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The Impact of Blackouts on Urban Energy Resilience: Case Studies from Spain, Portugal, and Poland

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Abstract

Long-term and large-scale power outages (blackouts) pose a significant threat to the functioning of modern cities, exposing the level of their preparedness for crisis situations. A blackout is a systemic phenomenon whose cascading impacts extend far beyond the energy sector, affecting multiple interdependent domains of urban operations. Therefore, this study aims to evaluate the resilience of urban systems to electricity supply disruptions across infrastructural, institutional, social, and functional dimensions, based on blackout case studies from selected cities in Poland, Spain, and Portugal. Utilising data spanning the period 2008–2025, a qualitative cross-case comparison was conducted based on indicator coding and the identification of recurrent patterns. The results indicate that a blackout simultaneously impacts all four dimensions of urban resilience. The highest vulnerability was observed within the social and functional dimensions, manifested by the limited preparedness of residents for prolonged power deprivation, as well as disruptions in information flow and municipal service delivery. Furthermore, the findings reveal that a high level of infrastructural resilience does not guarantee effective crisis response without adequate institutional and social support. Based on these insights, it is recommended to develop a European Union-level framework to secure financial resources aimed not only at mitigating the consequences of blackouts—which frequently exhibit cross-border characteristics—but primarily at funding proactive prevention and preparedness measures against power grid failures.

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1. Introduction

Cities have long been and remain to be perceived as the primary engines of human development. Indeed, Europe has transformed into a continent predominantly charac-

terised by urban areas; it is estimated that approximately 70% of the EU population—equivalent to around 350 million individuals—reside in urban agglomerations with a population exceeding 5000 inhabitants [1]. Urban infrastructure must be adapted to meet these demographic needs. However, this infrastructure is exposed to a wide range of hazards, including natural disasters, technical failures, and armed conflicts. Therefore, evaluating the level of urban resilience against these threats based on European cities is highly warranted. Consequently, the issue of urban resilience is becoming a key priority in contemporary urban policy implementation. Within this context, the concept of resilience should be treated as a multidimensional attribute encompassing adaptability, defined as the capacity of a region and its stakeholders to adapt to shocks and ensure continuous development. Furthermore, resilience involves preparing for shocks and capitalising on post-crisis opportunities [2]. This broader approach to resilience defines the scope adopted by the authors of this article. Specifically, this study focuses on the phenomenon of urban resilience to contemporary threats related to interruptions or total failures in power supply. This hazard is of critical importance for the functioning of all operational areas in modern cities. Moreover, energy infrastructure constitutes a systemic component of the so-called critical infrastructure [3].

The contemporary energy crisis exposes the structural constraints inherent in the traditional paradigm of energy systems. Heavily reliant on fossil fuels, highly susceptible to geopolitical dynamics, and frequently underpinned by ageing infrastructure, this system is becoming increasingly fragile in the face of disruptions. Consequently, the systemic vulnerability of economies and societies to volatile energy supplies is escalating, engendering multifaceted economic, social, and security risks. Within this context, a blackout must be conceptualized not merely as an isolated technical incident but rather as a systemic phenomenon encompassing technological, socio-economic, and institutional dimensions. This phenomenon highlights the misalignment of current frameworks with the escalating complexity and dynamics of contemporary urban and energy systems.

Therefore, a comprehensive examination of this subject matter—incorporating the following core components—can significantly enrich the academic contribution of this study:

1. A critical review of European Union legislative frameworks and regulations governing blackouts.
2. An assessment of urban resilience to blackouts, operationalised as a systemic phenomenon across infrastructural, institutional, social, and functional dimensions.
3. The selection of EU member states for empirical analysis, characterized by diverse energy mix structures and documented blackout events.
4. A longitudinal or differentiated temporal analysis of the specific periods during which blackouts occurred across the examined EU nations.

Given that this topic is highly relevant in light of the ongoing energy crisis—exacerbated, *inter alia*, by geopolitical and armed conflicts [4]—the empirical findings of this study may be of significant value to a broad spectrum of stakeholders involved in developing urban blackout resilience frameworks. These include representatives from the following sectors:

1. EU institutions, as well as national and regional public administration bodies responsible for shaping urban and energy policies.
2. The banking and financial sector, which provides funding and capital support for urban energy transition projects within the EU.

3. The energy sector, encompassing both power generation companies and transmission/distribution system operators (TSOs and DSOs) engaged in upgrading grids to integrate renewable energy sources (RESs).
4. Academia and the scientific community, conducting research on the financing of urban policies within the frameworks of resilience theory and the formulation of adaptive strategies for emerging disasters.
5. Social media platforms and digital communication channels, which actively shape public perception and attitudes towards solutions implemented to enhance urban resilience against blackouts.

2. Literature Review

2.1. Blackout as a Systemic Phenomenon

In the literature, blackouts are treated as a systemic phenomenon. The research approach within this framework focuses primarily on three aspects:

- (1) The nature of the power law,
- (2) The multi-faceted causes and consequences of blackouts,
- (3) The method of blackout projection.

Regarding the first aspect, the research conducted by I. Dobson, B.A. Carreras, V.E. Lynch, and D.E. Newman demonstrates that power transmission systems represent critical infrastructure, and that failures within these systems can have severe consequences for economic stability and national security. Their studies further show that the size distribution of blackouts follows a power law over a significant part of its range, indicating that power systems exhibit characteristics of complex dynamic systems. In fact, in certain cases, measures aimed at mitigating small outages may actually increase the frequency of large-scale power disruptions [5].

The aforementioned researchers attributed the causes of large-scale transmission grid blackouts to cascading failures, demonstrating that the frequency of major outages obeys a power law. According to this law, the risk of large-scale blackouts is substantial, as the power system operates as a complex system designed and managed near its critical point.

Although the system's operational margins evolve slowly towards this criticality, this evolution is driven by continuous load growth, economic pressure to maximise grid utilisation urbanisation, and engineering responses to blackouts that drive system upgrades. Consequently, mitigation strategies aimed at reducing outage risks must account for the dynamic phenomena inherent in complex, self-organising critical systems [6].

The inherent complexity of power systems has naturally driven research interest towards identifying the multi-faceted causes and consequences of blackouts. In this context, a power outage is conceptualised as a socio-technical-environmental phenomenon [7]. According to D. Złotecka and K. Sroka, the inevitability of power system failures stems from factors such as extreme weather events, human error, and technical faults, posing a tangible threat not only to the power grid itself but also to public safety and security in a broader sense [8]. A subset of the detailed analyses in this field focused on establishing a direct correlation between the failure rates of power system components, total system demand, and wind speed. Furthermore, evidence showed that restoring system components within 13 h can reduce load shedding stemming from cascading events in the national grid by up to 52% [9].

In turn, N.D. Fita, I. Utu, M.D. Marcu, D. Pasculescu, I.O. Mila, F.G. Popescu, T. Lazar, A.M. Schiopu, F. Muresan-Grecu, and E.A. Cruceru expanded the range of blackout causes in their research. They identified instability in the functioning of the National Power System, terrorist attacks on the National Power System, extreme weather

conditions, natural calamities, energy insecurity, and political/military insecurity. The authors emphasised the necessity of an interdisciplinary approach to the analysis of blackout causes, addressing socio-economic, technological, and political issues to provide an integrated view of the phenomenon [10]. The consequences of blackouts can be far-reaching. In contemporary societies, which are increasingly dependent on information technology and, by extension, on electricity, power outages can trigger uncontrolled cascading failures across systems reliant on technological components. These systems are critical for the biological survival of the population, safety and defence, social development, and the economy. Consequently, this can unleash chains of destructive events with an open-ended timeframe, capable of breaching any man-made protective barrier and threatening everything within their sphere of influence [11].

Bearing this in mind, some researchers make concerted efforts to apply blackout projection methods. A compelling case in this field involves scenario planning and role-playing exercises conducted with German and French university students to investigate potential human behavioural responses and expectations of government during a hypothetical three-day blackout [12]. Another prominent approach involves estimating electricity interruption costs for households by determining the average annual Value of Lost Load (VoLL) [13].

The literature review demonstrates a clear consensus among researchers regarding the conceptualisation of blackouts as a systemic phenomenon.

2.2. EU Legal Frameworks for Power System Security and Blackout Prevention

In the era of energy transition and increasing reliance on renewable energy sources (RES), the stability of the European power system has become a priority for both national and Union security. The European Union has shifted from fragmented national regulations towards an integrated crisis management model, as reflected in the “Clean Energy for all Europeans” package and subsequently in the “Fit for 55” legislative package. This model mandates the coordination of actions during extreme scenarios, ensuring that non-market measures (e.g., mandatory load shedding) are employed strictly as a last resort, without compromising the integrity of the internal market (ACER, 2024) [14].

A key legal act within the discussed package, concerning the mitigation of systemic failure risks, is Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector [15]. Pursuant to Article 3 of this Regulation, Member States are required to identify all relevant electricity crisis scenarios at both national and regional levels (ENTSO-E). The act further mandates the development of risk-preparedness plans, which must be established based on the principle of solidarity. According to Article 15, Member States are obliged to offer mutual assistance to safeguard public security, provided that “fair compensation” is agreed upon. Furthermore, the Regulation introduces a requirement to draft National Risk-Preparedness Plans. Under the established procedure, Member States are compelled to successively update their national crisis scenarios (e.g., extreme weather events, hybrid attacks).

While Regulation (EU) 2019/941 establishes the political framework, the technical aspects of blackout protection are regulated by Commission Regulation (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration (NC ER) [16]. The Code defines specific system states (normal, alert, emergency, blackout, and restoration). According to Article 11, each Transmission System Operator (TSO) is required to develop a system defence plan, which includes, among others: automatic low-frequency load shedding procedures, reactive power management to prevent voltage collapse, and strategies for mitigating the effects of

cascading failures. In the event of national or regional power supply disruptions, EU law mandates the application of “black start” procedures. Article 23 of Regulation 2017/2196 specifies the requirements for generating units with black-start capability. Member States must ensure that their systems possess a sufficient number of such units to enable island operation and the gradual restoration of power supply to consumers. The legal structure grants specific powers to the Agency for the Cooperation of Energy Regulators (ACER) and the European Network of Transmission System Operators for Electricity (ENTSO-E) in compliance with Regulation (EU) 2019/943 on the internal market for electricity [17]. ENTSO-E is responsible for developing periodic European Resource Adequacy Assessments (ERAA). As required by Article 9(1) of Regulation (EU) 2019/943, TSOs are obliged to maintain operational security, which in practice entails strict adherence to inter-regional exchange limits. This is essential to avoid transmission line overloads, which are the most common cause of cross-border blackouts.

Another legal act, Regulation (EU) 2024/1747 [18], constitutes part of the Electricity Market Design (EMD) reform and serves as an amending act. Its primary function is the incorporation of new regulatory mechanisms into the legal framework established by Regulation (EU) 2019/943 on the internal market for electricity [17] and Regulation (EU) 2019/942 establishing ACER [19]. Through this integration, the EU legislator does not create a separate system but rather performs an evolutionary modification of the existing market architecture, adapting it to the requirements of security and resilience against external shocks. The direct impetus for the reform was the 2022 energy crisis, which exposed the European economy’s excessive exposure to fossil fuel price volatility and the flaws of the marginal pricing model (merit-order), which threatened the financial stability of consumers and the adequacy of system resources (Regulation 2024/1747, Recital 5; Widuto, 2024, p. 2) [18,20].

The role of Regulation 2024/1747 [18] in ensuring security of supply extends beyond purely technical aspects, serving as the economic foundation of the security of the system. While operational procedures for emergency states are governed by network codes (such as NC ER), Regulation 2024/1747 ensures capacity adequacy during critical situations by optimising investment mechanisms. A key tool in this regard is streamlining the application of capacity mechanisms, which—as a structural market element—aim to guarantee that generation units essential for grid stability remain viable and operationally ready, even amidst high penetration of variable renewables. Articles 19d and 19e, introduced by Regulation 2024/1747 into Regulation (EU) 2019/943, oblige Member States to perform assessments of system flexibility needs and to set national targets for energy storage. These mechanisms serve as a direct tool for mitigating blackout risks by stabilising the grid during periods of peak demand.

The implementation of mandatory two-way contracts for difference (CfDs) under Article 19b of Regulation (EU) 2019/943 (as introduced by Regulation (EU) 2024/1747, p. 26) remains a subject of debate among leading research institutions. While Meeus et al. (2023, p. 7) from the Florence School of Regulation (FSR) [21] argue that this mechanism is crucial for de-risking investments and ensuring resource adequacy, ACER (2024, p. 15)[22]. ACER, places greater emphasis on the necessity of designing these contracts in a way that does not undermine the operational flexibility of the system, which is essential for preventing emergency states and blackouts, notably by ensuring that generators remain responsive to real-time price signals.

Directive (EU) 2024/1711 [23] serves as an amending act, modifying, *inter alia*, Directive (EU) 2019/944 on common rules for the internal market for electricity. Its implementation aims to stabilise demand and modernise distribution grids, which directly translates into a reduced risk of systemic failures. While Regulation (EU) 2024/1747 [18] focuses on ensuring resource adequacy in the wholesale market, Directive

(EU) 2024/1711 complements the Union's security framework at the local level. The incorporation of the prohibition of disconnections for vulnerable customers (Article 28a) and the modernisation of Distribution System Operators' (DSOs) tasks regarding smart grids (Article 31) allow for the creation of a system resilient to both social and technical shocks. These measures are an essential prerequisite for mitigating the risk of decentralised grid failures.

Directive (EU) 2022/2557 [24] on the resilience of critical entities aims to strengthen the physical resilience of entities essential for the maintenance of vital societal functions and economic activities within the internal market. This regulation serves as a response to evolving hybrid, terrorist, and climate-related threats. The Directive shifts the focus from purely infrastructural protection to the resilience of entities, defined as their ability to prevent, resist, respond to, and recover rapidly from incidents. It establishes a comprehensive framework for oversight and support by imposing specific obligations on both Member States and critical entities. These obligations include the adoption of a resilience-enhancing framework (Article 4), the conduct of regular national risk assessments for essential services (Article 5), the identification of critical entities (Article 6), and the implementation by those entities of appropriate technical, security, and business continuity measures (Articles 12 and 13). By virtue of Article 22, Member States are required to lay down a system of penalties for infringements of national provisions adopted under this Directive.

Regulation (EU) 2024/1366 (Network Code on Cybersecurity—NCCS) [25] aims to establish a uniform cybersecurity framework for cross-border electricity flows, encompassing risk management and incident response planning (Article 1). The act introduces an obligation to conduct regular risk assessments at both national and Union levels to identify high-impact and critical-impact entities (Articles 7 and 8). Furthermore, it requires system operators (TSOs and DSOs) and critical entities to implement advanced protection measures for control and grid automation systems (Article 24). The Regulation also introduces stringent incident reporting rules and the obligation to develop business continuity and recovery plans in the event of a cyberattack (Articles 35 and 37).

An analysis of the seven pillars of the EU legal order—ranging from technical network codes (NC ER, NCCS) and operational frameworks (Regulations 2019/941 and 2019/943) to the latest structural reforms (Regulation 2024/1747, and Directives 2024/1711 and 2022/2557)—reveals the emergence of an integrated electricity security architecture. Its evolution signifies a paradigm shift from reactive crisis management towards proactive mitigation of systemic failure risks. Driven by regulatory synergies, security of supply has transcended the exclusive jurisdiction of individual Member States. It has transformed into the baseline foundation for the operational integrity of the entire European interconnected grid. Despite the 17-year temporal gap separating the investigated events, the legislative structure maintains profound operational consistency. The regulations addressing blackout phenomena have not undergone disruptive or radical upheavals over this period; rather, they have evolved continuously upon stable, well-established legal and technical foundations.

2.3. Urban Resilience to Blackouts

In the existing literature, the analysis of urban resilience to blackouts constitutes an interdisciplinary discourse. This is evident in the choice of research subjects, the selection of methodologies and the formulation of recommendations based on the analytical results. Four dimensions of urban resilience to blackouts can be distinguished:

1. **Infrastructural**—a review of research on the infrastructural dimension of urban resilience to blackouts highlights two main areas of analysis: (1) primary energy

generation technologies (photovoltaic, solar thermal, wind, hydroelectric, nuclear, combined cycle, coal)/forms of energy; and (2) the adaptation of energy infrastructure to weather conditions and urbanisation. Within the first area, researchers demonstrate that conventional sources, such as nuclear and combined cycles, exhibit low variability, with daily fluctuations of less than 1%. By contrast renewable sources display significant variability [26]. Furthermore, scholars indicate that urban resilience is influenced by the evolution of primary energy infrastructure forms (thermal, electrical and chemical), which were originally developed as independent networks but currently interact with one another. This applies to both generation and storage units, as well as transmission systems. Multi-energy systems—sometimes referred to as smart energy systems—provide a framework within which various energy vectors interact at different levels, making it difficult to precisely determine the time of failure occurrence [27]. Conversely, within the second research area, it has been demonstrated that the combined effects of climate change and urbanisation highlight the need to develop sustainable and resilient energy systems. Urban overheating and rising living standards, coupled with the increasing installation of air conditioning systems in summer, lead to a non-linear growth in cooling demand. According to researchers, there are two primary challenges in this regard: (1) the integration of multi-sectoral models with diverse spatial and temporal resolutions; and (2) the requirement for high-quality datasets to construct reliable models. However, as authors emphasise, meeting these requirements will be difficult in urban areas due to their complex and interdependent infrastructure systems, which in turn hinders the acquisition of accurate and timely data [28].

2. Institutional—in analyses of the institutional dimension of urban resilience to blackouts, researchers primarily focus on identifying operational weaknesses within these institutions and proposing improvements. Authors argue that approaches based on coordination in critical infrastructure risk management—including those essential to energy system resilience—often fail in practice due to persistent barriers to information sharing, unclear accountability structures and organisational constraints. Therefore, they propose the implementation of a multidimensional governance framework for blackout risk management that: (1) utilises context-aware planning logic to adapt resilience-enhancing measures to local conditions; (2) implements participatory governance mechanisms to co-develop strategies and enhance adaptive capacity; and (3) ensures analytical integration by combining regulatory requirements, spatial assessments and stakeholder knowledge within a unified decision-support framework [29]. Furthermore, a shift in the approach to developing urban crisis management strategies is proposed. Rather than merely striving for the decarbonisation of energy systems and climate change mitigation, it is also crucial to plan for climate change adaptation, especially in urban areas characterised by complex energy flows and interactions. Climate change mitigation and adaptation strategies should be evaluated in parallel, accounting for a wide range of measures from supply to demand [30]. Scholars emphasise that implementing an integrated regulatory framework for resilience, supported by technical upgrades and governance reforms, will significantly reduce the risk of grid failure amid the escalation of extreme weather events [31].
3. Social—in the study of human responses to the phenomenon of blackouts, three main strands can be distinguished. The first strand highlights the vast population affected by the consequences of failures induced by various causes. Ranging, for example, from the effects of flooding in Germany (Cologne) in 1993 and 1995 [32] to

natural hazards in Japan (the 2018 Eastern Iburi earthquake in Hokkaido and Typhoon Faxai in 2019) [33]. Given the large scale of affected populations, particularly among households utilising photovoltaic systems, researchers recommend raising awareness that the installation itself does not increase household resilience until they prepare for emergency situations with the assistance of distributors. Consequently, distributors should instruct households on how to operate photovoltaic systems during emergencies. Conversely, the second research strand highlights the selection of new methodologies to assess the psychological reactions and behavioural attitudes of individuals affected by blackouts. Interesting studies in this field, using the New York blackout as a case study, were conducted by L. Li, Z. Ma and T. Cao, who indicated that leveraging social media data offers new opportunities for evaluating community resilience to crises [34]. Meanwhile, A. Rudolph-Cleff, M. Knodt, J. Schulze and A. Engel highlighted the significant role of out-of-home (OoH) advertising media as a crisis communication channel, using the city of Darmstadt as a case study [35]. Within the third research strand, drawing on Elinor Ostrom's theory of goods, authors indicated that only a small proportion of respondents perceive self-generated electricity as a private good. Therefore, the vast majority are willing to share their resources as a club good or a common-pool resource to make their city more resilient to blackouts [36]. The academic community suggests that assessing the social dimension of blackouts has substantial developmental potential. However, its findings may exhibit limited predictive value for direct application to other, unstudied cities due to the highly diverse nature of living conditions across different urban areas globally.

4. Functional—research on this dimension of urban resilience to blackouts focuses primarily on identifying areas that require operational enhancement. In these studies, the improvement system is frequently linked to the root causes of power grid failures. For instance, Y. Song, C. Wan, X. Hu, H. Qin and K. Lao identified two main causes of failure: (1) extreme weather conditions and natural disasters; and (2) deliberate man-made attacks and social crises. Based on this, researchers recommended conducting analyses regarding electronically controlled distribution networks, flexible aggregation of distributed resources, cyber-physical-social systems, multi-energy systems, smart electric transportation, artificial intelligence and Big Data technologies [28,37]. In contrast, A. Silvest linked the improvement system to evaluating the effects of an increasing share of renewable energy within the energy mix, the concurrent decentralisation of energy systems and the growing digitisation of energy infrastructure. He noted that these factors can either enhance or diminish the capacity of urban energy infrastructure to respond to various stresses and shocks, thereby determining its resilience [38]. Meanwhile, research by A.M. Feldpausch-Parker, T.R. Peterson, J.C. Stephens and E.J. Wilson addressed the critical need for a shift in the approach to assessing urban resilience to blackouts. The researchers recommended moving away from measures aimed at mitigating the consequences of power failures (i.e., actions focused on electricity demand issues) towards configuring energy systems for climate change adaptation [39].
5. Although the four-dimensional structure organises the key components of resilience, its theoretical value is not limited to a classificatory function. The case study findings indicate that the individual dimensions remain interrelated, with the nature of these relationships depending on the system's operational context. This implies that resilience is relational and emergent—it does not result from the simple summation of the characteristics of individual dimensions, but rather from their mutual interaction. The conducted analysis also revealed the occurrence of trade-offs. Actions enhancing one dimension of resilience may temporarily

constrain the development potential of another, whereas in other situations, synergistic effects are observed, leading to a simultaneous increase in resilience across multiple dimensions. Consequently, the effectiveness of a management strategy depends not on maximising a single component, but on maintaining a balance between them. In this light, the proposed model extends existing concepts of resilience. Rather than treating the four dimensions as distinct categories of description, we propose interpreting them as interdependent elements forming a dynamic architecture of resilience. The case study enabled the identification of the mechanisms underlying these interdependencies and demonstrated that analysing the interactions between dimensions provides a more comprehensive explanation of the system's capacity for adaptation, reorganisation, and maintenance of core functions than analysing each dimension in isolation. Thus, the study contributes a novel element to resilience theory, shifting the focus from the identification of resilience components to the analysis of the relationships and mechanisms linking these components.

3. Methodology

The objective of this research is to evaluate urban system resilience to power supply disruptions, based on a comparative case study of blackouts in Poland (Szczecin), Spain (Madrid, Barcelona, Seville), and Portugal (Lisbon, Porto). Given this objective, the study aims to address both theoretical and practical gaps by answering four key research questions:

1. How do blackouts affect urban resilience in the infrastructural dimension?
2. How do blackouts affect urban resilience in the institutional dimension?
3. How do blackouts affect urban resilience in the social dimension?
4. How do blackouts affect urban resilience in the functional dimension?

Based on a literature review, the following research hypothesis was formulated: The highest level of urban resilience to blackouts is achieved by urban systems where technical infrastructure development is coordinated with institutional measures and the strengthening of social capital. To operationalize the concept of urban resilience, a set of analytical indicators (based on secondary data) was applied, categorised according to the dimensions of urban blackout resilience established by the authors:

1. **Infrastructural dimension**—the analysis included an assessment of critical infrastructure, whose condition, availability, and robustness are fundamental to the effectiveness of crisis response. The list of indicators for evaluating the infrastructural dimension of blackouts is presented in Table 1.

Table 1. List of indicators for the assessment of the infrastructural dimension of blackouts.

Assessment Area	Indicator	Description	Measurement Method	Unit/Scale
Critical Infrastructure	Infrastructure operability	The degree of functionality of key systems (power, water, transport)	number of functional elements/total	%
	Recovery time	The speed of infrastructure restoration after a failure	average time to restore	hours/days
	Infrastructural robustness	The capacity to operate under crisis conditions	event analysis/testing	scale (e.g., 1–5)
	System redundancy	The existence of backup systems	number of alternative sources/systems	count
	Infrastructure accessibility	The degree of service availability for the population	% of population with access	%

Failure rate	Frequency of failures	number of failures per period	count
Failure response time	The speed of initiating corrective actions	average response time of technical services	minutes/hours
Technical condition	Infrastructure wear and tear level	technical assessment/inspections	scale or %

Source: own study based on: [40–48].

2. Institutional dimension—the analysis included an assessment of the crisis management system covering five key areas: planning, inter-institutional coordination, communication, operational readiness, and response effectiveness. The list of indicators for the assessment of the institutional dimension of blackouts is presented in Table 2.

Table 2. List of indicators for the assessment of the institutional dimension of blackouts.

Assessment Area	Indicator	Description	Measurement Method	Unit/Scale
Crisis management plans	Plan validity	The extent to which documents are up to date	Ratio of updated plans to total plans	%
	Exercise frequency	Frequency of drills and simulations	Number of exercises per year	count
	Procedural compliance	The degree of practical implementation of procedures	Analysis of actual events or exercises	%
	Documentation accessibility	Speed of access to documentation	Average time to retrieve documents	minutes
Inter-institutional coordination	Joint exercises	The level of inter-institutional cooperation	Number of joint exercises	count
	Information exchange time	Efficiency of information flow	Average time to transmit information	minutes
	Coordination disruptions	Occurrence of cooperation failures or obstacles	Number of reported problems	count
	Cooperation assessment	Subjective evaluation of collaboration	Survey research/Questionnaires	scale (1–5)
Communication effectiveness	Communication time	The speed of information dissemination	Time from incident to message issuance	minutes
	Communication channels	Diversity of information methods	Number of channels utilised	count
	Message clarity	Degree of understanding by recipients	Survey research	% or scale
	Communication errors	Number of imprecise or inaccurate messages	Content analysis of messages	count
Operational readiness	Equipment availability	The level of technical readiness	Ratio of operational units to total units	%
	Staff competency level	Personnel preparedness and qualifications	Ratio of trained personnel to total staff	%
	Mobilisation time	The speed of resource deployment	Elapsed time from alarm to operational status	minutes
Response effectiveness	Incident containment time	Efficiency of operational activities	Total duration of the incident	minutes/hours
	Number of affected persons	Scale of the incident's impact	Statistical data analysis	count

Material losses	Level of economic damage	Estimated value of losses	currency (e.g., PLN/EUR)
Operational objective attainment	The degree to which goals were achieved	Post-action analysis	%

Source: own study based on:[40–47]; [48](p. 59,p.62); [49].

3. Social dimension—the analysis included an assessment of public risk awareness, community engagement, and trust in public institutions, which significantly impact the effectiveness of crisis management. The list of indicators for the assessment of the social dimension of blackouts is presented in Table 3.

Table 3. List of indicators for the assessment of the social dimension of blackouts.

Assessment Area	Indicator	Description	Measurement Method	Unit/Scale
Social dimension	Public risk awareness	Residents' knowledge of potential threats and response protocols	Survey research	% or scale (e.g., 1–5)
	Training participation rate	Public engagement in educational and preparedness activities	Ratio of participants to total population	%
	Information accessibility	Ability to obtain timely information regarding threats	Communication channel analysis	count/%
	Trust in authorities	Level of trust in emergency services and public administration	Survey research	scale (e.g., 1–5)
	Public response patterns	Population behaviour and compliance during a crisis	Event analysis/drill observation	qualitative/%
	Volunteer mobilisation	Community-led social activity in crisis situations	Number of active volunteers	count/%
	Access to assistance	Ease and speed of obtaining emergency support	Time to receive help/aid point density	minutes/count
	Vulnerable group inclusion	Consideration and support for highly exposed populations	Proportion of vulnerable persons covered by support	%
	Disinformation prevalence	The scale and impact of false information	Media monitoring/report analysis	count

Source: own study based on: [40–47]; [48] (pp. 25–31).

4. Functional dimension—the analysis included an assessment of response speed, decision-making efficiency, and the capacity to maintain operational continuity and flexibility. The list of indicators for the assessment of the functional dimension of blackouts is presented in Table 4.

Table 4. List of indicators for the assessment of the functional dimension of blackouts.

Assessment Area	Indicator	Description	Measurement Method	Unit/Scale
Functional dimension	System response time	The speed of deploying measures following threat detection	Elapsed time from reporting to action initiation	minutes
	Decision-making efficiency	The effectiveness of the decision-making process	Time required to reach critical decisions	minutes
	Operational continuity	The capacity of the system for uninterrupted operation	Frequency of system operational interruptions	count
	Operational flexibility	The ability to adapt to dynamic	Incident/exercise analysis	scale (e.g., 1–5)

	situational changes	ysis	
Procedural effectiveness	The degree of execution of pre-defined actions	Operational flow analysis	%
Resource utilisation	The efficiency of using available assets	Ratio of utilised to available resources	%
Information flow	The efficiency of information circulation within the system	Duration and frequency of disruptions	minutes/count
Integration of actions	Coherence of activities across diverse entities	Operational synergy analysis	scale (e.g., 1–5)

Source: own study based on: [1–8]; [9](pp. 59–61).

The applied indicator framework is synthetic and constitutes the authors' own adaptation of established crisis management assessment models.

Secondary data were retrieved for the years 2008 and 2025 (corresponding to the blackout occurrences in the analysed EU countries). Certain indicator values, however, are presented over a broader temporal horizon, which was necessary to account for the specific nature of particular dimensions—such as training-related indicators.

The analysis was conducted on three EU Member States: Poland, Spain, and Portugal. The selection of these research cases was purposive, based on the following criteria:

- (1) Event-related—the occurrence of large-scale blackouts with significant socio-economic consequences (Szczecin: [50,51], Spain and Portugal: [52]).
- (2) Comparability—the capacity to analyse similar phenomena across diverse systemic contexts within EU Member States;
- (3) Heterogeneity—the variation in institutional, technological, and geographical conditions regarding the development of cities impacted by blackouts (Spain: Madrid, Barcelona, and Seville; Portugal: Lisbon, Porto; Poland: Szczecin);
- (4) Energy diversity—the variety of primary energy sources and access to energy commodities [53], including Poland: coal 55.9% [54] and for Spain and Portugal: oil and petroleum products 44.1% [55, 56];
- (5) The impact of high-emission energy sources on final energy costs [57].

The selection of these research cases facilitates a comparative analysis to identify both common vulnerability mechanisms and factors differentiating urban resilience to blackouts. Comparing the same phenomenon—the blackout—across different countries and timeframes constitutes a spatio-temporal comparative analysis. Research encompassing diverse spatial units and periods allows for capturing the complexity of the analysed phenomena by simultaneously accounting for their temporal variability and contextual differentiation. Thus, analyzing blackouts across various countries and periods enables a simultaneous understanding of the influence of systemic conditions and longitudinal changes. The coding process was based on a predefined set of indicators corresponding to the four dimensions of resilience. For each indicator, an operational definition and criteria for assigning individual evaluation categories were developed. The coding was conducted based on the analysis of qualitative secondary data, comprising institutional reports, technical documents, as well as scientific and press publications regarding the analysed events. To ensure consistency, all cases were evaluated according to identical criteria and the same analytical procedure. In situations where information was derived from multiple sources, the assessment was based on cross-verification and compliance with available documentation. In ambiguous cases, a cautious interpretation was applied, based on the best-documented sources. The objective of the coding was not to obtain precise quantitative values but to systematically organise qualitative information in a manner that enables a comparison of the analysed cases. Since the coding was

performed by a single researcher, a formal inter-coder reliability analysis was not conducted. This limitation was taken into account when interpreting the results.

The research objective was pursued through systematic data collection, processing, and presentation methods. The data collection phase involved a literature review on urban system resilience to power supply disruptions (blackouts), focusing on three specific thematic areas:

- (1) Blackout as a systemic phenomenon;
- (2) EU legal regulations regarding blackouts;
- (3) Urban resilience in the context of blackouts.

The data processing method utilised a qualitative approach to analyse case-specific data from the three EU Member States whose cities experienced blackouts. Qualitative content analysis was applied [58], which involved data coding (based on the defined indicators) and the identification of recurrent patterns. Subsequently, a comparative analysis was conducted using a qualitative cross-case comparison based on indicator coding [45,47]. This methodology enabled the identification of similarities and differences among the analysed urban cases and the determination of factors influencing urban resilience levels. The indicators were utilised as coding categories in the qualitative analysis, facilitating a systematic cross-case comparison, the identification of systemic gaps, and the assessment of urban preparedness for blackouts. The analysis was grounded in a systems approach, treating the city as a network of interconnected subsystems; this allowed for capturing cascading effects and their implications for critical infrastructure functionality. Consequently, the research adopted an interpretive approach [59], focusing on the analysis of processes, relationships, and adaptive mechanisms emerging during crisis situations. The primary research strategy employed was a multiple case study, following the methodological principles formulated by Robert K. Yin (When applying the discussed research approach, its limitations must be taken into account. The analysis was based on secondary data derived from various sources, whose scope, level of detail, and accessibility were not uniform across all analysed cases. The compared blackout events occurred in different periods, which may have influenced the regulatory and technological contexts. Although uniform evaluation criteria were adopted for all cases, the indicator coding process involves an element of expert interpretation inherent to qualitative research. For this reason, the obtained results should be treated as the product of a structured comparative analysis rather than a fully objective measurement. The study does not include a formal inter-coder reliability assessment; however, this does not affect the validity of the identified mechanisms and interdependencies) [60]. This method is particularly effective for analyzing complex phenomena deeply embedded in their real-world context, especially when the boundaries between the phenomenon and its context are not clearly defined. In turn, the data presentation method utilised both tabular and graphical formats. The analyses were conducted from a normative perspective, facilitating the identification of conditions essential for designing new solutions, including those within the financial sphere [61].

4. Results

4.1. The Specificity of the Blackout Phenomenon in Spain, Portugal and Poland

Based on a comparative analysis of the regional blackout in Szczecin (Poland) on 8 April 2008 and the large-scale blackout in Spain and Portugal on 28 April 2025, both similarities in the mechanisms of power system vulnerability and significant differences resulting from the level of infrastructure development, the degree of power grid integration, and the scale of the events' impact can be identified. The primary distinction lay in the spatial and demographic scale of the failures. The blackout in Szczecin was

inherently regional, affecting approximately half a million end-users [62], whereas the systemic blackout across Spain and Portugal impacted an estimated 50–60 million residents [63,64], thereby constituting one of the most severe disruptions to power system operations in 21st-century Europe [65–67].

The second significant difference lay in the root causes of the failures. In the case of Szczecin, infrastructure-related issues predominated, specifically limited network redundancy, the technical condition of the infrastructure, and localised damage to the transmission system [51,68]. From a critical infrastructure security perspective, the Szczecin blackout constituted a classic example of a system losing its resilience due to the concurrent occurrence of a natural factor (extreme weather conditions), technical deficiencies in the infrastructure, and the operator's limited organisational capacity to respond to a crisis situation [49,62,69]. A specific characteristic of this failure was its highly pervasive impact across all critical infrastructure sectors. The power outage resulted in the suspension of tram and partial rail transport, disruptions in heat and water supply, limitations in hospital operations, issues with telecommunications networks and Internet connectivity, the halting of operations in public offices, schools, and enterprises, and operational constraints at industrial plants (including the Police chemical plant, where the sudden voltage drop posed a risk of an industrial accident within ammonia-based installations) [70]. The power restoration process lasted from several hours within the city area to several days in suburban and rural districts [71]. Despite organisational and infrastructural constraints, no casualties were recorded, and the social response remained relatively stable [72].

Conversely, the blackout in Spain and Portugal resulted from a complex confluence of multiple technical factors, encompassing power system oscillations, voltage regulation issues, inadequate reactive power management, and the cascading disconnection of generation sources [66,73,74]. According to the ENTSO-E report, the event was the outcome of the interaction between a series of concurrent processes within the power system rather than a single infrastructure failure [75]. In this blackout scenario, the transboundary dimension assumed paramount importance, necessitating coordinated actions among multiple transmission system operators (TSOs) functioning within the internal European energy market [53]. The power system restoration process took from several to more than twelve hours, whereas achieving full network stability required nearly 24 h.

Despite the contrasting causes and scale of the consequences of the blackouts in Spain, Portugal, and Poland, the resilience of modern power systems does not depend solely on the quality of technical infrastructure. Consequently, the adaptive capacities of institutions, the efficiency of crisis management procedures, the level of public preparedness, and the effectiveness of cooperation between operators are also of crucial importance. Therefore, a comparative analysis of the various dimensions of blackout resilience across different urban areas is essential for both cognitive and practical applications.

4.2. The Impact of Blackouts on the Infrastructural Resilience of the Studied Cities

The first issue subjected to a comparative analysis for the investigated cities in Spain, Portugal and Poland was their resilience to blackouts from an infrastructural perspective. A compilation of the indicators utilised to conduct the comparative analysis for the infrastructural dimension of blackouts is presented in Table 5.

Table 5. Indicators of the infrastructural dimension of blackouts for the studied cities in Spain, Portugal and Poland.

Indicator	Values in Spain and Portugal	Values in Poland	Interpretation for Both Cases
Infrastructure efficiency	Dropped sharply, down to 30%	40% across 7 operational areas	Significant loss of stability in both cases
Restoration time	From 12 to 24 h, depending on the region	The city of Szczecin: 14 h Outside Szczecin: 7 days	Restoration within 24 h in urban areas, whereas in non-urban areas, restoration times extended to days, up to one week
Resilience	Low, score of 2 on a 5-point scale	Low, score of 2 on a 5-point scale	Cascading effects and low resilience, yielding identical scores despite the substantial temporal gap between the events
Redundancy	Limited; lack of safeguards and systemic diversification; total system load of Spain (25.2 GW) and Portugal (5.9 GW)	Significantly limited; lack of safeguards and systemic diversification	Lack of safeguards and a very low score, despite a substantial temporal gap between the occurrences of the events
Service availability	Very low (10%) and disruption of secondary services	Very low, with only up to 8% of residents retaining access to primary services	Complete power outage and a very low score, despite a substantial temporal gap between the occurrences of the events
Failure rate	High, score of 4 on a 5-point scale	Very high, score of 5 on a 5-point scale	Systemic event
Technical response time	Fast, score of 3 on a 5-point scale	From 50 min to 7 days, score of 2 on a 5-point scale	Moderate restoration efficiency given the adverse environmental and terrain conditions
Technical state	Moderate; however, comprehensive data remain limited	Significant degradation of transmission infrastructure in non-urban areas	Moderate in urban areas and significant infrastructure degradation in non-urban areas

Source: own elaboration based on [48,49,52,63–67,69,73–86].

Based on a comparison of the infrastructural resilience indicators, it is evident that despite the chronological, geographical, and technological disparities between the blackouts in Spain and Portugal and the blackout in Szczecin, both events exhibited strikingly similar systemic characteristics. In both cases, a sudden loss of power system stability occurred, resulting in a significant reduction in the availability of public and commercial services, alongside a cascading effect that led to widespread blackout. The most prominent similarity pertains to infrastructure resilience. In both instances, it received a score of 2 on a 5-point scale, indicating an insufficient capacity of the power systems to absorb disturbances and mitigate their consequences. Despite technological advancements and substantial investments implemented within European power systems after 2008, issues related to grid resilience against large-scale, widespread outages have persisted.

Similar conclusions can be drawn regarding the assessment of system redundancy. In both the Iberian and Szczecin cases, a limited number of safeguards and inadequate diversification of power sources and supply routes were identified. In Spain and Portugal, the immense scale of the system load, exceeding 31 GW, was of paramount significance. By contrast in Szczecin, the primary challenges were the sparse number of alternative power sources and the limited transmission capacity of the region. This implies that regardless of the power system's magnitude, the lack of adequate redundancy remains a primary factor amplifying the risk of blackout propagation.

Conversely, significant differences emerge regarding the power restoration time. In Spain and Portugal, the majority of end-users had their power restored within 12–24 h, demonstrating a relatively high system recovery capability. In Szczecin, the situation was more fragmented; the urban area regained power after approximately 14 h, whereas the restoration process in non-urban areas lasted up to seven days. This highlights a higher vulnerability of local grids and a lower level of preparedness among operators and the infrastructure of peripheral regions.

The infrastructural resilience analysis indicates a relatively low resilience of the power system to cascading disturbances. The loss of a large share of generation capacity within a short timeframe destabilised the entire grid, which underscores limited redundancy and insufficient compensatory mechanisms. Concurrently, it should be emphasised that the system restoration process proceeded relatively efficiently, as the majority of power supplies were restored within several hours, and a substantial portion of critical infrastructure regained functionality on the very same day. This reflects a relatively high level of technical preparedness among the personnel responsible for system recovery [64, 80]. However, the event exposed the imperative for further investments to enhance infrastructure resilience, particularly through the development of backup systems and the improvement of grid operational stability under highly volatile load conditions.

Research indicates that electrical power infrastructure constitutes the cornerstone of modern urban functionality. In both events, the loss of power led to severe disruptions in transport, telecommunications, water supply, healthcare, and public services. A comparison of both cases demonstrates that the level of infrastructural resilience does not solely depend on the degree of technical advancement of the infrastructure. System redundancy, the capability to island failures, and the availability of backup sources are also of critical importance.

These observations are particularly relevant in the context of Europe's ongoing energy transition, which is characterised by the increasing complexity and interdependence of energy systems. Despite a seventeen-year gap between the investigated events, the fundamental vulnerabilities of power systems remain similar. In both cases, low infrastructure resilience, limited redundancy, and a high dependence of public services on the continuity of electricity supply emerged as the core issues. The disparities primarily concern the scale of technical preparedness for system restoration and the condition of the transmission infrastructure. The analyses reveal that modern power systems, despite technological progress, remain vulnerable to the propagation of cascading failures, and enhancing infrastructure resilience and diversification should constitute one of the primary priorities of energy security policy. It is worth emphasising that although power systems underwent gradual modernisation between 2008 and 2025 (encompassing the development of digitisation, network automation, and an increasing share of renewable energy sources), their fundamental architecture (based on energy transmission and distribution) remained unchanged.

4.3. The Impact of Blackouts on the Institutional Resilience of the Studied Cities

The second issue subjected to a comparative analysis for the investigated cities in Spain, Portugal, and Poland was their resilience to blackouts from an institutional perspective. A compilation of the indicators utilised to conduct the comparative analysis for the institutional dimension of blackouts is presented in Table 6.

Table 6. Indicators of the institutional dimension of blackouts for the studied cities in Spain, Portugal and Poland.

Indicator	Values in Spain and Portugal	Values in Poland	Interpretation for Both Cases
Up-to-dateness of emergency plans	High (80%)	High (100%)	Operational national and EU procedures; in Poland, additional industry-specific and regional procedures are implemented
Testing of emergency plans	Regular (twice per year)	Tested at least once every 2 years	The system had been previously exercised in terms of separate components; however, it had not been comprehensively tested on a full aggregate (metropolitan) scale
Action compliance with emergency plans	Partial (approx. 70%)	Partial (approx. 70%)	Not all emergency procedures functioned effectively, and certain entities failed to execute actions in accordance with the pre-established protocols
Availability of emergency plans	High	Access time of approx. 10 min following the convening of the crisis management team	Rapid access for relevant institutions
Joint exercises	Moderate (once every three years)	None	Existing but insufficient
Information exchange time	Delayed; lack of coordination	Significantly delayed; complete lack of connectivity between entities in certain areas	Operational issues during crises; in Poland, radio communication was routed exclusively through the Police for all crisis management entities
Coordination issues	High	High, particularly during the initial hours of the blackout	Domino effect; unsatisfactory backup power infrastructure of mobile network operators
Cooperation assessment	Moderate, score of 3 on a 5-point scale	Moderate, score of 3 on a 5-point scale	Limited effectiveness in the execution of ad hoc and contingency measures
Communication time	Significantly delayed, particularly during the initial 5 h following the outage	Significantly delayed, particularly during the initial 4 h following the outage	Occurrence of severe technical issues
Communication channels	Limited technology dependent on the electrical power grid	Based on emergency services' voice messages; limited functioning of broadcast media and the Internet	Disruptions of ICT channels; lack of power supply and absence of mandates for telecommunication operators to maintain access to information
Message understandability	Moderate (60%)	Transmitted only within the necessary scope; reached approx. 50% of residents	Absence of comprehensive information
Communication errors	Occurrence of inconsistent information	Absence of information	Absence of information or inconsistent information

Source: own elaboration based on [48,49,52,63–67,69,73–86].

A comparative analysis of the institutional dimension of blackout resilience indicates that while formal operational readiness was high in all examined cases, severe practical vulnerabilities emerged regarding inter-agency coordination, data exchange, and crisis communication. A fundamental misalignment was observed between the theoretical existence of emergency protocols and their actual deployment efficacy during a systemic crisis. This discrepancy is heavily reflected in the inter-institutional

cooperation indicators. Across both the Spanish–Portuguese and the Szczecin events, information transfer suffered critical delays, particularly during the initial hours of the power outages when organisational networks experienced severe traffic saturation.

In the Polish case, this bottleneck escalated into a complete loss of communication across several administrative zones, which constrained emergency units to route their primary operational traffic exclusively through police radio networks. Furthermore, the data regarding joint emergency training underscore a structural deficiency in large-scale system readiness.

While the Iberian transmission system operators (TSOs) conducted inter-institutional drills on an average cycle of once every three years, the Polish administrative and utility sectors lacked any aggregated, metropolitan-scale exercise frameworks prior to the failure.

This empirical gap confirms that the absence of holistic, real-world simulation models remains a primary vulnerability in modern emergency management. Consequently, the quality of inter-agency cooperation in both events was evaluated at an identical score of 3 on a 5-point scale, proving that despite the divergent technological paradigms of 2008 and 2025, the baseline operational efficiency of institutional crisis response remained similarly constrained.

The escalation of these crises also exposed the strict reliance of institutional stability on technical infrastructure assets. In Szczecin, the organisational response was heavily impeded by the fact that emergency telecommunication channels lacked robust power redundancy, a vulnerability directly tied to the inadequate backup power infrastructure of mobile network operators. Conversely, the primary institutional challenge during the Iberian blackout centered on transboundary governance, requiring synchronized decision-making among multiple independent TSOs operating within a unified European energy market.

Ultimately, these findings demonstrate that institutional adaptive capacity is as vital to blackout mitigation as physical grid architecture. Modernised power grids cannot guarantee system security if the surrounding governance framework fails to secure rapid information flows and decisive command structures. Despite the seventeen-year temporal gap separating the analyzed blackouts, the core institutional vulnerabilities—namely, fragmented crisis communication and limited multi-sectoral interoperability—remain critically unchanged.

An analysis of the institutional blackout resilience indicators reveals that both events were characterized by a relatively high level of formal preparedness among administrative bodies and critical infrastructure operators. However, in practice, significant constraints emerged regarding operational coordination, information exchange, and crisis communication.

Both the blackouts in Spain and Portugal and the blackout in Szczecin revealed a significant gap between the existence of emergency procedures and their effective implementation during the crisis. Substantial similarities are evident in terms of inter-institutional cooperation. In both cases, the information exchange time was delayed, and the coordination of actions encountered numerous difficulties. This was particularly evident during the initial hours of the crisis, when rapid overloading of both communication and organisational systems transpired.

In Poland, this problem was further exacerbated by a partial or complete lack of connectivity among certain entities responsible for crisis management, forcing emergency services to utilise police radio networks as their primary communication channel. An analysis of the joint exercises indicator underscores the insufficient preparedness of both systems to cooperate during large-scale events.

In Spain and Portugal, inter-institutional exercises occurred on average once every three years, whereas in Poland, they were not conducted at all on a scale encompassing the entire metropolitan area. This confirms that the insufficient verification of protocols under conditions closely resembling a real crisis remains one of the primary challenges in contemporary crisis management.

The evaluation of cooperation among entities achieved an identical score of 3 on a 5-point scale in both cases. This demonstrates a moderate effectiveness of interaction and a limited capacity for the rapid implementation of corrective measures. Despite the technological and organisational differences separating the two events, the efficiency of institutional cooperation remained at a similar level.

Furthermore, institutional constraints related to the coordination of crisis management operations emerged in both analysed cases. Despite the formal existence of emergency protocols and crisis management plans, disruptions occurred regarding information flow, cooperation among entities, and decision-making under rapidly evolving crisis conditions.

In Szczecin, institutional weaknesses stemmed primarily from the limited preparedness of critical infrastructure operators and an insufficient number of exercises encompassing a prolonged blackout scenario. Communication issues between emergency services and the dependence of communication systems on electrical power supplies were particularly prominent.

Conversely, in the case of Spain and Portugal, the greatest challenge proved to be the coordination of actions among multiple transmission system operators (TSOs) and institutions functioning across different nations.

Consequently, institutional resilience constitutes one of the most critical factors mitigating the outcomes of a blackout. Even modern technical infrastructure is incapable of guaranteeing high system resilience if the institutions responsible for crisis management are unprepared for rapid decision-making and effective operational coordination. Despite a seventeen-year temporal gap between the two blackouts, similar constraints related to crisis communication and inter-institutional cooperation persist.

4.4. The Impact of Blackouts on the Social Resilience of the Analyzed Cities

The third aspect subjected to a comparative analysis for the studied cities in Spain, Portugal, and Poland was their resilience to blackouts in the social dimension. The compilation of indicators used to conduct the comparative analysis for the social dimension of blackouts is presented in Table 7.

Table 7. Indicators of the social dimension of blackouts for the analysed cities in Spain, Portugal and Poland.

Indicator	Values in Spain and Portugal	Values in Poland	Interpretation for Both Cases
Risk awareness	Moderate (65%)	Varied (approx. 50%)	Insufficient public awareness and preparedness
Participation in training	Low (30%)	Very low (10%)	Limited engagement; moreover, in Poland, it remains outside the crisis management system, coupled with an absence of training
Access to information	Limited (35%), including inconsistent institutional information	Limited to 10% of the population during the initial 6–8 h	Communication issues resulting from the total loss of power
Trust in institutions	Moderate, score of 3 on a 5-point scale	Moderate, score of 3 on a 5-point scale	Partial criticism driven by the lack of timely information
Public reaction	Stable, absence of general panic, but partial chaos	Stable, sense of uncertainty, partial chaos	Absence of panic, disinformation resilience

Volunteering	Limited, score of 2 on a 5-point scale	Limited, score of 2 on a 5-point scale	Minor role in both cases
Availability of assistance	Moderate, score of 3 on a 5-point scale	Moderate, score of 3 on a 5-point scale	Disruptions and assistance resulting from priorities established by the crisis management team
Vulnerable groups	Exposed (85%)	Exposed (100%)	Protection issues
Disinformation	Moderate, score of 3 on a 5-point scale	Moderate, score of 2 on a 5-point scale	Occurrence of misinformation
Containment time	24 h and 17 min elapsed until full containment	Szczecin: 14 h; outside Szczecin: 7 days	The containment process was relatively efficient, though highly varied in the case of Poland
Number of casualties	8 fatalities; the consequences affected 60 million people in Spain and Portugal	The consequences affected 512 thousand people	Fatalities occurred due to the large scale of the event in Spain; absence of casualties in Poland
Material losses	High (estimated: EUR 1.6 billion in Spain, EUR 1.1 billion in Portugal)	PLN 54.1 million (approx. EUR 12.5 million)	High losses in the case of Spain and Portugal (large area of the event); minor losses in the case of Poland (limited area of the event)
Goal achievement	Partial, score of 3 on a 5-point scale	Partial, score of 3 on a 5-point scale	Effectiveness was incomplete, and the exact scale remains difficult to estimate.

Source: own elaboration based on [48,49,52,63–67,69,73–86].

An analysis of indicators in the field of social resilience to blackouts reveals that despite significant differences in geographical scale and the number of people affected by the outage, public reactions and problems related to the functioning of the population were remarkably similar in both cases. Both cases—the blackout in Spain and Portugal, and the one in Szczecin, exposed a limited level of public preparedness for functioning under conditions of prolonged power shortages, as well as a high dependence of access to information on the efficiency of telecommunication systems.

The level of risk awareness was moderate in both cases. In Spain and Portugal, it was estimated at approximately 65%, whereas in Poland, it stood at around 50%. This implies that a substantial portion of society possessed only basic knowledge regarding the consequences of blackout and procedures for action in a crisis situation. Even more pronounced differences occur regarding participation in training and educational activities. In Spain and Portugal, public participation in training related to crisis response was approximately 30%, while in Poland, it reached only about 10% (reflecting an almost complete absence of systemic educational initiatives aimed at residents outside the crisis management structures).

Access to information during the outage constituted one of the most serious social issues. In Spain and Portugal, only about 35% of the population had access to current information, with some messages being inconsistent and mutually contradictory. In Szczecin, the situation was even more challenging—during the initial 6–8 h, information reached only about 10% of the residents. In both cases, the primary cause stemmed from disruptions in the functioning of telecommunication systems and the dependence of information infrastructure on electrical power supply. Despite these difficulties, the level of trust in public institutions remained at a moderate level, evaluated at a score of 3 on a 5-point scale.

In both cases, criticism of the actions of authorities and infrastructure operators also emerged; however, it was primarily related to an insufficient flow of information rather than a complete loss of credibility in the institutions responsible for crisis management.

A particularly interesting element of the comparison is the description of public reaction. In Spain and Portugal, as well as in Poland, no phenomena of mass panic, rioting, or serious public order disruptions were recorded. A sense of uncertainty and local organisational chaos dominated; however, urban residents demonstrated substantial psychological resilience. The analyses indicate that even under conditions of prolonged disruption to the functioning of critical infrastructure, society is capable of maintaining relative social stability.

The stability of society constitutes a highly significant element of the urban resilience system to blackouts. Disruptions in electrical power supply directly influenced the daily functioning of residents by limiting access to information, public services, transport, and healthcare. Research shows that access to reliable information represents one of the most critical factors influencing social behaviour during a crisis.

Communication issues led to an increased sense of uncertainty and elevated the risk of the occurrence of misinformation. This implies that social resilience is not solely the result of residents' awareness, but also of the effectiveness of crisis communication systems. Strengthening social capital, civic education, and risk awareness should be treated as an integral element of energy security policy and urban resilience.

The comparative analysis of the social aspects of blackouts indicates that regardless of the scale of the event, societies react in a similar manner to a prolonged absence of electrical power. Unfortunately, technological development and the experience gained after previous blackouts have not eliminated the fundamental social problems related to functioning during power grid failures. Consequently, educational activities, the development of crisis communication systems independent of the electrical power grid, and the creation of effective support mechanisms for groups particularly vulnerable to the consequences of prolonged power outages are of paramount importance.

4.5. The Impact of Blackouts on the Functional Resilience of the Analyzed Cities

The fourth aspect subjected to a comparative analysis for the studied cities in Spain, Portugal, and Poland was their resilience to blackouts in the functional dimension. The compilation of indicators used to conduct the comparative analysis for the functional dimension of blackouts is presented in Table 8.

Table 8. Indicators of the functional dimension of blackouts for the analysed cities in Spain, Portugal and Poland.

Indicator	Values in Spain and Portugal	Values in Poland	Interpretation for Both Cases
Response time	Blackout fully developed within 1 min 17 s (<90 s)	Blackout fully developed between 21:25 and 04:43 UTC	Extremely rapid escalation in the case of Spain and Portugal; missed window of opportunity for response in the case of Poland, followed by cascading outages across successive areas (facilities)
Decision-making efficiency	Reduced, score of 2 on a 5-point scale	Score of 1 on a 5-point scale	Criticism of the operator; lack of preparedness and decisiveness within the operator's dispatch centres
Business continuity	Total operational failure	Critical operational failure, particularly during the initial hours of the event	Total blackout in the case of Spain; blackout covering 90% of the area of Szczecin in the case of Poland
Flexibility	Very low, score of 2 on a 5-point scale	Very low, score of 2 on a 5-point scale	A critical lack of adaptive capacity was observed in both systems
Procedural effectiveness	Partial, 60%	Crisis management: 90% Operator: 30%	Limited effectiveness and efficiency of action, particularly during the initial 6 h of

ness			the event
Resource utilisation	Moderate, 75%	Approximately 90% of available resources utilised	Suboptimal resource allocation in the case of Spain, resource shortages in Poland resulting from insufficient preparedness of the operator and the crisis management system
Information flow	Disrupted; technology dependent on power supply without the possibility of diversifying communication channels	Disrupted; technology dependent on power supply, with the TETRA (Terrestrial Trunked Radio) system serving as the sole communication channel	Systemic vulnerabilities; power supply failures combined with the absence of regulatory obligations for telecommunications operators to maintain access to information
Integration of actions	Moderate, score of 3 on a 5-point scale	Moderate, score of 3 on a 5-point scale	Partial cooperation; progressive collaboration as the situation developed

Source: own elaboration based on [48,49,52,63–67,69,73–86].

An analysis of indicators regarding functional resilience to blackouts indicates that in both cases, a severe disruption occurred in the capacity of power systems and crisis management structures to effectively respond to the developing failure. Despite differences in spatial scale and technical progression, both the blackout in Spain and Portugal and the blackout in Szczecin revealed similar systemic vulnerabilities related to decision-making processes, information flows, and the capacity to adapt to dynamically changing circumstances.

The most significant divergence concerns the rate of failure propagation. In Spain and Portugal, the loss of power system stability occurred within a mere 1 min and 17 s, which rendered the implementation of effective preventive measures virtually impossible. This served as an example of an extremely rapid, instantaneous systemic failure.

Conversely, in the case of Szczecin, the blackout propagation process lasted from 21:25 to 04:43 CET, spanning several hours. Theoretically, this provided the operator with a window of opportunity to implement measures mitigating the consequences of the event. However, the analysis of the blackout progression in Szczecin demonstrates that this opportunity was not fully utilised. Subsequent infrastructure outages were cascading in nature, leading to a gradual expansion of the area affected by the blackout.

Regarding decision-making efficiency, both of the examined cases had been evaluated negatively. In Spain and Portugal, this indicator reached a score of 2 on a 5-point scale, whereas in Poland it achieved only a score of 1 on the same scale. This indicates that both scenarios generated substantial criticism of the transmission and distribution system operators' actions; however, decision-making deficiencies were particularly pronounced in Szczecin. Post-incident reports highlighted a lack of preparedness among dispatching services to manage a failure of such magnitude, as well as a limited capacity to predict the consequences of subsequent infrastructural damage. The low evaluation of decision-making efficiency and the limited effectiveness of the operator's procedures point to insufficient preparedness for managing cascading failures. Concurrently, the effectiveness of the crisis management structures themselves should be evaluated positively, with their efficiency quantified at approximately 90%.

In terms of business continuity, both incidents caused critical disruptions to the functioning of crucial infrastructure. In Spain and Portugal, a virtually total blackout occurred, encompassing the entire affected system. In Szczecin, the consequences were slightly less extensive, yet approximately 90% of the metropolitan area was deprived of power.

In both cases, the operations of transport, telecommunications, public administration, and certain medical services were either halted or significantly curtailed. The system flexibility indicator reached an identical score of 2 on a 5-point scale in both analysed cases. This reflects a highly constrained capacity to adapt to rapidly changing crisis conditions.

Both grid operators and institutions responsible for crisis management primarily implemented reactive measures, focusing on mitigating the consequences of the failure rather than actively constraining its development.

The differences between the cases studied stem primarily from the inherent nature of the failures. In Spain and Portugal, the event progressed with extreme rapidity, precluding any effective response from the operators, whereas in Szczecin, a temporal window existed to limit the scale of the failure, which was not fully utilised.

Consequently, the Szczecin blackout should be evaluated not merely as an infrastructural failure, but also as an example of insufficient effectiveness in decision-making and organisational processes. A comparative analysis of both cases implies that effective blackout management requires not only extensive technical infrastructure, but primarily streamlined decision-making procedures, independent communication systems, and the ability to adapt rapidly to dynamically changing crisis conditions.

These specific elements proved to be the weakest link both in the case of Szczecin and the blackout encompassing Spain and Portugal. Consequently, securing urban business continuity demands a transition from reactive emergency response to proactive framework isolation. Therefore, the functional resilience of a city to a blackout should depend on its capacity to deliver core services independently of grid power availability.

What is more, emergency power supply systems, energy storage facilities, business continuity procedures, and organisational adaptability become of paramount importance.

The conducted comparative analysis of the blackout phenomena in Spain, Portugal, and Poland yields the following conclusions:

1. The development of the European power system must focus not only on increasing the share of renewable energy sources but also on reinforcing transmission grid resilience, developing automatic voltage regulation systems, expanding energy storage capacity, and establishing mechanisms that ensure grid stability under crisis conditions.
2. The future energy security of Europe will depend on the ability to integrate technical, organisational, and social aspects. The blackouts in Poland and the Iberian system confirm that even highly developed energy systems remain vulnerable to cascading effects. Furthermore, effective urban resilience requires the simultaneous development of infrastructure, crisis management procedures, and social competences. These findings align with the core tenets of resilience theory, which emphasizes building the capacity of systems to absorb disruptions, adapt, and rapidly restore functionality following a crisis event.

5. Discussion

From the perspective of urban resilience, a city should be treated as a complex adaptive system whose resilience depends on the interlinkages between the economic, social, spatial, and institutional spheres [87,88]. Adopting this research perspective, the results obtained regarding the assessment of the impact of blackouts on urban resilience in the infrastructural, institutional, social, and functional dimensions fit into the current of resilience theory initiated by Holling. In this theory, resilience denotes the capacity of a system to absorb disturbances without transitioning to an alternative state of

functioning [89]. In the context of social–ecological systems, this also implies the capacity for reorganisation while maintaining core functions, structures, and feedbacks [46]. According to the approach proposed by Baho, resilience assessment requires the simultaneous consideration of the scale of processes, adaptive capacity, critical thresholds, and potential alternative system states [90].

The context of resilience, in conjunction with natural resource management, highlights similarities and differences in how this concept is understood across various disciplines. The conceptual frameworks proposed in the literature encompass environmental factors, managerial actions, and systemic responses, as well as a decision-making process that enables learning from experience and applying this knowledge in management practice. Thus, a distinction is made between ecological resilience, social-ecological systems resilience, and disaster resilience, emphasising their importance for effective natural resource management [91].

When interpreting the obtained research findings as a contribution to resilience theory, the asymmetry between the analysed cases must be taken into account. The blackout in Szczecin occurred in 2008, whereas the blackout on the Iberian Peninsula took place in 2025—a period during which power systems underwent a profound technological and regulatory transformation. These changes encompassed, among others, the development of smart grids, an increasing share of renewable energy sources, the progressive digitisation of infrastructure, and the evolution of the European regulatory framework concerning power system security and resilience. Additionally, the analysed events differed in their spatial scale and the number of affected consumers. For this reason, the comparison should not be interpreted as a direct evaluation of comparable power failures, but rather as an analysis of resilience mechanisms emerging within distinct socio-technical contexts. The value of this comparison stems from the opportunity to investigate which resilience elements remain relatively stable despite technological and institutional changes, and which are highly context-dependent. Thus, the study is analytical and exploratory in nature—its objective was to identify the mechanisms and relationships between resilience dimensions rather than to generalise technical parameters or the scale of the analysed events.

To enhance the contribution to resilience theory when interpreting the results, it is worth emphasising that the selection of blackout cases was based on a purposive sampling strategy designed to ensure maximum variation. Rather than focusing on similar failures, cases representing distinct power system configurations were chosen in terms of disruption scale, grid integration levels, energy mix structures, institutional frameworks, and the nature of the event. Such an approach enables the assessment of resilience under diverse operational conditions of power systems and allows for determining which mechanisms are relatively universal and which are strictly context-dependent. The cases were not selected as a representative sample of all blackouts in Europe. Instead, the goal of this selection was to establish contrasting analytical contexts that allow for an exploration of how the proposed resilience framework operates.

Relating the results of research on blackouts to urban resilience theory can constitute an important step towards addressing the research gap in analyses of power system failures. This is particularly important when, as a result of the conducted analysis, it was possible to group the barriers that must be overcome to achieve the operational stability of power systems (technical, organisational and managerial, regulatory and institutional, economic, technological, social, environmental and climatic). This provides further confirmation of how crucial an integrated approach is in building power system resilience. In previous publications on blackouts in Poland, Spain, and Portugal, the authors focused primarily on the technical, infrastructural,

meteorological, and systemic causes of these events [71,92–95]. In the case of Poland, these were mainly issues related to climatic loads, the technical condition of the grid, structural redundancy, and the cascading nature of infrastructure damage [71,94,95]. Conversely, in the case of Spain and Portugal, the analyses primarily addressed the weaknesses of a highly integrated system dependent on stable voltage regulation, reactive power management, protection coordination, and the misalignment of the power system architecture with the high penetration of renewable energy sources [92,93]. Therefore, the existing literature has not sufficiently highlighted the perspective of resilience theory or a multidimensional analysis of urban resilience. Meanwhile, it is precisely this research trend that enables the interpretation of a blackout not only as a power failure but also as a critical test of the resilience of a city as a socio-technical system.

Developing the theoretical foundations of the proposed urban resilience framework represents a significant step toward deepening our understanding of the mechanisms that ensure the continued operation of urban systems during power disruptions. While previous research has focused primarily on empirically assessing the effectiveness of individual technical and organizational solutions, a contemporary approach to urban resilience requires the development of a coherent theoretical model integrating engineering, social, economic, and environmental perspectives. The theoretical development of the resilience framework is based on the assumption that the city should be treated as a complex adaptive system, whose components—energy, transportation, ICT, water and sewage infrastructure, healthcare, and administration—exist in dynamic interdependencies. In this approach, the failure of one subsystem can initiate a cascading effect, leading to disruptions in the functioning of subsequent elements of critical infrastructure [96]. Therefore, a city's ability to avoid a blackout does not stem solely from the reliability of the power grid, but from the resilience of the entire socio-technical system.

The proposed resilience framework expands on classic risk management models by incorporating four complementary dimensions of resilience: technical, organizational, social, and institutional resilience. Technical resilience encompasses the redundancy of power infrastructure, the integration of distributed energy sources, energy storage, and smart grids, enabling rapid disruption detection and automatic system reconfiguration. Organizational resilience refers to the ability of power system operators, local authorities, and emergency services to coordinate actions in crisis situations, utilizing crisis management procedures and scenario planning. Social resilience, in turn, emphasizes the role of social capital, citizen awareness, and their willingness to respond to prolonged power outages. The fourth dimension—institutional resilience—emphasizes the importance of legal regulations, cross-sectoral cooperation mechanisms, and the ability of public administration to make decisions under conditions of high uncertainty. An important element of theoretical development is the shift away from the linear perception of resilience as a process solely involving system recovery after a failure. In the proposed framework, resilience is defined as the dynamic ability of an urban system to anticipate threats, absorb disruptions, adapt to changing conditions, and transform. This approach draws on contemporary theories of socio-ecological and organizational resilience, according to which a crisis can provide the impetus for a sustained improvement in infrastructure security and the improvement of management processes.

The theoretical development also incorporates the concept of multi-level resilience, which assumes that the effectiveness of preventive measures depends on simultaneous impacts at the local, regional, and national levels. At the local level, urban energy management systems, local microgrids, and critical infrastructure equipped with emergency power supply play a key role. The regional level encompasses the

coordination of distribution and transmission system operators and cooperation between local government units. The national level, on the other hand, focuses on energy policy, energy security regulations, and mechanisms for supporting investments that increase the resilience of the power system. The proposed framework also places particular emphasis on the theory of critical infrastructure interdependence. It assumes that a city's resilience to blackouts depends not only on the state of the power grid but also on the relationships between telecommunications, water, transportation, healthcare, and digital services systems. Disruptions in energy supply can lead to a loss of functionality in these systems, increasing the risk of cascading effects. A theoretical resilience framework therefore considers the analysis of functional dependencies between individual infrastructure components and the identification of critical points whose failure could have disproportionately large social and economic impacts.

The theoretical foundations of the resilience framework have also been expanded to include the perspective of energy transition and the development of smart cities. The integration of renewable energy sources, energy storage, vehicle-to-grid technology, local microgrids, and digital energy management systems transforms urban resilience from reactive to proactive. In this model, resilience is not merely a response to threats but becomes a systemic feature developed through continuous monitoring, real-time data analysis, and the use of artificial intelligence tools to predict outages and optimize grid operation. Consequently, the developed theoretical framework creates a comprehensive model of urban resilience, integrating technical, organizational, social, and institutional aspects to reduce the risk of blackouts and minimize their impact. This model goes beyond the traditional approach focused on the reliability of power infrastructure, presenting resilience as a dynamic property of the urban system capable of learning, adapting, and transforming in response to changing threats. This approach provides a solid foundation for further research on urban resilience modeling and the development of methods for assessing the effectiveness of blackout prevention strategies in the face of ongoing energy transitions and the increasing complexity of critical infrastructure.

In conclusion, it is worth emphasising that the conducted study was not limited to an empirical illustration of existing theoretical assumptions, but allowed for a refinement of the understanding of resilience under real-world conditions. Through the analysis, it was demonstrated that the resilience mechanism manifests as a dynamic process—dependent on the local ecological context and management practices—rather than merely a static system property. Indeed, the system's capacity to maintain its functions results from the interaction of multiple factors operating simultaneously. This, therefore, revises the existing approach to assumptions in resilience theory that focuses on individual resilience components.

6. Conclusions and Policy Implications

The resilience of urban systems to electricity supply disruptions (blackouts) remains a highly relevant, interdisciplinary research area. Therefore, this study aims to evaluate urban system resilience during blackouts through a comparative analysis of power grid failures across diverse EU countries. These events occurred with a time gap of over a decade, analyzing Szczecin in Poland alongside Madrid, Barcelona, and Seville in Spain and Lisbon and Porto in Portugal. This objective was achieved by conducting a comparative, indicator-based analysis of blackout impacts across four distinct dimensions of urban resilience: infrastructural, institutional, social, and functional.

The research demonstrates that access to electricity is a fundamental prerequisite for modern urban resilience. However, technical infrastructure alone is insufficient to guarantee overall system robustness. Within the infrastructural resilience dimension, a

blackout abruptly reduces urban stability by severely disrupting critical infrastructure. Cascading effects occurred in all analysed cases, causing major disruptions in transport, telecommunications, water supply, healthcare, and public services. System redundancy, backup power availability, grid technical condition, and black-start capabilities prove to be of paramount importance.

In the institutional resilience dimension, discrepancies emerged between formal procedures and their practical effectiveness. Coordination failures, information bottlenecks, and crisis communication breakdowns occurred across Poland, Spain, and Portugal. Consequently, institutional resilience depends not only on emergency management plans but primarily on joint inter-institutional drills and the capacity of stakeholders to operate under severe time constraints.

Regarding the social resilience dimension, blackouts restrict citizen access to vital information, services, and daily resources. Public risk awareness, trust in authorities, and community self-organisation can significantly mitigate crisis impacts. Therefore, regular emergency drills, public education, and “training” urban resilience are crucial for enhancing community adaptive capacity.

In the functional resilience dimension, blackouts exposed limited urban capacities to maintain critical service continuity. Response speed, decision-making efficiency, information flow, operational flexibility, and resource integration proved decisive. Functional resilience demands real operational capabilities, emergency communication networks, and redundant power sources, rather than mere paper procedures.

The results support the proposed research hypothesis. The highest level of urban resilience to blackouts is achieved when technical infrastructure development is synchronised with institutional frameworks and social capital enhancement. The cross-case analysis of Poland, Spain, and Portugal demonstrates that vulnerability in any single component—infrastructure, institutions, communication, social preparedness, or business continuity—compromises the entire urban socio-technical system. The most resilient cities concurrently invest in grid modernisation, crisis management protocols, inter-institutional coordination, emergency communication channels, and citizen education.

The comparative analysis of the investigated blackout cases reveals that the greatest difficulties did not stem solely from the power outage itself but from cascading effects and the limited capacity of urban systems to rapidly contain them. Across the analysed cases, recurring issues emerged regarding the coordination of actions, information flow, and maintaining the continuity of critical service delivery. Consequently, measures taken only after a blackout has occurred have limited effectiveness, which underscores that greater emphasis should be placed on preparedness and preventive actions.

Therefore, public policy should focus to a greater extent on preparedness and preventive actions aimed at strengthening the resilience of urban systems before disruptions occur. The implementation of such measures requires securing financial resources that encompass all four analysed dimensions of urban resilience. Based on the identified weaknesses, areas requiring priority financial support can be pointed out. Financial resources must be allocated among other things to:

- (1) Increasing power grid redundancy;
- (2) Modernising transmission and distribution infrastructure;
- (3) Developing independent emergency communication systems;
- (4) Conducting regular inter-institutional crisis simulations;
- (5) Expanding redundant and backup power supplies;
- (6) Educating the public on prolonged power outage preparedness.

The analysed case involving Spain and Portugal confirmed that modern blackouts can be cross-border in nature, with their impacts extending beyond the borders of a

single nation. This implies that strengthening the resilience of power systems should not be perceived solely as a task for individual Member States but also as an element of the European Union's common energy security policy.

In this context, a critical question arises regarding the ultimate funding source for blackout prevention. Should this remain the sole responsibility of individual EU member states, or should dedicated funds be allocated under the EU energy policy, considering the transboundary nature of major blackouts? The cross-border nature of the analysed blackout indicates that actions coordinated at the European Union level can provide more effective organisational and financial support than measures implemented solely at the national level. The justification for such a course of action is reflected in European Union policy, within which instruments aimed at strengthening the resilience of energy systems are being deployed, such as The Recovery and Resilience Facility (RRF) [97]—a financial instrument designed to fund technological modernisation, enhance power grid capacity to manage renewable energy source (RES) volatility, and improve demand–response mechanisms to optimize grid flexibility and efficiency.

- (1) The REPowerEU Plan [98]—a strategic framework based on three core pillars: reducing energy consumption, diversifying energy supply sources, and accelerating the deployment of renewable energy; its financial support targets investments in power distribution grids, energy storage systems, cross-border interconnections, and critical infrastructure.
- (2) The Connecting Europe Facility for Energy (CEF Energy) [99]—a funding instrument specifically geared towards the construction and modernisation of transmission lines, cross-border infrastructure, and smart power grids.

Although these highlighted programs and financial instruments function primarily as indirect mechanisms to mitigate (exclusively) the cascading consequences of blackouts, their systematic implementation could successfully curb the escalation of future recovery costs. Consequently, evaluating the long-term cost-efficiency of these EU frameworks provides a highly promising research path. Further exploration of large-scale urban blackout vulnerabilities and prevention dynamics will significantly contribute to the ongoing advancement of urban resilience theory. Future research should also take into account that the contemporary energy transition requires the simultaneous consideration of two interrelated aspects: increasing the share of low-emission technologies and ensuring the resilience of systems responsible for energy supply [100, 101]. Indeed, the COP26 climate conference highlights the necessity to accelerate the development of renewable energy sources (RESs), which also demands infrastructure modernisation and enhancing its capacity to operate under disruptive conditions. Research on improving the efficiency of RES technologies (including photovoltaic systems) [102] therefore constitutes an important complement to analyses concerning the resilience of energy infrastructure in the event of a blackout.

Based on the obtained research findings, practical implications can also be formulated for various groups of decision-makers responsible for critical infrastructure resilience. These pertain to the development and implementation of:

1. Electricity, fuel, and heat supply plans by local government units.
2. Procedures and actions for dispatch services of electricity generation and transmission entities regarding the reliability of communication systems (failures, network overloads, long response times). This also applies to telecommunications operators offering services to the public, whose systems should be equipped with independent, reliable power sources.
3. Islanding solutions enabling the supply of electricity to key consumers during a failure.

4. Systematic exercises checking the readiness of electricity generation and transmission entities to verify adopted procedures and plans. Such exercises should involve the broadest possible range of entities, including those responsible for crisis management and civil protection. This is of paramount importance for building local community resilience and also possesses a cross-border dimension.

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References

1. United Nations, Department of Economic and Social Affairs. World Urbanisation Prospects: The 2009 Revision; UN: New York, NY, USA, 2010. Available online: https://ec.europa.eu/regional_policy/sources/studies/citiesoftomorrow/citiesoftomorrow_final_pl.pdf (accessed on 15 May 2026).
2. Bristow, G.; Healy, A. Building resilient regions: Complex adaptive systems and the role of policy intervention. *Raumforsch. Raumordn.* **2014**, *72*, 93–102. <https://doi.org/10.1007/s13147-014-0280-0>.
3. Ustawa z Dnia 26 Kwietnia 2007 r. o Zarządzaniu Kryzysowym; Dz.U.2023, poz. 122; Dz.U. 2024, poz. 834, 1222, 1473, 1572, 1907. Available online: <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20070890590/U/D20070590Lj.pdf> (accessed on 20 May 2026).
4. Fotis, G.; Vita, V.; Maris, T.I. Risks in the European Transmission System and a Novel Restoration Strategy for a Power System after a Major Blackout. *Appl. Sci.* **2023**, *13*, 83. <https://doi.org/10.3390/app13010083>.
5. Newman, D.E.; Carreras, B.A.; Lynch, V.E.; Dobson, I. Exploring Complex Systems Aspects of Blackout Risk and Mitigation. *IEEE Trans. Reliab.* **2011**, *60*, 134–143. <https://doi.org/10.1109/TR.2011.2104711>.
6. Dobson, I.; Carreras, B.A.; Lynch, V.E.; Newman, D.E. Complex systems analysis of series of blackouts: Cascading failure, critical points, and self-organization. *Chaos* **2007**, *17*, 026103. <https://doi.org/10.1063/1.2737822>.
7. Buoncompagni, G. From the Light to the Dark: Blackouts in the Pre-Connection Era. *J. Digit. Inf. Manag. (JDIM)* **2026**, *24*, 11–39. <https://doi.org/10.6025/jdim/2026/24/1/11-39>.
8. Złotecka, D.; Sroka, K. The characteristics and main causes of power system failures basing on the analysis of previous blackouts in the world. In Proceedings of the International Interdisciplinary PhD Workshop (IIPHDW), Świnoujście, Poland, 9–12 May 2018. <https://doi.org/10.1109/IIPHDW.2018.8388369>.
9. Stankovski, A.; Gjorgiev, B.; Locher, L.; Sansavin, G. Power blackouts in Europe: Analyses, key insights, and recommendations from empirical evidence. *Joule* **2023**, *7*, 2468–2484. <https://doi.org/10.1016/j.joule.2023.09.005>.
10. Fita, N.D.; Utu, I.; Marcu, M.D.; Pasculescu, D.; Mila, I.O.; Popescu, F.G.; Lazar, T.; Schiopu, A.M.; Muresan-Grecu, F.; Cruceru, E.A. Global Energy Crisis and the Risk of Blackout: Interdisciplinary Analysis and Perspectives on Energy Infrastructure and Security. *Energies* **2025**, *18*, 4244. <https://doi.org/10.3390/en18164244>.
11. Majchrzak, D.; Michalski, K.; Regina-Zacharski, J. Readiness of the Polish Crisis Management System to Respond to Long-Term, Large-Scale Power Shortages and Failures (Blackouts). *Energies* **2021**, *14*, 8286. <https://doi.org/10.3390/en14248286>.
12. Mahdavian, F.; Platt, S.; Wiens, M.; Klein, M.; Schultmann, F. Communication blackouts in power outages: Findings from scenario exercises in Germany and France. *Int. J. Disaster Risk Reduct.* **2020**, *46*, 101628. <https://doi.org/10.1016/j.ijdr.2020.101628>.

13. Shivakumar, A.; Welsch, M.; Taliotis, C.; Jakšić, D.; Baričević, T.; Howells, M.; Gupta, S.; Rogner, H. Valuing blackouts and lost leisure: Estimating electricity interruption costs for households across the European Union. *Energy Res. Soc. Sci.* **2017**, *34*, 39–48. <https://doi.org/10.1016/j.erss.2017.05.010>.
14. Monitoring Report: Security of EU Electricity Supply, ACER European Union Agency for the Cooperation of Energy Regulators. 2024. Available online: https://www.acer.europa.eu/sites/default/files/documents/Publications/Security_of_EU_electricity_supply_2024.pdf (accessed on 20 April 2026).
15. Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on Risk-Preparedness In The Electricity Sector and Repealing Directive 2005/89/EC (Text with EEA relevance). PE/73/2018/REV/1. *Off. J. Eur. Union* **2019**, *L158*, 1–21. Available online: <http://data.europa.eu/eli/reg/2019/941/oj> (accessed on 12 May 2026).
16. Commission Regulation (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration (Text with EEA relevance). C/2017/7775. *Off. J. Eur. Union* **2017**, *L312*, 54–85. Available online: <http://data.europa.eu/eli/reg/2017/2196/oj> (accessed on 17 May 2026).
17. Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast) (Text with EEA relevance). PE/9/2019/REV/1. *Off. J. Eur. Union* **2019**, *L158*, 54–124. Available online: <http://data.europa.eu/eli/reg/2019/943/oj> (accessed on 22 May 2026).
18. Regulation (EU) 2024/1747 of the European Parliament and of the Council of 13 June 2024 Amending Regulations (EU) 2019/942 and (EU) 2019/943 as Regards Improving the Union’s Electricity Market Design (Text with EEA Relevance). PE/1/2024/REV/1, OJ L, 2024/1747. Available online: <http://data.europa.eu/eli/reg/2024/1747/oj> (accessed on 15 April 2026).
19. Regulation (EU) 2019/942 of the European Parliament and of the Council of 5 June 2019 Establishing a European Union Agency for the Cooperation of Energy Regulators. *Off. J. Eur. Union* **2019**, *L158*, 22–53. Available online: <http://data.europa.eu/eli/reg/2019/942/2024-08-04> (accessed on 22 April 2026).
20. Widuto, A. Improving the Design of the EU Electricity Market. Briefing: EU Legislation in Progress 2024. European Parliamentary Research Service (EPRS).europa.eu. Available online: [https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/745694/EPRS_BRI\(2023\)745694_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/745694/EPRS_BRI(2023)745694_EN.pdf) (accessed on 20 April 2026).
21. Meeus, L. Electricity Market Reform: What Is (Not) in the European Commission Proposal. European University Institute 2023. Available online: <https://cadmus.eui.eu/server/api/core/bitstreams/2b735bd9-6664-5d98-b882-dee9adf24b92/content> (accessed on 27 May 2026).
22. Final Report: Final Assessment of the EU Wholesale Electricity Market Design. ACER European Union Agency for the Cooperation of Energy Regulators, 2022. Available online: <https://www.acer.europa.eu/events-and-engagement/news/press-release-acer-publishes-its-final-assessment-eu-wholesale> (accessed on 20 April 2026).
23. Directive (EU) 2024/1711 of the European Parliament and of the Council of 13 June 2024 Amending Directives (EU) 2018/2001 and (EU) 2019/944 as Regards Improving the Union’s Electricity Market Design (Text with EEA Relevance). PE/2/2024/REV/1, OJ L, 2024/1711. Available online: <http://data.europa.eu/eli/dir/2024/1711/oj> (accessed on 16 May 2026).
24. Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC (Text with EEA relevance). PE/51/2022/REV/1. *Off. J. Eur. Union* **2022**, *L333*, 164–198. Available online: <http://data.europa.eu/eli/dir/2022/2557/oj> (accessed on 18 April 2026).
25. Commission Delegated Regulation (EU) 2024/1366 of 11 March 2024 Supplementing Regulation (EU) 2019/943 of the European Parliament and of the Council by Establishing a Network Code on Sector-Specific Rules for Cybersecurity Aspects of Cross-Border Electricity Flows. C/2024/1383, OJ L, 2024/1366. Available online: http://data.europa.eu/eli/reg_del/2024/1366/oj (accessed on 28 May 2026).
26. Álvarez Fernández, R.; Giménez, B.D. Stochastic Assessment of Availability Factors: The Case of Spain. *Sustainability* **2026**, *18*, 4527. <https://doi.org/10.3390/su18094527>.
27. Guelpa, E.; Bischi, A.; Verda, V.; Chertkov, M.; Lund, H. Towards future infrastructures for sustainable multi-energy systems: A review. *Energy* **2018**, *184*, 2–21. <https://doi.org/10.1016/j.energy.2019.05.057>.
28. Javanroodi, K.; Perera, A.T.D.; Hong, T.; Nik, V.M. Designing climate resilient energy systems in complex urban areas considering urban morphology: A technical review. *Adv. Appl. Energy* **2023**, *12*, 100155. <https://doi.org/10.1016/j.adapen.2023.100155>.
29. Gazzola, V.; Menoni, S.; Melzi, C.; Broggi, M. Planning Resilient Territories Against Weather-Related Power Outages: Insights from Lombardia Region. *Urban Sci.* **2026**, *10*, 186. <https://doi.org/10.3390/urbansci10040186>.

30. Nik, V.M.; Perera, A.T.D.; Chen, D. Towards climate resilient urban energy systems: A review. *Natl. Sci. Rev.* **2021**, *8*, nwaa134. <https://doi.org/10.1093/nsr/nwaa134>.
31. Azuatalam, D.; Shreeve, A.; Lyster, R.; Azuatalam, J.; Verbic, G. Electricity infrastructure resilience to bushfire and extreme weather: Impacts and stakeholder-driven recommendations. *Util. Policy* **2026**, *101*, 102195. <https://doi.org/10.1016/j.jup.2026.102195>.
32. Fekete, A.; Tzavella, K.; Baumhauer, R. Spatial exposure aspects contributing to vulnerability and resilience assessments of urban critical infrastructure in a flood and blackout context. *Nat. Hazards* **2016**, *86*, 151–176. <https://doi.org/10.1007/s11069-016-2720-3>.
33. Kotani, H.; Nakano, K. Household resilience realized by photovoltaic and battery energy system in natural hazard-triggered blackouts: Evidence from Japan. *Int. J. Disaster Risk Reduct.* **2023**, *90*, 103656. <https://doi.org/10.1016/j.ijdrr.2023.103656>.
34. Li, L.; Ma, Z.; Cao, T. Leveraging social media data to study the community resilience of New York City to 2019 power outage. *Int. J. Disaster Risk Reduct.* **2020**, *51*, 101776. <https://doi.org/10.1016/j.ijdrr.2020.101776>.
35. Rudolph-Cleff, A.; Knodt, M.; Schulze, J.; Engel, A. Crisis communication in a blackout scenario—An assessment considering socio-spatial parameters and the vulnerabilities of the population. *Int. J. Disaster Risk Reduct.* **2022**, *72*, 102856. <https://doi.org/10.1016/j.ijdrr.2022.102856>.
36. Knodt, M.; Stöckl, A.; Steinke, F.; Pietsch, M.; Hornung, G.; Stroscher, J.P. Power blackout: Citizens' contribution to strengthen urban resilience. *Energy Policy* **2023**, *174*, 113433. <https://doi.org/10.1016/j.enpol.2023.113433>.
37. Song, Y.; Wan, C.; Hu, X.; Qin, H.; Lao, K. Resilient Power Grid for Smart City. *IEnergy*, 2022. Available online: https://www.sciopen.com/local/article_pdf/10.23919/IEnergy.2022.0043.pdf (accessed on 30 April 2026).
38. Silvast, A. Energy dimensions of urban resilience. In *The Routledge Handbook of Urban Resilience*; Routledge: London, UK, 2019. <https://doi.org/10.4324/9780429506666>.
39. Feldpausch-Parker, A.M.; Peterson, T.R.; Stephens, J.C.; Wilson, E.J. Smart grid electricity system planning and climate disruptions: A review of climate and energy discourse post-Superstorm Sandy. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1961–1968. <https://doi.org/10.1016/j.rser.2017.06.015>.
40. The European Programme for Critical Infrastructure Protection (EPCIP), Brussels, 2006, MEMO/06/477. Available online: https://ec.europa.eu/commission/presscorner/detail/en/memo_06_477 (accessed on 15 April 2026).
41. Report OECD: Economic Resilience. 2026. <https://www.oecd.org/en/topics/economic-resilience.html> (accessed on 15 April 2026).
42. Report: 28 April 2025 Blackout, ENTSO-E, 2026. <https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/> (accessed on 15 April 2026).
43. Konecki, K.T. Studia z metodologii badań jakościowych. In *Teoria Ugruntowana*; Wydawnictwo Naukowe PWN: Warszawa, Poland, 2020.
44. Silverman, D. *Prowadzenie Badań Jakościowych*. Wydawnictwo Naukowe PWN: Warszawa, Poland, 2008; pp. 167–181.
45. Kwiotkowska, A. Jakościowa analiza porównawcza jako koncepcja metodologiczna w naukach o zarządzaniu. *Pr. Nauk. Uniw. Ekon. WE Wrocławiu* **2014**, *340*, 65–77. <http://dx.doi.org/10.15611/pn.2014.340.06>.
46. Walker, B.; Holling, C.S.; Carpenter, S.R.; Kinzing, A.; Resilience, Adaptability and Transformability in Social-ecological Systems. *Ecol. Soc.* **2004**, *9*, 5. Available online: <http://www.ecologyandsociety.org/vol9/iss2/art5/> (accessed on 29 May 2026).
47. Berg-Schlosser, D.; De Meur, G.; Rihoux, B.; Ragin, C.C. Qualitative Comparative Analysis (QCA) as an Approach. In *Configurational Comparative Methods*; SAGE Publication, Inc.: Thousand Oaks, CA, USA, 2009; pp. 1–18. <https://doi.org/10.4135/9781452226569.n1>.
48. Raport Zespołu ds. Zbadania Przyczyn i Skutków Katastrofy Energetycznej Powołanego Zarządzeniem Wojewody Zachodniopomorskiego nr 154/2008 z Dnia 22 Kwietnia 2008 Roku. Szczecin, 2008. pp. 23, 25–31, 59–622. Available online: https://www.cire.pl/pliki/2/68F0D1ED_Raportkoncowy-cz1.pdf (accessed on 15 April 2026).
49. Miejski Plan Zarządzania Kryzysowego Gminy Miasto Szczecin. 2023. Part 1, pp. 36–40, Part 2, pp. 17–23, 29–31, 34–37, 76–82, 86–87, 93–94, 130. Part 3, pp. 5–63, 83–115, 121–138. Available online: <https://pe.szczecin.pl/zarządzanie-kryzysowe/miejski-plan-zarządzania-kryzysowego> (accessed on 15 April 2026).
50. Zakrzewska, M. Uwarunkowania rozwoju kapitału społecznego w Polsce. Studia i Prace Wydziału Nauk Ekonomicznych i Zarządzania, Wydawnictwo Naukowe Uniwersytetu Szczecińskiego, 2013, 32. [studia_i_prace_wydzialu_nauk_ekonomicznych_i_zarządzania-r2013-t32-n2-s76-96.pdf](https://pe.szczecin.pl/zarządzanie-kryzysowe/miejski-plan-zarządzania-kryzysowego) (accessed on 15 April 2026).
51. Pietrek, G. Blackout w Szczecinie 2008 r. Wnioski dla Systemu Zarządzania Kryzysowego. In *Zagrożenie Niemilitarne Bezpieczeństwa Polski na Przełomie XX I XXI w*; Wydawnictwo Typografia Pułtusk: Pułtusk, Poland, 2015; pp. 287–298.

52. Report: Grid Incident in Spain and Portugal on 28 April 2025: Final Report. ENTSO-E, 2026. Available online: https://eiscouncil.org/iberian-grid-failure/?utm_source=google_ads&utm_medium=22340306799&ad_group=&ad=&device=c&key-word=&gad_source=1&gad_campaignid=22346769038&gbraid=0AAAAAosyObZNWKer5IhUw36zXYLK7xj8t&gclid=CjwKC AjwmozTBhAeEiwAkEGZzm1eullMSLnZoE_Bg9hlSXyvuhYgvfjRteZ7SA6EpgNEfRWDxMwziBoCs4YQAvD_BwE (accessed on 19 April 2026).
53. Miciuła, I.; Wojtaszek, H.; Bazan, M.; Janiczek, T.; Włodarczyk, B.; Kabus, J.; Kana, R. Management of the Energy Mix and Emissivity of Individual Economies in the European Union as a Challenge of the Modern World Climate. *Energies* **2020**, *13*, 5191. <https://doi.org/10.3390/en13195191>.
54. Report: Countries and Regions/Poland. IEA. Available online: www.iea.org/countries/poland/energy-mix (accessed on 19 April 2026).
55. Report: Countries and Regions/Spain. IEA. Available online: www.iea.org/countries/spain/energy-mix (accessed on 19 April 2026).
56. Report: Countries and Regions/Portugal. IEA. Available online: www.iea.org/countries/portugal/energy-mix (accessed on 19 April 2026).
57. Błażejowska, M.; Czarny, A.; Kowalska, I.; Michalczewski, A.; Stepień, P. The Effectiveness of the EU ETS Policy in Changing the Energy Mix in Selected European Countries. *Energies* **2024**, *17*, 4243. <https://doi.org/10.3390/en17174243>.
58. Mayring, P. Qualitative Content Analysis: Theoretical Background and Procedures. In *Approaches to Qualitative Research in Mathematics Education; Advances in Mathematics Education*; Bikner-Ahsbahr, A.; Knipping, C.; Presmeg, N., Eds.; Springer: Dordrecht, The Netherlands, 2014. https://doi.org/10.1007/978-94-017-9181-6_13.
59. Burrell, G.; Morgan, G. *Sociological Paradigms and Organisational Analysis*; Ashgate Publishing Company: Burlington, VT, USA, 2008; p. 28. Available online: <https://madmunifacs.wordpress.com/wp-content/uploads/2016/03/burrell-morgan-sociological-paradigms-and-organisational-analysis.pdf> (accessed on 18 May 2026).
60. Yin, R.K. *Case Study Research. Design and Methods (Fourth Edition)*; Sage Publications: Thousand Oaks, CA, USA, 2009.
61. Owsiak, S. *Finanse*; PWE: Warszawa, Poland, 2015; p. 86.
62. The Szczecin Blackout. It Has Been 14 Years Since the Major Power Cut. GS24.pl. 2022. Available online: <https://gs24.pl/blackout-w-szczecinie-minelo-14-lat-od-wielkiej-awarii-zobacz-zdjecia-i-wideo-z-tamtych-czasow/ar/c1-9848468> (accessed on 20 May 2026).
63. Lague, P. Power being restored to Portugal and Spain as focus turns to cause, Power Engineering International. Enlit, 2025. Available online: <https://www.enlit.world/library/power-being-restored-to-portugal-and-spain-as-focus-turns-to-cause-of-outage> (accessed on 20 May 2026).
64. Report on the Blackout in Spain and Portugal—Material from ENTSOe. 2025. Available online: <https://sep.com.pl/photo/files/BLACKOUT%2028%20kwietnia%202025%20r.pdf> (accessed on 20 May 2026).
65. Brezar, A. Spain, Portugal and Parts of France Hit by Massive Power Outage. Euronews. 2025. Available online: <https://www.euronews.com/my-europe/2025/04/28/spain-portugal-and-parts-of-france-hit-by-massive-power-outage> (accessed on 12 May 2026).
66. Breakdown of Generation and Cumulative Storage (MW) at 9:40 p.m.—April 27, 2025. Available online: <https://demanda.ree.es/visiona/peninsula/demandaau/acumulada/2025-04-28> (accessed on 20 May 2026).
67. Sánchez, L.; Guillermo, J. Spain-Portugal Blackouts: What Actually Happened, and What Can Iberia and Europe Learn from It? The Conversation, 2 May 2025. Available online: <https://theconversation.com/spain-portugal-blackouts-what-actually-happened-and-what-can-iberia-and-europe-learn-from-it-255666> (accessed on 20 May 2026).
68. Madejski, M. Blackout w Polsce Zdarzył się Naprawdę. Dekadę Temu Zgasł Cały Szczecin. „Nie Było Niczego”. Money.pl 2019. Available online: <https://www.money.pl/gospodarka/blackout-w-polsce-zdarzyl-sie-naprawde-dekade-temu-zgasl-caly-szczecin-nie-bylo-niczego-6396070270957185a.html> (accessed on 20 May 2026).
69. Guźniczak, C.; Bartłomiejski, R.; Stępiński, Sz.; Kowalewski, M. Trenowanie miejskiej odporności: ćwiczenia w dużych miastach Polski z reagowania na zdarzenia kryzysowe. *Athenaeum. Pol. Stud. Politol.* **2025**, *85*, 192–208. <https://doi.org/10.15804/athena.2025.85.12>.

70. A Whole Day Without Electricity. 17 Years Since the Major Blackout in Szczecin. TVP 3 Szczecin. 2025. Available online: <https://szczecin.tvp.pl/86066910/17-rocznica-blackoutu-w-szczecinie-najwieksza-awaria-pradu-w-historii-miasta> (accessed on 20 May 2026).
71. Bachmatiuk, M. Zimowy Blackout w Szczecinie—Case Study. Obserwator 2023. Available online: <https://obserwator.imgw.pl/2023/05/10/zimowy-blackout-w-szczecinie-case-study/> (accessed on 24 May 2026).
72. Stecyk, A.; Miciuła, I. Harnessing the Power of Artificial Intelligence for Collaborative Energy Optimization Platforms. *Energies* **2023**, *16*, 5210. <https://doi.org/10.3390/en16135210>.
73. Baltarejo, B. Ministra da Saúde Pedu Investigação a Morte de Mulher Ventilada Durante o Apagão. Público. 2025. Available online: <https://www.publico.pt/2025/05/01/sociedade/noticia/ministra-saude-pede-investigacao-morte-mulher-durante-apagao-2131646> (accessed on 12 May 2026).
74. Lombardi, P.; Latona, D. Miscalculation by Spanish Power Grid Operator REE Contributed to Massie Blackout, Report Finds. Reuters, 2025. Available online: <https://www.reuters.com/business/energy/investigation-into-spains-april-28-blackout-shows-no-evidence-cyberattack-2025-06-17> (accessed on 20 May 2026).
75. Report ENTSO-E Publishes Expert Panel Final Report on 28 April 2025 Blackout in Spain and Portugal. 2026. Available online: <https://www.entsoe.eu/news/2026/03/20/entso-e-publishes-expert-panel-final-report-on-28-april-2025-blackout-in-spain-and-portugal/> (accessed on 15 May 2026).
76. Blackout in Spanish Peninsular Electrical System the 28th of April 2025. Available online: <https://www.ree.es/en> (accessed on 15 May 2026);
77. System Data for Portugal—REN. 2026. Available online: <https://www.ren.pt/en-gb/activity/electricity> (accessed on 15 May 2026).
78. Las Autoridades Investigan la Vinculación de la Muertes en Galicia y Madrid de Siete Personas con el Gran Apagón. RTVE.es/AGENCJE. 2025. Available online: <https://www.rtve.es/noticias/20250429/muerto-heridos-gran-apagon-electrico-investigan/16559113.shtml> (accessed on 12 May 2026).
79. Al Menos Cinco Muertes se Vinculan al Apagón Histórico que Sufrió España. Telemund. 2025. Available online: <https://www.telemundo.com/noticias/edicion-noticias-telemundo/internacional/video/al-menos-cinco-muertes-se-vinculan-al-apagon-historico-que-sufrio-espana-tmvo12917153> (accessed on 12 May 2026).
80. Report: Non-Confidential Version of the Report by the Committee Set Up to Analyse the Circumstances Surrounding the Electricity Crisis of 28 April 2025. Available online: <https://www.lamoncloa.gob.es/consejodeministros/resumenes/Documents/2025/Informe-no-confidencial-Comite-de-analisis-28A.pdf> (accessed on 20 May 2026).
81. Bian, Y.; Wyman-Pain, H.; Li, F.; Bhakar, R.; Mishra, S.; Padhy, N.P. Demand Side Contributions for System Inertia in the Gb Power System. *IEEE Trans. Power Syst.* **2018**, *33*, 3521–3530. <https://doi.org/10.1109/TPWRS.2017.2773531>.
82. Final Blackout Report by European Operators Confirms Event Was Caused by Multiple Factors, Recommends Improving Oversight and Coordination. Science Media Centre Spain. 2026. Available online: <https://sciencemediacentre.es/en/final-blackout-report-european-operators-confirms-event-was-caused-multiple-factors-recommends> (accessed on 18 May 2026).
83. Straty Spowodowane Przez Ogromną Awarię Zasilania w Hiszpanii Sięgnęły Około 1,6 Miliarda euro. UA.NEWS. 2025. Available online: <https://ua.news/pl/world/zbitki-vid-masshtabnogo-blekautu-v-ispantiyi-syagnuli-blizko-e1-6-mlrd> (accessed on 18 May 2026).
84. Iberyjski Blackout Wykazał Słabości Systemu i dał Europie Sygnał Alarmowy. Obserwator Gospodarczy, 2025. Available online: <https://obserwatorgospodarczy.pl/2025/05/11/iberyjski-blackout-wykazal-slabosci-systemu-i-dal-europie-sygnal-alarmowy> (accessed on 18 May 2026).
85. Pastucha, T. Europejskie Konsekwencje Iberyjskiego Blackout. The Polish Institute of International Affairs 2025. Available online: <https://www.pism.pl/publikacje/europejskie-konsekwencje-iberyjskiego-blackoutu> (accessed on 12 June 2026).
86. Stańczuk, M.; Escudero, R.M. Eksperci: Jak ograniczyć ryzyko blackoutu, takich jak ten sprzed roku w Hiszpanii? Publicystyka 2026. Available online: <https://www.rp.pl/opinie-ekonomiczne/art44111651-eksperci-jak-ograniczyc-ryzyko-blackoutow-takich-jak-ten-sprzed-roku-w-hiszpanii> (accessed on 19 May 2026).
87. Capoani, L.; Fantinelli, M.; Giordano, L. The concept of resilience in economics: Comprehensive analysis and systematic review of economic literature. *Contin. Resil. Rev.* **2025**, *7*, 121–145.

88. Drobnia, A. The Urban Resilience—Economic Perspective. *J. Econ. Manag.* **2012**, *10*, 5–20.
89. Holling, C.S. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Evol. Syst.* **1973**, *4*, 1–23. <https://doi.org/10.1146/annurev.es.04.110173.000245>.
90. Baho, D.L.; Allen, C.R.; Garmestani, A.S.; Fried-Petersen, H.B.; Renes, S.E.; Gunderson, L.H.; Angeler, D.G. A quantitative framework for assessing ecological resilience. *Ecol. Soc.* **2017**, *22*, 17. <https://doi.org/10.5751/ES-09427-220317>.
91. Brown, E.D.; Williams, B.K. *Resil. Resour. Management. Environ. Manag.* **2015**, *56*, 1416–1427. <https://doi.org/10.1007/s00267-015-0582-1>.
92. Morao, H. The 2025 Iberian Peninsula Blackout: Lessons for Modern Power Systems and Policy Implications. *Utilities Policy* **2026**, *101*, 102196. <https://doi.org/10.1016/j.jup.2026.102196>.
93. Rouco, L.; Echavarren, F.M.; Lobato, E. The prologue of the Iberian Peninsula blackout on 28th April 2025. *Sustain. Energy Grids Netw.* **2026**, *46*, 1–7. <https://doi.org/10.1016/j.segan.2026.102295>.
94. Bartodziej, G.; Tomaszewski, M. Blackout w Rejonie Szczecina. Uwagi i Wnioski. *Energetyka* **2008**, *10*, 682–688. Available online: https://www.cire.pl/pliki/2/blackout_szczecin.pdf (accessed on 24 May 2026).
95. Paczkowska, T.; Paczkowski, W. Aspekty Budowlane Katastrofy Energetycznej w Rejonie Szczecińskim. XXIV Awaryjne Budowlane 2009. Available online: https://awaryjne.zut.edu.pl/files/ab2009/referaty/00_referaty_problematyczne/10_Paczowska_T_i_inni_Aspkty_budowlane_katastrofy_energetycznej_w_Rejonie_Szczecinskim.pdf (accessed on 22 May 2026).
96. Wojtaszek, H.; Borowski, P.F.; Handschke, M.; Miciuła, I.; Stecyk, A.; Bielawa, A.; Ozdyk, S.; Kowalczyk, A.; Czepło, F. Wind Energy in Transition: Development, Socio-Economic Impacts, and Policy Challenges in Europe. *Energies* **2025**, *18*, 2811. <https://doi.org/10.3390/en18112811>.
97. European Commission. Recovery and Resilience Facility. 2026. Available online: https://energy.ec.europa.eu/topics/funding-and-financing/recovery-and-resilience-facility-clean-energy_en?utm_source=chatgpt.com#national-recovery-and-resilience-plans-2026 (accessed on 2 June 2026).
98. European Commission. REPowerEU Plan: Energy Policy in EU Countries' Recovery and Resilience Plans. 2026. Available online: https://www.consilium.europa.eu/en/policies/repower-eu-plan/?utm_source=chatgpt.com (accessed on 2 June 2026).
99. European Commission. CEF Energy: Connecting Europe for an Affordable, Secure, and Green Future. European Climate, Infrastructure and Environment Executive Agency 2026. Available online: https://cinea.ec.europa.eu/cef-energy-connecting-europe-affordable-secure-and-green-future_en (accessed on 2 June 2026).
100. Maśloch, P.; Maśloch, G.; Kuźmiński, Ł.; Wojtaszek, H.; Miciuła, I. Autonomous Energy Regions as a Proposed Choice of Selecting Selected EU Regions—Aspects of Their Creation and Management. *Energies* **2020**, *13*, 6444. <https://doi.org/10.3390/en13236444>.
101. Jałowicz, T.; Wojtaszek, H.; Miciuła, I. Analysis of the Potential Management of the Low-Carbon Energy Transformation by 2050. *Energies* **2022**, *15*, 2351. <https://doi.org/10.3390/en15072351>.
102. Praveenkumar, S. Enhancing the thermal and electrical efficiency of solar photovoltaic panels by integrating super max foam and zinc oxide nanofluids: An experimental approach. *Renew. Energy* **2026**, *256*, 124499. <https://doi.org/10.1016/j.renene.2025.124499>.

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