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Review

Towards Resilient Critical Infrastructure in the Face of Extreme Wildfire Events: Lessons and Policy Pathways from the US and EU

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Abstract

Escalating extreme wildfires, fueled by the confluence of climate change, land use patterns alterations, ignitions by humans, and flammable fuels accumulation, pose significant and increasingly destructive risks to critical infrastructure (CI). This study presents a comprehensive comparative analysis of wildfire impacts and the corresponding CI resilience strategies employed across the EU and the US. It examines the vulnerability of CIs to the devastating effects of wildfires and their inadvertent contribution to wildfire ignition and spread. The study evaluates the EU's CER Directive and the US National Infrastructure Protection Plan and assesses European Commission wildfire resilience-related initiatives, including FIRELOGUE, FIRE-RES, SILVANUS, and TREEADS flagship projects. It synthesizes empirical evidence and extracts key lessons learned from major wildfire events in the EU (2017 Portuguese fires; 2018 Mati wildfire) and the US (2023 Lahaina disaster; 2025 Los Angeles fires), drawing insights regarding the effectiveness of various resilience measures

and identifying areas for improvement. Persistent challenges impeding effective wildfire resilience are identified, including governance fragmentation, lack of standardization in risk assessment and mitigation protocols, and insufficient integration of scientific knowledge and data into policy formulation and implementation. It concludes with actionable recommendations aimed at fostering science-based, multi-stakeholder approaches to strengthen wildfire resilience at both policy and operational levels.

Keywords: wildfires; critical infrastructure; climate change; resilience; CER directive; policy recommendations

1. Introduction

Wildfires are an escalating threat, especially in Mediterranean regions, which account for over 80% of the EU's burned area [1]. Historically, fire was part of landscape ecology and management [2,3], but trends like rural abandonment, climate-driven droughts, and increased fuel loads have intensified fire events, threatening critical infrastructure (CI) and ecosystems [4–6]. In the US, burned areas and fire frequency vary regionally, with Alaska showing the largest burned areas and the Eastern states recording the highest number of incidents [7]. Wildfire annual reports, databases, and statistics are primarily managed by EFFIS in the EU, dating back to 2000 [8], and NIFC, dating back to 1983 in the US [9].

Statistics from the EU and the US (Figure 1) show a decreasing trend in the number of wildfires in the US after 2002, and in the EU after 2010. In the US, a clear increase in the burned area exists, while in Europe, the situation is not that simple, as there is no clear trend in the Mediterranean regions. Potentially, a slight decrease in the burned area may exist, which can be partially attributed to improvements in fire prevention, law reinforcement, education and awareness, fire-fighting measures, advances in technology, and cross-border collaboration [10]. An increase in the number of fires for EU Member States other than the southern ones is clear, as well as an increase in the number of fires larger than 30 ha. Similarly, the burned area for wildfires larger than 30 ha seems to show an increasing trend. Based on the current report of JRC on wildfires (updated on a weekly basis) for the year 2025, until 27 August 2025, 1025,036 ha have been burned from 1868 fires (larger than 30 ha) emitting 38.68 Mt CO_2. To showcase the problem, the average burnt area in Europe for the last 19 years (2006–2024) is 277,976 hectares for this time of year (19–27 August), clearly showing a rising trend [11].

In the EU, Mediterranean countries (Southern European countries)—Portugal, Spain, Italy, and Greece—account for nearly 80% of total burned areas, with around 39,000 fires across approximately 340,000 hectares annually [12]. The 2022 wildfire season, marked by extreme weather anomalies, saw significant activity in southern Europe, particularly in the Iberian Peninsula [13].

Large fire data from the European Forest Fire Information System (EFFIS) for 2000–2024 show that regions in Central and Northern Portugal, as well as Galicia in Spain, together account for about one-third of the total burned area. The most fire-prone 25% of the EU accounts for over 90% of burned areas, while less fire-prone regions (50% of the EU) contribute to less than 2%. Over the same period, the largest 0.3% of fires caused 25% of the total burned area, with the worst season in 2017 burning 10% of the total area (Figure 2).

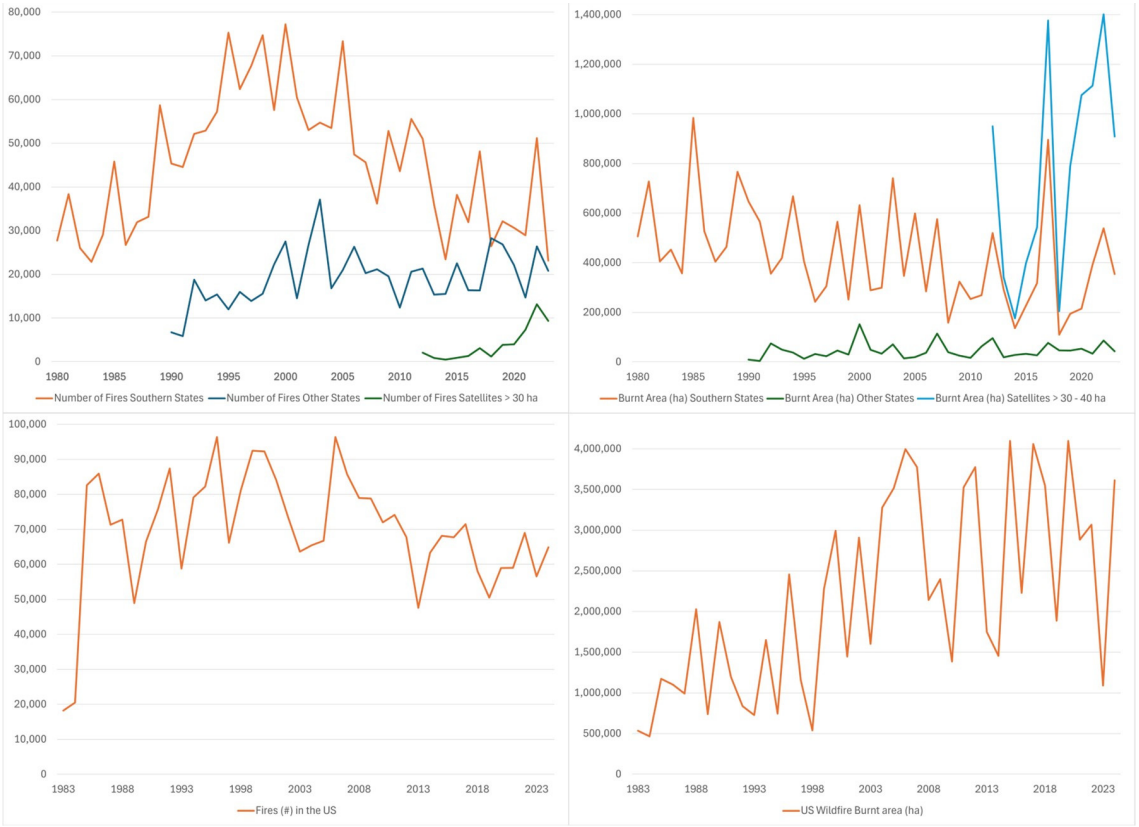


Figure 1. Wildfire statistics per year. (**Top**): EU number of wildfires per year (**left**) and burned areas in ha (**right**). Data for the EU are provided from EFFIS [14,15]. Southern States are considered to be the following: Greece, Italy, France, Spain, and Portugal. (**Bottom**): US number of wildfires per year (**left**) and burned areas in ha (**right**) for the time period 1983–2024. Data for the US are available from NIFC [9].

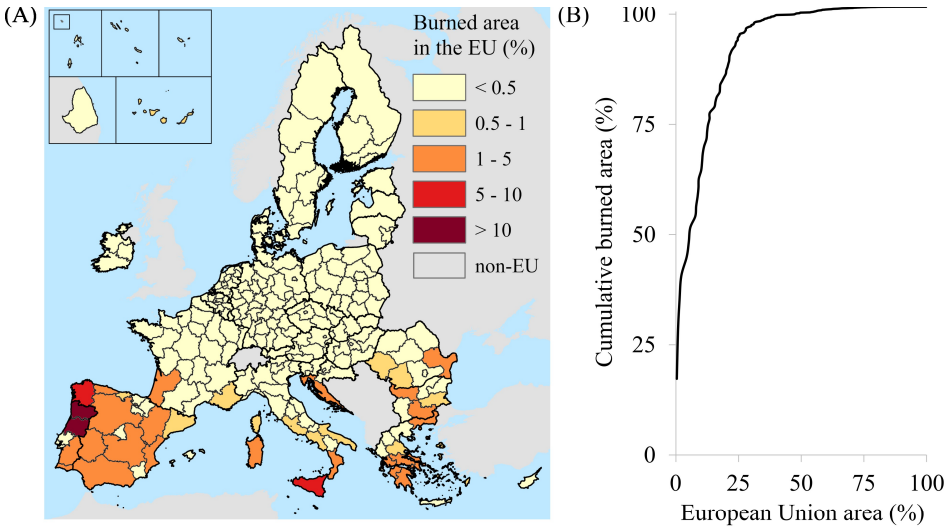


Figure 2. Percentage of burned area in NUTS2 regions (**A**) and the cumulative burned area ranked from highest to lowest percentage of burned area (**B**) in the EU. The figure is based on remote sensing-derived burned area data from large fire events recorded between 2000 and 2024 [16].

In the US, the difference between East and West States in terms of burned areas is extremely clear, with the largest burned areas observed in the western part (Figure 3).

Wildfires cause USD billions in losses, especially in the US. Global wildfire losses for the period 2015–2024, only, cost USD 136 bn, with insurers paying out USD 80 bn. Moreover, the costs of both insured and overall losses have increased dramatically after 2016, worldwide. The US has the record of the five costliest wildfires worldwide in both overall and insured losses for the period 1980–2024 (MunichRe, n.d.) [17]. The loss potential of wildfires is growing, and high building density in areas at risk is a key stone in contributing to high losses (MunichRe, n.d.) [17]. In addition to loss of damage, the death toll due to wildfires in both the EU and the US is also heavy. In the EU, from 1981 up to 2023, 739 persons have lost their lives according to Climate ADAPT [18], while in the US, 643 persons lost their lives from 1999 to 2023 [19–22] (Figure 4).

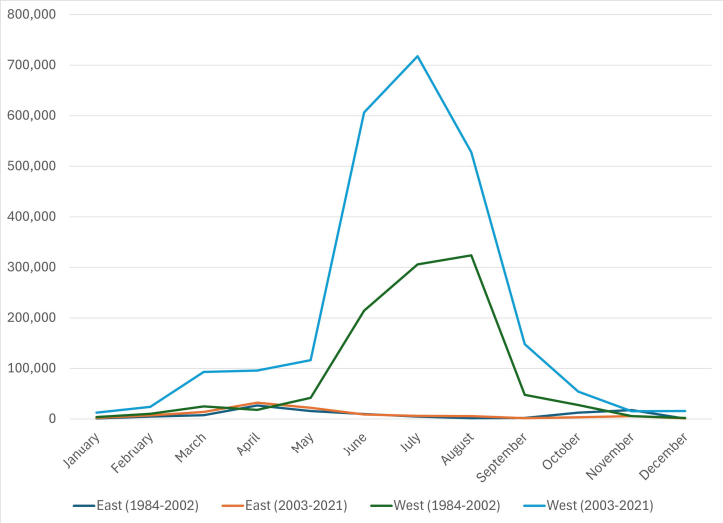


Figure 3. Monthly burned area in ha, in the West and East United States, between the time periods 1984–2022 and 2003–2021. Light blue line accounts for burned area in the West for the time period 2003–2021, green line accounts for burned area in the West for the time period 1984–2002, while dark blue line and orange line account for burned area in the East for the time period 1984–2022 and 2003–2021, respectively (Source: MTBS (Monitoring Trends in Burn Severity), 2023) [23]. www.mtbs.gov/direct-download or https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires, accessed on 3 September 2025).

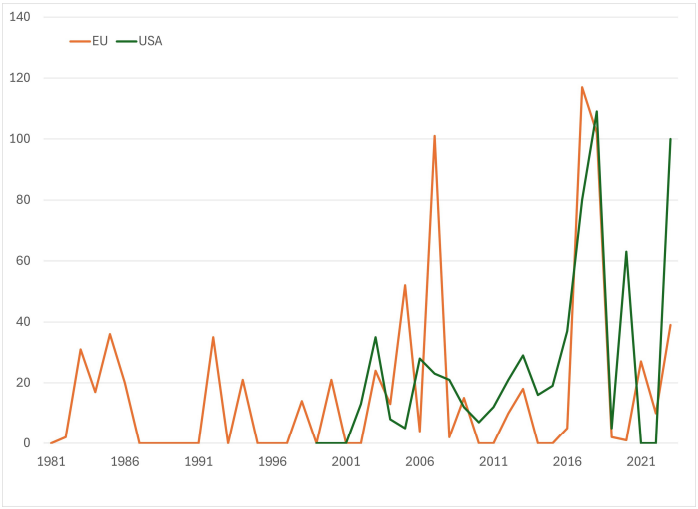


Figure 4. Fatalities due to wildfires. Orange line: EU for the period 1981–2023 [18]. Green line: US wildfire-related fatalities for the period 1999–2023 (Data source: [19–23]).

1.1. Wildfire Ignition and Spread—Key Drivers

Wildfire ignition and spread are influenced by a mix of environmental factors, fuel characteristics, weather, topography, and human activities. Fine dead fuels, particularly in herbaceous areas, are highly susceptible to ignition due to their high surface area to volume ratio [24–26]. Weather conditions such as droughts, high temperatures, and low humidity decrease fuel moisture, increasing ignition risk [27], while strong winds promote fire spread. South-facing slopes, with lower moisture, also increase fire risk.

Longer, warmer, and drier fire seasons are exacerbating these trends through heat waves and water shortages [28–31]. This convergence of factors accelerates fire spread and increases fire intensity, resulting in more destructive fires. Fuel accumulation in fire-prone areas is driving extreme wildfires, marked by rapid spread, high intensity, toxic smoke, and long-distance ember spotting. For instance, in the Mediterranean, rural depopulation and land abandonment have disrupted complex mosaic landscapes, which previously acted as firebreaks [32]. Today, areas once dominated by discontinuous patterns and low fuel loads are increasingly covered by dense, unmanaged forests [33]. Fire exclusion policies have led to more accumulated fuel, increasing the risk of large, high-intensity fires [34]. As conditions worsen, firefighter responses become overwhelmed, exacerbating the so-called "fire paradox" [35].

Human activities, including unattended campfires, discarded smoking materials, and agricultural practices, are major ignition sources [36,37]. Proximity to roads, power lines, and railroads increases ignition likelihood [38]. The growth of the Wildland Urban Interface (WUI) has led to more fire incidents and larger burned areas [39,40].

Moreover, climate change worsens ignition and spread by altering weather patterns and fuel conditions [41]. Advances in spatiotemporal modeling, considering local winds, solar radiation, and fuel continuity, improve prediction accuracy and risk management [42,43]. Moisture content is crucial in both ignition and fire spread, with higher moisture slowing the spread [44–46]. Wind speed and direction are key in fire dynamics, influencing intensity and spread by supplying oxygen and transporting embers [47]. Wind can also cause fire channeling and vorticity-driven spread [48–50]. Atmospheric instability can exacerbate fire behavior during extreme weather events [51–54]. Steep slopes accelerate fire movement due to changes in fluid dynamics and gravity around flames [55]. Fuel type and arrangement significantly impact fire behavior. Fine fuels like dried leaves are key during ignition, while overall fuel load determines fire intensity and spread [56]. Vegetation composition affects fire hazard; mixed forests behave differently than monoculture coniferous stands [57]. Extreme wildfire events, marked by pyro-convective behavior and high fireline intensity (>10,000 kW/m) and spread rates (>50 m/min), exceed local control capacities and demand coordinated, cross-border responses [58].

Ignition sources, both natural and human-made, are critical, with small ignition points like power line sparks or heat from machinery often causing wildfires [59]. Firebrands, especially in the WUI, can ignite structures ahead of the main fire [60,61], underlining the importance of understanding ignition processes and ember spread dynamics in fire management.

1.2. The Wildland–Urban Interface Problem

Global wildfire activity has surged in both frequency and severity, especially in WUI areas. The proportion of fires occurring in the WUI rose by 23% between 2005 and 2020, highlighting the growing threat to communities and infrastructure [40,62]. Recent catastrophic wildfires, such as those in Los Angeles (2017, 2018, 2025), Attica (2018), Australia (2019–2020), and more recently in Greece and Canada (2023), have underscored the devastating impacts on lives, property, and ecosystems [6,62]. Key events include the Black

Saturday bushfires (2009) in Australia, the Fort McMurray wildfire (2016) in Canada, the Pedrógão Grande wildfire (2017) in Portugal, and the Camp Fire (2018) in the United States [6,62].

1.2.1. Fire Behavior in WUI Areas

Fire regimes in WUI areas present unique challenges for management [63,64]. Despite suppression efforts having limited success or failing, full suppression policies remain common in fire-prone regions such as the western US, south-east Australia, and southern Europe [63]. The presence of CI, such as electricity, navigation aids, IT, and communication infrastructure, often limits the use of controlled burns due to their high vulnerability to fires and significant potential losses [64].

While initial firefighting efforts are effective in early stages of fires up to moderate intensity, catastrophic fires can rapidly spread, causing significant damage. The frequency of such events is expected to increase due to shorter rainy seasons and prolonged droughts, which enhance the availability of dry vegetation as fuel [65]. Wildfires have become more frequent and widespread, particularly in WUI areas [39,66]. The WUI represents a critical zone where human habitation and assets, including CI, intersect with wildland vegetation, posing distinct challenges for fire management. The rising prevalence of WUI fires is linked to urban expansion into wildland areas, human activities, and the vulnerabilities of structures in these zones [67–70].

WUI areas are typically divided into two types: the intermixed WUI, where communities extend into forested ecosystems, and the boundary WUI, where developed areas are situated at the vegetation transition. The intermixed WUI presents a complex fuel matrix, facilitating rapid fire spread, while the boundary WUI creates a distinct boundary between built and natural environments, presenting unique management challenges [67,71]. These areas are particularly vulnerable to wildfires. Over 90% of wildfires in Mediterranean Europe are attributed to human activities, with the large proportion of human-caused fires underscoring the need for effective fire risk management [72]. The WUI is defined by a housing density of at least one structure per 40 acres (16 ha) or 6.17 housing units/km^2, combined with vegetation cover exceeding 50%, both of which contribute to rapid fire spread [66,67,73–75].

1.2.2. Fuel Management Strategies in WUI Zones

Complementing CI-focused strategies, WUI zones demand robust fuel management and building code enforcement to minimize structure exposure and fire spread. Recent studies from Mediterranean landscapes demonstrate the effectiveness of GIS-based Multicriteria Decision Analysis (MCDA) combined with stochastic fire simulation tools like Minimum Travel Time (MTT) for optimizing fuel treatment allocations [76,77].

In Greece, for example, the designation of Fuel Treatment Grids (FTGs) has enabled the local forest services to prioritize high-risk areas based on ecological suitability, economic feasibility, and proximity to populated zones. Treatments have been most effective in coniferous forests and Mediterranean maquis, which exhibit high fuel continuity and combustibility. Local constraints such as steep topography, land tenure fragmentation, and road accessibility were integrated into the decision-making process, as illustrated by the "AntiNERO" national prevention program, which allocated EUR 1.4 million for proactive interventions in the Kassandra Peninsula. However, field implementation revealed logistical and administrative limitations: high-priority treatments alone could require up to 50 years and EUR 35 million using current mechanical methods, underscoring the need for cost-effective alternatives such as prescribed burning and adaptive silviculture [76,77].

1.2.3. Building Code Enforcement in WUI Areas

In tandem, building codes must enforce resilient design features to improve structural survivability in WUI areas [78]. Recommended measures by Fire-Res [79] include the installation of double-glazed windows, aluminum shutters, and the use of non-combustible materials for gutters and roof eaves. Regular maintenance and the exclusion of flammable materials within defensible space zones are critical. Vegetation management protocols should incorporate guidelines for spacing between trees and shrubs, consider species-specific combustibility and height, and reflect topographic variations, as fire behavior differs significantly between upslope and downslope conditions. Monitoring foliar moisture content can further refine risk assessments and inform adaptive strategies.

Cost-efficient fuel treatment networks in rural WUI areas must be co-designed with stakeholders to align protection priorities with economic constraints. This necessitates the use of performance metrics, trade-off models, and participatory planning frameworks. Importantly, successful implementation requires localized contextualization, cross-sectoral governance, and integration with the broader stages of the Integrated Fire Management (IFM) value chain, particularly in planning and prevention.

1.3. CI and Wildfires

CI systems such as energy, water, telecom, health, finance, and transport are vital to society but increasingly vulnerable to wildfire disruptions [80]. Failures in these systems can produce widespread consequences, affecting public safety, economic activity, and emergency response [81]. Rising hybrid threats and climate impacts further underscore the need for robust infrastructure resilience [82,83].

CIs are increasingly exposed to wildfires due to their location in fire-prone areas, the expansion of the wildland–urban interface, and the shifting fire regimes under the prism of climate change [84,85]. Wildfires can inflict severe direct damage—melting or toppling power lines, buckling bridges, degrading road surfaces, and destroying telecommunications towers—while also causing indirect service disruptions through heat, smoke, or impaired access. Recent events illustrate the scale of these impacts: the 2018 Camp Fire (Butte County, CA, US) destroyed power distribution assets, triggering blackouts that hindered evacuations; and the 2018 and 2021 wildfires in Greece severed road and rail connections, isolating communities, disrupting and causing telecommunications outages in remote towns. Such incidents demonstrate how wildfire disruptions propagate through interdependent systems, affecting sectors such as health care, finance, and transport, and amplifying risks to public safety, economic stability, and emergency response—particularly in remote or rural settings [86,87]. This relationship is bi-directional: infrastructure is both at risk from wildfires, but can also act as an ignition source. Electrical faults, equipment failures, sparks from transport operations, and infrastructure weakened by extreme weather have all triggered large-scale fires [88–90], as seen in the 2019 Kincade Fire (California) and similar events in southern Europe, such as in Mati (Attica) (Table 1). Despite well-documented risks, prevention and control measures remain insufficient. Vegetation management around critical assets is often inconsistent, underfunded, or constrained by regulatory and land use barriers. Risk assessments may fail to integrate evolving fire regime projections, leaving assets designed for historical rather than future conditions. Detection and response systems—including satellite-based fire monitoring, ground-based thermal sensors, and aerial surveillance—are frequently fragmented, under-resourced, or too slow to match the rapid escalation of extreme wildfires. Cross-sector contingency planning is limited, producing reactive rather than anticipatory protection, while post-event recovery frameworks often lack the capacity to address cascading, multi-sector failures and genuinely "build back better".

Table 1. EU and US events, CI impacts, and lessons.

Year, Event, Location	Affected CI Sectors	Type of Disruption	Key Lessons Learned/Future Challenges
2018 Campfire, CA, USA	Energy, Transport, Emergency Services	Power lines destroyed; blackouts hindered evacuation and emergency communications	Harden and underground grid assets in fire-prone areas; balance power shutoff protocols with public safety
2018 Wildfires, Kineta and Mati, Greece	Energy, Transport, Emergency Services, Residential Infrastructure	Oil refinery threatened; Narrow roads and blocked evacuation paths trapped residents; mismanaged response coordination	Improve evacuation accessibility and road design; ensure coordinated emergency response and land-use planning; allocation of resources
2019 Kincade Fire, CA, USA	Energy	Electrical equipment fault ignited wildfire; mass evacuations	Prioritize predictive maintenance, vegetation clearance, and automated fault detection
2021 Attica and Evia wildfires, Greece	Transport, Telecom, Health	Road and rail links severed; telecom outages disrupted emergency calls; hospital access restricted	Build redundancy into transport routes and deploy mobile communications during crises
2023 Maui Wildfire, HI, USA	Telecom, Water, Emergency Services	Cell towers burned; water pressure loss due to power failure hindered firefighting	Address CI interdependencies to prevent cascading failures

These cases reveal systemic vulnerabilities across diverse geographic and governance contexts. First, wildfire impacts on CIs are frequently cascading, whereby the failure of one sector (e.g., energy) rapidly compromises others (e.g., water supply, telecommunications, transport). Second, ignition sources can be infrastructure-related, reinforcing the need for predictive maintenance, vegetation clearance, and climate-adapted design standards. Third, the absence of redundancy in lifeline networks means that single-point failures can produce widespread, prolonged disruptions, especially in remote or insular settings. Finally, a sound understanding of prevention and wildfire risk reduction, systematically implemented over time, is lacking. Addressing these deficiencies demands integrated risk governance, investment in hardening and redundancy, and regulatory frameworks that reflect the accelerating pace and scale of wildfire threats.

Both the EU and the US have developed frameworks to address wildfire-related risks to CI. The recent EU CER Directive [91] strengthens resilience at the entity level from both natural and human-caused disruptions, including wildfires. The US approach to critical infrastructure protection has undergone significant updates recently. While historically guided by the NIPP [92] and PPD-21 [93], in 2024, the National Security Memorandum 22 (NSM-22) [94] replaced PPD-21 [93], introducing a renewed strategic framework for CI resilience. Furthermore, NIPP [92] is being phased out and replaced by the National Infrastructure Resilience and Modernization Plan (NIRMP) [95], expected to be finalized by the end of 2025. These developments mark the most substantial changes in US CI protection policy since 2013, reflecting evolving threats and emphasizing resilience to extreme events such as wildfires. Although full details of NIRMP [95] are forthcoming, initial public documents indicate a stronger integration of physical and cyber risks and enhanced coordination among federal, state, and local stakeholders. This study incorporates the implications of NSM-22 [94] and anticipates the forthcoming NIRMP [95] framework to ensure an up-to-date comparative analysis.

Through governance, the entire wildfire risk management cycle can be supported from prevention and preparedness to response, restoration, and adaptation. In general, the legal framework sets the basis for the actions that must be taken prior to, during, and

after an incident and provides the necessary jurisdiction of the involved stakeholders. In this aspect, effective governance integrates advanced modeling, early warning systems, real-time monitoring, and regional cooperation to support policy choices [96].

To address these challenges, the European Commission has recently launched various research and innovation initiatives like FirEUrisk (https://cordis.europa.eu/project/id/101003890 accessed on 3 September 2025), FIRELOGUE (https://cordis.europa.eu/project/id/101036534 accessed on 3 September 2025), FIRE-RES (https://cordis.europa.eu/project/id/101037419/results accessed on 3 September 2025), TREEADS (https://cordis.europa.eu/project/id/101036926 accessed on 3 September 2025), and SILVANUS (https://cordis.europa.eu/project/id/101037247 accessed on 3 September 2025) at an EU level. These research projects aim to foster multidisciplinary collaboration and develop tools, methodologies, and policy recommendations to address and mitigate wildfire risk, as well as to enhance CI resilience, especially in the wildland–urban interface, and reduce the wildfire triggering factors associated with CIs.

In parallel to these EU-led initiatives, the US implements several federally and state-supported programs addressing wildfire risk to critical infrastructure. Examples include the Firewise USA program, which promotes community-level ignition resistance; the USDA Wildfire Crisis Strategy, targeting high-risk areas for fuel reduction; and the Joint Fire Science Program, funding applied research on infrastructure protection. These efforts are supported by sector-specific mitigation plans from utilities, coordinated through public-private partnerships under federal guidance. Key institutions such as FEMA, the US Forest Service, the Department of Energy, and NIST lead research, risk assessment, and resilience-building efforts, such as the NIST WUI Fire Group, on reducing fire hazards in WUI communities. Notable programs like FEMA's Building Resilient Infrastructure and Communities (BRIC) have been cancelled by the current presidential administration, while the US Forest Service's Wildland Fire Research & Development remains important to enhancing critical infrastructure resilience, particularly in rural areas. These institutions, while operating under different governance models, share a common goal of improving CI resilience.

In addition, efforts of the Global Fire Management Hub (Fire Hub) are being supported by various countries, such as Portugal (AGIF), the United States, and Canada, to create an "one-stop shop" (the Fire Hub) that promotes the IFM approach and will support countries to incorporate IFM activities [96].

1.4. Research Objectives

This study delves into the intricate relationships between wildfires and CIs, examining the dual role of infrastructure as both a potential ignition source for wildfires and a vulnerable asset threatened by them. The analysis extends to current efforts within the European Union to mitigate wildfire risks affecting CIs, alongside a comparative examination of corresponding measures employed in the United States. The research is structured around three main analytical components: an "As-Is" policy review mapping wildfire-related CI policies in the EU and US; a comparative analysis benchmarking institutional structures and resilience strategies; and a case study synthesis examining significant wildfire events to extract lessons learned. Through this comprehensive approach, the document gains insights from real-world evidence while highlighting innovative initiatives aimed at enhancing infrastructure resilience. Ultimately, this analysis proposes potential policy pathways seeking to strike a balance between resilient CIs and minimizing the risk of extreme wildfire occurrence. By promoting science-based policies and collaborative efforts among policymakers, scientists, and practitioners, this work aims to strengthen the capacity

of communities and infrastructures to build resilience, contributing to a more resilient and sustainable future.

The roadmap diagram (Figure 5) illustrates how the study progresses from global wildfire context and drivers, through WUI and CI challenges, governance and policy frameworks, evidence from case studies and research, and culminates in a comparative analysis with actionable policy recommendations.

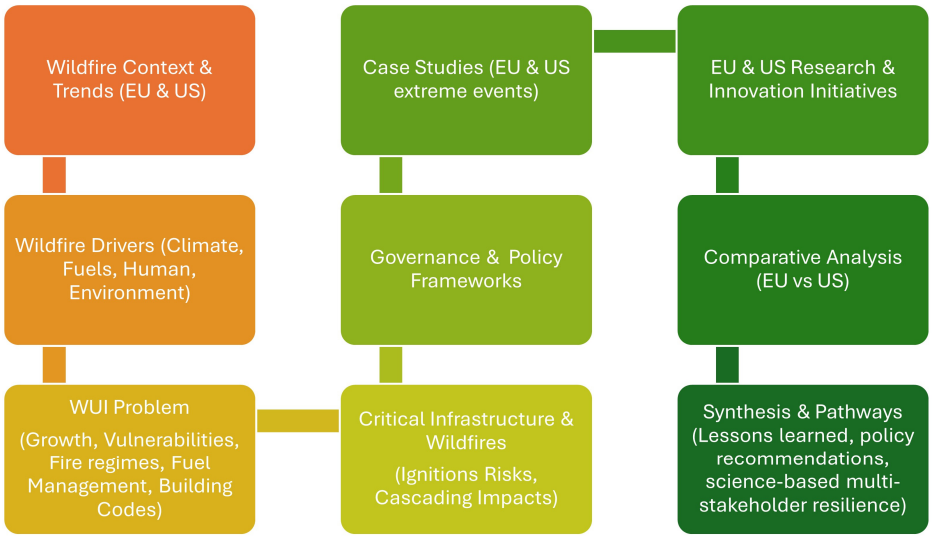


Figure 5. Study roadmap.

2. Methodology

This study explores the dual role of critical infrastructure (CI) in wildfires—as both ignition sources and vulnerable assets. It examines wildfire risk mitigation efforts in the EU and compares them to those in the US.

This research follows a three-part analytical framework, which is also schematically depicted in Figure 6:

1. "As-Is" Policy Review: Analyzes wildfire-related CI policies in the EU and US—such as the CER Directive [91], the Union Civil Protection Mechanism (UCPM) [97,98], the US PPD-21 [93] and NSM-22 [94], as well as NIPP [92] and NIRMP [96] to assess strengths and gaps in addressing wildfire risks;
2. Comparative Analysis: Benchmarks institutional structures, governance, funding, and resilience strategies across both regions to identify best practices and areas for improvement;
3. Case Study Synthesis: Reviews major wildfire events—including the 2018 Camp Fire, Portugal 2017, and Greece 2018—to derive insights on wildfire causes, impacts on CI, response effectiveness, and lessons learned.

A data-driven, multi-source methodology has been followed with sources that include scientific literature, national/international policy documents, project reports, and post-fire event data. This work is part of the Infrastructure Working Group, one of the five Working Groups of the FIRELOGUE project. The other four working groups are related to the environment, society, insurance, and civil protection topics. Among the key objectives of FIRELOGUE is to integrate innovation and findings of the EU's Green Deal-funded project for the prevention of wildfires under the prism of just transition.

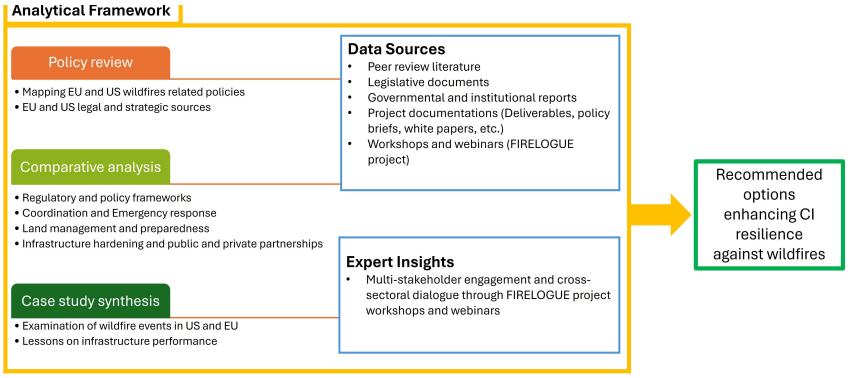


Figure 6. The methodological framework.

To fulfill the objectives set out in the FIRELOGUE project, two hybrid (physical and remote attendance) stakeholder workshops took place in Solsona (Spain) and Nea Makri (Greece), each engaged 13 and 17 participants, respectively, involving emergency responders, CI operators, planners, researchers, and WUI residents. These workshops utilized cross-sectoral dialogue formats to foster collaboration and understanding among a diverse range of the aforementioned stakeholders. The workshops were structured around four key thematic strands: socioeconomic factors, climate policy (both mitigation and adaptation), technology, and earth observation. These themes guided discussions within and across the working groups, ensuring that parallel processes were maintained while also promoting cross-working group exchange of ideas and perspectives. The primary objective of these workshops was to identify synergies and conflicts related to Wildfire Risk Management (WFRM) and CIs, using a gradual, structured dialogue format to explore these dynamics and foster more integrated and effective risk management strategies [99].

Participants in the workshops were grouped to balance sectoral expertise, with facilitated sessions combining topical presentations, brainstorming, scenario exercises, and consensus-building. Outputs were documented in detailed proceedings, summarizing identified synergies, conflicts, and priority actions. These proceedings are publicly available via the FIRELOGUE platform (https://lessonsonfire.firelogue.eu/ accessed on 3 September 2025).

Given the fundamental structural differences between the European Union and the United States—the EU operates as a supranational union where sovereign member states share specific competences, while the US functions as a federal system with centralized legislative and executive authority—this study employs a multi-level comparative framework to ensure analytical rigor. At the supranational and federal levels, the paper compares EU policies such as the Civil Emergency Response Directive, Union Civil Protection Mechanism [97,98], and Horizon Europe research initiatives against US federal policies, including NSM-22 [94], the forthcoming National Integrated Risk Management Plan [96], and Federal Emergency Management Agency programs. At the sub-national level, wildfire governance is examined in EU member states (Portugal and Greece) alongside US state-level approaches (California and Hawaii). This methodological design enables direct comparison between equivalent governance tiers, revealing how coordination mechanisms, funding structures, and enforcement capabilities differ across these distinct political systems while controlling for structural variables that might otherwise confound the analysis.

3. Wildfire and Critical Infrastructures

3.1. Critical Infrastructure (CI) and Wildfire Ignition Risks

The proximity of critical infrastructure (CI) to forested and protected areas, along with the mobility of people and goods in rural and remote regions, increases the likelihood of

CI causing or facilitating wildfire ignition [38,100–102]. Infrastructure such as power lines, utility substations, roads, and railways is particularly vulnerable to causing wildfires, either accidentally or intentionally.

The most common ignition sources from CI are power lines, which can spark wildfires through three primary faults: electric arcs, structural failures, and external objects falling onto lines [84,103,104]. Electric arcs occur when electrical discharges bridge air gaps, often due to high voltage or strong winds causing conductors to sway or clash together. These arcs can ignite vegetation without direct contact. Structural failures, such as cables tearing or pole breakage, can lead to live wires touching the ground or flammable materials, often exacerbated by aging infrastructure or extreme weather [94]. External objects like trees or branches falling on power lines can create unintended conductive paths that spark or overheat, igniting nearby vegetation [105].

To reduce wildfire risks, effective mitigation strategies include regular inspection, advanced fault detection systems, and vegetation management around power lines, especially in high-fire-risk areas. This is essential to protect communities and ecosystems from catastrophic fires, as these types of ignitions tend to occur on days of very high fire danger, mainly due to strong winds.

3.2. Impacts of Wildfires on Critical Infrastructures and Society

Wildfires present direct and indirect risks to physical infrastructure and may trigger cascading effects, impacting systems like telecommunications, power, and water supply. Protecting both physical and digital infrastructure from wildfire impacts is crucial. Strategies include using stronger poles, reducing spans between poles, and burying power lines where possible. Increasing the connectivity of networks and grids can reduce the impact of wildfires, providing system redundancies. While wildfires may damage electricity systems, they can also lead to cascading failures in drought-prone regions, where fire from electrical faults may not be contained swiftly. The loss of power supply can affect telecommunication networks, transport systems, and critical infrastructure, increasing risks to communities during both the event and recovery phases [106].

The economic and social impacts of wildfires on CI depend on the size, duration, and resilience of the systems involved. Fast resource deployment, stakeholder communication, and early warning systems can reduce the effects of climate-induced events [107]. Funding allocation in fire prevention may be perceived as inefficient by resource managers because the tangible benefits of such investments in prevention are not immediate. Nevertheless, fire prevention investments can reduce suppression costs by 88% and overall spending by 55%, showing that investment in prevention can offset rising suppression costs [107].

Energy, transport, and telecommunication infrastructures are highly vulnerable to wildfires. Economic losses include property damage, income loss, and increased costs for insurance companies and energy utilities, ultimately affecting consumers [108–110]. Wildfires also disrupt supply chains, affecting businesses and industries.

Wildfires can harm public health by damaging power lines and substations, which impacts drinking water, wastewater systems, and food supply chains. Disruptions to medical equipment and medication transport also occur. Power system disruptions are particularly costly, especially for vulnerable groups who depend on electricity-dependent medical equipment [111]. Real-time data systems are needed to coordinate evacuations and health responses [112]. Without proper planning, power outages during wildfires threaten community safety and well-being.

Therefore, reinforcing and protecting CIs' grid (digital and physical assets) from the impacts of wildfires becomes pivotal. Potential approaches focus on stronger poles and system components, reduction of spans between poles, and bundling or burying power

lines where possible. Investing in upgrades to the power system provides protection against service disruption (e.g., by increasing the resilience to these for hospitals, communication centers, and fuel terminals). These measures may include the adoption of enhanced powerline safety settings (known as fast trip), underground distribution lines, and creating multiple remote grids to create redundancy where other alternatives are not feasible.

3.3. Vegetation Management and Critical Infrastructure

Critical infrastructure management plays a key role in wildfire risk reduction, particularly in implementing fuel treatments to minimize fire ignitions [113,114]. Treating vegetation near infrastructure, such as power lines and railways, poses challenges, including safe access for crews, operational restrictions, and coordination with infrastructure operators to avoid disrupting services. Environmental considerations and regulatory compliance also add complexity. Effective public and stakeholder engagement, along with adequate funding, is necessary for long-term maintenance and success. Optimizing vegetation management near CI—such as electrical grids, roads, and rail systems—is crucial for reducing wildfire risk. Determining Acceptable Safety Distances (ASDs) for vegetation clearance depends on factors like vegetation type, climate, and infrastructure requirements. These distances are dynamically calculated using a multiplier system to account for fuel load and combustibility, supporting scalable vegetation management across European regions.

Operationally, a zonal prioritization methodology incorporating historical ignition density, fire spread modeling (Rate of Spread—ROS), and topographic hazard overlays has been applied to delineate intervention buffers along linear infrastructure. High-priority zones typically include substation vicinities, WUI transition corridors, and rail-adjacent unmanaged woodlands. Targeted mitigation actions within these zones include mechanical clearance, prescribed burning, non-flammable ground cover applications, and protective infrastructure coatings. Maintenance protocols such as UAV-based ASD monitoring, seasonal inspections, and preemptive shutdown strategies are recommended, supported by legal instruments for liability and cross-sector coordination.

3.4. Critical Infrastructure as Firebreaks

Critical infrastructures like roads and utility corridors can also serve as effective firebreaks, hindering wildfire spread. Major highways, due to their width and maintained surfaces, can prevent fire progression [115]. Even smaller, well-maintained forest roads can delay fire spread and provide access for firefighting teams [116]. Infrastructure in or near forested areas can support suppression efforts by fuel loads around them being reduced and properly maintained [117]. Personnel working in these areas can also act as first responders, aiding early fire control [118,119]. This coordinated approach boosts the effectiveness of wildfire management.

3.5. FIRELOGUE Infrastructure Working Group Workshops Results

In the first workshop in Solsona (Spain, July 2023), discussions focused on identifying sector-specific challenges, particularly the vulnerabilities of energy, transport, and communications systems, and exploring how early-warning technologies, vegetation management, and policy coherence can reduce risks. Cross-WG sessions highlighted interdependencies between infrastructure and environmental management, especially regarding renewable energy siting.

The second workshop in Nea Makri (Greece, April 2024), built on the Solsona outcomes and high-level recommendations, was refined into actionable measures for policymakers, operators, and local authorities. Participants examined implementation pathways, stakeholder responsibilities, and justice considerations in infrastructure resilience. Attention was

given to the role of Nature-based Solutions (e.g., green firebreaks, ecological restoration) and the integration of real-time data into operational planning.

The Infrastructure Working Group's work intersects with all the aforementioned four thematic strands (Section 2) as follows:

Policy coherence—ensuring infrastructure, energy, and WFRM policies avoid creating new ignition risks.

Technology—deploying advanced monitoring, modelling, and interoperable communication systems.

Community engagement—involving local stakeholders in prevention, preparedness, and emergency planning.

Nature-based Solutions—using green buffers, ecological restoration, and fire-resistant landscaping to protect assets and support biodiversity.

Building on the discussions within the working groups, the two workshop cycles included discussions on a cross-WG level to debate and understand the cross-links between different stakeholder groups, as well as the synergies and conflicts that may arise from specific WFRM measures. Policy highlights as a result of the workshop's discussion include [120–122] the following:

- To promote a multi-governance approach to wildfire prevention and infrastructure resilience, policymakers should encourage collaboration and coordination among government agencies, follow a multi-risk governance approach and policy coherence, encourage community engagement in the whole cycle of disaster management, and develop comprehensive support systems for policymakers.
- To strengthen legal frameworks for promoting critical infrastructure resilience against wildfire risk and support the development and implementation of new/updated codes for infrastructure upgrading or safeguarding against wildfires, policymakers should ensure the full implementation and monitoring of CER and SEVESO III EU Directives, develop and implement new policies and regulations that address the wildfire–infrastructure interface, and consider data sharing and cooperation of stakeholders in the regulations.
- To advance technology usage in the whole cycle of wildfire risk management for critical infrastructures, policymakers should improve knowledge on the effectiveness of fire prevention technologies by integrating scientific advancements into policy frameworks.
- To enhance risk assessment for managing wildfires for critical infrastructures, policymakers should promote better data accessibility for fire management research and promote landscape management.
- To address the lack of standardization in wildfire risk management and critical infrastructure resilience, policymakers should take the lead in creating certification schemes for personnel and systems involved in wildfire management.
- To focus more on research and innovation, policymakers should use legislation to support the need for wildfire data collection and availability covering ignition points and causes.

4. The EU and the US Management Pathways: An Outlook and Comparative Analysis

4.1. EU Critical Infrastructure and Resilience

Challenges of Disasters on Critical Infrastructure (CI): Disasters pose significant challenges to the functioning of vital CI systems, with natural and human-made threats leading to substantial loss of life and property damage [114]. These challenges are compounded by escalating risks, exacerbating societal consequences, creating new vulnerabilities, and

increasing social inequalities. The evolving nature of these risks affects nations on an unprecedented global scale, making the multi-hazard framework for CI increasingly systemic [123].

The European Union (EU) has long recognized the importance of CI across Europe. This recognition led to the establishment of the European Programme for Critical Infrastructure Protection (EPCIP) in 2006, followed by the Directive on the identification and designation of European Critical Infrastructures [124], which has since been repealed and replaced by the CER Directive [91] focusing on CI resilience. The NIS2 Directive [125], which repeals the 2016 NIS Directive (2016/1148) [126], expands cybersecurity requirements for essential services, emphasizing the need for cross-border cooperation to enforce national resilience strategies.

The CER Directive mandates that EU Member States ensure the resilience of critical entities by taking necessary steps to maintain essential services without interruption. This framework encompasses all potential risks, including natural disasters, public health emergencies, hybrid threats, and terrorism [91].

Expanding Scope of Critical Infrastructure: Unlike the earlier ECI Directive [124], which focused on energy and transport sectors, the CER Directive expands the scope to cover 11 sectors, including health, drinking water, wastewater, banking, financial services, digital infrastructure, public administration, space, and food production [91]. The identification of critical entities, defined by their mandate to provide essential services, is a key obligation under this Directive. These entities must be classified based on criteria that assess potential cross-sectoral or cross-border disruptions.

Defining Resilience in CI: The CER Directive defines resilience as "a critical entity's ability to prevent, respond to, resist, mitigate, absorb, accommodate, and recover from incidents" [91]. Globally, various definitions exist related to the resilience of CIs [81,93,123,127–132]. For instance, the UNDP defines CI resilience as "the ability to anticipate, withstand, and recover from shocks, adapting to new conditions for better future coping with both chronic stresses and acute shocks" [123]. The CER Directive emphasizes a comprehensive approach, requiring entities to adopt technical, security, and organizational measures that align with the risks they face, ensuring effective incident response and continuity of essential services. The CIP ecosystem is evolving rapidly in response to emerging threats and technological advancements. Key trends include the following:

1. Convergence of Physical and Cybersecurity: The integration of physical and cyber systems is driving a more holistic approach to CI protection;
2. Use of Advanced Technologies: The adoption of technologies like artificial intelligence, machine learning, IoT, and blockchain is enhancing threat detection, early warnings, and rapid responses;
3. Increased Collaboration: There is a growing trend of public-private collaboration and knowledge sharing to strengthen CI resilience;
4. Focus on Resilience: There is an increasing focus on not just protecting CI but also ensuring that it can recover quickly and maintain functionality during disruptions;
5. Regulatory Compliance: The development of standards and regulations is becoming more important to ensure a harmonized approach to CI resilience across sectors and countries;
6. Increased Awareness and Education: Efforts are being made to raise awareness among the general public and stakeholders about the importance of CI and its resilience.

4.2. Wildfire Management Pathways in Europe

In the EU, wildfire and land management fall under shared competences of the Union and Member States (Articles 191 and 192 of [133]), with national authorities holding primary

operational responsibility. No binding EU legislation directly governs wildfire protection, but several frameworks support prevention, preparedness, and response. The European Forest Fire Information System (EFFIS) was launched in 1998 and later integrated into the Copernicus Emergency Management Service. EFFIS now brings together 43 countries to collect and forecast fire data [134].

The EU Biodiversity Strategy for 2030 [135] identifies forest fires as major climate-related threats. It mandates strict protection of high-value forests, restoration of degraded ecosystems, and integration of fire risk into forest management plans. Complementing this, the EU Forest Strategy for 2030 [136] sets actions for sustainable forest management, including fuel control, fire-resilient species, and silvicultural adaptation.

The Union Civil Protection Mechanism (UCPM), established by Decision No. 1313/2013/EU [97] and strengthened by Regulation (EU) 2021/836 [98], serves as the main EU framework for mobilizing firefighting assets across borders. National efforts are supported by rescEU, coordinated through the Emergency Response Coordination Centre (ERCC). Early warnings are generated via EFFIS and Copernicus Emergency Management Service, which provide daily forecasts, satellite fire mapping, and situational awareness.

Wildfire risk management in the EU begins with prevention, using fire behavior models, historical data, vegetation and climate mapping, and infrastructure risk analysis [1,137]. Preparedness includes strategic prepositioning of resources and deployment of early warning systems integrating meteorological and satellite data (Di Giuseppe et al., 2020; Rodrigues et al., 2019; 2020) [119,138,139]. In 2023, the Wildfire Peer Review Assessment Framework (PRAF) was introduced under UCPM. It enables voluntary self-assessments and peer reviews of national wildfire governance across seven dimensions, including prevention, response, and recovery [66,140–142]. Recovery efforts, guided by UCPM protocols, include rapid damage assessments, restoration of electricity, transport, and communications infrastructure, and ecological rehabilitation such as reforestation and erosion control. Long-term monitoring uses satellite and ground-based tools to inform adaptive wildfire management.

4.3. US Critical Infrastructures Policy and Wildfire Risk

Update on US Policy Framework: In April 2024, Presidential Policy Directive 21 [93] was replaced by NSM-22 [94], which establishes updated federal priorities for critical infrastructure security and resilience. NSM-22 [89] mandates a sector-by-sector risk management approach, requires regular national risk assessments, and explicitly incorporates climate-driven hazards such as extreme wildfires. Concurrently, the NIPP [87] is being superseded by the forthcoming NIRMP [95]. The NIRMP [95] will integrate physical, cyber, and natural hazard resilience under a unified framework and introduce enhanced coordination mechanisms between federal, state, and tribal authorities, with explicit provisions for wildfire mitigation in high-risk sectors such as energy, water, and communications.

The US has several federal policies that apply at the federal level but have more nuanced applications at state and local levels, especially as implemented for individual sectors and in private–public collaborations. The NIPP, first established in 2006 and updated in 2009, covers 16 critical infrastructure sectors, integrating both physical and cybersecurity measures [92].

Presidential Directives and Executive Orders (EO) have emphasized resilience and the integration of planning to support collaborative, risk-based standards development [93,143,144]. Recently, ref. [145] further focuses on wildfire response and mitigation, requiring the Federal Government to enhance its support for state and local leaders by streamlining federal wildfire capabilities. This order also encourages local, technology-enabled strategies for land management and the identification of policies that hinder

wildfire prevention, detection, or response. Additional policies and EOs have addressed cybersecurity specifically as AI is rapidly integrating into government and private sector operations [146,147]. The energy sector has a cross-cutting function and enables the function of many other critical infrastructure sectors; thus, the protection of its reliability of both distribution and generation is a central focus of US policy [148].

NSM-22 [94] promotes the enhancement of CI resilience through the increasing adoption of requirements. Due to the decentralized management of the different sectors, most have a public–private partnership that provides guidance and sets forward best practices and incentives, but there is limited enforcement. The US framework allows greater customization, flexibility, and more adaptability driven by industry rather than top-down policy, which may take longer time periods to initiate and enact.

4.4. Wildfire Management Pathways in the US

In the US, wildfire risk is addressed through policies and procedures developed by state and local governments, public utility commissions, land management agencies, and electric utilities. The Wildfire Crisis Strategy [149] builds on the National Fire Plan and the National Cohesive Wildland Fire Management Strategy. It sets out a 10-year, multi-agency framework for fuel treatments and forest health efforts to reduce fire risks, using controlled burns, mechanical thinning, and community engagement.

High-risk landscapes—where ignitions may endanger homes, infrastructure, and essential services—were identified for prioritized treatment. The USDA Wildfire Crisis Strategy targets these areas to protect power lines, major roads, and drinking water sources from wildfire-related disruptions [149].

To strengthen wildfire governance, Congress established the Wildland Fire Mitigation and Management Commission through the 2021 Infrastructure Investment and Jobs Act [150]. The Commission, composed of 50 members, produced policy recommendations covering all phases of wildfire risk—mitigation, response, and recovery. It advocated a proactive, multi-scalar approach to wildfire management, recognizing that no single cause or solution exists. Key recommendations include improved coordination, interoperability, and system simplification [151].

The US Fire Administration (USFA), part of DHS/FEMA (Department of Homeland Security/Federal Emergency Management Agency), supports local outreach by providing educational materials—from GIS-based wildfire maps to training for fire-adapted communities [152–154]. The National Fire Protection Association (NFPA) has published WUI-specific codes and standards [155] aligned with the International Wildland–Urban Interface Code [156]. While federal codes exist, states and cities adopt and adapt them voluntarily through zoning and land use regulations, promoting the use of fire-resistant materials and vegetation buffers.

There is no central US agency responsible for electric utility infrastructure hardening. Instead, resilience efforts operate through public–private partnerships. The Federal Energy Regulatory Commission (FERC) plays a key role, overseeing standards set by the North American Electric Reliability Corporation (NERC). NERC also works with the Department of Energy, DHS, and the Cybersecurity and Infrastructure Security Agency (CISA) to address evolving threats.

Despite having one of the world's most complex electrical grids [157], the US has taken limited systematic action to wildfire-proof its infrastructure [158]. However, adaptation is advancing. Utilities implemented are

- Enhanced Powerline Safety Settings in high-risk areas;
- Removal of overhead assets when alternatives exist;
- Undergrounding distribution lines, though expensive (USD 2.6 M–6.1 M per mile);

- Covered conductors and fire-resistant poles, which cost ~USD 480,000 per mile [159].

California utilities lead in wildfire hardening. Though undergrounding is part of their plans, most rely on more affordable methods such as covered conductors and replacing wood poles with steel [160].

The Firewise USA Program [161], administered by NFPA and supported by the US Forest Service and state agencies, helps neighborhoods increase ignition resistance. It promotes defensible space, fire-resistant construction, and community engagement. Programs are run by volunteers using local outreach and educational campaigns [162].

4.5. Comparative Analysis

The comparative analysis presented here incorporates the 2024 transition from NIPP [92] and PPD-21 [93] to NSM-22 [94] and NIRMP [95] on the US side. This change significantly reshapes federal critical infrastructure resilience governance, including wildfire risk integration as part of an all-hazards risk approach at the national level, expanded interagency coordination requirements, and new performance metrics for resilience investments. These developments bring US federal policy somewhat closer to the EU's CER Directive [91] in terms of mandatory risk assessment cycles, though enforcement remains more sector-specific and incentive-based in the US.

Across both the EU and the US, wildfire strategies intersect with broader critical infrastructure resilience policies. However, their legal foundations, coordination mechanisms, funding models, and approaches to land management, preparedness, and infrastructure hardening differ (Table 2).

Table 2. Comparison of EU's harmonized resilience objectives implemented by member states versus the US's centralized whole-of-government framework with strong federal leadership and private-sector incentive structures. US policy references updated to reflect NSM-22 [94], replacing PPD-21 [93] and the transition from NIPP [92] to the forthcoming NIRMP [95]. NSM-22 [94] introduces stronger integration of climate-driven hazards, including wildfires, into national critical infrastructure risk management.

Aspect	EU	US
Policy Basis	Shared competence (TFEU Arts 191–192); CER Directive 2022/2557 (11 sectors)	NSM-22 all-hazards policy, whole of government approach; NIPP 2013 risk-management framework (16 sectors)
Response Coordination	UCPM (Decision 1313/2013/EU; rescEU; ERCC); EFFIS/Copernicus early warning	NIFC; ICS under USFS/BLM/FEMA; mutual aid via EMAC; sector councils
Funding	National budgets; EU rescue pools; research grants (Horizon Europe; ISF)	FEMA grants (Assistance to Firefighters); Firewise program; utility cost recovery via state commissions
Land Management and Preparedness	Member State forest laws; Forest Strategy 2030 fuel guidelines; EFFIS/Copernicus monitoring	Federal land agencies (USFS, BLM) fuel treatments; prescribed burns; state/local wildfire risk maps under NIPP
Infrastructure Hardening and PPP	CER Directive requires resilience planning, assessments, penalties; limited EU-level mandates	NIPP-driven public–private partnerships; Sector/Government Coordinating Councils; FERC/NERC CIP reliability standards

4.5.1. Regulatory and Policy Frameworks

In the EU, resilience obligations for essential services are now outlined in the Critical Entities Resilience (CER) Directive, which requires Member States to transpose it into national law and sets the framework for the creation of national contact points, important sectors at national level and at EU level, incident reporting for disruptive events, and additionally sets the framework for cross-sector and cross-border collaboration [91]. Wildfire management, per se, remains a competence of Member States and regions, with no binding EU-level regulation specifically to forest fire protection; nevertheless, wildfires are an existing threat and should be accounted for in respective risk assessment and management plans.

The US framework, updated recently, with NSM-22 [94] replacing PPD-21 [93], mandates a whole-of-government approach for CIs; it reaffirms the 16 designated CI sectors, establishes a federal contact point for managing risks within each sector, and sets the framework of minimum security and resilience for secure CIs within and across the different sectors. It also provides the jurisdiction to sector-specific contact points to create risk assessment and management plans. In general, the US takes a sector-specific approach, compared to the broader EU approach, reflecting the differences in policy and oversight between the two regions.

4.5.2. Coordination of Emergency Response

The EU's Union Civil Protection Mechanism (UCPM), established by [98] and reinforced by [98], pools firefighting resources (rescEU) and delivers early warnings via EFFIS and the Copernicus Emergency Management Service. Deployment is coordinated through the Emergency Response Coordination Centre (ERCC) when national capacities are exceeded [91]. In the US, inter-agency coordination is structured around the National Interagency Fire Center (NIFC) and the Incident Command System (ICS), with FEMA, USFS, and BLM contributing personnel and assets under unified command. PPD-21 [93] directs the Department of Homeland Security to integrate these efforts, while the NIPP promotes critical infrastructure protection, mutual-aid agreements, and sector-specific councils to streamline resource sharing [87,88].

4.5.3. Funding and Incentive Mechanisms

EU wildfire prevention and response are financed principally at the national level, with limited earmarked EU funding: the UCPM's rescEU pool is funded from the EU budget, and broader resilience research may be supported under Horizon Europe (Reg (EU) 2021/695) and the Internal Security Fund (Reg (EU) 2021/1149). The CER Directive does not establish a dedicated wildfire fund. In the US, Congress authorizes federal grants (e.g., FEMA's Hazard Mitigation Grant Program and the USFS State Fire Assistance grants) and voluntary programs such as Firewise USA to incentivize community risk reduction. Utilities may cost-recover wildfire mitigation investments through state public-utility commissions under NIPP-aligned guidelines [92,93].

4.5.4. Land Management and Preparedness

EU land use planning and fuel-management guidelines flow from the EU Forest Strategy for 2030 and national forest laws, but implementation rests with Member States. Preparedness leverages EFFIS fire-danger indices and satellite-based monitoring via Copernicus to trigger national and regional readiness measures [91]. In the US, roughly half of western landscapes are managed by federal agencies (USFS, BLM), which, under the FLAME Act and National Fire Plan, conduct mechanical thinning and prescribed burns. NIPP's risk-management framework guides states and localities in mapping wildfire exposures and integrating them into broader emergency-management plans [92,93].

4.5.5. Infrastructure Hardening and Public–Private Partnerships

The CER Directive mandates that critical entities take resilience measures, perform risk assessments, and face penalties for non-compliance, fostering stronger public–private cooperation in resilience planning [91]. The US model relies heavily on sector-specific partnerships under NSM-22 [94]: Sector Risk Management Agencies have the primary role to drive the effort towards secure CIs, while the Secretary of Homeland Security coordinates the national effort. Other agencies and Coordinating Councils and Government Coordinating Councils bring together utilities, emergency services, and regulators to agree

on hardening standards and to integrate cybersecurity and physical security under FERC-backed NERC CIP reliability standards [92,93].

5. Case Studies: Lessons from Extreme Wildfire Events

The following case studies illustrate the impact of wildfires on CI and the effectiveness of different resilience strategies:

California Wildfires (US): The 2017 and 2018 wildfires in California, leading to power outages, communication failures, and transportation disruptions, caused USD 13 billion in insured losses [163]. The 2017 fires were exacerbated by strong winds and power infrastructure failures [164], while the 2018 Camp Fire revealed weaknesses in aging transportation infrastructure [163]. These events highlight the need for fuel management, grid hardening, and infrastructure resilience to prevent cascading impacts. Policy context: At the time, wildfire-related CI hardening in California was guided by state Public Utilities Commission mandates and voluntary federal frameworks under PPD-21 [93] and NIPP [92]. The scale of outages revealed gaps in grid safety settings and vegetation management, prompting acceleration of utility wildfire mitigation plans under state legislation SB901 signed in 2018.

2017 Pedrógão Grande Wildfire Complex (Portugal): On 17 June 2017, one of the most severe wildfire events in Portugal's history began when at least five separate fires merged in the central region, ultimately consuming more than 45,000 ha. The human toll was heavy: 66 people lost their lives, many while attempting to flee, over 250 were injured, and more than 1000 structures, including 263 homes, were damaged or destroyed. Direct losses to housing and private property were estimated at around EUR 200 million [7]. Critical infrastructure also suffered extensive damage. Municipal assets—such as local roads, public lighting, water distribution systems, and urban equipment—required approximately EUR 21.7 million in repairs, while restoration of the national road network cost an additional EUR 2.6 million, and mobilizing firefighting and emergency services added another EUR 4.5 million [165]. The disaster disrupted roads, water supply, power, and telecommunications. In response, the Portuguese government launched a ten-year National Plan for Integrated Rural Fire Management (2020–2030), with two primary targets: to reduce the occurrence of large fires (over 500 ha) to less than 0.3% of all incidents, and to limit the total burned area to under 660,000 ha during the plan's duration. To coordinate implementation, in 2018, the Agência de Gestão Integrada de Fogos Rurais (AGIF) was created to promote integrated rural fire management through a territorial governance model involving both public institutions and local communities in protecting Portugal's landscape and infrastructure.

Policy context: Portugal's catastrophic 2017 fire season, including the Pedrógão Grande complex wildfires, predated the EU CER Directive. At that time, community and critical infrastructure resilience planning was shared between the National Authority for Emergency and Civil Protection (ANEPC) and the Institute for Nature Conservation and Forests (ICNF), largely through municipal Forest Fire Defense Plans (PMDFCI) and ICNF technical guidance. In response, the government created the Agency for Integrated Rural Fire Management (AGIF) in 2018, approved the National Plan for Integrated Rural Fire Management (PNGIFR) in 2020, and established the Integrated Rural Fire Management System (SGIFR) in 2021 to coordinate, monitor, and close governance and operational gaps between prevention and suppression, national agencies and municipal authorities, and public and private infrastructure operators.

2018 East Attica Wildfires (Greece): The 2018 Attica wildfires caused significant fatalities and property damage. In the morning of the 23rd of July, a wildfire ignited in a dense forest of pines in the Western part of Attica. The fire damaged houses in

the broader Kineta area, spotted over a six-lane highway, and threatened an oil refinery located in the area. The same day, in the afternoon around 17:00 h local time, another wildfire ignited in the east of Attica, at the Penteli mountain. Due to the combination of extreme weather conditions (high temperatures, unusually strong western winds), vegetation type and structure, and topography, the fire spread rapidly towards the East and South, moved towards the sea (Mati area) where it entered the WUI community of Mati (total fire duration of about 3 h) [166]. This extreme wildfire event resulted in the death of 103 people, burned residential buildings, vehicles, and vegetation. In the affected area of Rafina-Pikermi and Marathonas municipalities, 4691 buildings were inspected, and only 50% were characterized as usable after the event occurrence. Specifically, in the Mati locality, 23% of the inspected buildings have been categorized as "not to be used until repaired" and 28% as "dangerous/heavily damaged" [167]. The event highlighted the need for improved land use planning, building codes, awareness issues, evacuation, and other emergency response capabilities.

Policy context: Response and CI protection measures were governed by national law with EU support via UCPM assets. The disaster prompted a review of building codes and evacuation protocols, aligning with emerging EU-wide resilience priorities.

2023 Evros Wildfires (Greece): The wildfire disaster that affected the Dadia-Lefkimi-Soufli Forest National Park in August 2023 represents one of the most extensive and destructive wildfire events ever recorded in Europe. The fire ignited on 19 August 2023 and remained active for over 15 days, ultimately burning approximately 93,880 hectares, with an estimated 71,000 hectares located within the boundaries of the protected forest park. The fire, fueled by extreme meteorological conditions—including multiple heatwaves, prolonged drought, and strong winds—was characterized by flame lengths observed to exceed 40 m and fireline intensities over 90,000 kW/m, making suppression efforts impossible at the peak of the event [168]. Ecologically, the wildfire devastated one of Europe's most significant biodiversity hotspots, home to endangered avian species such as the Black Vulture (Aegypius monachus), Egyptian Vulture (Neophron percnopterus), and Griffon Vulture (Gyps fulvus). The destruction of breeding and feeding habitats is expected to have long-term implications for the viability of these species within the region. The societal impacts were also considerable. Multiple settlements in the municipality of Alexandroupolis were evacuated, and infrastructure damage was reported across several sectors. The extensive fire perimeter disrupted road access, affecting both local transportation and emergency logistics. Power outages occurred due to the destruction of electricity distribution lines and utility poles, impacting both residential zones and emergency coordination centers. Telecommunications were temporarily disabled in several localities, complicating evacuation efforts and the dissemination of warnings. Additionally, the fire resulted in degraded air quality across northeastern Greece and neighboring regions, exposing populations to elevated levels of particulate matter (PM2.5), with potential short- and long-term health effects. This burden was particularly acute for vulnerable groups such as the elderly, children, and individuals with respiratory conditions. This wildfire was declared the largest in the European Union since systematic records began under the framework of the European Forest Fire Information System (EFFIS) [168]. The scale and intensity of the event underscored the urgent need for enhanced wildfire risk governance, adaptive land management practices, and investment in climate-resilient infrastructure systems.

Policy context: Occurred under the new CER Directive framework, though Member State transposition was ongoing. The event underscored the need for binding integration of wildfire risk into CI resilience planning.

2023 Hawaii wildfires: The Lahaina wildfire of 8–9 August 2023, in Maui, Hawaii, stands among the most destructive wildfire events in recent US history. Fueled by se-

vere drought, hurricane-force downslope winds from Hurricane Dora, and highly combustible non-native grasses, the fire swept through Lahaina in less than 24 h. It resulted in 100 fatalities, making it the deadliest US wildfire since 1918 [169]. More than 2200 structures were destroyed, causing an estimated USD 5.5 billion in total damage, of which USD 3.4 billion were insured losses [170,171]. The wildfire had severe consequences for critical infrastructure. Power lines, likely both the ignition source and casualties of the fire, collapsed during the blaze, leading to prolonged outages across West Maui. Water distribution systems also failed: firefighting hydrants ran dry in several areas due to melted mains and depressurization [172]. The telecommunications network suffered significant damage, with fiber-optic cables and mobile towers destroyed, halting emergency alerts and severely impairing public communication. Notably, the state's emergency outdoor siren system, despite being functional, was not activated [173]. Evacuation attempts were severely obstructed by narrow streets, blocked roads, and fast-moving flames. Many residents were forced to abandon vehicles and escape on foot, with some entering the ocean to avoid the fire. In the aftermath, the Maui Fire Department issued a formal report listing 111 specific recommendations, citing deficiencies in equipment, coordination, and mutual-aid frameworks [174]. Social and health consequences have persisted. A statewide survey in early 2025 reported that over 40% of affected residents experienced worsening physical or mental health, with elevated levels of post-traumatic stress, anxiety, and food insecurity [175]. Cultural and historical losses were also substantial, including the destruction of the 1901 Pioneer Inn and the Lahaina Heritage Museum, both of which held deep significance to Native Hawaiian identity and local tourism.

Policy context: State and local preparedness operated under U.S. federal support mechanisms, but the absence of a unified wildfire–utility safety standard at the national level hindered coordinated prevention.

2025 Los Angeles area, California, wildfires: In early January 2025, Southern California experienced two of the most devastating wildfire events in recent state history—the Palisades Fire in Pacific Palisades and the Eaton Fire in the Altadena–Pasadena corridor. Both fires ignited on 7 January 2025, amid extreme Santa Ana wind conditions, prolonged drought, and abnormally low humidity, which created ideal circumstances for rapid fire spread. The Palisades Fire burned approximately 23,448 acres (9489 hectares), destroying 6837 structures and damaging over 1000 more. It caused 12 confirmed fatalities and at least four injuries, with forced evacuations affecting over 105,000 residents across multiple districts [176,177]. Simultaneously, the Eaton Fire consumed more than 14,000 acres, destroyed 9418 structures, and resulted in 17 fatalities and nine injuries. It has been classified as California's second-most destructive and fifth-deadliest wildfire on record [178]. The fires inflicted widespread damage on critical infrastructure. Electrical power systems suffered extensive outages as overhead lines collapsed or were shut down preemptively to reduce ignition risk. In several neighborhoods, these power cuts hindered both suppression and communication operations. Water infrastructure also failed in parts of the fire zone, where melted distribution lines and reduced pressure rendered fire hydrants non-operational at key moments during suppression efforts. Telecommunications networks, including mobile towers and fiber-optic cables, were compromised, leading to communication blackouts that disrupted evacuation notifications and real-time coordination [179]. Post-fire hazards further amplified the disaster's impact. In the days following containment, heavy rainfall triggered debris flows and landslides in severely burned terrain, destroying additional structures and cutting off access roads. These cascading effects complicated the recovery process and delayed the reactivation of essential services such as water treatment and power restoration [176]. Shelter capacity also proved inadequate. Spatial disparities in access to emergency shelters left vulnerable populations in both urban and hillside communities

underserved, highlighting inequities in preparedness infrastructure [177]. Economic losses from both fires were estimated at approximately USD 4.9 billion, with insurance claims mounting and reconstruction expected to take several years. Daily population exposure to fire conditions peaked at nearly 4300 individuals in the Eaton Fire zone and over 3900 in the Palisades perimeter [178].

Policy context: Occurred during early NSM-22 implementation, with utilities deploying enhanced safety settings and selective undergrounding. Persistent infrastructure vulnerabilities exist despite these measures and highlight the need for sustained investment, implementation, and enforcement.

All these extreme fire events collectively underscored the urgent need for systemic improvements in wildfire preparedness, including fuel management, infrastructure hardening, building codes, expansion of defensible space, early warning systems, and more equitable shelter and evacuation planning. They also reinforced the critical importance of integrating Earth observation data and climate forecasting into regional disaster risk reduction strategies.

6. Research and Innovation Projects Addressing Wildfires

The European Union is making a major effort to combat the growing threat of destructive wildfires with several important research projects focused on addressing important societal issues. Funded by the Horizon 2020 Green Deal call, these programs—which include FIRELOGUE, FIRE-RES, SILVANUS, and TREEADS—share the objective of reducing the risk of wildfires while enhancing community and landscape resilience. In addition to the Green Deal projects, another EU flagship project, FirEUrisk, provided insights and results relevant to the relations between critical entities and wildfires. The amount of funding for these flagship projects reaches approximately EUR 72 million, while for the time period 2006–2022, the EU has invested an additional EUR 103.2 million in 56 projects [179] related to wildfires.

In the US, there are various funds at federal level and organizations, such as the National Science Foundation, NASA, the JSFP, and NIST, providing funding on different research aspects from awareness, education, and networking to advanced modeling, WUI fire research and resilience, data and AI methods, and community governance for wildland fire, including cross-sector teams and workforce development activities. Together, these programs, complemented by interagency efforts and practitioner engagement, create a coordinated federal ecosystem that links basic science, technology, and operations to improve fire behavior prediction, infrastructure protection, and community adaptation while promoting open data, standards, and repeatable pilot demonstrations [180].

The following sub-sections provide information on key EU and US projects, as well as a brief comparative analysis (Table 2). The EU projects presented are the most recent at the EU level and related to FIRELOGUE. Projects at the EU Member State or cross-border level are not included.

6.1. EU Wildfire Prevention and CI Resilience Related Innovation Projects

SILVANUS—Integrated Technological and Information Platform for Wildfire Management (Grant Agreement No. 101037247, CORDIS) revolutionizes wildfire management by adopting an Integrated Fire Management (IFM) approach, combining multi-source data, advanced risk assessment models, and stakeholder engagement strategies. Utilizing a diverse set of sensor networks, remote sensing data [181,182], IoT devices [183], and AI-driven analytics, SILVANUS enhances environmental monitoring to identify high-risk areas before fires ignite [184]. The platform integrates citizen-reported fire events via mobile applications and social media, fostering community participation and a collaborative

approach to wildfire prevention. It provides decision-makers with comprehensive insights through a unified GIS-based platform, enabling proactive and data-driven fire prevention strategies. Additionally, SILVANUS advances wildfire response capabilities by integrating real-time fire detection through IoT-enabled sensors, UAVs/UGVs, and advanced communication support [185], and edge computing, optimizing resource allocation, evacuation planning, and health impact [186,187] through AI-based simulations and dynamic risk assessments.

Beyond immediate response, SILVANUS supports post-fire restoration and climate adaptation through long-term ecosystem monitoring and biodiversity protection. It enables automated tools for assessing fire impact, air quality degradation, and vegetation recovery, aiding in reforestation planning, soil rehabilitation, and adaptive land management. The platform also integrates ecological data into GIS layers [188], supporting sustainable landscape management strategies that mitigate future wildfire risks. Furthermore, it strengthens CI resilience by integrating early warning systems and real-time risk assessments, enabling proactive mitigation measures and minimizing service disruptions in wildfire-prone regions.

TREEADS—Intelligent Ecosystem for Fire Management (Grant Agreement No. 101036926, CORDIS) is aimed at developing a comprehensive fire management ecosystem for the prevention, detection, and restoration of environmental disasters, particularly wildfires. By integrating state-of-the-art technologies and socio-technological resources, TREEADS focuses on optimizing strategies across the three critical phases of wildfire management: Prevention and Preparedness, Detection and Response, and Restoration and Adaptation. The project's innovative solutions, such as real-time risk evaluation tools, low-altitude drones, and advanced decision support systems, are being tested and validated in eight complex pilot campaigns across diverse European and Taiwanese environments. These pilots, including those in Norway and Italy, address specific challenges such as protecting wooden infrastructure in the Wildland–Urban Interface (WUI) and ensuring the safety of critical transport systems in fire-prone areas.

To support the dissemination and exploitation of these solutions, TREEADS has developed the Knowledge Marketplace Repository (KMR), an open platform that serves as a resource center and promotional channel for wildfire management technologies, including a range of educational materials, such as online mini-courses, webinar recordings, and training programs, as well as standards and guidelines for wildfire management. Additionally, the project emphasizes the development of fire-resilient materials and passive fire protection strategies to enhance the resilience of critical infrastructure, ensuring continued functionality during and after wildfires.

FIRE-RES—Innovative Technologies and Socio-Ecological Strategies for Extreme Wildfire Events (Grant Agreement No. 101037419, CORDIS) aims to accelerate the socio-ecological transition of the European Union towards a fire-resilient continent, giving emphasis on Extreme Wildfire Events (EWE) [189]. At its basis, it demonstrates and implements 34 innovation actions that are evaluated in 11 different living labs. These innovations, centered on Integrated Fire Management, cover prevention, preparedness, detection, response, restoration, and adaptation efforts [190].

In order to transition to an Integrated Fire Management approach, FIRE-RES has taken on four important pillars: (a) Behavior and drivers of extreme wildfires: this includes analyzing the factors that allow extreme wildfires to occur and spread; (b) Optimizing emergency services: this focuses on evaluating and enhancing emergency services' responses to extreme wildfires; (c) Landscapes and economies of resilience: this comprehends the function of landscape management and its viability from an economic standpoint in incorporating resilience measures for communities and areas that are prone to fires;

(d) comprehend the role that governance and social action play during intense wildfire events.

FirEUrisk—Developing a Holistic, Risk-Wise Strategy for European Wildfire Management (Grant Agreement No. 101003890, CORDIS) provides a harmonized framework for wildfire risk assessment and mitigation across Europe. Coordinated by the University of Alcalá, the project integrates satellite-based hazard modeling, socio-economic vulnerability metrics, and climate–land use projections to inform risk governance. FirEUrisk innovations include European-scale fuel maps, a WUI-focused public alert app, a firefighter operations manual, and a pan-European wildfire observatory [191]. Demonstrations across 26 pilot sites in five fire-prone regions validate tools for spatially explicit planning and adaptation.

FIRELOGUE—Cross-sector Dialogue for Wildfire Risk Management (Grant Agreement No. 101036534, CORDIS) serves as a coordination platform enhancing wildfire hazard management and reducing wildfire risks across Europe by coordinating efforts, exchanging critical information, and developing comprehensive solutions through the EUFireProjectsUnited initiative.

The **European Knowledge Hub and Policy Testbed for Critical Infrastructure Protection (EU-CIP)** network represents significant advancements in the domain of Critical Infrastructure Protection (CIP). EU-CIP, a three-year Coordination and Support Action (CSA) funded by the European Commission, aims to establish a pan-European knowledge network that supports resilient infrastructures. This network will enable policymakers to develop data-driven, evidence-based policies while enhancing the innovation capacity of CI operators, authorities, and innovators, including SMEs. In tackling the resilience of critical infrastructures, EU-CIP addresses several key challenges posed by wildfires. These include the vulnerability of energy and communication systems to fire damage, which can lead to service disruptions and safety hazards. The interconnectedness of infrastructures means that a wildfire in one CI sector can have cascading effects across others, intensifying the overall impact. Effective wildfire management requires significant resources and coordinated action among various stakeholders, which can be challenging to achieve consistently. Additionally, developing infrastructures capable of adapting to and recovering from wildfire incidents remains a continuous challenge, especially in regions increasingly affected by climate change. EU-CIP supports wildfire risk management through data analysis, policy development, innovation support, and stakeholder engagement. By collecting and analyzing data on wildfire incidents and their impacts, EU-CIP generates insights into vulnerabilities and areas for improvement, supporting proactive risk management. The program also provides evidence-based recommendations for policies and standards that help mitigate wildfire risks, ensuring a cohesive approach to critical infrastructure protection (CIP) that incorporates natural hazards. The EU-CIP Knowledge Hub (KH, https://knowledgehub.eucip.eu/ accessed on 3 September 2025) serves as a central resource for advancing wildfire resilience within the European CIP community. It offers a centralized information repository for data, research outcomes, and best practices related to wildfire risk management, facilitating collaboration among CI operators, policymakers, researchers, and innovators.

6.2. US-Related Research Initiatives

In parallel to the European-funded initiatives, the United States has launched several large-scale federally funded, state-supported, and philanthropic research programs addressing wildfire prevention, resilience, and response. These programs emphasize technology integration, ecosystem restoration, and community resilience, supported by significant investments through the Bipartisan Infrastructure Law, Inflation Reduction Act, and philanthropic foundations.

LANDFIRE—Landscape Fire & Resource Management Planning Tools has historically and continues to be a long-standing interagency partnership between the USGS and US Forest Service, which produces nation-wide vegetation, fuels, and disturbance datasets to the wildfire planning community as geospatial products. This project has been ongoing since the mid-2000s and provides annual updates, which are critical for risk modeling, planning, and fuels treatment assessment by both utilities and public agencies. LANDFIRE is also commonly used by other countries as a baseline for foundational modeling tools. The model is well-established by experts and is now funded only for annual updates and fuel calibrations [192].

Joint Fire Science Program—a partnership between the US DOI Office of Wildland Fire and the US Forest Service. The grant program has operated since 1998 to deliver funding directly to researchers at universities, national labs, and state and federal agencies to improve future practices in applied fire science. JFSP provides ongoing competitive research cycles for projects related to smoke, fuels, WUI, and science, as well as social science applications. The intent of this funding is to address emerging questions of practitioners in real time who are working in fire-impacted ecosystems or managing wildland fire. JSFP manages the Fire Science Exchange Network, connecting fifteen regional fire science groups with current topically relevant information [193].

Bureau of Land Management (BLM) Wildfire Research Programs—Nearly USD 11 million awarded annually in FY2024 and FY2025 under the Bipartisan Infrastructure Law to advance wildland fire research priorities. Focus areas include accelerating science-to-action in fire-prone ecosystems, integrating Indigenous Knowledge into fire management, studying invasive plants and fire regimes, and addressing wildfire-related social equity impacts. Three primary funding categories are supported: Primary Research, Graduate Research Innovation, and Regional Fire Science Exchange [194]. In addition, USD 9 million was awarded in FY2023 to support wildfire prevention and post-fire restoration research [195].

National Science Foundation—Fire Science Innovations through Research and Education (FIRE) Program—A multi-agency collaborative initiative with NASA, the US Department of Defense, and the Gordon and Betty Moore Foundation. Research priorities include assessing socio-economic disparities in wildfire impacts, testing and modeling building materials under fire conditions, and developing retrofitting technologies [196]. In FY2023, fourteen FIRE-PLAN awards were issued to support cross-sector teams and frameworks for wildfire challenges [197].

NASA Wildfire Programs—The FireSense Technology Program (2023 solicitation) provided USD 14.4 million across seven projects, focusing on AI-driven wildfire risk mapping, UAV-based canopy-penetrating radar, real-time detection, and stratospheric wildfire monitoring. The Wildfire, Ecosystem Resilience, and Risk Assessment Initiative (WERK) complements this effort, integrated within the broader NASA Research Opportunities in Space and Earth Science (ROSES) program [198].

NOAA Wildfire Initiatives—The NOAA Weather Program Office received USD 15 million through the Bipartisan Infrastructure Law for fire-weather observing systems across the Western US [199], alongside USD 34 million awarded jointly to NOAA and the Department of Commerce for wildfire preparedness and forecasting improvements [200].

Department of Energy—Wildfire Grid Security Initiative—A USD 2.25 million program funding four projects to protect the U.S. electric grid from wildfire risks. Research includes AI-based grid vulnerability mapping (SLAC National Lab with Southern California Edison), advanced fire-risk sensors (Oak Ridge National Lab with PG&E), and autonomous drone inspections [201].

Environmental Protection Agency (EPA) Wildfire Smoke Programs—Over USD 7 million in 2023 was awarded to research community-level protection from wildfire smoke exposure, involving leading universities. In 2024, an additional USD 10.67 million was distributed through the Wildfire Smoke Preparedness in Community Buildings Grant Program, with Congress appropriating USD 7M annually for FY2024–2025 [202].

USDA Forest Service Programs—The Community Wildfire Defense Grant Program invested USD 197 million in 2023 across 22 states and seven tribes to support local wildfire protection planning and implementation of the National Cohesive Wildland Fire Management Strategy by improving home hardening, defensible space, fuel breaks, and evacuation readiness. This grant program is directed to build local capacity where federal agencies cannot control land management (there is no federal presence), but can collaborate to facilitate Community Wildfire Protection Plans through grant funding. This program targets areas specifically underserved and/or identified as having a high wildfire potential [203].

The **Wildfire Crisis Strategy** (Inflation Reduction Act & Bipartisan Infrastructure Law) has committed USD 2.4 billion to date, targeting fuel reduction, community risk reduction, and resilience at the landscape scale, in 21 priority landscapes [204]. It is a combined effort with the USFS and Department of Interior agencies, states, Tribes, and local partners. The funding will be provided in multiple tranches to treat up to 50 million acres and can be used for planning, implementation, workforce development, and monitoring. Focusing on public–private partnerships, the program intends to reduce community risk and provide forest restoration at the landscape scale [149].

Bipartisan Infrastructure Law (BIL) Investments—Provides a historic USD 5 billion over five years for wildfire management, split between the USDA Forest Service (USD 3.5B) and Department of the Interior (USD 1.5B) [150,205]. In 2023, USD 185 million was allocated to nationwide wildfire resilience planning and mitigation [206].

California Wildfire Prevention Grants—At the state level, California allocated USD 117 million in FY2023–24 to local wildfire prevention grants, primarily funded through California Climate Investments [207].

Private and Philanthropic Funding—The Gordon and Betty Moore Foundation Wildfire Resilience Initiative committed USD 110 million over six years (launched 2023), the largest private wildfire research initiative to date [208]. The Bezos Earth Fund launched a USD 100 million AI for Climate and Nature Grand Challenge (2024), supporting wildfire-related AI applications and ecosystem restoration [199]. The California Community Foundation Wildfire Recovery Fund pledged USD 30 million for 2025 recovery efforts [209]. Private equity and corporate R&D partnerships (e.g., utilities with DOE national labs) have contributed an additional USD 100+ million in wildfire technology investments since 2023.

Key Trends (2023–2025): Across federal, state, and private initiatives, wildfire innovation funding in the U.S. emphasizes (i) AI and advanced sensor technologies, (ii) community resilience and Indigenous Knowledge integration, (iii) wildfire smoke and health protection, (iv) utility grid hardening, and (v) cross-sector public–private partnerships. Collectively, federal investments exceed USD 3 billion (2023–2025), complemented by approximately USD 400 million in private and philanthropic funding.

6.3. Comparative Analysis

The comparative overview of EU and US wildfire research projects (Table 3) highlights several fundamental differences in strategy, scope, and governance:

1. Scale and Funding Mechanisms – The US invests at a significantly larger scale, with over $3 billion in federal funds (2023–2025) complemented by approximately $400 million in private and philanthropic contributions. In contrast, the EU's flagship projects are smaller in scope, with individual grants in the range of €0.2–€20 million

(all projects since 2006), or the range of €10–€20 million (for the recent projects related to Green Deal), though collectively forming a robust innovation ecosystem under Horizon 2020 and Horizon Europe.

2. Governance Models – The EU approach reflects its supranational framework, emphasizing cross-border harmonization, stakeholder engagement, and integration within EU-wide policy directives (e.g., CER Directive, UCPM). By contrast, the US system is federal and sector-driven, relying on strong federal investments but with execution shaped by state, tribal, and local entities, and often facilitated through public–private partnerships.
3. Research Priorities – European projects focus strongly on Integrated Fire Management (IFM), landscape resilience, and socio-environmental dimensions such as community engagement and biodiversity protection. US programs, while also community-oriented, place more emphasis on technological innovation, including AI, advanced sensors, and grid hardening, reflecting the scale of infrastructure at risk.
4. Community and Social Integration – Both regions support community-level resilience, but their pathways differ: the EU foregrounds citizen engagement platforms and workshops (e.g., FIRELOGUE), while the US leverages grant-based mechanisms such as the Community Wildfire Defense Fund and Firewise USA.
5. Private and Philanthropic Role – A distinctive feature of the US landscape is the large-scale involvement of philanthropic and private sector actors (e.g., Moore Foundation, Bezos Earth Fund, utility partnerships), which adds significant complementary funding. In the EU, wildfire research remains largely publicly funded through EU and national programs.

Table 3. Comparison of funding for wildfire research between the EU and the US. Information provided herein is not exhaustive.

Aspect	EU Projects	US Projects
Funding programs	Horizon 2020 / Horizon Europe Green Deal (e.g., FIRELOGUE, FIRE-RES, SILVANUS, TREEADS, FirEUrisk), FP7, FP6	Bipartisan Infrastructure Law, Inflation Reduction Act, NSF FIRE, NASA FireSense, DOE Grid Security, EPA Smoke Programs
Funding scale	Each project €10–20 M; EU Green Deal portfolio ~€80M+ total (2021–2025)	Federal > $3B (2023–2025); Private/Philanthropic ~$400M
Research focus	Integrated Fire Management, AI/IoT wildfire detection, landscape resilience, WUI protection, post-fire restoration	AI-driven risk mapping, fire-weather forecasting, wildfire smoke health, grid hardening, Indigenous Knowledge integration
Agencies/institutions	European Commission (DG RTD, DG ECHO, JRC), national agencies, universities, private sector	USDA, USFS, BLM, NSF, NASA, NOAA, DOE, EPA, state agencies (e.g., CAL FIRE), philanthropic foundations
Community focus	Citizen engagement apps, resilience hubs, stakeholder workshops (FIRELOGUE)	Firewise USA, Community Wildfire Defense Grants, smoke preparedness in schools and community buildings
Innovation highlights	Knowledge Marketplace Repository, GIS-based risk modeling, green firebreaks, multi-stakeholder workshops	AI grid monitoring, UAS canopy-penetrating radar, autonomous vegetation inspection drones, stratospheric sensors

While both continents pursue multi-stakeholder and interdisciplinary approaches, the EU emphasizes policy coherence, governance integration, and ecological resilience, whereas the US prioritizes large-scale investments, advanced technology deployment, and private sector engagement. Together, these contrasting models provide complementary lessons: Europe demonstrates the value of harmonized, cross-border governance, while the US illustrates how scale, technology, and private–public synergies can accelerate innovation. Bridging these perspectives could foster more globally coordinated wildfire resilience strategies in the face of escalating climate-driven fire risks.

7. Recommendations for Critical Infrastructure Resilience in the EU

Based on the comparative analysis, deployment of the two FIRELOGUE workshops in Solsona, Spain, and Nea Makri, Greece, webinars and case study findings, the following rec-

ommendations that could be considered for policymaking at the EU level are summarized in the next options (Table 4).

Table 4. Recommended options to enhance infrastructure resilience.

Option	Benefit	Implementation Strategies
Option 1: Promoting a multi-governance approach to wildfire risk management and infrastructure resilience, and improving collaboration among relevant stakeholders.	This option provides an integrated approach for the enhancement of wildfire risk management and critical infrastructure resilience by making sure that all relevant stakeholders are involved in, and no one is left behind. It also enhances the collaboration between them, which is extremely important during the response phase.	Create fora where stakeholders can exchange knowledge, resources, and strategies on a regular basis. Implement comprehensive training programs for infrastructure operators to ensure they are equipped with the latest knowledge and skills with a strong focus on wildfire prevention, preparedness, and response strategies. Enhance participatory processes by establishing legal, scientific, and other related committees to develop a common approach on wildfire risk management for experts and CI operators, through directives, standards, etc. Secure necessary funding to support the establishment and maintenance of collaboration platforms, training programs, and resource-sharing initiatives. Create policy frameworks that outline the roles and responsibilities of various stakeholders in wildfire risk management for CIs. This will help ensure accountability and streamline collaboration efforts.
Option 2: Strengthening CI resilience to wildfire through standardization, data strategies, and incentives	This approach promotes common understanding, improved cooperation, and enhanced situational awareness across sectors and jurisdictions.	Support the creation and updating of building codes and standards aimed at a) reducing ignition hazards, b) hardening existing infrastructures, and c) taking into consideration the results of wildfire risk assessment for new CIs in a "security by design" concept. Stricter regulations and zoning laws that account for fire risks should be considered, along with a process for regularly reviewing and adapting codes and standards based on evolving wildfire risk as well as advancements in technology and practices. Facilitate data sharing, interoperability, and collaboration among various stakeholders. This will reduce data fragmentation and enhance the comparability of information, leading to improved understanding, communication, and coordination. Ultimately, this enables a more integrated approach to wildfire risk management. Introduce financial incentives for property and CI owners to invest in fire-resistant materials, protective barriers, and monitoring tools. This can include grants, insurance reduction, tax breaks, or low-interest loans aimed at promoting infrastructure resilience. Create certification schemes for personnel and systems involved in wildfire management (e.g., register of specialists, cooperation agreements, peer-review frameworks). This will ensure that those responsible for firefighting and prevention possess the necessary skills and knowledge across the EU. Create new standards that outline qualifications and competencies (e.g., training programmes, exercises) required for wildfire management personnel (first and second responders) specifically for events involving CIs. Ensure consistent definitions and terminologies among all stakeholders. Develop standardized formats for incident reporting and data collection to facilitate a common understanding. Promote and incentivize the collection and sharing of wildfire data, focusing specifically on ignition points and causes, including impacts on affected CIs. Create tax incentives for individuals to harden their homes and residences. Promote insurance innovation to recognize individual home hardening as a basis for premium cost reduction.
Option 3: Advancing research and technology usage in the whole cycle of wildfire risk management for CIs.	This recommendation improves fuel reduction, prevention technology, early ignition detection, early warning, support suppression efforts of response teams (situation awareness, coordination, resources allocation, evacuation), reducing impacts. Developing innovative solutions to be implemented.	Allocate more funding, specifically for research and technology initiatives focused on wildfire risk management and technology development and implementation. This investment should support innovative projects that aim to enhance resilience of CIs against wildfires. Develop test beds for wildfire technology to ensure efficacy, performance, and safety while providing third-party certification or validation. Develop policies and incentives that encourage the adoption of advanced wildfire risk management and critical infrastructure-related technologies (e.g., early detection through Internet of Things or Long Range networks, monitoring of smoke and heat, installation of real-time transmission meteorological stations, automated sprinklers, real-time fire danger calculation). This could include incentives to utilize innovative practices or technologies in daily operations.
Option 4: Enhancing assessment and management of wildfire risk to CIs	This recommendation improves risk assessment and management, improves planning and suppression, and protects infrastructure assets and the surrounding area. Understanding wildfire impacts on critical infrastructure.	Promote guidelines on wildfire risk assessment affecting CI. This will require regular updates based on evolving wildfire risks and scientific insights. Investigate the socio-economic impacts of wildfires to understand how they affect communities and infrastructures. This assessment would inform risk management strategies and enhance community and infrastructure resilience. Develop best practices for reducing the risk of wildfires, including fuel management, across the EU. Promote data collection and sharing, focusing specifically on ignition points to identify the probable cause and simulate fire spread.
Option 5: Strengthening International Cooperation and Knowledge Transfer	Building on the comparative analysis between EU and US approaches, enhanced international cooperation is essential.	Establish formal cooperation agreements between EU and US agencies for sharing wildfire–CI protection best practices. Develop joint research initiatives leveraging US experience with utility-specific wildfire mitigation plans and EU regulatory frameworks. Create transnational training programs for CI operators and emergency responders. Facilitate technology transfer and innovation exchange between regions. Strengthen the Wildfire Peer Review Assessment Framework (PRAF) with international components.

Linkage to Evidence: The recommended options in Table 4 derive directly from the updated comparative policy analysis (Section 4, specifically Section 4.5), statistical trends (Section 1), case study findings (Section 5), and workshop outputs (Section 3.5). For example, Option 2 on standardization responds to identified gaps in US voluntary frameworks under NSM-22 [94], while Option 4 builds on FirEUrisk-derived risk assessment tools validated

in EU Member State contexts. Cross-regional relevance is noted where recommendations align with both EU and US practices, enabling targeted policy transfer.

8. Discussion and Conclusions

Wildfire threats to critical infrastructure are accelerating, driven by the compounding effects of climate instability, urban expansion into the wildland–urban interface, and underlying socio-economic vulnerabilities. This study reveals how infrastructure systems, while vital to societal functioning, are often unprepared for the cascading disruptions caused by extreme wildfires, leading to widespread economic losses, social hardship, and environmental degradation.

Through a comparative assessment of EU and US policy and practice, we find a convergence of overarching goals—namely, resilience and service continuity—but a marked divergence in enforcement mechanisms, funding allocation, and governance models. The EU's CER Directive [91] mandates a systemic approach to resilience, emphasizing preparedness and risk management across all sectors. The US (NSM-22 [94]) relies more heavily on sector-specific, incentive-driven programs, often prioritizing reactive measures and post-disaster recovery. However, significant implementation gaps remain in both regions, hindering the effective translation of policy into tangible on-the-ground improvements.

Integrated Risk Assessments and Cascading Infrastructure Threats: Beyond assessing immediate wildfire impacts on infrastructure, it is crucial to consider the interconnected nature of risks that extend further than direct fire damage.

Stochastic wildfire modeling supports integrated risk assessments by simulating many plausible fire footprints under observed extreme fire weather, which allows probabilistic estimates of the likelihood that wildfires threaten communities or critical infrastructure [1,137]. Overlaying simulated perimeters with assets such as homes, transmission lines, substations, and other critical facilities yields exposure probabilities and potential service disruption metrics [78,101]. In parallel, incorporating modeled burn severity within drinking water source watersheds and reservoir catchments supports postfire erosion and runoff modeling to estimate sediment and turbidity loads, which indicate the likelihood of water treatment challenges and temporary supply interruptions. Together, these elements link primary wildfire hazards to secondary infrastructure impacts within a transparent probabilistic framework.

Preparedness of Emergency Services to Protect Infrastructure and Populations: A crucial element of resilience is the ability of emergency services to manage the complex challenge of simultaneously protecting both critical assets and human lives. The dual responsibility of emergency services—to protect both critical infrastructure and societies—creates significant operational challenges. Emergency services are generally organized into two disciplines, wildland firefighting and structural or urban firefighting. Wildland firefighters are trained to contain fires moving through vegetation and often use fire as a tool, such as burnout and backfiring, to limit its spread. Structural firefighters are trained to suppress fires in buildings and industrial facilities, where hazards such as energized electrical systems, gas releases, toxic smoke, flashover, and explosion risk require specialized tactics and equipment.

Protecting critical infrastructure while safeguarding the public usually involves joint operations. Wildland crews manage perimeter control and fire spread pathways, while structural and HazMat teams defend and harden facilities. Civil protection and law enforcement handle evacuations, traffic control, and shelter-in-place orders. Preparedness varies by jurisdiction, but common best practices include pre-incident plans with utility operators, priority asset lists, coordinated incident command, and cross-training. In some countries, specialized units within the armed forces (e.g., the Unidad Militar de Emergencias UME in

Spain) provide surge support during national emergencies and maintain training for both wildland and structural firefighting operations.

Our analysis shows that current preparedness levels vary, often limited by resource constraints and the difficulty of protecting multiple objectives at once. Improving the capacity of firefighting and emergency response units requires specific training, better inter-agency coordination, and strategic resource allocation to effectively balance these competing priorities during wildfires.

International Collaboration and Knowledge Exchange: Building resilience requires strong international cooperation. Cooperation between the US and the EU has become essential for wildfire and critical infrastructure resilience. Platforms for data sharing, joint training exercises, and standardized emergency response protocols enable the exchange of knowledge and best practices. These collaborative efforts boost adaptive capacity by fostering unified response frameworks, improving early warning systems, and aligning policy goals to reduce wildfire risk and enhance CI resilience.

Cross-Regional Learning Potential: Europe can draw from the US experience with utility-specific wildfire mitigation plans, innovative financing mechanisms, and incentive-based public-private partnerships to encourage infrastructure resilience investments. Conversely, the US can benefit from the EU's regulatory frameworks, looking towards harmonized resilience requirements, all-hazards approaches, and risk assessment iterations (as embodied in the CER Directive), and from finding comprehensive, multi-sectoral projects such as FIRELOGUE.

Integration of Emerging Technologies–Digital Twins and Predictive Fire Models: Recent technological advancements offer innovative opportunities to enhance traditional wildfire risk management. Emerging technologies such as digital twins and predictive fire spread models are promising areas for wildfire resilience research. Digital twins create virtual replicas of physical infrastructure systems, allowing for high-fidelity simulations of wildfire scenarios without physical risks. When combined with predictive models that forecast fire propagation and system vulnerabilities in real time, these technologies support proactive risk assessment and operational decision-making. Integrating these tools into current resilience frameworks can significantly improve situational awareness, strengthen mitigation strategies, and reduce the chances of catastrophic infrastructure failures during wildfires.

Paradigm Shift Requirements: Ultimately, enhancing the resilience of critical infrastructure to wildfires requires a fundamental paradigm shift, moving away from a sole reliance on suppression strategies towards a more proactive approach that emphasizes adaptation in the frame of new fire regimes. This means embracing forward-looking land-use planning reforms that limit development in high-risk areas, investing in resilient infrastructure designs that can withstand extreme fire events, and promoting sustainable land management practices that reduce fuel loadings and enhance ecosystem health.

Above all, it requires fostering a culture of adaptability and preparedness across all levels of society, ensuring that communities build resilience from the ground up. Only coordinated, transdisciplinary action can build robust infrastructure in both developed and developing regions facing increasingly extreme wildfire events. The evidence presented demonstrates that effective wildfire-critical infrastructure resilience depends not only on technological solutions but on integrated governance frameworks that bridge policy, science, and community engagement for sustainable protection of essential services and societal functions.

Wildfire threats to critical infrastructure are accelerating due to climate instability, urban expansion into the wildland–urban interface, and underlying socio-economic vulnerabilities. This study reveals that infrastructure systems, while vital to societal functioning,

are often unprepared for cascading disruptions caused by extreme wildfires, leading to widespread economic losses, social hardship, and environmental degradation.

Future Challenges and Opportunities: Future challenges include projected increases in fire season lengths, coupled with escalating frequency and intensity of wildfires driven by climate change [30,31]. Addressing these challenges requires targeted involvement from governments at all levels, infrastructure operators, scientists, emergency responders, and local communities. The success of EU research initiatives like FIRELOGUE, FIRE-RES, SILVANUS, TREEADS, and FirEUrisk demonstrates the value of coordinated, multidisciplinary approaches to wildfire risk management.

Opportunities lie in the strategic integration of advanced technologies—AI-powered early warning systems developed through projects like SILVANUS, real-time satellite monitoring via EFFIS and Copernicus, and drone-based reconnaissance tested in TREEADS pilots—which can radically improve wildfire management effectiveness. However, technological innovation must be coupled with strengthened institutional capacity, regulatory alignment across jurisdictions, and inclusive governance structures prioritizing community needs and vulnerabilities.

Research and Innovation Contributions: The analysis demonstrates that EU wildfire research projects have made substantial contributions to addressing CI resilience challenges. SILVANUS has developed integrated technological platforms combining IoT sensors, AI analytics, and citizen engagement tools [180,183] across eight European and three international pilots. FIRE-RES has tested 34 innovation actions across 11 living labs, providing evidence-based approaches to extreme wildfire management [188]. TREEADS has advanced multi-phase fire management frameworks with demonstrated applications across eight pilot sites. Furthermore, FirEUrisk has created harmonized risk assessment tools and European-scale fuel maps [190].

These projects, coordinated through FIRELOGUE's EUFireProjectsUnited (https://firelogue.eu/wfrm-key-projects.php#EUFireProjectsUnited accessed on 3 September 2025) initiative, demonstrate the value of integrated research approaches combining technological innovation with policy development and stakeholder engagement. The EU-CIP Knowledge Hub provides a model for sustained knowledge transfer and capacity building that could be replicated in wildfire-specific domains.

Policy Implementation Priorities: Based on the case study analysis, several implementation priorities emerge for policymakers:

1. Immediate Actions (2025–2026): Member States should prioritize CER Directive transposition, focusing on wildfire risks, establish critical entity identification processes, and strengthen cross-border cooperation mechanisms through UCPM and rescEU frameworks.
2. Medium-term Development (2026–2030): Implement standardized risk assessment methodologies informed by FirEUrisk tools, develop integrated early warning systems building on EFFIS and Copernicus capabilities, and establish comprehensive training programs for CI operators and emergency responders.
3. Long-term Transformation (2030–2035): Achieve full integration of wildfire considerations into CI planning and design, establish sustainable funding mechanisms for resilience investments, and create adaptive governance frameworks capable of responding to evolving climate and technological conditions.

Only through coordinated, transdisciplinary action can robust infrastructure systems be built in both developed and developing regions facing increasingly extreme wildfire events. The evidence presented demonstrates that effective wildfire-critical infrastructure resilience depends not only on technological solutions but on integrated governance frame-

works that bridge policy, science, and community engagement for sustainable protection of essential services and societal functions.

Limitations and Future Research: This analysis acknowledges several limitations. The comparative assessment focuses primarily on EU and US frameworks, with limited consideration of other international approaches that may offer valuable insights. The case studies, while comprehensive, represent specific regional contexts that may not be fully generalizable to all EU Member States or US jurisdictions.

Future research should explore the effectiveness of implemented recommendations through longitudinal studies, investigate the role of emerging technologies (artificial intelligence, machine learning, autonomous systems) in enhancing CI resilience, and assess the integration of wildfire considerations into broader climate adaptation strategies. Additionally, research on social equity dimensions of wildfire–CI interactions, particularly regarding vulnerable populations and environmental justice concerns, would strengthen the policy framework.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AGIF	Agência para a Gestão Integrada de Fogos Rurais
ANEPC	Autoridade Nacional de Emergência e Proteção Civil
ASDs	Acceptable Safety Distances
BLM	Bureau of Land Management
CI(s)	Critical Infrastructure(s)
CIP	Critical Infrastructure Protection
CISA	Cybersecurity and Infrastructure Security Agency
CER	Critical Entities Resilience Directive of the EU (EU 2022/2557)
Copernicus EMS	Copernicus Emergency Management Service
CSA	Coordination and Support Action
DHS/FEMA	Department of Homeland Security/Federal Emergency Management Agency
EFFIS	European Forest Fire Information System
EMAC	Emergency Management Assistance Compact
EO	Executive Order
EPCIP	European Programme for Critical Infrastructure Protection
ERCC	Emergency Response Coordination Centre of the EU
EU	European Union
ICNF	Instituto da Conservação da Natureza e das Florestas
ICS	Incident Command System
IFM	Integrated Fire Management
IoT	Internet of Things
FEMA	Federal Emergency Management Agency (USA)
FERC	Federal Energy Regulatory Commission
FTGs	Fuel Treatment Grids
FY	Financial Year
GIS	Geographic Information System
JFSP	Joint Fire Science Program of the US
JRC	Joint Research Centre of the European Union
KMR	Knowledge Marketplace Repository
MCDA	Multicriteria Decision Analysis
MTT	Minimum Travel Time
NERC	North American Electric Reliability Corporation
NIFC	National Interagency Fire Center
NIPP	National Infrastructure Protection Plan (2013) of the USA
NIRMP	National Infrastructure Risk Management Plan
NUTS2	Nomenclature of territorial units for statistics level 2
NSM-22	National Security Memorandum on Critical Infrastructure Security and Resilience
PMDFCI	Planos Municipais de Defesa da Floresta contra Incêndios

PNGIFR	Plano Nacional de Gestão Integrada de Fogos Rurais
PPD-21	Presidential Policy Directive 21 (2013) of the USA
PPP(s)	Public–Private Partnership(s)
PRAF	Peer Review Assessment Framework
rescEU	Reserve of Civil Protection assets under the UCPM
ROS	Rate of Spread
SGIFR	Sistema de Gestão Integrada de Fogos Rurais
TFEU	Treaty on the Functioning of the European Union
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UCPM	Union Civil Protection Mechanism of the EU
US	United States of America
US DOI	United States of America, Department of the Interior
USFS	United States Forest Service
WFRM	Wildfire Risk Management
WG	Working Group
WUI	Wildland Urban Interface

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