THE IBERIAN PENINSULA BLACKOUT: CAUSES, IMPACTS, AND SOLUTIONS

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Abstract

On April 28, 2025, a massive grid instability event swept across the Iberian Peninsula and parts of Southern Europe, plunging millions into a blackout lasting up to 24 hours. As one of the most significant grid-wide outages in European history, this event exposed critical vulnerabilities in regional energy reliability amidst the rapid transition to renewable energy. This paper investigates the root causes of the grid collapse and power outage—specifically the challenges of high penetration of the renewable power generation, especially the solar photovoltaic (PV) power generation—and evaluates the far-reaching socio-economic impacts of the blackout. Furthermore, it explores potential solutions, including the integration of smart grids, energy storage systems, and emerging technologies like AI and robotics as essential frameworks for mitigating future grid instability and ensuring long-term grid resilience.

Keywords: power outage, renewable energy penetration, smart grid, energy storage, AI, robotics

1. Introduction

The April 28, 2025 Iberian Peninsula blackout represents a watershed moment for European energy security. The event caused a sudden loss of approximately 15 GW of generation—nearly 60% of national demand—plunging millions of people into darkness and severely disrupting economic and social activities (Kirby, 2025). As one of the largest recent power system failures in Europe, the incident provides a critical stress test for modern electricity grids undergoing rapid transitions toward high shares of inverter-based renewable resources, which typically lack the natural rotational inertia of conventional synchronous generators (Euroconsumers, 2025).

Existing studies have primarily focused on the social and political consequences of the blackout (Santos et al., 2025; Llantada and Sánchez, 2025). Erokhin (2025) examined the reactions of affected communities and the broader governance challenges associated with large-scale grid failures. However, significant gaps remain in understanding the underlying technical mechanisms that triggered and propagated the system collapse, particularly the overvoltage conditions that bypassed existing automated protection and defense schemes.

Recent technical studies suggest that this event may represent the first grid-wide blackout in history initially triggered by solar power overvoltage in a power system with high renewable penetration (Rouco et al., 2025; Gedundez et al., 2026). The resulting disturbance subsequently led to the cascading disconnection of renewable generation operating under power-factor control, accelerating system instability and ultimately contributing to the widespread outage. Understanding the dynamics of this failure is therefore essential for improving grid resilience in power systems with increasing levels of inverter-based generation.

This paper investigates the technical root causes and broader implications of the April 28 blackout. Through a systematic analysis of the overvoltage dynamics, protection responses, and cascading disconnection mechanisms, the study identifies key vulnerabilities in current grid integration practices for renewable energy. Based on these findings, the paper proposes resilient integration strategies and policy considerations aimed at enhancing system stability. By

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linking technological failure mechanisms with institutional and operational responses, this study contributes to the development of more robust and reliable power systems in an era of rapidly expanding renewable energy deployment.

2. Causes of the Blackout

The exact cause of the Iberian Peninsula blackout is still being investigated, but several factors contributed to the grid's failure. The leading cause was a chain reaction of failures triggered by a voltage surge that the grid could not handle, exacerbated by insufficient voltage control from traditional power plants. Although the initial surge was mitigated, it triggered a series of disconnections, ultimately leading to a total grid collapse. Weak electrical connections to the rest of Europe and the loss of some generation due to transformer problems also increased the vulnerability. Recent reports, including ENTSO-E's October 3, 2025, factual analysis, confirm this was the first known blackout caused by excessive voltage rather than shortages, stemming from planning errors by Red Eléctrica de España (REE) and a shortage of thermal plants for voltage regulation (ENTSO-E, 2025a).

The primary trigger was an overvoltage transmission failure, which refers to a breakdown in the large power lines that carry electricity over long distances at high voltages to minimize energy loss (Larson, 2025). This failure, possibly in the Aragón-Catalonia corridor or southwestern Spain, caused a rapid drop of 15 gigawatts—approximately 60% of Spain's electricity demand—in just five seconds, leading to a cascading failure where one disruption triggers others, ultimately collapsing the entire grid (ENTSO-E, 2025b).

A significant factor was the heavy reliance on renewable energy, especially solar, which provided 78% of electricity, with solar alone supplying 60% (Buenestado, 2025; Blackburn, 2025). However, investigations have ruled out renewables as the leading cause, noting that solar and wind levels were consistent with seasonal norms and did not exceed production levels. While renewables offer benefits such as lower prices (Spain's electricity was 32% below EU averages in H1 2025 due to decoupling from gas), they can reduce grid inertia—a stabilizing force provided by spinning turbines in traditional plants—when not equipped with advanced controls (Larson, 2025). Unlike traditional power plants, solar panels generate less grid inertia, a key grid-stabilizing force that helps the grid handle sudden changes in electricity supply or demand (Curum, 2025; Porter, 2025). At that time, most solar plants operated in a fixed-power-factor mode, meaning they produced electricity without adjusting to stabilize the grid's voltage—the electrical "pressure" that ensures smooth power flow (Larson, 2025). In contrast, actively controlling voltage involves adjusting the power output to maintain stable voltage levels, a capability better provided by traditional generators, such as gas or nuclear plants (Larson, 2025). The lack of this control, along with low conventional generation (only 15%), made the grid vulnerable to instability (Blackburn, 2025).

The Iberian Peninsula's grid is relatively isolated from the broader European network. This isolation limited its ability to draw stabilizing power from neighboring countries, such as France (Jolly, 2025). It exacerbated the collapse, as the grid was unable to compensate for the sudden power loss quickly. Some speculated that a cyberattack was responsible, given Spain's geopolitical position, but officials, including Red Eléctrica de España (REE) and the European Council, found no evidence, although investigations continue (Clark and Weise, 2025; Llantada and Sánchez, 2025). Other theories include a cable fault or an imbalance in the European grid, but these issues remain unconfirmed (Al Jazeera Staff, 2025).

While high renewable penetration contributed to lower inertia, experts emphasize that the core issue was obsolete infrastructure and REE's failure to schedule adequate thermal support. Renewables have driven down costs and emissions, underscoring the need for integration tools rather than reduction (PV Tech, 2025; ENTSO-E, 2025).

3. Sequence of the Blackout Outbreak

3.1 Generation Trips

A series of initial events involved the tripping or disconnection of generation units, primarily in southern Spain. These trips resulted in a sudden loss of generation capacity, causing frequency and voltage disturbances within the Iberian grid.

3.2 Grid Disconnection

As the system frequency continued to drop and voltage fluctuations worsened, the Iberian grid eventually disconnected from the rest of the interconnected European system. This separation further destabilized the Iberian grid.

3.2 Automatic Load Shedding

The very measure, automatic load shedding, designed to prevent a grid failure (Bevrani, 2014), was automatically activated and caused the complete collapse of the grid. The automatic load shedding involved intentionally disconnecting parts of the load (electricity consumers) from the grid to reduce demand and potentially stabilize the system. However, in this case, the load shedding was not sufficient to prevent the complete collapse of the Iberian grid. **Table 1** shows the details of the chain of events leading to the Iberian blackout and its impacts.

Table 1: Events Leading to Blackout

Time (CEST)	Event	Impact
12:03–12:07	First voltage oscillations (0.64 Hz) detected in Spain-Portugal grid.	Localized instability, mitigated by TSO actions.
12:19–12:22	Second inter-area oscillation (0.21 Hz) affecting entire Iberia detected. Since then, the grid appeared stable, with no oscillations detected.	Grid operators reduced France-Spain power flows.
12:32:57	Transformer trip in Granada (355 MW loss).	Triggered overvoltage and frequency drop in southern Spain.
12:33:16	PV and solar-thermal plants disconnect in Badajoz (720 MW loss).	Worsened voltage surge and frequency drop.
12:33:17	Wind and solar farms trip in Sevilla (1,100 MW loss).	Caused frequency collapse (<48 Hz) and automatic load shedding activation.
12:33:21	France-Spain interconnectors trip.	Led to islanding Iberian grid.
12:33:21	Grid collapsed completely, the HVDC between France and Spain tripped.	Triggered full blackout.

To sum up, the sequence of events that contributed to the complete blackout (see **Figure 1**) reveals the technical vulnerabilities of the Iberian grid in the face of high variable solar PV generation (ENTSO-E, 2025; Planelles and Fariza, 2025).

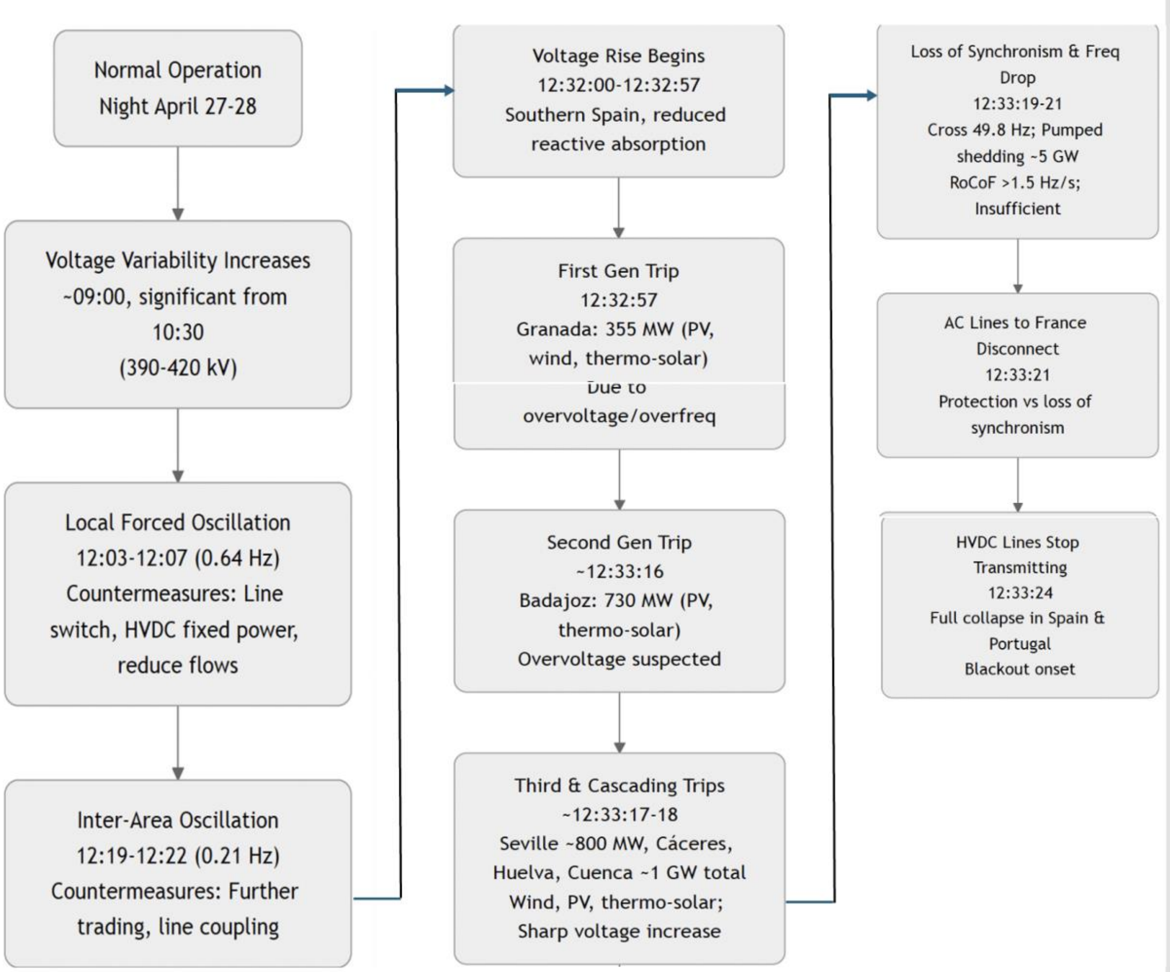

Figure 1: Blackout Onset Sequence

4. Event Unfolding

The blackout began at 12:33 CEST on April 28, 2025, when the Iberian electricity system experienced a "total zero," meaning no power flowed through the grid (ENTSO-E, 2025b). At the time, the grid was exporting surplus power to Portugal, France, and Morocco, with negative electricity prices due to high solar output (Blackburn, 2025). Within five seconds, three central generators and the France connection decoupled, triggering the collapse (Larson, 2025).

The black start to repower the grid began around 57 minutes after the initial blackout through the Spanish hydro plant and lasted several hours. The power restoration effort was supported by international power supplies, including 900 megawatts from Morocco and 2 gigawatts from France, which repowered regions like Aragón-Cataluña and Galicia-

León (Gea et al., 2025). By 4:30 PM, 50% of Spain's electricity consumption was restored, and by early April 29, nearly all power was back online (Moench and Pomeroy, 2025).

Spain declared a national emergency, deploying 30,000 police to maintain order, while Portugal declared an energy crisis (Macias, 2025; Madeira, 2025). Spanish Prime Minister Pedro Sánchez urged citizens to stay home and avoid speculation, while Portugal's Prime Minister Luís Montenegro called for an EU audit of electrical systems (Llantada and Sánchez, 2025; NTSO-E, 2025a). The rapid response, which utilized hydropower and gas turbines, was crucial to the recovery (Gea et al., 2025).

5. Impacts on Society and Economy

The blackout's societal and economic impacts were profound, touching nearly every aspect of life and highlighting the vulnerability of modern societies to energy disruptions, particularly for those reliant on essential services. At least eight deaths were reported: seven in Spain, including three from carbon monoxide poisoning in Galicia due to a generator, and one in Portugal when a 77-year-old woman's ventilator failed (Huaxia, 2025; Jolly, 2025). Hospitals relied on backup generators, but some, such as one in Setúbal, Portugal, lost both water and internet access, which complicated care and underscored the risks to vulnerable populations, including the elderly and those with medical needs (Jolly, 2025).

Transportation was severely disrupted. Public transport, including subways and trains, stopped, stranding passengers on 116 trains in Spain (Moench and Pomeroy, 2025). Airports, such as Madrid-Barajas and Lisbon's Humberto Delgado, closed, canceling flights (NBC News Staff, 2025). Failed traffic lights caused chaos, requiring Spain's Civil Guard to manage traffic and escort fuel tankers to hospitals (Llantada and Sánchez, 2025) and severely disrupted The Portuguese National Health Service (Santos et al., 2025). Telecommunications faltered, with mobile and internet outages affecting residents and even Greenland's villages due to a loss of connection with Gran Canaria's Maspalomas Station (ENTSO-E, 2025a).

Economically, the blackout shaved €1.6 billion (0.1% of GDP) off Spain's economy, with businesses such as Madrid's ice cream shops losing perishable goods (Jolly, 2025). Manufacturing, retail, and payment systems halted, with ATMs and stores closing (Macias, 2025). Socially, daily life came to a halt: people were trapped in elevators, schools closed, and events like the Madrid Open tennis tournament were interrupted (Moench and Pomeroy, 2025). At Madrid's Atocha station, police and the Red Cross provided blankets and water to stranded travelers (Llantada and Sánchez, 2025).

6. Post-Event Responses

Following the collapse, there has been renewed political pressure to accelerate delayed projects. The blackout served as a "sentinel event" that accelerated massive infrastructure investments:

- *Funding*: In June 2025, the European Investment Bank (EIB, 2025) committed €1.6 billion to the Bay of Biscay interconnector to double the exchange capacity between Spain and France.
- *Grid Upgrades*: Portugal announced €137 million in grid upgrades, specifically aimed at increasing the number of black-start power stations and integrating more battery storage into critical infrastructure (CNESA, 2025)
- *Bay of Biscay Link*: This project aims to double the France-Spain capacity to 5,000 MW and received an additional €1.6 billion from the European Investment Bank in June 2025 (EIB, 2025).
- *New "Energy Highways":* In late 2025, the EU announced eight priority energy highways to address urgent infrastructure gaps like those in the Pyrenees (EIB, 2025).

7. Global Perspectives on Blackouts

To contextualize the Iberian blackout, comparing it to other significant outages, such as Australia's 2016 blackout and Texas's 2021 winter storm, reveals common vulnerabilities and effective solutions. This comparison is crucial for understanding how grid failures transcend regional contexts, highlighting universal challenges like insufficient grid inertia, weak interconnections, and inadequate resilience planning. For instance, Australia's adoption of large-scale battery storage post-2016 offers a model for rapid black-start capabilities, while Texas's 2021 experience underscores the need for weather-resilient infrastructure. These cases inform the Iberian context by demonstrating the importance of integrating renewables with advanced controls and storage, alongside policy reforms to enhance grid interconnectivity. Table 2 summarizes these comparisons, highlighting triggers, durations, economic impacts, and the role of renewables, with lessons for enhancing grid stability and integration (PV Tech, 2025).

Table 2. Global Blackout Comparisons

Aspect	Iberian 2025	Australia 2016	Texas 2021	Key Lesson
Trigger	Overvoltage surge, low voltage control	Storm-induced faults	Extreme cold, generation failures	Invest in weather-resilient infrastructure
Duration	10-24 hours	Up to 2 weeks in parts	4-5 days	Faster black-start with batteries (milliseconds vs. hours)
Economic Impact	€1.6B (0.1% GDP)	AUD 367M	USD 195B	Enhance interconnections (Iberia 8% vs. EU targets)
Renewables Role	High penetration reduced inertia but not primary cause	Contributed to instability without storage	Limited during freeze	Integrate grid-forming tech and storage for stability (PV Tech, 2025)

8. Critical Lessons

8.1 Dynamic Voltage Control

The Iberian blackout demonstrated that fixed power-factor renewables are unable to stabilize voltage spikes caused by high PV power generation. The lack of synchronous reactive absorption capacity, the low-loaded transmission grid, and the operation of renewable generation with a fixed power factor not providing dynamic voltage control, are identified as the critical leading factors to overvoltage-driven blackout (Gegundez et al. 2026)

8.2 Interconnections Disparity

The stark difference in interconnection capacity between Iberia and Northern Europe highlights a structural vulnerability in the EU's energy union.

Iberia's "Energy Island" Status

- In 2025, Iberia's interconnection capacity with Central Europe (primarily through France) remained at approximately 3.4% to 8%., which is far below the EU target of 15% set for 2030. (Lara et al., 2025)
- The total transfer capacity with France was roughly 2.8 GW to 3.8 GW, a fraction of Iberia's ~40 GW peak demand.
- The ratio of the grid investment in Spain was not only far below those of Italy (more than 3 times higher), France (more than 2 times higher), the UK and Germany (more than 1 times higher), but also much lower than that of other EU countries, which is the expected 2025-2030 ratios for Europe in BloombergNEF's Net Zero Scenarios (Ruiz, and Hutters, 2025).

The Netherlands Benchmark:

- In contrast, countries such as the Netherlands and those in the Baltic region maintained connectivity levels ranging from 40% to 60% in 2025 (Ember, 2025).
- High connectivity allows these nations to instantly "export" excess voltage or "import" stability from neighbors during rapid generation shifts.

The lack of robust links to the rest of the ENTSO-E network exacerbated the crisis in several ways:
Failed Voltage Absorption: The 2025 event was an "overvoltage-driven" blackout. With limited links to France, Iberia was uncapable of exporting the sudden surge in voltage to its neighbors, the imbalance triggered a cascading disconnection of renewable and nuclear plants.
Frequency Instability: The sudden loss of 15 GW of generation capacity islanded the peninsula within seconds. Without the "synthetic inertia" or support that stronger physical links provide, the grid lacked the buffer to prevent a total shutdown.

8.3 Black-Start Inefficiency

The Iberian blackout event revealed a slow hydro-plant black start (several hours), in contrast to the milliseconds required for battery black-start systems. The delayed recovery process highlighted a significant performance gap between traditional and modern restoration technologies.

- *Hydro-Plant Delays*: Following the total shutdown, Portugal and Spain relied on traditional "black start" resources, including hydro-plants and gas turbines. These systems often require several hours to synchronize and stabilize enough to begin restoring the wider load.
- *Battery vs. Hydro*: Technical reports contrasting the event noted that while hydro-plants took hours, modern Battery Energy Storage Systems (BESS) can provide black-start capabilities in milliseconds. BESS can immediately inject power to stabilize frequency and provide the "grid-forming" strength needed to restart other generators.

8.4 Policy and Market Restrictions

Lack of Fault Ride-Through Capacity. Reports on the blackout suggest that, despite the existing EU grid codes requiring renewables to support voltage/frequency, there were issues related to grid resilience and how the system responded to the surge in voltage that triggered the event (Lara et al., 2025; ENTSO-E, 2025a).

Real-Time Grid Monitoring. Low-frequency oscillations were detected 30 minutes before the 2025 blackout but were not mitigated.

9. Solutions for a Resilient Future

The analysis of the root causes of the Iberian Peninsula grid failure and power blackout reveals the lack of the robustness and resilience and of the current grid required by the rapid renewable penetration. To prevent future blackouts, several necessary grid improvements are proposed.

9.1 Enhancing Grid Stability

It is crucial to deploy grid-forming inverters, i.e., devices that enable renewable sources to emulate traditional generators by stabilizing voltage and frequency (Larson, 2025). Synchronous condensers, machines that provide grid inertia without generating power, and large-scale batteries and energy storage facilities can further stabilize the grid, as seen in Australia after its 2016 blackout (Larson, 2025; Fariza et al., 2025). Shifting renewable plants to control voltage actively will also reduce overvoltage risks (Larson, 2025). For instance, Spain's June 12, 2025, update to Operational Procedure 7.4 now enables renewables to provide voltage services, potentially preventing similar events from occurring. Batteries offer quantified benefits, such as providing synthetic inertia and millisecond responses (ENTSO-E, 2025a; PV Tech, 2025).

8.2 Improving Black-Start Capabilities

It is essential to improve black-start capabilities, i.e., the ability to restart the grid without external power. Renewable energy penetration needs synthetic inertia grid support through mandatory storage buffers. Portugal plans to maintain and expand black-start facilities at Tapada do Outeiro, Alqueva Dam, and Baixo Sabor Dams, and Spain should follow suit with gas turbines and hydro plants (Madeira, 2025). Portugal's July 2025 €400 million plan, which includes a 750 MW battery expansion and doubling of black-start stations, exemplifies proactive measures (XXV Governo Constitucional, 2025; CNESA, 2025).

8.3 Strengthening Interconnections

Expanding the interconnections with European grids will reduce the Iberian Peninsula’s grid isolation, allowing it to access stabilizing power (Jolly, 2025).

8.4 Enhance Comprehensive System Planning

Comprehensive system planning, including dynamic stability assessments, is essential for managing high levels of renewable energy penetration. Funding these upgrades is challenging because renewable energy generators may resist contributing to grid stability costs (Larson, 2025). Related policy and regulation reforms can help resolve this challenge.

8.5 Grid Security

Although no cyberattack was confirmed, robust cybersecurity measures, such as real-time monitoring, must be taken proactively (Clark and Weise, 2025).

8.6 Public Preparedness Campaigns

Citizens must be educated on emergency protocols, such as maintaining backup power for medical devices, while improved emergency coordination can ensure timely and proper responses (Jolly, 2025).

8.7 Leverage AI and Robotics

Advanced AI and robotic applications should be developed and deployed in renewable energy generation and grid management systems for real-time grid optimization, instability prediction, anomaly detection, robotic transmission inspection, and generator deployment during outages (Larson, 2025; NBC News, 2025).

9. Conclusion

This paper analyzed the causes, impacts, and solutions of the Iberian Peninsula blackout. The Iberian blackout highlighted the fragility of modern electricity grids as they transition to renewable energy sources. High solar PV penetration and generation, grid isolation, and potential transmission failures created a perfect storm, resulting in devastating technical, economic, and social consequences. This event serves as a wake-up call for nations worldwide to strike a balance between renewable ambitions and robust grid infrastructure, ensuring power reliability for all. However, because the exact cause of the Iberian Peninsula blackout is still under investigation, this paper cannot exhaustively examine all aspects of this blackout. Future studies should be conducted to expand the international comparison of challenges and strategies for renewable energy penetration and grid integration in Spain with those in other countries. By investing in grid stability, black-start capabilities, interconnectivity, and public preparedness, Spain and Portugal can build a more resilient energy future. Through ongoing lessons from events like this, emphasizing empathy for affected communities and balanced innovation, Europe can move toward sustainable and reliable energy systems.

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