG&E had trouble with an actively operating transmission line located northeast of Geyserville, where the Kincade fire had been allegedly ignited. At 21:20 on the 23rd of October, PG&E became aware of a transmission level outage on the Geysers #9 Lakeville 230-kV line, near Kincade Road and Burned Mountain Road.

This is the exact Sonoma County location where firefighters had been first dispatched to, only moments before the Kincade fire started [30].

Figure 7. Firefighters searching around the area of Soda Rock Winery during the initial stages of its ignition around the area [56].

On 24th of October at 7:30, a “PG&E troubleman” went to scan the situation at the location where CAL FIRE had taped the zone at the Kincade Road, around the transmission tower [30]. By 9:30, 25th of October, only five percent of the near 22 thousand-acre wind-driven fire was contained, but there was no record of injuries or casualties. Even if PG&E had initially restored the power back to customers after a blackout, they were forced into repeating their earlier actions as a result of expected wind storms from the 26th till 28th of October, with 680 thousand paying customers being cut off from the power supply [30]. The transmission line to start the Kincade Fire was carrying 230 kV, one of the largest conduits in the electric grid of PG&E. The lower-capacity transmission lines, which were pre-emptively de-energized by PG&E, carried electricity of approximately 115 kilovolts [31]. As a result of efficient and tireless work morale of the first responders, the wildfire was finally hundred percent contained, but it left heavy consequences for the state of California to reap.

4.1.2 Consequences of the wildfires

The aftermath of the Kincade fire revealed a catastrophic trace of destruction, leading to major financial and socio-economic implications, as well as mental trauma as a result from property loss and widespread evacuations, for Californians and Sonoma County residents. On the ground, by the time of full containment, the fire had turned 77,758 acres of land into ashes [46]. It has also reportedly destroyed nearly 374 structures, and injured four people,

[47]. As a result of PG&E's actions on the eve of Kincade fire's ignition, several law firms filed lawsuits against the power supply company. Jack Weaver, a partner at Welty Weaver & Currie stated on July 15 that "*PG&E's safety record is an abomination, and its continuing practise of putting profit before people reinforces that conclusion*" [47]. The Kincade fire itself had put on a financial burden worth of 600 million dollars [47]. In a typical manner, like previous wildfire seasons have been dealt with, the financial muscles were put under extreme stress in order to get peoples normal lives back on track as quickly as possible. The damage done by California wildfires in 2019 on an economical level was estimated to hit the colossal 80 billion dollars mark by AccuWeather's Joel N. Myers [32]. Customers, to whom PG&E provided services to throughout the wildfires, were paid a sum of 13, 5 billion dollars [33]. PG&E were said to owe approximately 7500 million dollars to the different federal, state and local agencies who had taken care of victims and put out fires allegedly incited by the equipment owned by the company [34]. There were claims that compensation would be paid in the form of stock, but this idea was not received well on the receiving end, under the argument that stocks are volatile. Ultimately, receiving parties opted for getting cash compensations [34].

4.1.3 Mitigation actions

After this disastrous fire managed to wreak so much havoc, a firm stance was taken by various governmental agencies in order to stop wildfires of this calibre from happening in the future. PG&E stated that it would complete mitigation work inside the territory of their service [35]. This work includes modernization on every possible front where a link may exist to potential wildfire activity i.e. where outmoded equipment could facilitate wildfire ignition or where system operations could potentially get affected by wildfires. More specifically, the plan released by PG&E includes taking safety measures around new grid technology, hardening the electric system, efficient inspections of electric infrastructure, scanning and monitoring in real-time the vegetation around power lines, and building tools for understanding of weather effects in the PG&E's system [37].

Allegedly, PGE's mitigation plan anticipates 1300 million dollars in expenses and 1400 million dollars in capital expenditures [35]. PG&E also stated in its earnings presentation of 2020 that if the weather patterns from 2019 are repeated in the near future, their mitigation efforts *"should reduce the number of customers impacted by those PSPS events by approximately one-third*".

PG&E will also attempt to make PSPS events shorter, duration-wise, and smarter in action, while maintaining power distribution to paying customers at times of severe weather and high wildfire risk [36]. PG&E is targeting the reduction of PSPS events' customer impacts in various ways. For example, 23 transmission switches were installed that are capable of redirecting power and keeping substations and transmission lines energized during a PSPS event, expanding PG&E's ability to provide backup power to critical service providers, such as major transportation thoroughfares, water systems, medical centers, and fire departments, during stressful circumstances.

The utility is also interested in enhancing their weather forecasting abilities for the benefit of PSPS events, and work with local communities to take additional microgrids into operation, which would allow paying customers and communities to stay connected to the power grid during a PSPS event [37]. In addition, many customers were unaware of the wildfire when the intentional blackout was launched by PG&E. As a response to this situation, PG&E wishes to improve customer notifications and awareness, in the cases when power needs to be shut off for safety and when will it be restored again [37].

To reduce potential ignitions, the mitigation plan addresses multiple wildfire risk factors, contemplating immediate and future measures. Among the measures taken by PG&E, were installing more than 386 kilometres of resilient poles and covered power lines, some of them underground. Also, pruning or removing more than one million trees to keep them away from power lines. PG&E puts emphasis as well on the installation of almost 400 new weather stations during 2020, which would keep the company on track for the targeted total of 1300 new weather stations by 2021. This translates into having one weather station for every 32 circuit-kilometres in high fire-risk areas [37].

Among the previous measures, promised for implementation in 2019, were clearing of the vegetation around power lines through the Enhanced Vegetation Management program, making the electric system more robust and resilient through grid modernisation, and using microgrids temporarily. Microgrids were deployed to serve power to more than 4800 customers in the areas of Placerville, Grass Valley, Calistoga and Angwin. For the benefit of PG&E's wildfire monitoring command center, new technology was adopted which would help with improved coordination and communication with the field staff [37].

Despite the planned mitigation measures, the also record-setting 2020 California wildfire season went on to become the worse ever recorded in California's modern history, according to CAL FIRE [55].

4.2 Central Portugal fires, 2017

In late June 2017, Portugal was the target of a wildfire which saw no remorse on the victims and areas it swept through. It was called the deadliest fire ever in Portugal [38]. The wildfire had its initial ignition in the small municipality of Pedrógão Grande and from there it burned through the mountain towns of Arganil, Góis, and Pampilhosa da Serra, all neighbouring areas to Pedrógão Grande [39]. Later that year, the area of Lousã also fell prey to wildfires, which were deemed to have similar ignition conditions to those of the fire of Pedrógão Grande [40].

4.2.1 The course of events

On the 17th of June 2017, wildfires flared up in the areas of Castanheira de Pêra and Pedrógão Grande, in the district of Leiria. The areas were ablaze with uncontrollable fast-spreading fires for eight consecutive days, being finally contained only on the 25th of June [38]. The wildfires of Pedrógão Grande involved a massive multi-country containment operation, requiring the assistance from very large logistics teams, which used up unheard amounts of resources for a small country such as Portugal.

The second set of multiple wildfires happened later on during the year on 15th of October. The area of Lousã, a town 210 km north of Lisbon, was struck with multiple violent wildfires, in what was deemed on of the worst days on record in Portuguese wildfire containment history [40].

Figure 8. A front of the June 2017 wildfire seen near Pedrógão Grande [57].

Not only Portugal was affected by these wildfires; many areas of Northwestern Spain were also struck [41]. Wildfires in the Iberian belt took place for five days.

4.2.2 Consequences of the wildfires

Alongside the loss of enormous amounts of land, as a result of these highly destructive wildfires, many innocent people have tragically lost their lives when caught by surprise in an attempt to escape the area by road or by simply driving through the region unaware of the full extent of the fire. The wildfires of Pedrógão Grande brought more than a thousand firefighters to the field and more than a hundred people were taking part in vehicle maintenance, food and fuel distribution [38]. During these fires, reports show that 66 people had passed away, 200 people were injured, and 500 houses were turned into ashes. 74 thousand acres of forest were demolished by the wildfires [38]. On a later occasion, Portugal's prime minister stated that alerting the public early on had been made frustratingly impossible, due to burned down phone lines and communication towers all across the region. There was also criticism of the National Republican Guard's actions, due to their failure to block roads on which multiple disoriented victims fell prey to the furious flames [39]. The

total cost for the containment was estimated to be around twenty million euros [38]. This was said to be the deadliest fire ever to be experienced by Portugal.
Over 900 operating firemen were needed for the containment of the fires, with neighbouring countries France and Spain aiding Portugal with additional firemen sent to targeted areas [38]. During the wildfires of Lousã, 45 people lost their lives. This added to the unprecedented tally of deceased in Portugal's 2017 wildfires, which amounted to more than 100 people, a level of human tragedy Portugal had never seen before in this context. As a result from these statistics, the Portuguese minister in charge of emergency services presented their resignation. Approximately 700 firefighters were brought on the field to contain the Lousã fires [40, 41]. According to the European Union's Emergency Management Service, wildfires burned a record amount of Portuguese territory during the year of 2017. The amount was described to more than six times the annual average for the last eight years by the Management Service [41]. The Lousã fires caused some 50 million euros-worth of widespread damage [42].

In January 2018, Paulo Fernandes, a Professor and Scientific Researcher at Universidade de Trás os Montes e Alto Douro, who integrated the technical commission tasked by the government with identifying the reasons for the fires, told the media that the October 2017 Lousã events had been caused by an electrical accident [40]. The fire behaviour expert told local reporters that the wildfires were ignited by "*a high tension cable hitting a tree or a tree falling on the cable*". He also added that the weather conditions, hot and windy, were optimal for the spreading of fires during the Lousã and Pedrógão Grande's wildfires [40]. In response to these allegations, Portugal's main electricity distribution operator, Energias de Portugal (EDP), rebuffed the claims. The company published a statement to the Portuguese Lusa News Agency that reads "*Given the information available to EDP Distribuição regarding the behaviour of its electricity lines on the days the fires occurred in October, we can state unequivocally that no fire was caused by trees falling on our network cables in the Lousã area*" [42]. The independent technical commission's report delivered to the Portuguese parliament cited that the fire in Lousã had started when a tree fell on a medium-tension electricity line, and that it was EDP's responsibility to make sure that trees were reduced around such cables. This was the second time during the year of 2017 that EDP was deemed responsible for causing wildfires as a result of operational unpreparedness (an independent commission also found EDP responsible for events in Pedrógão Grande) [42]. Another large set of fires that season had been found to be ignited by people who burned pastures for farming purposes in conditions of high winds and sweltering temperatures [42].

Both wildfires of Pedrógão Grande and Lousã are surrounded by controversy related to the key reason behind their ignitions. Portuguese media appears to have embraced the thesis that the fires were caused by an electric discharge of the power lines, being that from that point onward, strong winds contributed to aggravate the phenomena. EDP continues to deny this explanation. The same has been pointed as the main trigger of the Iberian wildfires, even though other potential reasons have been advanced, which include lighting by arsonists and abnormal weather conditions [38].

4.2.3 Mitigation actions

The analysis report submitted to Portuguese policy and decision-makers as a part of an independent inquiry, described ways in which wildfires of this magnitude can be averted. It stated that 40 percent of the fires that were reignited after extinguishing measures, could be prevented by keeping firefighting methods and vigilance services improvement under surveillance. It also said that deliberately started fires pose great, unparalleled mitigation challenges, due to the unpredictable and incomprehensible behaviour of arsonist individuals [42].

WWF suggested certain mitigation actions to be taken in the forest and rural areas. Among the many suggestions, one indicates that a responsible forest management should be encouraged through internationally recognized certification processes and that stakeholder platforms should be created to encourage collaboration between forest and territorial management teams [43]. Other mitigation actions would be through fuel and vegetation management and by making communities' surrounding environments more fire-enduring. This is extremely challenging for those who reside in hilly and mountainous areas.

The Portuguese Government also included potential mitigation actions in their comments to the abovementioned independent technical commission's report. These recommendations included the establishment of the Agency for the Integrated Management of Rural Fires, with the duty of analysing, planning, evaluating and coordinating the Integrated Management System of Rural Fires, or SGIFR, and intervene in potentially high risk events. Two other measures recommended in the report were the creation of the Rural Fires Management and Rural Fire Protection agencies.

The former is meant to focus on the sustainability of forest spaces, while the latter is meant to address the safety of people and their assets [44]. According to the recommendations, a Head Safety Officer should also be appointed, who should operationalize both a warning system and awareness campaigns targeted at communities potentially facing greater wildfire risks [44]. While on paper these measures have merit, it will be expensive, challenging, and time-consuming to put them fully in practice. At the same time, much work needs to be done directly with affected communities, as means to restore trust and confidence in government actors and their actions; people who feel the government has failed them might need stronger levels of engagement before they adopt any renewed government agenda.

5. ELECTRICITY GRID INNOVATION FOR WILDFIRE MITIGATION

Wildfires have the capability to significantly compromise basic infrastructure. The electric grid is particularly vulnerable, being at great risk of at least partial damage, as the approached case studies have shown. Among the many facets the mitigation of wildfires can have, grid innovation is one of the most important, due to the vital role the power grid plays in our daily lives. For example, renewables and microgrids are more and more sought out as viable means of mitigation. A microgrid is a self-sufficient electrical system that distributes own-generated power to nearby homes and businesses. The aim is to make communities more resilient, by allowing them to operate as an "electrical island" during any precautionary interruptions of electricity supply by the utility [48].

Unprecedented technical and economic developments of microgrid technologies have made of these systems an attractive alternative for computerized, carbon-free, decentralized backup power [46]. In addition, as the age of ubiquitous digitalization nears, microgrid barriers related to information and communication technologies are starting to fade away. In the past, public safety systems with utility price signals were hurdles for the integration of microgrids as auxiliary power systems [46]. On the other hand, regulatory aspects still pose serious obstacles to microgrids. Excessively complex and inadequate regulation makes it difficult for engineers and installers to navigate the implementation environment. Furthermore, according to the most traditional sale models, communities require significant amounts of upfront capital to acquire such technologies, which is often more than what could be gathered. This can be overturned via business model innovation targeted at removing capital risks off the shoulders of adopting customers, with for instance energy-as-a-service models.

According to Mark Feasel, President of Smart Grid for Schneider Electric North America, "*one reason why renewable energy is so important is because it doesn't require fuel*". Additionally, he claims that "*the greatest benefit of the energy-as-a-service business model is that it transfers all of these risks to someone else*" [46]. Marybel Batjer, President of the CPUC mentioned that "*the use of microgrids coupled with the work to hold utilities accountable for creating and implementing wildfire mitigation plans, will help make communities more resilient in advance of the 2020 wildfire season*" [45]. The different DER available to microgrids include battery storage, solar panels and small wind turbines, which deliver energy to buildings within the premises. Despite the potential positive effects of renewable microgrids' deployment, the Brattle Group claims that natural gas, for its reliability over longer periods of time, may be a preferred option. Natural gas is expected to continue to play an important role during power outages, as a result from its use for fueling generators [45].

The smart grid is a new all-encompassing concept that in many ways is also being used to mitigate wildfire risks. Smart grid sensors are being adopted by utility companies in their territories for visuals of their transmission lines, especially those situated in remote areas. Installing these sensors is easy and quick for the workers in the area, and in addition, these sensors can be adjusted remotely by the circuit owners [47]. There are three major ways in which intelligent grid sensors help mitigating wildfire threats: 1) They recognize disturbing patterns occurring on transmission lines, which could potentially lead to a fire. They can also handle vegetation and other hindrances that are in the risk group of inducing fires. Smart grid sensors are also capable of spotting faulty power lines; 2) They provide data about the load and voltage in actual time, which helps utilities processing information from problematic areas, mobile substations or generators; and 3) They are competent in certifying switching operations and outage restoration verifications, while the power circuits are returning to their natural modus operandi [47].

Lastly, benefits from renewable energy and microgrids do not resort only to those immediately and directly quantifiable. At a societal level, there will be benefits for example in the form of skilled local jobs, zero-emissions electricity and secured energy independence, all which will lead more toward energy and resilient communities [48].

6. CONCLUSIONS

This Bachelor's thesis raised awareness to the discussion on the increasingly important relation between electricity distribution and wildfires. This was done through surveying two real-world case studies, depicting their sequence of events, and further elaborating on consequences and preventive action taken by authorities and policy-makers. In one of the case studies (California's Kincade fire, 2019) the electric utility took full responsibility over the events. In the other case study (Portugal's 2017 fires), the reason for the wildfire is still disputed, even though an independent commission had concluded before the Portuguese parliament that the utility's lack of preventive action is to blame.

Regardless of culpability, the two studied incidents seem to suggest that vulnerable or poorly maintained power grids pose substantial wildfire risks to surrounding communities and regions. On the other hand, these risks are greatly exacerbated by an array of climate change-related phenomena, where unexpectedly extreme winds, overly dry and hot summers, and the fading away of seasons could be included. This explosive combination is putting fire containment programs and operations under great pressure, not only in California and Portugal, but also in Australia, Greece, and other world locations. Under these stressful circumstances, forest management, National Guard, and a range of public authorities, all central to fire containment operations, have been widely underperforming, which further aggravated an already dark scenario. The lack of coordination and preparedness for a context of a rapidly changing climate has in the studied cases resulted in high numbers of fatalities, lasting psychological trauma, and vanishing trust in public authorities.

The societal challenges imposed by climate change have burdened the world economy in unprecedented ways. Human ingenuity, however, sees no barriers, and this context has only but exacerbated technology innovation. For the reasons explained above, electricity grid innovation, in particular, could play a key role in wildfire mitigation:

- Microgrids can make communities more resilient, by allowing them to operate isolated from the distribution grid whenever precautionary utility interruptions of electricity supply happen;
- Renewable energy technologies and other distributed resources, such as energy storage, are enablers of microgrids, but have individual merit and can be adopted individually. Today, novel business models such as *energy-as-a-service* can greatly facilitate their adoption;
- Smart grid technologies enhance monitoring, control, and intelligence capabilities of the grid, helping the identification and tracking of faulty sections, risky patterns, and other liabilities.

To effectively tackle the problems raised in this thesis will require significant advancements both at the technology and policy levels, as well as improved coordination between various public authority branches during wildfire emergency situations. Parallelly, there is renewed need for scientific research addressing the behaviour and mitigation of wildfires under the new climate change reality.

These changes are not to take place in isolation, but under a new paradigm of concerted action at both at the preventive and operational levels. If such a path is not immediately pursued by the competent actors, the loss of property and infrastructure, as well as of natural and human life may very well find its way to new locations of the globe, while continuing its record-breaking trends.

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