energies

MDPI

Review

Energy Resilience in Telecommunication Networks: A Comprehensive Review of Strategies and Challenges

Ana Cabrera-Tobar , Francesco Grimaccia and Sonia Leva *

Department of Energy, Politecnico di Milano, Via Lambruschini 4, 20156 Milan, Italy;
anacabrera.t@gmail.com (A.C.-T.); francesco.grimaccia@polimi.it (F.G.)
* Correspondence: sonia.leva@polimi.it

Abstract: As telecommunication networks become increasingly critical for societal functioning, ensuring their resilience in the face of energy disruptions is paramount. This review paper comprehensively analyzes strategies and challenges associated with achieving energy resilience in telecommunication networks. It explores various aspects, including policies, energy backup systems, renewable energy integration, and energy management techniques. This paper discusses how these strategies can be implemented to build resilience across three phases: preparedness (referring to the proactive measures taken in advance), response and relief, recovery and reconstruction. Additionally, it discusses the challenges associated with implementing energy resilience measures, taking into account policies, sustainability and environment, and climate change. By synthesizing existing research and identifying research gaps, this review paper aims to provide insights into the state-of-the-art practices and future directions for enhancing energy resilience in telecommunications, enabling robust and uninterrupted communication services.

Keywords: resilience; energy; telecommunication; policies

check for updates

Citation: Cabrera-Tobar, A.; Grimaccia, F.; Leva, S. Energy Resilience in Telecommunication Networks: A Comprehensive Review of Strategies and Challenges. *Energies* **2023**, *16*, 6633. https://doi.org/10.3390/en16186633

Academic Editor: Álvaro Gutiérrez

Received: 31 July 2023
Revised: 7 September 2023
Accepted: 11 September 2023
Published: 15 September 2023

1. Introduction

According to the European Union Agency for Cybersecurity (ENISA) [1], Europe experienced 168 reported telecommunication incidents in 2021. The effects of these failures are measured in user hours, given by the number of users' times the number of hours each failure lasts. In 2021, it accounted for 5106 million user hours. The root causes of these incidents are classified into four categories: system failures, human errors, malicious actions, and natural phenomena. Among these categories, system failures caused approximately 59% of the telecommunication incidents, while human errors caused 23%. Natural phenomena and malicious actions constituted 10% and 8% of the incidents, respectively. Although system failures contributed to the highest number of telecom incidents, they only resulted in a mere 7% of the total user hours lost. In contrast, human errors accounted for 91% of the lost user hours (Table 1). Regarding the power outages, which caused 60 million lost user hours, 35% were attributed to natural phenomena, 51% to hardware failures, and 13.3% to human errors (Table 2).

Table 1. Percentage of incidents and user lost hours per root cause [1].

Category	Percentage of Incidents	User Lost Hours
System failures	59%	7%
Human errors	23%	91%
Malicious actions	8%	1%
Natural phenomena	10%	1%

Table 2. Percentage of user lost hours due to only power outages [1].

Cause	Percentage of User Lost Hours
Natural phenomena	35%
Hardware failure	51%
Human error	13.3%

However, the number of power outages due to natural phenomena may rise in the coming years due to climate change and severe weather events, affecting the electrical grid and, thus, as a consequence, the reliability of the telecommunication network. Figure 1 shows the variability of the natural disasters affecting Europe, where storms and floods characterized 2021. Meanwhile, 2022 was also marked by extreme temperatures [2]. The effects of extreme natural phenomena such as high temperatures, floods, stronger winds, and increased rainfall can affect all stages of the electrical grid (generation, transmission, and distribution), affecting its reliability in the long term. For instance, hydropower depends on the erratic rainfall variation affecting the river flows. In 2021, there was a decrease of 15 TWh in the global hydropower generation due to droughts, and it continued in 2022 [3]. On the other hand, when heavy and prolonged rainfall exceeds a dam's capacity, uncontrolled overtopping can occur, leading to downstream flooding and infrastructure damage, as was the case in Montedoglio dam, a reservoir on the Tiber River in Italy, in 2010 [4].

Thus, measures to enhance resilience in the power supply for telecommunication networks are extremely important, paying attention to power autonomy and response in case of disaster [5]. One of the common measures is the use of diesel generators as a backup power supply. For instance, Telecom Italia (TIM) recently deployed mobile stations powered by diesel generators in the Region Emilia Romagna in Italy, which experienced widespread flooding [6]. Besides mobile emergency diesel generators [7], other methods for restoration in cases of emergency are electric vehicle fleets or mobile energy storage systems [8,9]. Additionally, off-grid microgrids are also used in the case of emergency, but they are also the primary energy providers in remote areas [10].

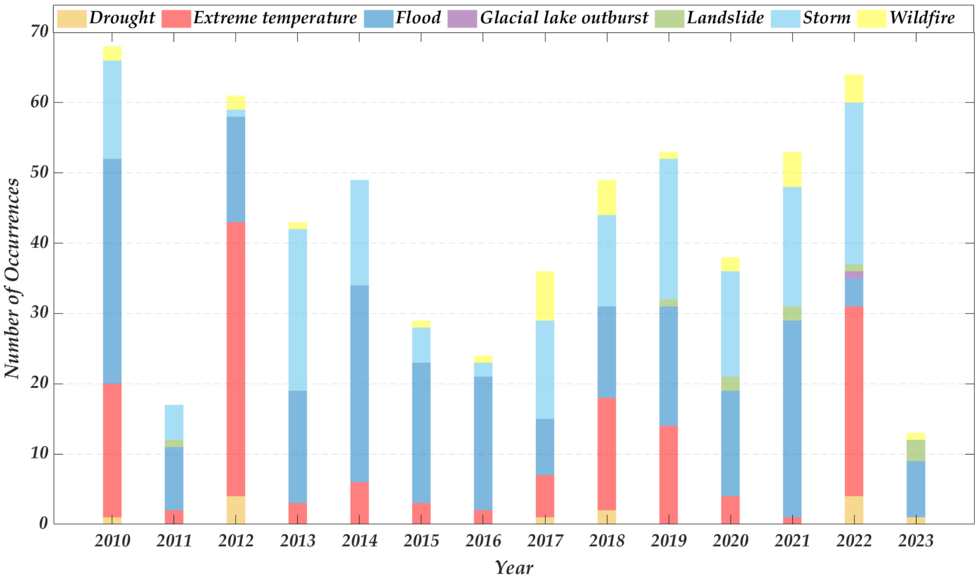

Figure 1. Number of natural disasters in Europe since 2010 [2].

Recent review papers have delved into efficiency and sustainability in telecommunication networks. For instance, Gandotta et al. [11] conducted a comprehensive review focusing on various techniques to curtail energy consumption in telecommunication networks, thus enhancing their efficiency. The study covered diverse areas such as device-to-device communication, spectrum sharing, ultra-dense networks, massive MIMO, and the Internet of Things. Meanwhile, Zahed et al. [12] scrutinized caching strategies for green networks. Conversely, a comprehensive exploration of green networks and the integration of renewable energy configurations and control with energy efficiency techniques, including sleeping modes, was presented by [13–15]. Prasad et al. [15] also included a discourse on enhancing energy consumption at base station control centers, with considerations for thermal and power management. Furthermore, the augmentation of telecommunication network performance using machine learning techniques was discussed in [16,17]. Table 3 summarizes the review papers presented in the literature considering three main areas: efficiency, resilience, and sustainability.

Table 3. Review papers in the area of telecommunication and energy since 2016.

Reference	Efficiency	Resilience	Sustainability
[11]	✓	-	✓
[12]	✓	-	-
[13]	✓	-	-
[14]	✓	-	✓
[15]	✓	-	-
[16]	✓	-	-
[17]	✓	-	-
[18]	✓	-	-
[19]	-	✓	-
[20]	-	-	✓
[21]	✓	-	-
[22]	✓	-	✓
[23]	✓	-	✓

However, a critical analysis of the current technical strategies, energy management, and policies for building a resilient power supply for telecommunication networks is still missing. In the case of power systems, various review papers tackle this issue but from the broad system perspective and not from the telecommunication network (e.g., [5,24,25]). Moreover, Liu X., et al. [19] approach the interdependency between the electric power grid and the communication network to enhance the resilience of the former but not of the latter. By addressing this gap in the literature, this paper looks to provide valuable insights into technical strategies that can withstand and recover from disasters, ensuring reliable telecommunication services even under challenging circumstances.

Because of the lack of studies on energy resilience in telecommunication, the current article aims to provide a narrative literature review to approach various topics such as technical strategies, energy management challenges, and current policies. For the literature review, the databases used were Scopus, IEEE Xplore, and Google Scholar. The search was restricted to the years from 2009 to 2023. The search strings created were: (i) Power Systems and Resilience and Natural Disasters and Critical loads and (ii) Telecommunication and Resilience and Natural Disasters. We found 1104 and 369 publications for the first and second strings, respectively. The assessment of these publications was focused on considering the main policies and energy management for telecommunication networks and energy solutions for critical loads, paying particular attention to the three phases of resilience: preparedness, response and relief, recovery, and reconstruction. After the quality assessment, 115 articles were used for further review and analysis. Moreover, we also paid attention to press releases from Telecommunication Network Operators (TNOs) and Transmission System Operators (TSOs) covering natural disaster management. Additionally, we reviewed 12 reports from various countries regarding resilience and services for TNO and TSO (Table 4).

Table 4. Reports analyzed for this paper.

Ref.	Report	Institution	Country	Telecom	Energy	Year
[26]	Green power for mobile bi-annual report	GSMA	Worldwide	✓	**X**	2014
[27]	Impact of Hurricane Katrina on Communication Network	Independent	USA	✓	✓	2006
[28]	Sustainability Report	Telecom Italia	Italy	✓	**X**	2021
[1]	Annual report telecom security incidents 2021	ENISA	Europe	✓	**X**	2021
[29]	Sustainability Report 2017	NTT DOCOMO	Japan	✓	**X**	2017
[30]	Measurement Frameworks and Metrics for Resilient Networks and Services: Challenges and Recommendations	ENISA	Europe	✓	**X**	2010
[31]	Connecting everyone in the Netherlands to a sustainable future	KPN	Netherlands	✓	**X**	2022
[32]	Focus Group on Environmental Efficiency for Artificial Intelligence and other Emerging Technologies	ITU	Worldwide	✓	✓	2021
[33]	The impact of the 2011 floods, and flood management on Thai households	Independent	Thailand	✓	✓	2015
[34]	The State of Mobile Internet Connectivity 2022	GSMA	Worldwide	✓	**X**	2020
[35]	India Energy Security Scenarios 2047 - User Guide for Transport Sector	The National Institution for Transforming India	India	✓	✓	2012
[36]	Focus Group on Disaster Relief Systems, Network Resilience and Recovery Requirements	ITU	Worldwide	✓	✓	2014

The analysis of these publications is in the following sections. Section 2 reviews the main policies and guidelines for resilience in the Telecommunication Network (TN). Section 3 explains the various technical strategies such as micrgrids and backup systems. Meanwhile, Section 4 discusses the main Energy Management System's techniques. Section 5 discusses the main practices to build a resilient system based on three phases: (i) preparedness, (ii) response and relief, and (iii) recovery and reconstruction. Then, the sustainability, policies, and climate change challenges are explained in Section 6. Section 7 will draw out the main conclusions.

2. Policies for Energy Resilience in the TN

TN resilience refers to the capacity of the communication network to maintain critical services, such as voice and data transmissions, while ensuring efficient operation even during challenging circumstances like natural disasters, cyber-attacks, or physical damage [37]. On the other hand, electric power system resilience is the ability of the electrical grid to withstand and recover from disturbances, disruptions, or disasters, thereby minimizing downtime, ensuring continuous power supply, and preserving the grid's essential functions, including frequency support, voltage regulation, and phase control [38]. For regular operation, both systems depend on each other; on the one hand, the electrical system communicates its data regarding power generation, demand, and state of the system in real time to the transmission and distribution system operator using the TN. On the other hand, the electrical grid commonly feeds the base station. Thus, if the electrical power system suffers damage, then the resilience of the TN is affected.

The International Telecommunication Union (ITU) mentions the interrelation between TN and electric power supply in its technical report for resilience during disaster [36]. The report mentions three main phases and the interaction between these two systems. The phases mentioned for resilience are (i) preparedness; (ii) response and relief; and (iii) recovery and reconstruction (Figure 2). Regarding power supply, the report mentions the installation of an emergency generator and battery for phase one with a backup time of 72 h. Meanwhile, phase two discusses that ensuring an electric power supply during a disaster is essential. However, it should also include a refueling method if backup power is considered.

Figure 2. Phases for Resilience.

The European Telecommunications Standards Institute (ETSI) also offers a framework of policies for power supply in the telecommunication sector, from its interconnection (EN 300 132-3 V2.2.1) [39] to the use of alternative power generation [40]. The backup time they recommend is 4 h for remote sites and one for urban areas using batteries, diesel generators, or alternative power generation. However, these policies do not consider the power supply operation for the resilience of the TN. In contrast, ENISA, in its report about resilience, only suggests the use of backup power as diesel generators and fuel cells but does not specify the duration.

After Hurricane Katrina, the Federal Communication Commission (FCC) in the United States revised and improved its Resilience and Reliability Framework. It reported the damages suffered in the power supply that affected the TN, the downtime, and the solutions established during the emergency or until the power system was recovered. After the situation and the response to Hurricane Katrina, the FCC established guidelines and best practices to reduce the downtime of the TN. Regarding the power supply, they also propose using diesel generators with a backup time of 8 h for rural base stations and 4 h for urban areas [27].

In the UK, the Electronic Communications Resilience & Response Group (EC-RRG) has released a comprehensive guideline to ensure the resilience of telecommunication systems before, during, and after emergencies [41]. One of the critical aspects highlighted in this guideline pertains to power supply considerations. The EC-RRG strongly recommends implementing a robust backup power system to counteract potential power outages. To achieve this, TNs should have a backup power solution designed to sustain operations for at least seven days. This timeframe considers the potential delay in the arrival of an emergency power supply to the incident location.

These are a few regulatory bodies that mention energy resilience for telecommunication. Only ETSI discusses off-grid or the use of microgrids for powering the base station, thus considering the preparedness stage for resilience. It is also essential to notice that the main guidelines for backup time differ from one to another, starting from 4 h in the case of ETSI but with seven days in the case of the UK. A summary of the various considerations is in Table 5.

Table 5. Energy resilience policies.

Standard/Guideline	ITU-2014	FCC	EC-RRG	ETSI
Build high-reliability power system	✓	✓	✓	-
Include backup system	✓	✓	✓	✓
Area analysis	✓	✓	-	-
Refueling method	✓	✓	✓	-
Maintenance	-	-	✓	-
Technology	DG Battery	DG Battery Fuel cell	General	DG Battery PV, wind power, hydropower
Backup Time	72 h	8 h (rural) 4 h (urban)	7 days	4 h (rural) 1 h (urban)

3. Microgrids and Backup Systems for Energy Resilience in TNs

The threats to telecommunication regarding energy supply are primarily related to the nature of power outages. According to [42], short power outages lasting up to 60 min are the most common in Italy, especially during summer. However, in the case of earthquakes, as reported in [43], the average recovery time can range from 1 to 4 days, while for floods, it can be as long as 24 h or 3 weeks. The recovery time is highly dependent on the location and the extent of the damage. Recently, space weather events like solar storms are also considered natural hazards for electrical equipment, capable of damaging transmission lines, transformers, and other critical components. The recovery time for such events could take a few hours to several weeks. Additionally, power cuts can occur inside the cabins of base stations due to factors such as high temperature, human errors, and inadequate equipment maintenance, such as the uninterruptible power supply (UPS) [44]. These damages could result in the loss of service for the base station, affecting millions of users. To address these challenges, microgrids, and the implementation of backup systems present a viable solution to enhance resilience and reduce dependence on the traditional electrical grid.

3.1. Microgrids

A microgrid is a decentralized energy system that operates standalone or grid-connected. The main components can be power generators based on photovoltaics, wind energy, fuel-based generators, energy storage, fuel cells, and localized load (neighborhoods or buildings) [45]. The main objectives of a microgrid for a base station are: (a) improve resilience, (b) reduce power consumption from the grid or diesel generators, and (c) reduce carbon emissions.

Three primary microgrid topologies have been discussed in the literature [11,14] (Figure 3). Firstly, Topology A represents a grid-connected microgrid that supplies energy to the base station while remaining connected to the main power grid. This configuration allows the base station to utilize its resources (renewable sources or fossil fuels) when available and switch to the grid during periods of energy scarcity. Excess power generated by the microgrid can also be fed back to the grid. It is crucial to mention that the energy consumption from the grid could increase costs and carbon emissions as the energy mix of the electrical grid can be highly based on fossil fuels [46]. Thus, the optimal use of the energy sources is controlled using an Energy Management System (EMS), which controls the power generation and storage from the microgrid and its integration with the electrical grid. The second topology, Topology B, involves an off-grid microgrid that exclusively powers the base station. It incorporates multiple energy sources, including renewable energy and energy storage, to provide continuous power to the base station. This solution is standard in remote areas where power lines from the electrical grid do not arrive or when the service from the electrical system is poor. In 2020, six hundred thousand off-grid base stations were installed worldwide, where the leading regions were sub-Saharan Africa, South Asia, and Latin America [47]. A third topology, Topology C, is a theoretical concept discussed in the literature but not yet implemented extensively. It entails an independent power network, such as a DC microgrid, supplying energy to multiple base stations via dedicated power lines which could also supply to other loads. While not widely implemented, this topology holds the potential for efficient power distribution among multiple telecommunication sites and in a community. However, this solution will require significant investment in equipment, lines, and control and operational costs, and thus not fully developed.

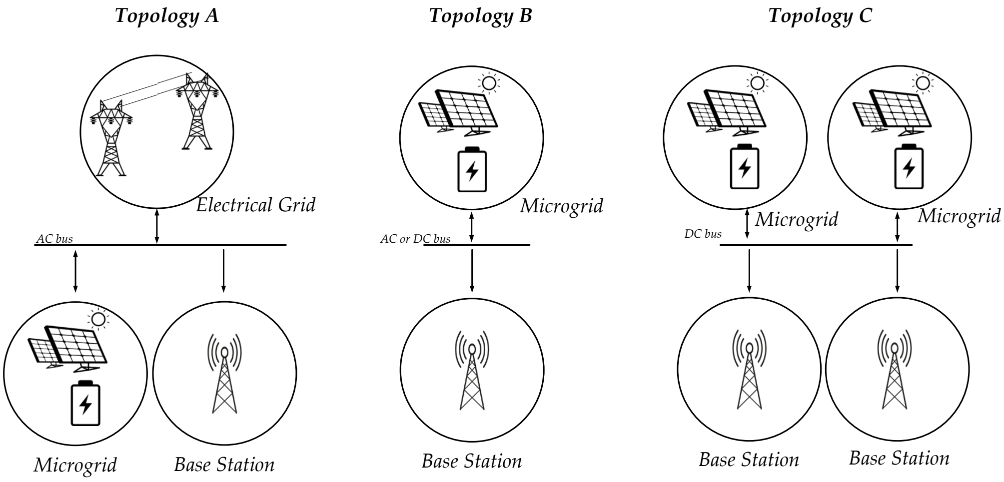

Figure 3. Topologies of microgrid for base stations. Topology (**A**): Grid-connected microgrid; Topology (**B**): off-grid; Topology (**C**): independent power network.

Microgrids can be either DC- or AC-based. In a DC microgrid, key components like photovoltaic panels, fuel cells, batteries, and telecommunication base stations connect to a common DC bus through a DC/DC converter. A DC/AC converter is used for AC loads and grid connection [48]. On the other hand, AC microgrids connect components to an AC bus. Components like batteries, PV panels, and fuel cells connect to a DC/AC converter, allowing grid connection and AC loads on the same bus.

These microgrids can include backup systems such as diesel generators, fuel cells, and energy storage. Photovoltaic systems, including energy storage, are commonly used to provide green energy for telecommunication base stations in rural areas. Other energy sources like wind power have also been employed [11]. For example, a PV system and a diesel generator were installed for a telecommunication base station on a mountaintop at Weasel Lake in Canada, with a power capacity of 10 kW aimed at improving energy resilience and reducing diesel operation costs during summer months [49].

However, despite the potential advantages of microgrids, they can face challenges due to natural hazards. Diesel generators and fuel cells, the critical components of microgrids, may encounter fuel shortages due to transportation issues, road damage, and logistical problems. For instance, during the fires in Australia in 2020, inadequate diesel generator operation and infrastructure damage contributed to significant power outages in base stations [50]. Similar issues were reported in cases of hurricanes and floods [51]. Even grid-connected microgrids, reliant on external grid connectivity, can suffer from damaged grid infrastructure after a natural disaster. This compromise in grid power access forces microgrids to rely on their energy supply. However, limitations on their power generation or energy storage capacity can lead to difficulties in meeting the energy demands of the base station. For instance, in the aftermath of Hurricane Maria in 2017, telecommunication base stations in Puerto Rico relying on grid-connected microgrids experienced extended outages due to damaged grid infrastructure. Conversely, the Coto Laurel PV power plant, with a capacity of 14.2 MW, experienced minimal damage to its solar modules. However, grid codes prevented reconnection until the main grid was re-established [52]. Table 6 summarizes the damage suffered in microgrids due to various natural disasters. It can be seen that, despite the use of microgrids, these are not inherently resilient, as they are not commonly designed for natural hazards. We analyze the common backup systems utilized as diesel generators, fuel cells, and energy storage in the following lines, considering advantages, disadvantages, and duration needs.

Table 6. Power supply performance during natural disasters.

Natural Disaster	Damage	Outage Time	Location	Ref.
Hurricane Maria	High winds, flooding, fuel shortages, broken PV panels, infrastructure damage	Days to months	Puerto Rico, USA	[52]
Hurricane Katrina	High winds, storm surge, infrastructure damage	Weeks to months	Gulf Coast, USA	[27,53]
Thailand Floods	Inundation, equipment damage, fuel shortages	Weeks to months	Thailand	[33]
Superstorm Sandy	High winds, storm surge, infrastructure damage	Days to weeks	Northeastern USA	[51,54]
Australian Bushfires	Fire damage to infrastructure, power line disruption, fuel shortages	Days to weeks	Australia	[50]
Chile Earthquake and tsunami	Structural damage, equipment failure, fuel shortages	Days to months	Chile	[55,56]
Western European Floods	Inundation, infrastructure damage	Days to months	Various locations	[57]

3.2. Backup Systems

To enhance energy resilience in base stations, a backup system can be located close to the base station to serve in the moment of an outage in the power grid or a problem related to the microgrid. The technologies analyzed are diesel generator (DG), fuel cells (FCs), and batteries.

3.2.1. Diesel Generators

DGs are widely used in the telecommunication industry as backup power sources during power outages or in remote areas with limited grid access. They provide immediate and reliable power, ensuring the uninterrupted operation of critical telecommunication equipment such as base stations and data centers. For instance, after the bushfires reported in Australia from 2019 to 2020, 93% of the power restoration actions were based on DG [50]. The runtime of diesel generators varies depending on factors such as generator capacity, fuel efficiency, and load demand. Smaller generators can provide power for around 8–12 h, while larger generators with larger fuel tanks can run for several days without refueling. DG's mature, reliable, and robust nature positions them as a prominent technology for resilient telecommunication systems. DG systems demonstrate notable autonomy, primarily attributed to their integral fuel storage capacity. Refilling these fuel reserves efficiently contributes to their rapid recovery during power outages. However, refill strategies should be planned to reduce logistic problems in an emergency. Moreover, the use of diesel generators is being scrutinized due to environmental concerns, and there is a growing interest in adopting cleaner and more sustainable power alternatives in the telecommunication industry [7].

3.2.2. Fuel Cells

FCs are electrochemical devices that generate electricity by reacting between a fuel source and an oxidizing agent, typically hydrogen and oxygen. In a microgrid, they can be used as power generators or energy storage. Their efficiency ranges from 50%—in the case of proton exchange membrane fuel cells—to 70%—for solid oxide. Fuel cells have a high energy density (up to 770 kWh/m^3). This means they can store significant energy within a relatively small volume or mass, benefiting applications like backup power systems in microgrids (up to 10 times) of continuous power than certain battery technologies, including lead-acid batteries [58].

Moreover, the lack of mechanical pieces, as in the case of diesel generators, results in a quiet operation, which makes it ideal for telecommunication applications. In addition, its modularity makes it flexible for portable and stationary solutions [59]. In the case of fuel cells, the power capacity for portable energy solutions in natural hazards ranges from 2 kW to 1 MW [60], with autonomy from 8 h to 72 h [61]. The operational hours depend on the fuel availability, the same as DG; fuel cells must be refilled. Thus, a refill schedule could help enhance its reliability.

Because of these advantages, FCs are especially used in remote areas and during emergencies (mobile FCs) [62]. One example is Telstra's project in Australia, where FCs ranging from 1 kW to 2 kW provide green backup power for base stations [63]. Companies like ReliOn have also contributed to telecommunication backup power using fuel cells. They have installed 431 fuel cell systems to supply power to 180 base stations by 2014 [64]. Other companies using Fuel Cells for telecommunication backup power are Serene [65], and WolfTank Group [61].

However, one of the main disadvantages of FCs in the telecommunication industry, particularly in remote areas, is hydrogen transportation, storage, and handling [66]. On the one hand, transporting hydrogen can present challenges due to its low-energy density, which means a large volume of hydrogen is required to store significant energy. This can result in logistical difficulties and increased costs for transporting and delivering hydrogen to remote locations [67]. It requires specialized infrastructure, such as dedicated storage and transportation systems, to ensure the safe and efficient handling of hydrogen. Moreover, hydrogen can be volatile and flammable, necessitating careful safety measures during transportation and storage. Ensuring proper handling procedures and compliance with safety regulations [68] are vital to mitigate any potential risks associated with hydrogen transportation. In contrast with diesel generators, it has a long start-up time. Thus, a battery is necessary for the transition, which could cause a short disconnection time [63].

3.2.3. Batteries

Batteries are vital components in the telecommunication industry, serving as energy storage solutions. They store electrical energy and backup power during outages from minutes to hours. Batteries offer advantages such as fast response times, compact size, and scalability. Lead acid batteries are telecom base stations' most common energy storage. The lead acid battery market can reach 20 GWh in 2030 [69]. However, with new communication technologies such as 5G, the space for installing batteries can be limited; thus, lithium-ion batteries could provide backup power during an emergency using less space (higher energy density). Moreover, lithium-ion batteries need less maintenance and have a higher operational life than lead acid, reducing the operational cost for the first one, thus making it more attractive for current utilization. However, temperature can impact their performance, making some locations less suitable. Extreme heat can accelerate battery degradation, while extreme cold can reduce their capacity and increase internal resistance [70]. Therefore, alternative backup power options like fuel cells or diesel generators may be more suitable in regions with extreme temperature conditions.

On the other hand, the allocation of batteries regarding the critical base station due to the probability of a power outage could enhance the resilience of the power supply for a base station. The authors in [71] present a solution for a dense network in China considering 4206 base stations. The optimal allocation is based on initial cost, maintenance, and reduction in power outage from 4.7 h to nearly 0.

4. Energy Management System

Energy management in a base station commonly aims to enhance efficiency [72], minimize cost, and reduce carbon emissions [73]. It controls the power balance in the base station, taking into account the various types of power supply and power consumption.

In this section, we discuss the conventional EMS for telecommunication base stations and focus on the EMS strategies for resilience discovered in the literature. A summary of the main strategies discussed in this section is in Table 7.

4.1. Conventional EMS

In the case the telecommunication base station relies on a microgrid, diesel generator, or any other backup system discussed before, it needs a local controller to manage the energy and the operational performance of the power supply. The main objective of energy management in microgrid-powered base stations is to maximize resource utilization and minimize the need to buy electricity from the grid (e.g., [74,75]). The EMS also plays an essential role in off-grid microgrids to reduce operational costs and increase reliability [76]. The authors in [77,78] proposed a new methodology to provide a flexible EMS for off-grid microgrids with critical loads. For instance, the microgrid built at Weasel Lake (Canada) for an off-grid base station optimizes energy use for summer and winter. In winter, the energy supply depends on diesel generators and, during the summer, on photovoltaics and batteries. The optimization of this system was focused on the reduction in operational costs due to fuel and helicopter transportation without affecting the quality of service of the communication, achieving a 60% reduction in the operational cost [49].

The typical configuration of an EMS for a base station and its microgrid resembles that shown in Figure 4), where it is necessary to have real-time measurements of the state of the system but also the forecast data of the ambient conditions and the power production (e.g., [77,79]).

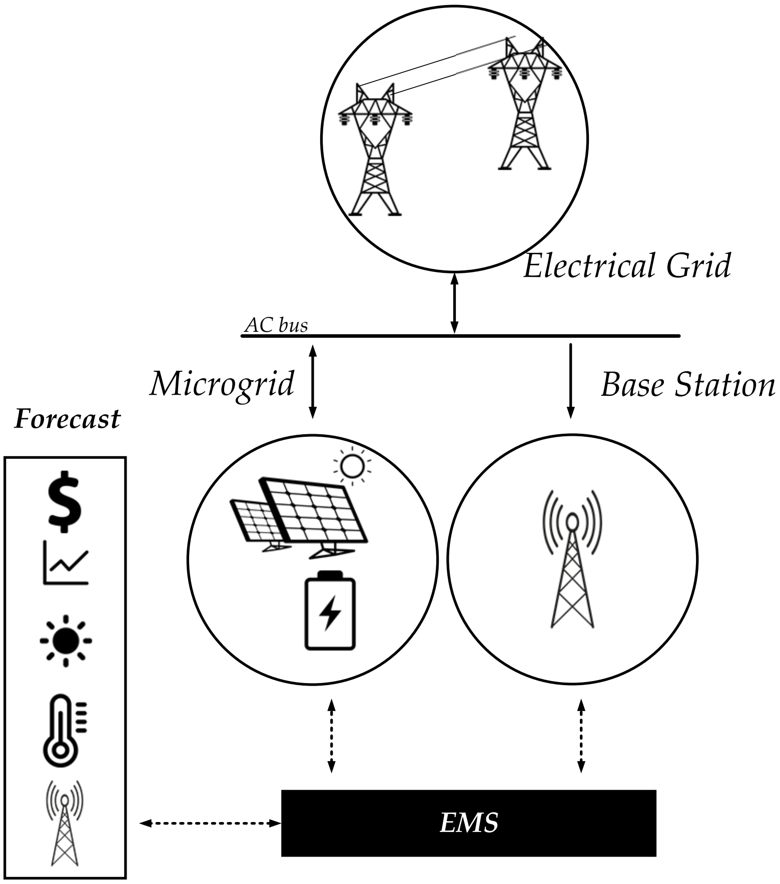

Figure 4. Conventional EMS for telecommunication base stations based on microgrids.

In the telecommunication base station, the demand response is focused on reducing power consumption by managing the data traffic and the operation of the base station during the day. In this regard, sleeping modes, caching strategies [12], and data re-routing [18] have been applied to reach a higher efficiency [80]. The sleep mode for base stations is a power-saving feature that allows them to conserve energy during idle periods. While it reduces power consumption and promotes sustainability, it may introduce latency and requires careful management to ensure uninterrupted network coverage. Thus, optimizing the switching mode is paramount to maintaining the quality of service. Profound studies about the recent literature on sleeping mode strategies are in [13,81,82].

Sleeping strategies and energy sharing between microgrids have been proposed in the literature, e.g., [83]. The concept of energy sharing is analog to a virtual power plant, which manages the energy from various prosumers to sell it or share it with others. Thus, it enters the electrical market, forming a virtual power plant. The microgrids are connected to the grid and supply power to the base station. If the base station is not consuming energy due to the activation of the sleeping mode, or there is a natural reduction in traffic, the surplus of energy can be managed by the virtual power plant (Figure 5). The sleeping modes can also be managed regarding energy availability inside the virtual power plant. Various authors proposed using the VPP to share/sell energy to the grid from the base station network when this is also connected to a microgrid [84–88]. Furthermore, the authors in [73] proposed an incentive policy strategy to enable base stations to use demand and energy response mechanisms to participate in VPP.

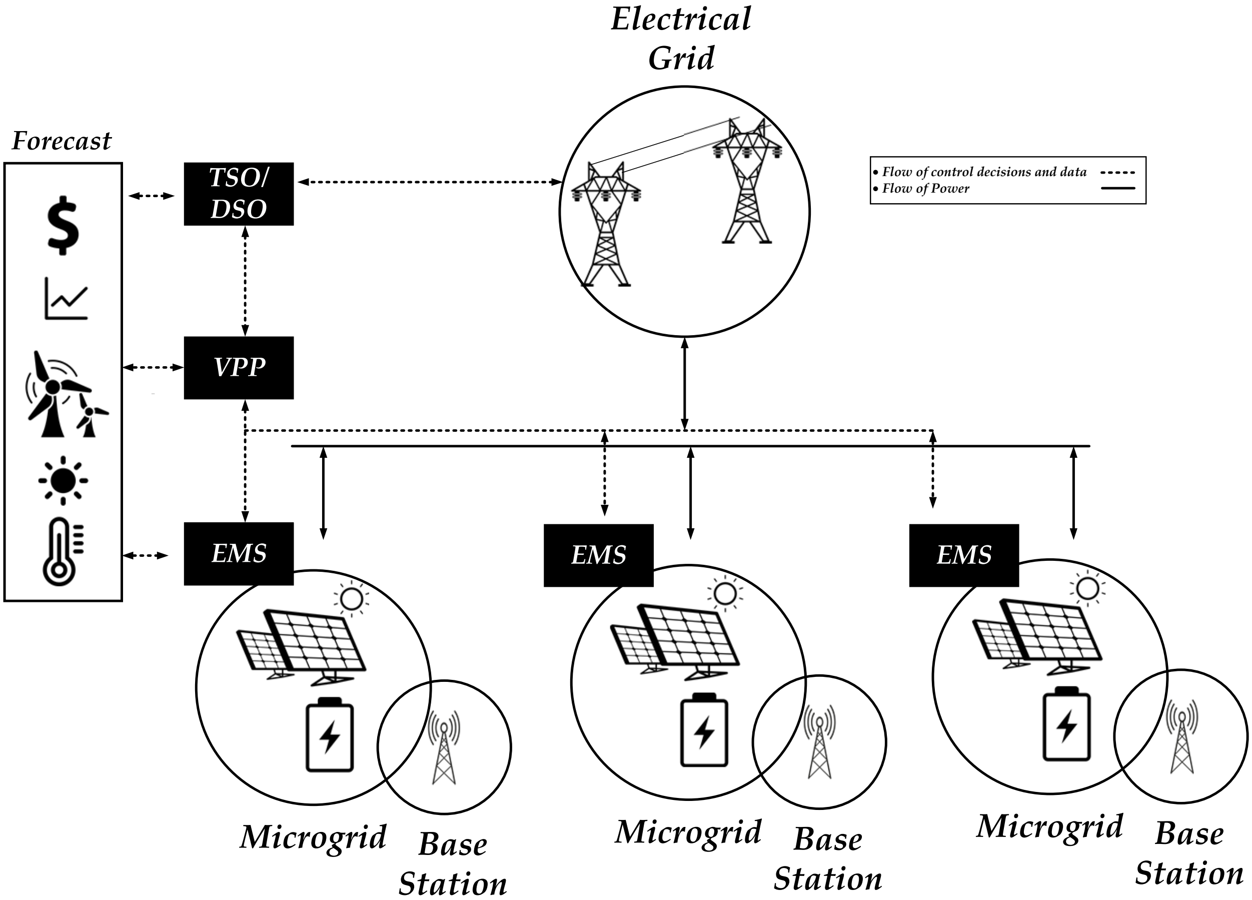

Figure 5. Virtual Power Plant for telecommunication base stations.

Besides energy sharing, computing sharing using Multi-Access Edge Computing (MEC) among diverse mobile operators can enhance the energy efficiency of the network. Gambin et al. proposed a joint solution between computing sharing and the energy management of a PV system linked to a macro cell using machine learning techniques. On the one hand, it shares the load among the different operators. It takes advantage of the power produced by the PV system, reducing the operational cost due to the purchase of energy from the grid [84]. On the other hand, ref. [89] have joined these strategies with sleeping modes to increase the reduction in the energy consumption but also taking into account the reduction in the latency, reaching a reduction in the energy consumption of up to 40%. Moreover, re-routing the data can also help reduce power consumption, especially in dense urban areas. For instance, ref. [90], proposes to re-route the excess traffic of a cell sector to another one to use the energy resources properly. The solution affects the latency of the communication response but increases the energy efficiency in densely populated areas. In addition to the traffic load due to communication, another component of the power consumption in a base station is the air conditioning (ac) unit. The ac unit is commonly located in the control room to maintain the temperature in a range to prevent the various electronic devices and batteries overheating. In [91], the authors proposed the energy management of a microgrid considering the load traffic and the ac unit, looking to reduce operational costs and the grid's reliability.

4.2. EMS For Resilience

Energy management during natural hazards has been a relatively underexplored topic in the literature, particularly in telecommunications. While limited in scope, there have been some notable efforts to address this issue within the telecommunications domain. For instance, Rahman et al. [92] proposed a comprehensive energy management solution explicitly tailored for telecommunication base stations. Their approach integrates an FC, a PV array, and a battery system to extend the backup period for up to 30 h, considering both normal and emergency periods.

In contrast, exploring energy management during natural hazards is more prevalent in other domains, such as home energy management. Researchers like Candan et al. [93] and Xu et al. [94] have investigated the utilization of electric vehicle (EV) batteries to provide energy resilience during emergencies, albeit with constraints on demand limitations. Similarly, strategies involving energy sharing from parking lots, microgrids, and demand curtailment have been proposed to enhance resilience for critical loads in dense urban areas [95,96].

Table 7 summarizes the recent literature using the mentioned strategies. It can be seen that there is a lack of studies considering energy management for natural hazards or power disruption, with a focus on telecommunication base stations. Mainly, the papers have focused on reducing power consumption but not on optimal energy management, considering both load traffic and energy availability. Moreover, resilience has not been proposed in recent studies.

Table 7. Summary of publications on demand response and energy management for telecommunications (S.M.: sleeping mode, RES: base station with renewable energy sources, VPP: virtual power plant, Unc.: uncertainties).

Ref.	Caching	S.M	Rerouting	MEC	RES	Resilience	Cost	VPP	Unc.
[12]	✓	-	-	-	-	-	-	-	-
[16]	-	-	-	-	-	-	-	-	-
[18]	-	-	✓	-	-	-	-	-	-
[13]	-	✓	-	-	-	-	-	-	-
[15]	-	-	-	-	✓	-	-	-	-
[90]	-	-	✓	-	-	-	-	-	-
[88]	-	-	-	-	✓	-	✓	✓	-
[97]	-	-	-	-	✓	-	-	✓	-
[98]	-	-	-	-	✓	-	✓	✓	-
[87]	-	-	-	-	-	-	-	-	-
[99]	-	-	-	-	✓	-	-	✓	-
[84]	-	✓	-	✓	✓	-	-	✓	-
[89]	✓	✓	-	✓	✓	-	✓	-	-
[100]	-	-	-	-	-	✓	-	-	-
[85]	-	✓	-	-	-	-	✓	-	-
[83]	-	✓	-	-	✓	-	-	✓	-

Table 7. *Cont.*

Ref.	Caching	S.M	Rerouting	MEC	RES	Resilience	Cost	VPP	Unc.
[101]	-	✓	-	-	-	-	✓	✓	-
[99]	-	-	-	-	-	-	✓	-	-
[82]	-	✓	-	-	-	-	-	-	-
[102]	-	✓	-	-	-	-	-	-	-
[10]	-	-	-	-	✓	✓	-	-	-
[103]	-	-	-	-	✓	-	✓	✓	-
[91]	-	-	-	-	✓	-	-	-	-
[104]	-	-	-	-	✓	-	-	✓	-
[73]	-	-	-	-	-	-	-	✓	-
[105]	-	-	-	-	✓	-	✓	✓	✓
[106]	-	-	-	-	✓	-	✓	✓	✓
[107]	-	-	-	-	✓	-	✓	✓	✓
[108]	-	-	✓	✓	✓	-	✓	-	✓
[109]	-	-	✓	✓	✓	-	✓	-	✓
[92]	-	-	-	-	-	✓	-	-	-
[86]	-	-	-	-	✓	✓	✓	✓	-

5. Build for Resilience

This section discusses the three phases of building a resilient power supply for telecommunications: (i) preparedness—before the emergency; (ii) response and relief—during the emergency; and (iii) recovery and reconstruction—post-emergency. The main actions of every phase discussed in this section are summarized in Figure 6.

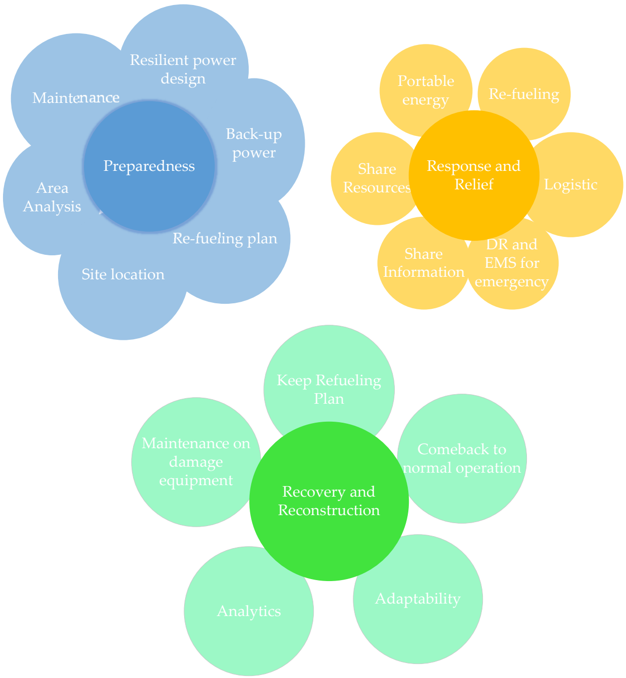

Figure 6. Actions in every resilience phase for energy resilience in telecommunications.

5.1. Preparedness—Before the Emergency

Specific measures should be adopted during the design to enhance resilience for energy in the telecommunication sector for the various natural disasters that could affect the performance of the energy solution (Table 8). In the case of an area where floods are predominant, base station sites should be carefully selected to avoid flood-prone areas and mitigate the risk of inundation. Constructing flood barriers and elevated equipment platforms protects rising water levels [110]. These measures prevent damage to critical infrastructure, including power supply components, ensuring uninterrupted energy flow to the base stations. For example, telecom operator KPN in the Netherlands implemented flood mitigation measures, safeguarding their base stations from the detrimental effects of flooding in various parts of the country [31].

Table 8. Best practices for resilience to natural hazards—preparedness.

Natural Hazard	Best Practices
Floods	- Careful site selection to avoid flood-prone areas - Construction of flood barriers and elevated equipment platforms
Earthquakes	- Design or retrofit buildings to withstand seismic activity - Incorporate seismic-resistant designs and vibration isolation systems
Hurricanes	- Reinforce structures and secure equipment mounting - Installation of hurricane-resistant antennas and regular inspections and maintenance
Optimization	- Utilize optimization techniques for energy management and demand response

In the case the area is prone to earthquakes, base station buildings and equipment shelters should be designed or retrofitted to withstand seismic activity. Telecom operators implemented earthquake-resistant measures in earthquake-prone regions, such as Japan. For instance, NTT Docomo implemented seismic-resistant designs and reinforced structural elements in their base stations to minimize the damage during earthquakes. They also incorporated vibration isolation systems to enhance the resilience of their infrastructure and the power supply [29,111]. In hurricane-prone regions, base stations should be designed with reinforced structures and secure equipment mounting to withstand high winds. For example, after Hurricane Maria struck Puerto Rico, telecom operators such as Claro and AT&T focused on strengthening their base stations. They reinforced structures, installed hurricane-resistant antennas and equipment shelters, and conducted regular inspections and maintenance to identify and address potential vulnerabilities. However, they still need to manage issues such as long-term power supply, refilling of DG's authorization, and the support of the TSO for enhancing their resilience [47,52].

Moreover, if a microgrid is used, the resilience could be improved by enlarging the installed power capacity and providing energy to non-critical loads besides the base station in normal operation. However, microgrids have been optimally designed for normal operation, as mentioned in [112]. Its dimensioning should consider the area's risks and the load's criticality, as explained in [113]. Moreover, other solutions include the possibility of feeding other loads like electric vehicles in non-emergency situations [114].

Situations like hurricanes and floods could be assessed and predicted; thus, mobile energy solutions should be transported near the area for quick deployment but stored in safe places before an emergency. Logistic consideration for the reaction after a disaster should also be part of the contingency plan, where the fuel transportation as diesel or hydrogen could challenge the utilization of the mobile diesel generators and fuel cells for a longer operational time. To reduce the logistic burden, it is recommended that different telecommunication operators join an effort to reestablish the most critical telecommunication base station in the damaged area [53].

5.2. Response and Relief

During an emergency, it is necessary that the system withstand natural hazards, and the backup system should operate in case the main power supply is lost. However, if the power supply or the backup system is not operating regularly, it is necessary to deploy portable power. Transportable energy storage, diesel generators, fuel cells, and microgrids hold significant potential for supplying energy during emergencies, scheduled maintenance, or new installations. Mobile energy solutions aim to support power supply before and after emergencies, particularly for critical loads. They also serve as a backup for the electrical system to restore service [9]. In the case of telecommunication, these solutions can provide power to critical base stations until the energy is restored. Moreover, they can support emergency response groups involved in rescue and service restoration efforts.

For mobile energy solutions, constraints such as location, transportability, and cost come into question. The most common practice is using truck-mounted diesel generators with power capacities ranging from 10 kVA to MVA due to their practicability and easy transportation [7]. Mobile diesel generators have been used in Telecommunication, especially after earthquakes, floods, and hurricanes in various countries such as Chile [55], United States of America [27], Germany [57], and Italy [6]. The main issue with this solution is the fuel refill, especially in areas that are difficult to arrive at due to natural disasters. The same situation occurs for mobile fuel cells with the additional problem of fuel management and its compliance with safety standards as National Fire Protection Association (NFPA), making it more difficult to operate for disaster management. However, it had already been used in pre-emergency during Hurricane Sandy, where the fuel cell and an extra hydrogen cabin were situated close to the affected area. The fuel cell was deployed when the outage occurred, and it was reported in [60] that it had more reliability than the diesel generator situated at the same location, covering 50 h of power outage.

In the case of mobile energy storage, they can be truck-mounted or towable battery storage systems [115]. The main advantage is the flexibility for transportation and its connection with the load. However, it is only for short-term outages (less than 8 h), as the batteries must connect to the grid or a microgrid nearby to recharge. Thus, this solution could not be suitable for a disaster where logistics could be problematic. For instance, it is more suitable for outages due to strong winds rather than floods. In the industry, there are various solutions to support the utility grid in case of disaster. For instance, in the solutions offered by Nomad Transportable Power System, the power capacity of their larger mobile energy storage is 1 MW with a maximum discharging power of 0.5 MWh [116].

5.3. Recovery and Reconstruction

The recovery and restoration phase is a critical period where efforts are focused on assessing the extent of the damage, repairing infrastructure, and gradually returning power supply and communication services to normalcy [117]. During the early recovery phase, damage assessment is a priority. Expert teams evaluate the condition of power lines, substations, transformers, and telecommunication infrastructure to determine the scope and scale of repairs required. Meanwhile, emergency solutions immediately implemented after the natural hazard may continue to serve as the main power supply and communication means until the system returns to normality. These temporary measures, such as mobile power generators and satellite communication systems, ensure critical services are available while permanent repairs are underway.

One of the primary tasks in power system recovery is to repair and restore power generation facilities, including thermal power plants, hydroelectric plants, and renewable energy sources [5]. This step is crucial to resume electricity generation and stabilize the power supply. Moreover, the repair of power lines is also taking place. In this stage, the equipment in the base station, such as batteries, rectifiers, and the backup system, is also assessed and repaired.

The recovery time could be an issue if it is longer than a few days. Thus, demand management to reduce power consumption could occur in non-critical areas. For instance, the study developed by [118,119] proposes the increase in energy efficiency by reducing the power consumption of the base station, considering key performance indicators such as number of users and type of power outage. Moreover, in the case of a microgrid, an energy management system to operate under these conditions could help restore the system. These strategies are discussed in the following subsection.

6. Challenges in Achieving Energy Resilience

In the coming years, TNs and the electrical power system will face various challenges regarding resilience due to climate change. In this section, we discuss the main challenges to overcome during the three phases of resilience discussed in this article regarding policies, sustainability and environment, and climate change.

6.1. Policies

The current standards and guidelines that explain resilience in telecommunications need to provide more policies to build energy resilience systems. As discussed in Section 2, the standards only consider backup systems to act in an emergency. However, they do not provide proper guidelines for building and planning energy resilience. Moreover, the common solution these policies and guidelines approach is using Diesel Generators without a specific plan for refueling. Thus, one of the main challenges is to update these standards and guidelines to enhance the base station's energy resilience since the planning stage. Moreover, it should also be mandatory to check the current installation of the base station to enhance their power supply systems.

Beyond strengthening TN policies, reviewing the electrical standards applicable to microgrids is imperative to understand their limitations in supporting telecommunication base stations. For instance, IEEE 1547 was designed for grid-connected microgrids capable of functioning independently for a limited duration. In contrast, IEC 62786 addresses off-grid microgrids, often used in remote areas, requiring high reliability and resilience. However, IEEE 1547 cannot support the grid during disturbances, leading to disconnections that can delay grid recovery when numerous microgrids are involved. On the other hand, the IEC 62898 series standards promote microgrids to assist the grid in voltage and frequency regulation while facilitating extended periods of off-grid operation with independent frequency and voltage control. While IEEE 1547 offers adequate protection measures, IEC 62898 provides better guidance for reliability, sensitivity, and rapid recovery [120]. Moreover, CIGRE under the C6 working group is considering enhancing energy resilience policies at the power grid using local distributed energy resources to help communities' faster recovery from natural disasters. CIGRE must investigate the role of DERs in an emergency and the actions to take before, during, and after a natural hazard, considering coordination among the various DERs that could operate in the damaged area [121].

Nevertheless, it is essential to acknowledge that different countries adopt various standards for microgrid installations. Consequently, it becomes essential to consider these standards' main characteristics and limitations to assess the resilience of the base station's power supply. This also raises an interesting debate concerning the need for specific standards for microgrids supporting critical loads, such as TNs, and advancements in operations, such as virtual power plants.

6.2. Sustainability and Environmental Consideration

Considering solutions with less carbon emissions is necessary to enhance the system's resilience. Thus, it is necessary to promote solutions such as microgrids based on RES and energy storage. These could also provide the power supply in regular operation; however, to increase the resilience, it could be necessary to increase the power capacity, thus affecting the dimensioning, installation, and cost. Thus, solutions should consider the optimal sizing of the microgrid to use in dense urban areas. The research developed in [122] discusses the optimal sizing regarding the traffic load, the ambient conditions, and the location. A multi-objective optimization was considered to guarantee the equality of service and the adequate use of the energy sources.

In the case where the microgrid is grid-connected, new energy management and demand response techniques should be used to reduce the consumption from the power grid. On the other hand, it is important to not only focus on minimizing operational costs but also on minimizing emissions when power is connected to the grid. The work in [123] studies a charging station's energy and demand management, considering the hourly emissions produced due to the grid mix. A similar approach could enhance the performance of the TN in terms of carbon emissions. Moreover, the energy management algorithm should be sustainable in time. Thus, it can adapt in real-time according to the necessities of the base station. Thus, including uncertainties in the algorithm could enrich its performance in real-time (e.g., [79,124]).

One of the main issues in today's solutions of the base stations is that the main causes of failures are not only natural hazards but also equipment failures. The maintenance of all the components, including batteries and all the power supply elements, is necessary to create a reliable system. Thus, digital twins could help provide the system's real state, take correction measures to increase the lifetime of the components, and schedule maintenance [125].

6.3. Climate Change

The response and relief phase during emergencies will also be influenced by the type of natural hazard faced. Having well-defined plans for the three phases—preparation, response, and recovery—is crucial to prepare to deal with significant disruptions adequately. However, the uncertainty brought about by climate change poses a significant problem in this context. As climate change leads to unpredictable and more extreme weather events, it becomes increasingly challenging to anticipate the exact nature and frequency of natural hazards [20]. For instance, in [126], the authors present a susceptibility study of a future hydropower power plant considering the effect of climate change. This uncertainty makes it difficult to effectively plan and prepare for all possible scenarios [127]. Nevertheless, TNs and power supply systems must be adaptable and flexible to respond promptly to unforeseen challenges. For instance, if the area is at risk of floods, it is advisable to install the base station as an aerial structure rather than a ground-based one, along with a backup power supply, to ensure continuous communication during such events. The key challenge lies in predicting the occurrence and severity of natural hazards in the coming years to design and build a truly resilient system.

A proactive approach should be taken to address the uncertainty posed by climate change. This involves continuously monitoring and analyzing climate data, collaborating with meteorological agencies, and using advanced predictive models to improve hazard forecasting [128]. Additionally, in the planning stage, robust planning and climate change uncertainty should become possible solutions to build a resilient solution for unpredictable natural events [74].

7. Conclusions

This paper covered the topic of energy resilience in Telecommunication networks. First, it focused on policies and guidelines that include energy resilience for TN, where the main findings were summarized in Table 5. Secondly, it provided an overview of the main technical strategies to enhance energy resilience in TN. The main strategies and technologies discussed were diesel generators, energy storage systems, fuel cells, and microgrids. The discussion included the struggles these techniques could face due to natural hazards. Thirdly, the various EMS techniques presented in the literature were summarized and discussed, paying attention to their focus on resilience (Table 7). Later, the discussion focused on the main actions that TN has to take to build a resilient power supply, where Figure 6 summarizes the main actions discussed. Finally, we discuss the main challenges to achieving energy resilience in TN regarding policies, sustainability, and environment, and finally, the challenge due to climate change. From this, the following conclusions can be drawn:

- The policies and guidelines set forth by international bodies such as ITU and FCC predominantly emphasize energy resilience enhancement through utilizing localized diesel generators and battery systems. While these technologies undoubtedly contribute to resilience, these regulatory bodies must broaden their perspective and consider alternative solutions that bolster resilience and align with global efforts to reduce carbon emissions. One viable alternative worth considering is fuel cell technology, which offers a clean and efficient means of generating power while minimizing the environmental impact. Furthermore, microgrids that rely on renewable energy sources (RESs) present another promising avenue. In contrast, ETSI has set a commendable example by formulating a framework of standards encompassing a diverse array of alternative energy technologies to enhance resilience. ETSI's approach acknowledges the need for flexibility and adaptability in the face of evolving challenges. Moreover, ETSI's standards encompass a wide range of backup times, from as short as one hour to as long as seven days, allowing for tailored solutions that can meet the specific needs of TNs scenarios.

- In reviewing the various EMS techniques within the scope of this paper, a notable observation arises: the predominant focus of these techniques centers on optimizing cost reduction and efficiency enhancement within telecommunications networks (TNs). While these objectives are undoubtedly crucial for sustainable network operations, a distinct gap emerges. The examined EMS strategies essentially bypass the consideration of the three critical stages of resilience—namely, preparedness, response, and recovery—that are imperative for ensuring the robustness and adaptability of TNs in the face of unforeseen disruptions. Our analysis reveals that existing EMS methodologies have primarily prioritized economic aspects, often neglecting the essential facets of risk mitigation and adaptability inherent to resilience. We must prioritize a holistic approach to fortify TNs against an increasingly volatile and uncertain landscape. This approach should encompass cost-effective and efficient energy management and robust strategies for preparing, responding to, and recovering from disruptions, ensuring the network's continuity under adverse conditions.
- In this paper, we examined the three stages of resilience: (i) preparedness, (ii) response and relief, and (iii) recovery and reconstruction within the context of energy resilience for TN. Our analysis underscores the imperative for the next generation of TNs to adopt a multifaceted approach, addressing each phase comprehensively to forge a resilient network. Among the critical actions to be taken, careful site selection, informed by the rigorous risk analysis of the area, emerges as a cornerstone. This proactive measure ensures that network infrastructure is strategically placed to withstand potential disruptions and recover swiftly in the face of adversity. Furthermore, implementing scheduled maintenance and pursuing optimal design strategies emerge as vital contributors to a resilient system. These measures bolster network performance and enhance its capacity to endure unforeseen challenges, ultimately safeguarding uninterrupted connectivity.
- The main challenges discussed in this paper regarding policies, sustainability, and climate change show the main gaps in the literature. First and foremost, the realm of policies requires a dedicated focus, particularly concerning the energy resilience for TNs, considering the use of renewable energy, fuel cells, and storage and their inherent constraints. Specific studies related to policies in the TN and power supply framework to enhance their joint resilience still need to be included in the literature. Secondly, our investigation into incorporating uncertainties within the energy management system (EMS) has unveiled opportunities to enhance the performance of backup systems and off-grid base stations. However, this also reveals an existing gap in the literature—the absence of comprehensive studies and models that fully harness the potential of uncertainty integration for increased system resilience. Lastly, examining climate change's impact on different regions highlights a crucial gap in current knowledge. While we recognize the necessity of building a more resilient TN to cope with climate-related disruptions, a more in-depth and region-specific analysis is imperative. Understanding the unique challenges posed by varying environmental conditions is essential for crafting tailored solutions that ensure the long-term sustainability and reliability of TNs.

Author Contributions: Conceptualization, S.L., F.G. and A.C.-T.; methodology, A.C.-T.; formal analysis, A.C.-T.; writing—original draft preparation, A.C.-T.; writing—review and editing, S.L., F.G. and A.C.-T.; supervision, S.L. and F.G.; funding acquisition, S.L. and F.G. All authors have read and agreed to the published version of the manuscript.

Funding: This article was supported by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on "Telecommunications of the Future" (PE00000001 - program "RESTART", Structural Project 6GWINET, Focused Project R4R).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ENISA	European Union Agency for Cybersecurity
TNO	Telecommunication Network Operator
TSO	Transmission System Operator
DSO	Distribution System Operator
GSMA	Global System for Mobile Communication Association
TIM	Telecom Do Communications over the Mobile network
KPN	Royal Dutch Telecom
ITU	International Telecommunication Union
ETSI	European Telecommunications Standards Institute
FCC	Federal Communication Commission
EC-RRG	Electronic Communications Resilience & Response Group
DG	Diesel Generator
EMS	Energy Management System
VPP	Virtual Power Plant
MED	Multi-Access Edge Computing
RES	Renewable Energy Systems
PV	Photovoltaic
SM	Sleeping Model

References

1. Malatras, A.; Bafoutsou, G.; Taurins, E.; Dekker, M. *ENISA—Annual Report Telecom Security Incidents 2021*; Technical Report July; ENISA: Attiki, Greece, 2021. [CrossRef]
2. Centre for Research on the Epidemiology of Disasters (CRED). Available online: https://public.emdat.be/ (accessed on 27 June 2023).
3. IEA. *Hydropower—Fuels & Technologies—IEA*; Technical Report; IEA: Paris, France, 2022.
4. Moramarco, T.; Barbetta, S.; Pandolfo, C.; Tarpanelli, A.; Berni, N.; Morbidelli, R. Spillway Collapse of the Montedoglio Dam on the Tiber River, Central Italy: Data Collection and Event Analysis. *J. Hydrol. Eng.* **2013**, *19*, 1264–1270. [CrossRef]
5. Xu, Y.; Xing, Y.; Huang, Q.; Li, J.; Zhang, G.; Bamisile, O.; Huang, Q. A review of resilience enhancement strategies in renewable power system under HILP events. *Energy Rep.* **2023**, *9*, 200–209. [CrossRef]
6. Gruppo TIM | TIM PER L'EMILIA ROMAGNA. Available online: https://www.gruppotim.it/it/gruppo/chi-siamo/news/TIM-EMILIAROMAGNA-ALLUVIONE.html (accessed on 27 June 2023).
7. Marqusee, J.; Jenket, D. Reliability of emergency and standby diesel generators: Impact on energy resiliency solutions. *Appl. Energy* **2020**, *268*, 114918. [CrossRef]
8. Saboori, H. Enhancing resilience and sustainability of distribution networks by emergency operation of a truck-mounted mobile battery energy storage fleet. *Sustain. Energy, Grids Netw.* **2023**, *34*, 101037. [CrossRef]
9. Yao, S.; Wang, P.; Zhao, T. Transportable Energy Storage for More Resilient Distribution Systems with Multiple Microgrids. *IEEE Trans. Smart Grid* **2019**, *10*, 3331–3341. [CrossRef]
10. Franceschi, J.; Rothkop, J.; Miller, G. Off-grid Solar PV Power for Humanitarian Action: From Emergency Communications to Refugee Camp Micro-grids. *Procedia Eng.* **2014**, *78*, 229–235. [CrossRef]
11. Gandotra, P.; Jha, R.K.; Jain, S. Green Communication in Next Generation Cellular Networks: A Survey. *IEEE Access* **2017**, *5*, 11727–11758. [CrossRef]
12. Zahed, M.I.A.; Ahmad, I.; Habibi, D.; Phung, Q.V.; Mowla, M.M.; Waqas, M. A Review on Green Caching Strategies for Next Generation Communication Networks. *IEEE Access* **2020**, *8*, 212709–212737. [CrossRef]
13. Lopez-Perez, D.; De Domenico, A.; Piovesan, N.; Xinli, G.; Bao, H.; Qitao, S.; Debbah, M. A Survey on 5G Radio Access Network Energy Efficiency: Massive MIMO, Lean Carrier Design, Sleep Modes, and Machine Learning. *IEEE Commun. Surv. Tutorials* **2022**, *24*, 653–697. [CrossRef]
14. Israr, A.; Yang, Q.; Li, W.; Zomaya, A.Y. Renewable energy powered sustainable 5G network infrastructure: Opportunities, challenges and perspectives. *J. Netw. Comput. Appl.* **2021**, *175*. [CrossRef]

15. Prasad, K.N.V.; Hossain, E.; Bhargava, V.K. Energy Efficiency in Massive MIMO-Based 5G Networks: Opportunities and Challenges. *IEEE Wirel. Commun.* **2017**, *24*, 86–94. [CrossRef]
16. Fowdur, T.P.; Doorgakant, B. A review of machine learning techniques for enhanced energy efficient 5G and 6G communications. *Eng. Appl. Artif. Intell.* **2023**, *122*, 106032. [CrossRef]
17. Andersson, C.; Bengtsson, J.; Bystrom, G.; Frenger, P.; Jading, Y.; Nordenstrom, M. Improving energy performance in 5G networks and beyond. *Ericsson Technol. Rev.* **2022**, *2022*, 2–11. [CrossRef]
18. Yan, J.; Zhou, M.; Ding, Z. Recent Advances in Energy-Efficient Routing Protocols for Wireless Sensor Networks: A Review. *IEEE Access* **2016**, *4*, 5673–5686. [CrossRef]
19. Liu, X.; Chen, B.; Chen, C.; Jin, D. Electric power grid resilience with interdependencies between power and communication networks—A review. *IET Smart Grid* **2020**, *3*, 182–193. [CrossRef]
20. Freitag, C.; Berners-Lee, M.; Widdicks, K.; Knowles, B.; Blair, G.S.; Friday, A. The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations. *Patterns* **2021**, *2*. [CrossRef] [PubMed]
21. Buzzi, S.; Chih-Lin, I.; Klein, T.E.; Poor, H.V.; Yang, C.; Zappone, A. A survey of energy-efficient techniques for 5G networks and challenges ahead. *IEEE J. Sel. Areas Commun.* **2016**, *34*, 697–709. [CrossRef]
22. Lorincz, J.; Capone, A.; Wu, J. Greener, energy-efficient and sustainable networks: State-of-the-art and new trends. *Sensors (Switzerland)* **2019**, *19*, 4864. [CrossRef]
23. Zhang, S.; Cai, X.; Zhou, W.; Wang, Y. Green 5G enabling technologies: An overview. *IET Commun.* **2019**, *13*, 135–143. [CrossRef]
24. Jasiūnas, J.; Lund, P.D.; Mikkola, J. Energy system resilience—A review. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111476. [CrossRef]
25. Osman, A.I.; Chen, L.; Yang, M.; Msigwa, G.; Farghali, M.; Fawzy, S.; Rooney, D.W.; Yap, P.S. Cost, environmental impact, and resilience of renewable energy under a changing climate: A review. *Environ. Chem. Lett.* **2022**, *21*, 741–764. [CrossRef]
26. GSMA. *Green Power for Mobile Bi-Annual Report*; Technical Report; GSMA: London, UK, 2014.
27. Victory, N.J. *Independent Panel Reviewing the Impact of Hurricane Katrina on Communications Networks—Report and Recommendations to the Federal Communications Commission*; US Federal Communications Commission Regulation: Washington, DC, USA, 2006.
28. Telecom Italia (TIM). *2021 Sustainability Report*; Technical Report; TIM: Milan, Italy, 2021.
29. Group, N.D. *Sustainability Report 2017*; Technical Report; NTT: Tokyo, Japan, 2017.
30. ENISA. *Enabling and Managing End-to-End Resilience*; Technical Report; ENISA: Attiki, Greece, 2010.
31. KPN. *Connecting Everyone in The Netherlands to a Sustainable Future*; Technical Report; KPN: Rotterdam, The Netherlands, 2022.
32. International Telecommunication Union. *ITU-T Focus Group on Environmental Efficiency for Artificial Intelligence and other Emerging Technologies*; Technical Report; ITU: Geneva, Switzerland, 2021.
33. Poaponsakorn, N.; Meethom, P.; Pantakua, K. The impact of the 2011 floods, and flood management on thai households. In *Resilience and Recovery in Asian Disasters: Community Ties, Market Mechanisms, and Governance*; Springer: Berlin, Germany, 2015; pp. 75–104. [CrossRef]
34. Bahia, K.; Delaporte, A. *The State of Mobile Internet Connectivity 2022*; GSMA Report; GSMA: London, UK, 2020; p. 61.
35. The National Institution for Transforming India. *India Energy Security Scenarios 2047—User Guide for Transport Sector*; Technical Report; The National Institution for Transforming India: New Delhi, India, 2012.
36. ITU. *Requirements of Network Resilience and Recovery*; Technical Report; ITU: Geneva, Switzerland, 2014.
37. Liang, Z.; Li, Y.F. Holistic Resilience and Reliability Measures for Cellular Telecommunication Networks. *Reliab. Eng. Syst. Saf.* **2023**, *237*, 109335. [CrossRef]
38. Cabrera-Tobar, A.; Bullich-Massagué, E.; Araǵués-Peñalba, M.; Gomis-Bellmunt, O. Review of advanced grid requirements for the integration of large scale photovoltaic power plants in the transmission system. *Renew. Sustain. Energy Rev.* **2016**, *62*, 971–987. [CrossRef]
39. *EN 300 132-3 V2.2.1*; Environmental Engineering (EE), Telecommunications and Datacom (ICT) Equipment. European Standard: Sophia Antipolis, France, 2016.
40. ETSI. *Environmental Engineering (EE); The Use of Alternative Energy Solutions in Telecommunications Installations*; Technical Report; European Telecommunications Standards Institute: Sophia Antipolis, France, 2012.
41. EC-RRG. *EC-RRG Resilience Guidelines for Providers of Critical National Telecommunications Infrastructure*; Technical Report 1; UK Government: London, UK, 2014.
42. Elmazaj, E. Managing Power Outages in Communication Networks. Ph.D. Thesis, Politecnico di Torino, Torino, Italy, 2021.
43. Karagiannis, G.M.; Chondrogiannis, S.; Krausmann, E.; Turksezer, Z.I. *Power Grid Recovery after Natural Hazard Impact*; Joint Research Center: Brussels, Belgium, 2017. [CrossRef]
44. Ferraro, M.; Brunaccini, G.; Sergi, F.; Aloisio, D.; Randazzo, N.; Antonucci, V. From Uninterruptible Power Supply to resilient smart micro grid: The case of a battery storage at telecommunication station. *J. Energy Storage* **2020**, *28*. [CrossRef]
45. Green G. *Next G Alliance Green G: The Path Toward Sustainable 6G*; Technical Report; Alliance for Telecommunications Industry Solutions: Washington, DC, USA, 2022.
46. *Global EV Outlook 2020*; Technical Report; IEA: Paris, France, 2020.
47. Gabriel, C. *Powering Off-Grid Mobile Networks and Universal Connectivity: A New Business Case*; Technical Report May; Rethink Technology Research: Bristol, UK, 2018.
48. Modu, B.; Abdullah, M.P.; Sanusi, M.A.; Hamza, M.F. DC-based microgrid: Topologies, control schemes, and implementations. *Alex. Eng. J.* **2023**, *70*, 61–92. [CrossRef]

49. Corporation, M. *Solar Powered Telecommunications*; Technical Report; Morningstar Corporation: Newtown, PA, USA, 2012.
50. Minister for Communications, Cyber Safety and the Arts. *Impacts of the 2019—20 Bushfires on the Telecommunications Network Report for the Minister for Communications, Cyber Safety and the Arts*; Technical Report April; Minister for Communications, Cyber Safety and the Arts: ACMA, Sydney, Australia, 2020.
51. Kwasinski, A. *Hurricane Sandy Effects on Communication Systems*; Technical Report; The University of Texas at Austin: Austin, TX, USA, 2012.
52. Aros-Vera, F.; Gillian, S.; Rehmar, A.; Rehmar, L. Increasing the resilience of critical infrastructure networks through the strategic location of microgrids: A case study of Hurricane Maria in Puerto Rico. *Int. J. Disaster Risk Reduct.* **2021**, *55*, 102055. [CrossRef]
53. Kwasinski, A.; Weaver, W.W.; Chapman, P.L.; Krein, P.T. Telecommunications power plant damage assessment for hurricane katrina-site survey and follow-up results. *IEEE Syst. J.* **2009**, *3*, 277–287. [CrossRef]
54. Van Nostrand, J. Keeping the Lights on During Superstorm Sandy: Climate Change Adaptation and the Resiliency Benefits of Distributed Generation. *NYU Environ. Law J.* **2020**, *23*, 92–154. [CrossRef]
55. Moreno, J.; Shaw, D. Community resilience to power outages after disaster: A case study of the 2010 Chile earthquake and tsunami. *Int. J. Disaster Risk Reduct.* **2019**, *34*, 448–458. [CrossRef]
56. Tang, A.K.; Eng, P.; Eng, C.; Asce, F. Lifelines performance of the MW 8.8 off shore Biobío, Chile earthquake. *Procedia Eng.* **2011**, *14*, 922–930. [CrossRef]
57. Koks, E.E.; Van Ginkel, K.C.; Van Marle, M.J.; Lemnitzer, A. Brief communication: Critical infrastructure impacts of the 2021 mid-July western European flood event. *Nat. Hazards Earth Syst. Sci.* **2022**, *22*, 3831–3838. [CrossRef]
58. Akinyele, D.; Olabode, E.; Amole, A. Review of fuel cell technologies and applications for sustainable microgrid systems. *Inventions* **2020**, *5*, 42. [CrossRef]
59. Sharaf, O.Z.; Orhan, M.F. An overview of fuel cell technology: Fundamentals and applications. *Renew. Sustain. Energy Rev.* **2014**, *32*, 810–853. [CrossRef]
60. Power, G.; Mobile, F. *Smarter Solutions for a Clean Energy Future Fuel Cell Systems for Telecom Backup Power*; Technical Report; Ballard: Washington, DC, USA, 2013.
61. Energy SFC. *Case Study: Back-Up Power Supply for Telecommunication Systems*; Energy SFC: Calgary, AB, Canada, 2023.
62. Leva, S.; Zaninelli, D. Hybrid renewable energy-fuel cell system: Design and performance evaluation. *Electr. Power Syst. Res.* **2009**, *79*, 316–324. [CrossRef]
63. Stroyov, L.; Patel, S.; Ali, R. Innovative fuel cell deployment in telstra's network and key learnings from the field. In Proceedings of the INTELEC, International Telecommunications Energy Conference (Proceedings), Broadbeach, QLD, Australia, 22–26 October 2017; pp. 47–53. [CrossRef]
64. Saathoff, S. ReliOn Fuel Cells Providing Reliable Power for Telecoms; *Fuel Cells Bull.* **2014**, *3*, 15–17. https://www.sciencedirect.com/science/article/pii/S1464285914700902. [CrossRef]
65. Solutions—Advent Technologies. Available online: https://serene.advent.energy/solutions/ (accessed on 4 July 2023).
66. Squadrito, G.; Andaloro, L.; Ferraro, M.; Antonucci, V. Hydrogen fuel cell technology. *Adv. Hydrog. Prod. Storage Distrib.* **2014**, 451–498. [CrossRef]
67. Gray, E.M.; Webb, C.J.; Andrews, J.; Shabani, B.; Tsai, P.J.; Chan, S.L. Hydrogen storage for off-grid power supply. *Int. J. Hydrog. Energy* **2011**, *36*, 654–663. [CrossRef]
68. Wang, D.; Liao, B.; Zheng, J.; Huang, G.; Hua, Z.; Gu, C.; Xu, P. Development of regulations, codes and standards on composite tanks for on-board gaseous hydrogen storage. *Int. J. Hydrog. Energy* **2019**, *44*, 22643–22653. [CrossRef]
69. Lead-acid Battery Market Size, Trends, Analysis | Industry Forecast 2025. Available online: https://www.technavio.com/report/lead-acid-battery-market-industry-analysis (accesed on 20 July 2023).
70. Townsend, A.; Gouws, R. A Comparative Review of Lead-Acid, Lithium-Ion and Ultra-Capacitor Technologies and Their Degradation Mechanisms. *Energies* **2022**, *15*, 4930. [CrossRef]
71. Wang, F.; Fan, X.; Wang, F.; Liu, J. Backup Battery Analysis and Allocation against Power Outage for Cellular Base Stations. *IEEE Trans. Mob. Comput.* **2019**, *18*, 520–533. [CrossRef]
72. Gati, A.; Salem, F.E.; Serrano, A.M.G.; Marquet, D.; Masson, S.L.; Rivera, T.; Phan-Huy, D.T.; Altman, Z.; Landre, J.B.; Simon, O.; et al. Key technologies to accelerate the ICT Green evolution—An operator's point of view. *arXiv* **2019**, arXiv:1903.09627.
73. Gong, F.; Chen, S.; Zhao, L.; Yao, G.; Tian, S.; Shao, J. Optimal Scheduling of Active Distribution Network with 5G Communication Base Station Participating in Demand Response Considering Carbon Benefit. In Proceedings of the EI2 2022—6th IEEE Conference on Energy Internet and Energy System Integration, Chengdu, China, 11–13 November 2022; pp. 2562–2568. [CrossRef]
74. Cabrera-Tobar, A.; Massi Pavan, A.; Petrone, G.; Spagnuolo, G. A Review of the Optimization and Control Techniques in the Presence of Uncertainties for the Energy Management of Microgrids. *Energies* **2022**, *15*, 9114. [CrossRef]
75. García-Triviño, P.; Sarrias-Mena, R.; García-Vázquez, C.A.; Leva, S.; Fernández-Ramírez, L.M. Optimal online battery power control of grid-connected energy-stored quasi-impedance source inverter with PV system. *Appl. Energy* **2023**, *329*, 120286. [CrossRef]
76. Moretti, L.; Polimeni, S.; Meraldi, L.; Raboni, P.; Leva, S.; Manzolini, G. Assessing the impact of a two-layer predictive dispatch algorithm on design and operation of off-grid hybrid microgrids. *Renew. Energy* **2019**, *143*, 1439–1453. [CrossRef]

77. Polimeni, S.; Moretti, L.; Martelli, E.; Leva, S.; Manzolini, G. A novel stochastic model for flexible unit commitment of off-grid microgrids. *Appl. Energy* **2023**, *331*, 120228. [CrossRef]
78. Polimeni, S.; Meraldi, L.; Moretti, L.; Leva, S.; Manzolini, G. Development and experimental validation of hierarchical energy management system based on stochastic model predictive control for Off-grid Microgrids. *Adv. Appl. Energy* **2021**, *2*, 100028. [CrossRef]
79. Cabrera-Tobar, A.; Massi Pavan, A.; Blasuttigh, N.; Petrone, G.; Spagnuolo, G. Real time Energy Management System of a photovoltaic based e-vehicle charging station using Explicit Model Predictive Control accounting for uncertainties. *Sustain. Energy, Grids Netw.* **2022**, *31*, 100769. [CrossRef]
80. Renga, D.; Umar, Z.; Meo, M. Trading off delay and energy saving through Advanced Sleep Modes in 5G RANs. *IEEE Trans. Wirel. Commun.* **2023**, 1–12. [CrossRef]
81. Wu, J.; Zhang, Y.; Zukerman, M.; Yung, E.K.N. Energy-efficient base-stations sleep-mode techniques in green cellular networks: A survey. *IEEE Commun. Surv. Tutorials* **2015**, *17*, 803–826. [CrossRef]
82. Han, F.; Zhao, S.; Zhang, L.; Wu, J. Survey of Strategies for Switching Off Base Stations in Heterogeneous Networks for Greener 5G Systems. *IEEE Access* **2016**, *4*, 4959–4973. [CrossRef]
83. Piovesan, N.; Lopez-Perez, D.; Miozzo, M.; Dini, P. Joint Load Control and Energy Sharing for Renewable Powered Small Base Stations: A Machine Learning Approach. *IEEE Trans. Green Commun. Netw.* **2021**, *5*, 512–525. [CrossRef]
84. Gambin, A.F.; Rossi, M. A Sharing Framework for Energy and Computing Resources in Multi-Operator Mobile Networks. *IEEE Trans. Netw. Serv. Manag.* **2020**, *17*, 1140–1152. [CrossRef]
85. Antonopoulos, A.; Kartsakli, E.; Bousia, A.; Alonso, L.; Verikoukis, C. Energy-efficient infrastructure sharing in multi-operator mobile networks. *IEEE Commun. Mag.* **2015**, *53*, 242–249. [CrossRef]
86. Kwon, Y.; Kwasinski, A.; Kwasinski, A. Coordinated Energy Management in Resilient Microgrids for Wireless Communication Networks. *IEEE J. Emerg. Sel. Top. Power Electron.* **2016**, *4*, 1158–1173. [CrossRef]
87. Zhang, X.; Wang, Z.; Zhou, Z.; Liao, H.; Ma, X.; Yin, X.; Lv, G.; Wang, Z.; Lu, Z.; Liu, Y. Optimal Dispatch of Multiple Photovoltaic Integrated 5G Base Stations for Active Distribution Network Demand Response. *Front. Energy Res.* **2022**, *10*, 1–13. [CrossRef]
88. Ma, X.; Duan, Y.; Meng, X.; Zhu, Q.; Wang, Z.; Zhu, S. Optimal configuration for photovoltaic storage system capacity in 5G base station microgrids. *Glob. Energy Interconnect.* **2021**, *4*, 465–475. [CrossRef]
89. Vallero, G.; Deruyck, M.; Meo, M.; Joseph, W. Base Station switching and edge caching optimisation in high energy-efficiency wireless access network. *Comput. Netw.* **2021**, *192*, 108100. [CrossRef]
90. Sharma, D.; Singhal, S.; Rai, A.; Singh, A. Analysis of power consumption in standalone 5G network and enhancement in energy efficiency using a novel routing protocol. *Sustain. Energy, Grids Netw.* **2021**, *26*. [CrossRef]
91. Ding, T.; Wang, J.; Matas, J.; Guerrero, J.M.; Qiao, R.; Wang, C. Multi-Time Scale Energy Management Strategy based on MPC for 5G Base Stations Considering Backup Energy Storage and Air Conditioning. In Proceedings of the IEEE International Conference on Predictive Control of Electrical Drives and Power Electronics (PRECEDE), Wuhan, China, 16–19 June 2023; pp. 1–6. [CrossRef]
92. Rahman, M.R.U.; Niknejad, P.; Barzegaran, M.R. Resilient Hybrid Energy System (RHES) for Powering Cellular Base Transceiver Station during Natural Disasters. In Proceedings of the IEEE Power and Energy Conference at Illinois, PECI 2021, Urbana, IL, USA, 1–2 April 2021. [CrossRef]
93. Candan, A.K.; Boynuegri, A.R.; Onat, N. Home energy management system for enhancing grid resiliency in post-disaster recovery period using Electric Vehicle. *Sustain. Energy Grids Netw.* **2023**, *34*, 101015. [CrossRef]
94. Xu, N.Z.; Chan, K.W.; Chung, C.Y.; Niu, M. Enhancing Adequacy of Isolated Systems with Electric Vehicle-Based Emergency Strategy. *IEEE Trans. Intell. Transp. Syst.* **2020**, *21*, 3469–3475. [CrossRef]
95. Tian, M.W.; Talebizadehsardari, P. Energy cost and efficiency analysis of building resilience against power outage by shared parking station for electric vehicles and demand response program. *Energy* **2021**, *215*, 119058. [CrossRef]
96. Dong, Z.; Zhang, X.; Zhang, N.; Kang, C.; Strbac, G. A distributed robust control strategy for electric vehicles to enhance resilience in urban energy systems. *Adv. Appl. Energy* **2023**, *9*, 100115. [CrossRef]
97. Zhou, C.; Feng, C.; Wang, Y. Spatial-Temporal Energy Management of Base Stations in Cellular Networks. *IEEE Internet Things J.* **2022**, *9*, 10588–10599. [CrossRef]
98. Li, Y.; Zhao, X.; Liang, H. Throughput Maximization by Deep Reinforcement Learning with Energy Cooperation for Renewable Ultradense IoT Networks. *IEEE Int. Things J.* **2020**, *7*, 9091–9102. [CrossRef]
99. Gambin, A.F.; Scalabrin, M.; Rossi, M. Energy Sustainable Mobile Networks via Energy Routing, Learning and Foresighted Optimization. *arXiv* **2018**, arXiv:1803.06173.
100. Hossain, M.S.; Jahid, A.; Islam, K.Z.; Rahman, M.F. Solar PV and Biomass Resources-Based Sustainable Energy Supply for Off-Grid Cellular Base Stations. *IEEE Access* **2020**, *8*, 53817–53840. [CrossRef]
101. Dlamini, T.; Gambin, A.F.; Munaretto, D.; Rossi, M. Online supervisory control and resource management for energy harvesting bs sites empowered with computation capabilities. *Wirel. Commun. Mob. Comput.* **2019**, *2019*. [CrossRef]
102. Salahdine, F.; Opadere, J.; Liu, Q.; Han, T.; Zhang, N.; Wu, S. A survey on sleep mode techniques for ultra-dense networks in 5G and beyond. *Comput. Netw.* **2021**, *201*, 108567. [CrossRef]
103. Liu, L.; Zhang, Z.; Wang, N.; Zhang, H.; Zhang, Y. Online Resource Management of Heterogeneous Cellular Networks Powered by Grid-Connected Smart Micro Grids. *IEEE Trans. Wirel. Commun.* **2022**, *21*, 8416–8430. [CrossRef]

104. Zhang, X.; Wang, Z.; Liao, H.; Zhou, Z.; Ma, X.; Yin, X.; Wang, Z.; Liu, Y.; Lu, Z.; Lv, G. Optimal capacity planning and operation of shared energy storage system for large-scale photovoltaic integrated 5G base stations. *Int. J. Electr. Power Energy Syst.* **2023**, *147*, 108816. [CrossRef]
105. Du, P.; Lei, H.; Ansari, I.S.; Du, J.; Chu, X. Distributionally robust optimization based chance-constrained energy management for hybrid energy powered cellular networks. *Digit. Commun. Netw.* **2023**, *9*, 797–808. [CrossRef]
106. Cong, Y.; Zhou, X. Event-Trigger Based Robust-Optimal Control for Energy Harvesting Transmitter. *IEEE Trans. Wirel. Commun.* **2017**, *16*, 744–756. [CrossRef]
107. Xu, J.; Duan, L.; Zhang, R. Energy Group Buying with Loading Sharing for Green Cellular Networks. *IEEE J. Sel. Areas Commun.* **2016**, *34*, 786–799. [CrossRef]
108. Cao, Y.; Jiang, T.; He, M.; Zhang, J. Device-to-device communications for energy management: A smart grid case. *IEEE J. Sel. Areas Commun.* **2016**, *34*, 190–201. [CrossRef]
109. Le, T.A.; Vien, Q.T.; Nguyen, H.X.; Ng, D.W.K.; Schober, R. Robust Chance-Constrained Optimization for Power-Efficient and Secure SWIPT Systems. *IEEE Trans. Green Commun. Netw.* **2017**, *1*, 333–346. [CrossRef]
110. Webber, J.L.; Chen, A.S.; Stevens, J.; Henderson, R.; Djordjević, S.; Evans, B. Targeting property flood resilience in flood risk management. *J. Flood Risk Manag.* **2021**, *14*, 1–18. [CrossRef]
111. Corporation and Telephone. *Social Challenge 6 Moving towards a Safe, Secure, and Resilient Society*; Technical Report; NTT: Tokio, Japan, 2022.
112. Javidsharifi, M.; Pourroshanfekr, H.; Kerekes, T.; Sera, D.; Spataru, S.; Guerrero, J.M. Optimum sizing of photovoltaic and energy storage systems for powering green base stations in cellular networks. *Energies* **2021**, *14*, 1895. [CrossRef]
113. Leva, S.; Grimaccia, F.; Rozzi, M.; Mascherpa, M. Hybrid Power System Optimization in Mission-Critical Communication. *Electronics* **2020**, *9*, 1971. [CrossRef]
114. Junid, A.; Yap, E.H.; Ng, P.K. Electric vehicle charging at telco base station and bidirectional charging at hillslope descent technical-commercial cost-benefit study and scheduling-reservation system. In Proceedings of the 2018 International Conference on Smart Grid and Clean Energy Technologies, ICSGCE 2018, Kajang, Malaysia, 29 May–1 June 2018; pp. 137–144. [CrossRef]
115. Dugan, J.; Mohagheghi, S.; Kroposki, B. Application of mobile energy storage for enhancing power grid resilience: A review. *Energies* **2021**, *14*, 6476. [CrossRef]
116. The Nomad System. Available online: https://www.nomadpower.com/the-nomad-system(accessed on 20 July 2023)
117. ENISA. *Measurement Frameworks and Metrics for Resilient Networks and Services: Challenges and Recommendations*; Technical Report February; ENISA: Attiki, Greece, 2010.
118. Grimaccia, F.; Giudici, F.; Mascherpa, M.; Leva, S. Energy efficiency for radio communication systems in mission-critical applications. In Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference, Venice, Italy, 1–5 November 2020. [CrossRef]
119. Rozzi, M.; Mascherpa, M.; Grimaccia, F.; Leva, S. Hybrid Renewable Power System for Radio Networks in Mission Critical Applications. In Proceedings of the 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2020, Madrid, Spain, 9–12 June 2020. [CrossRef]
120. Shi, J.; Ma, L.; Li, C.; Liu, N.; Zhang, J. A comprehensive review of standards for distributed energy resource grid-integration and microgrid. *Renew. Sustain. Energy Rev.* **2022**, *170*, 112957. [CrossRef]
121. Reich, K.; Pompili, M.; Bakic, K.; Bondarenko, Y. Development of resilience issues and challenges in the SEERC region: South East European regional council of CIGRE. *Elektrotechnik Und Informationstechnik* **2020**, *137*, 476–486. [CrossRef]
122. Bartolucci, L.; Cordiner, S.; Mulone, V.; Pasquale, S. Fuel cell based hybrid renewable energy systems for off-grid telecom stations: Data analysis and system optimization. *Appl. Energy* **2019**, *252*, 113386. [CrossRef]
123. Cabrera-Tobar, A.; Blasuttigh, N.; Pavan, A.M.; Lughi, V.; Petrone, G.; Spagnuolo, G. Energy Scheduling and Performance Evaluation of an e-Vehicle Charging Station. *Electronics* **2022**, *11*, 3948. [CrossRef]
124. Nespoli, A.; Ogliari, E.; Leva, S. User Behavior Clustering Based Method for EV Charging Forecast. *IEEE Access* **2023**, *11*, 6273–6283. [CrossRef]
125. Natgunanathan, I.; Mak-Hau, V.; Rajasegarar, S.; Anwar, A. Deakin Microgrid Digital Twin and Analysis of AI Models for Power Generation Prediction. *Energy Convers. Manag.* **2023**, *18*, 100370. [CrossRef]
126. Beheshti, M.; Heidari, A.; Saghafian, B. Susceptibility of Hydropower Generation to Climate Change: Karun III Dam Case Study. *Water* **2019**, *11*, 1025. [CrossRef]
127. Zhou, Y. Climate change adaptation with energy resilience in energy districts—A state-of-the-art review. *Energy Build.* **2023**, *279*, 112649. [CrossRef]
128. Leva, S.; Nespoli, A.; Pretto, S.; Mussetta, M.; Ogliari, E.G.C. PV plant power nowcasting: A real case comparative study with an open access dataset. *IEEE Access* **2020**, *8*, 194428–194440. [CrossRef]