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SHURA AGENDA

Iberian Peninsula Blackout

On Monday, April 28, 2025, a large-scale power outage affected the Iberian Peninsula, disrupting the electricity systems of Spain and Portugal. The incident began at 12:03 a.m., leading to a complete system failure that caused a 15 GW loss in generation capacity and disconnected the Iberian grid from the broader European network. This systemic collapse underscored the vulnerabilities of modern electricity systems, especially those with high shares of renewable energy and reignited concerns about energy security. A detailed report published by Spain's transmission system operator, Red Electrica (REE), in late June provided important technical insights into the event.

What lessons does this blackout offer for the energy transition and the future resilience of power grids?

What caused the power outage?

At the time of the blackout, approximately 70% of Spain's electricity was being generated by solar and wind energy plants. This initially led to speculation that the lack of system inertia—a common characteristic of renewable-based systems—was the main factor behind the collapse. However, the investigation by REE concluded that low inertia was not the root cause. Instead, the outage stemmed from a combination of voltage fluctuations, uncontrolled generation losses, and sudden shifts in reactive power within the transmission network. The report emphasized that even with higher system inertia, the collapse likely would not have been averted. These findings highlight the growing importance of voltage control and real-time grid observability in power systems with high shares of variable renewable energy.

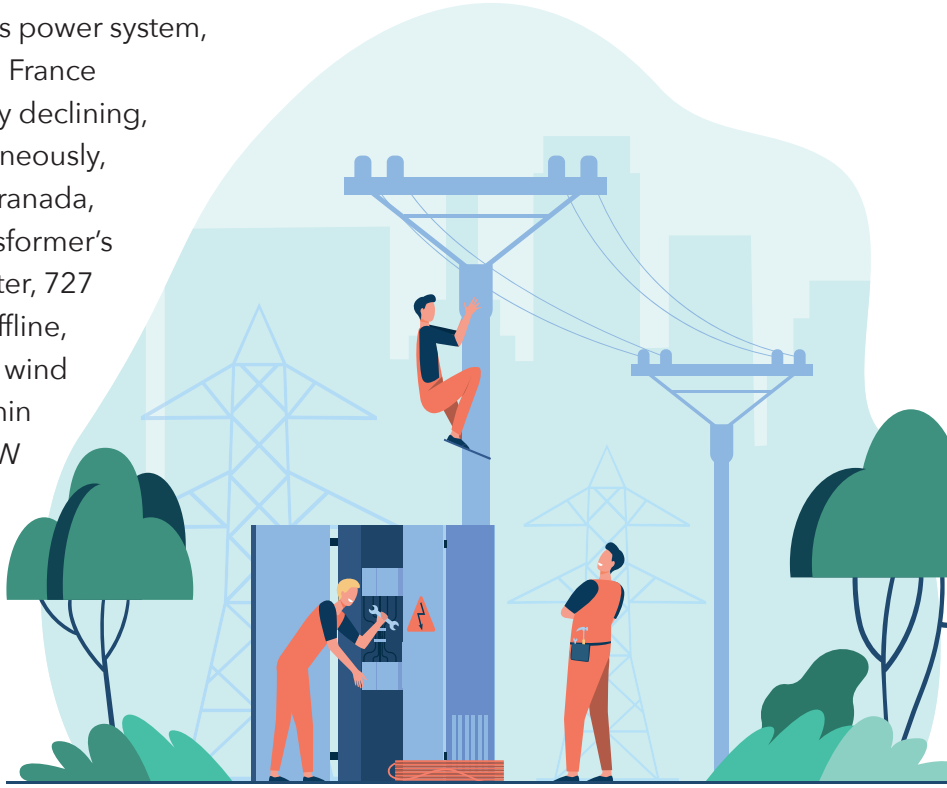
Timeline of events during the blackout

12:03–12:19 | Voltage fluctuations began
The first oscillation lasted around 5 minutes. Although the voltage was initially at nominal levels, the oscillation led to a noticeable drop in average voltage. In response, the system operator took corrective action by reducing electricity exports and adjusting power flows on key transmission lines. Due to low production costs, solar power plants in the south were the first to be curtailed. However, despite these interventions, voltage levels continued to fall.

12:19–12:22 | Second oscillation and renewed voltage drop
A second oscillation occurred—this time affecting frequency—within the European interconnection system. To stabilize voltage levels, electricity exports to France and Portugal through High Voltage Direct Current (HVDC) lines were reduced. By 12:22, the voltage in the system began to recover.

12:22–12:32 | Voltage fluctuations and losses in distributed generation
Voltage levels were further affected by changes in reactive power flows from the distribution system to the transmission grid. At the same time, a sudden drop in generation from self-consumption distributed energy resources (DERs) with capacities below 1 MW—whose output cannot be directly monitored—led to an abrupt 845 MW increase in demand. Efforts were made to start up natural gas power plants to restore system balance, but these attempts were unsuccessful due to a lack of synchronization (ramping up speeds), and the units could not be brought online in time.

12:32–12:33 | Peak energy exports to France, transformer failure, and cascading generation losses
Despite a frequency drop in Spain's power system, instantaneous electricity exports to France peaked at 1,500 MW before rapidly declining, triggering a voltage surge. Simultaneously, a transformer failure occurred in Granada, leading to overvoltage on the transformer's secondary side. Twenty seconds later, 727 MW of generation capacity went offline, followed by the shutdown of three wind farms and several solar plants. Within just 0.65 seconds, a total of 834 MW of generation was lost. Reduced reactive power absorption disrupted the system's south-to-north power flow, further destabilizing the grid.



Technical assessment: Why did the system collapse?

The collapse of the electricity system resulted from a combination of interlinked structural weaknesses. This event highlighted the vital importance of voltage and frequency control, particularly in systems with high shares of renewable energy. The primary cause of the incident was insufficient voltage control mechanisms—rather than low system inertia—though low inertia did exacerbate the situation by accelerating the growth of frequency and voltage oscillations.

Why did system vulnerability increase?

- Inadequate monitoring of distributed generation facilities hindered timely interventions by the system operator.
- Transformer failures and delays in activating reserve capacity—key to enhancing system flexibility—added to system fragility.
- The inability of inverter-based generation to effectively participate in voltage control exacerbated voltage imbalances.
- The HVDC line failed to provide frequency control support, resulting in asymmetric power flows.
- The lack of resilience-enhancing mechanisms, such as energy storage and demand-side response, delayed recovery efforts.

Impacts of the outage

- Approximately 35,000 people were stranded in metro and train systems, Renfe suspended all rail services.
- Flights were suspended at several airports, including Madrid Barajas Airport.
- Banking transactions and digital communications experienced widespread disruptions.
- Some hospitals could only offer emergency services, while some outpatient clinics were forced to close.
- Police forces were mobilized to maintain public safety in urban areas.

How did the system recover?

- Spain ramped up generation from hydropower and natural gas plants.
- Prior to the incident, France was importing 1 GW from Spain; during the crisis, it reversed the flow and exported 2 GW to support Spain.
- Morocco contributed 900 MW of electricity to the Spanish grid.
- By 7:30 a.m. on April 29, 99% of the system had been restored.

Technical solutions and recommendations

Smart grids and real-time monitoring

- Enhance integration and traceability of DERs and self-consumption facilities (particularly those < 1 MW) within the electricity system.
- Expand the deployment of smart meters and microgrid infrastructure to improve local control and visibility.
- Increase real-time monitoring of voltage and frequency conditions across both transmission and distribution networks through the wider adoption of PMU and SCADA systems.
- Plan and invest in grid expansion and modernization to accommodate the evolving needs of a flexible, decentralized energy system.

Next-generation storage and grid control systems

- Design battery energy storage systems not only for energy storage but also to actively support grid stability through **"grid-forming"** features.

Effective management of interconnection lines

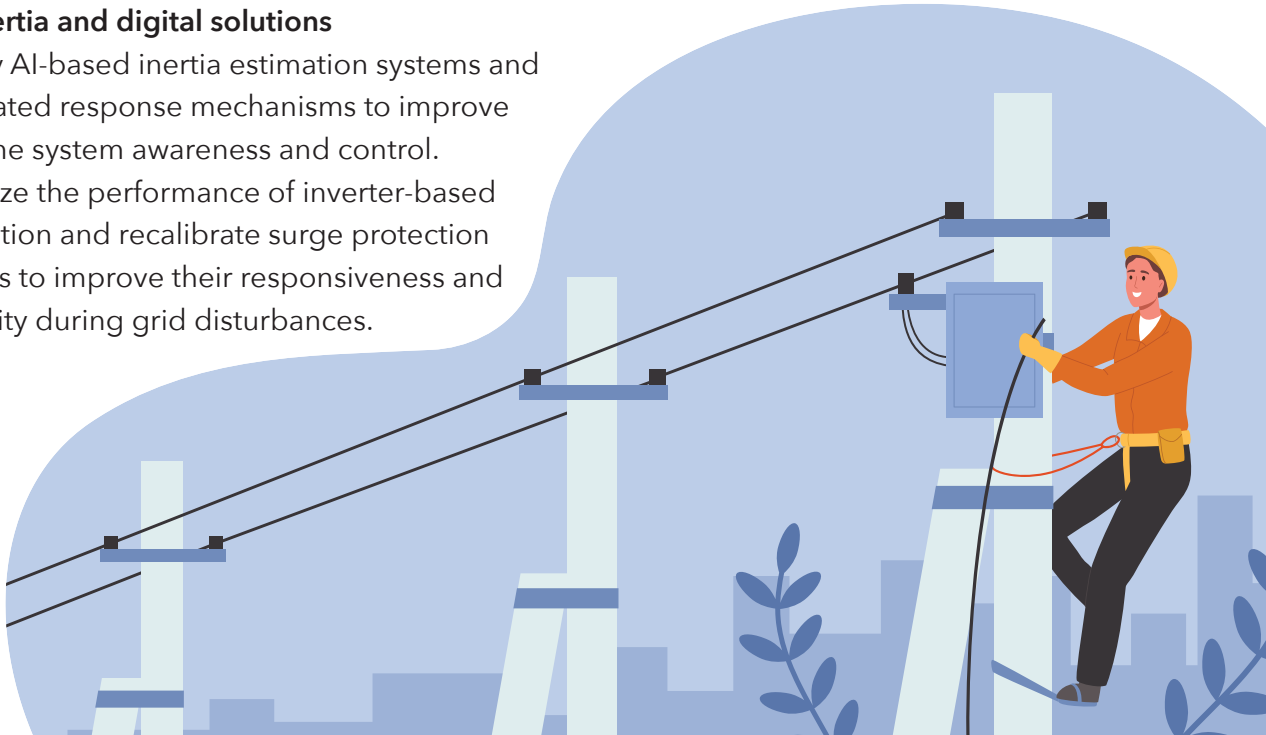
- Recognize the critical role of HVDC lines in supporting frequency control, particularly in island systems or border regions power-frequency control functions on these lines should be activated to support system stability.
- Improve cross-border coordination of ramping and voltage regulation to ensure more synchronized and effective responses to rapid changes in production and consumption.

Demand-side participation

- Implement dynamic pricing schemes to ensure consumers receive real-time market signals, encouraging more responsive electricity use.
- Guide households and SMEs in energy management through the use of smart meters.
- Promote aggregator models to enable market participation by small producers and consumers, thereby increasing grid flexibility and resilience.

Virtual inertia and digital solutions

- Deploy AI-based inertia estimation systems and automated response mechanisms to improve real-time system awareness and control.
- Optimize the performance of inverter-based generation and recalibrate surge protection systems to improve their responsiveness and reliability during grid disturbances.



What lessons can Türkiye learn from the blackout?

8 critical lessons from the April 28, 2025 Iberian Peninsula blackout

1. Plan Grid Expansion with DERs in Mind: Türkiye's grid modernization efforts must integrate the rising number of DERs, ensuring that grid planning reflects both central and decentralized generation capacities.
2. Improve Real-Time Visibility of Distributed Resources: Real-time visibility of distributed and self-consumption facilities should be ensured, and data flow from distributed energy resources to transmission and distribution operators should be increased.
3. Enhance TSO-DSO Coordination: Formal mechanisms for operational coordination and data sharing between TEİAŞ (TSO) and distribution companies (DSOs) should be strengthened to manage system-wide disturbances more effectively.
4. Expand and Deploy Grid Flexibility Options Rapidly: Türkiye needs a broader portfolio of flexibility tools—including battery storage and demand-side response—that can be mobilized in emergencies.
5. Scale Up Demand-Side Flexibility and Aggregator Participation: Rolling out dynamic pricing and smart metering infrastructure will allow consumers to react to price signals, while enabling aggregators to integrate small prosumers into the market.
6. Set Clear Standards for Inverter-Based Resources: As inverter-based renewable generation increases, Türkiye should clarify voltage control requirements and ensure these resources contribute to reactive power support at both transmission and distribution levels.
7. Strengthen Interconnection Capacities and Control Systems: Increasing cross-border interconnection capacity and equipping these lines with advanced control functionalities will improve Türkiye's ability to withstand regional disturbances.
8. Promote Smart and Microgrid Solutions for Critical Infrastructure: Smart and microgrid applications should be expanded nationwide with microgrid deployment considered mandatory for critical infrastructures (e.g., hospitals, airports).

Note from SHURA:

The success of the energy transition depends not only on increasing renewable energy capacity but also on building a planned, digitalized, and flexible system architecture. Transitioning from traditional fossil fuel-based structures to systems dominated by variable renewable energy sources requires a systematic approach and meticulous technical design. This transition should be guided by long-term planning and robust public policy, grounded in a clear strategic vision.

The large-scale power outage in the Iberian Peninsula on April 28, 2025, exposed the structural challenges that can emerge during this transition. However, such events are not a reason to abandon renewable energy goals –on the contrary, they highlight the urgent need to implement technical solutions that enhance system flexibility and reliability.

With the right investments and regulatory frameworks—particularly in areas such as voltage control, reactive power management, inverter-based generation synchronization, and monitoring of distributed generation—renewable-based power systems can be operated both safely and sustainably. Every crisis in the course of energy transition, when properly analysed, presents an opportunity to build more resilient systems for the future.

In this context, the Spanish blackout offers valuable lessons for Türkiye to proactively redefine and fortify its grid security as it advances toward a cleaner, more flexible energy future.