

The 2025 Iberian Peninsula blackout: lessons for modern power systems and policy implications

Policy note, *Utilities Policy* (2026)

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Motivation

Spain and Portugal lost power for 47 million people on 28 April 2025

- At **12:33**, Spain and Portugal lost power simultaneously: the largest blackout in over 20 years. Supply was not fully recovered until the following day
- The investigation identified a **novel failure mode**: cascading generation disconnections triggered by **overvoltage**, rather than the undervoltage collapse that grid codes and operator procedures are designed to prevent
- The note reads the root cause as **institutional rather than technical**

Question

What institutional failures enabled this crisis, and what reforms are necessary to prevent similar events as power systems undergo rapid decarbonization?

What the note does, and what it does not

- A **policy note** built on the **public investigation**: the ENTSO-E expert panel report (ENTSO-E 2026) and the Spanish committee report (Government of Spain 2025), plus preliminary analyses by REE (Red Eléctrica de España 2025) and NREL (National Renewable Energy Laboratory 2025)
- A **chronology** of the event, then **policy analysis**: three institutional failures, market structure, shared infrastructure, European coordination, priorities
- The note presents **no estimates or model of its own**: the numbers are the investigation's; the author's contribution is the policy reading and the counterfactual reasoning

How to read this deck

Numbers, times and quotes are the reports', as relayed in the note. Statements on what *would* or *could* have happened are the note's reasoning, not results.

Preview of the main messages

- **An overvoltage cascade:** generation tripped in clusters, starting at 12:32:57; zero voltage by 12:33:30. The system had been left with little room to absorb reactive power
- **Three institutional failures:** control authority (instructions by email, **24 GW** of renewable voltage-control capability unused), incentives (hourly compliance), enforcement (thermal units)
- **Also:** market timing and the operator's response, and fragmented governance of shared evacuation infrastructure
- **Reforms:** mandatory SCADA integration, continuous compensated service, monitoring with credible penalties; analysis beyond standard N-1; European coordination

The diagnosis and the reforms are the note's reading of the investigation, not estimates.

Related work: reports, event analyses, broader literature

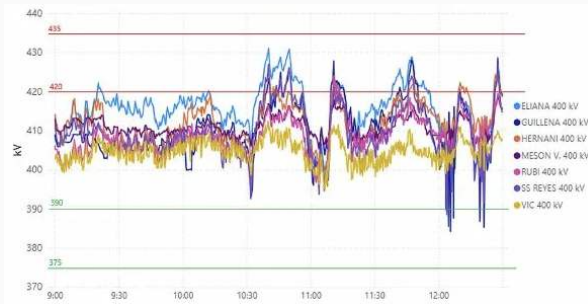
1. **Official investigations:** ENTSO-E and the Spanish committee are the note's evidence base (ENTSO-E 2026; Government of Spain 2025)
2. **Analyses of the event:** Rouco et al. (2026): an overvoltage-driven blackout, with load-flow evidence of an insufficient safety margin at 12:30; Batlle et al. (2026): renewable expansion without reform of ancillary services; Davi-Arderius and Jamasb (2026): day-ahead prices understate operating costs
3. **Broader literature:** overvoltage and reactive power at high renewable penetration (Katigbak et al. 2023; Till et al. 2020; Shun-Hsien Huang et al. 2012); wind and system strength (Akhmatov 2005; Akhmatov and Eriksen 2007; Dorile et al. 2021); the GB 2019 blackout and reduced synchronous inertia (Bialek 2020)

Contribution

An **institutional reading** of the investigation: three failures, each matched to a distinct reform.

The event

Voltage swings grew from 10:30, with few thermal plants on voltage control

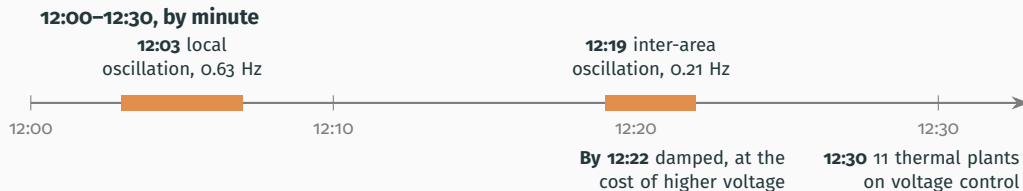


Notes: Voltage at the main 400 kV pilot nodes in Spain, 09:00–12:30, 28 April 2025; the figure marks the 435 kV and 420 kV levels. Source: ENTSO-E Expert Panel Report, as in the note.

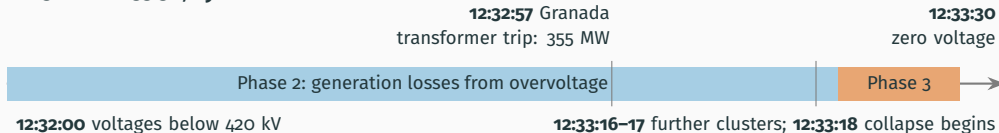
- High renewable output depressed day-ahead prices and pushed Spanish net exports to roughly **5 GW**
- Voltage swings rose after 09:00; after 10:30 pilot nodes approached the **435 kV** ceiling without breaching it
- At 12:30 only **11 thermal plants** (4 nuclear, 1 coal, 6 gas) provided dynamic voltage control: the lowest number since the start of the year
- Thermal capacity prepared for voltage control was at 50%, due to scheduled spring maintenance

Earlier warning signs

From the first oscillation to zero voltage took about 30 minutes



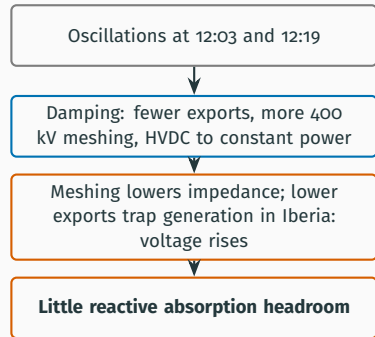
12:32:00–12:33:30, by second



Notes: Schematic from the times in the note; each bar has its own scale (12:30 to 12:32 not shown). Spanish time.

Damping the oscillations left the system at higher voltage

- **Two oscillations:** a local one from 12:03, dominant frequency 0.63 Hz; and a wide-area one from 12:19 at 0.21 Hz, the East-Centre-West inter-area mode
- **Operator response:** reduced exports to France, connected additional 400 kV circuits (more meshing), switched the HVDC link to constant power mode
- The actions restored stability, but left an **elevated-voltage state** with reduced capacity to absorb reactive power
- By 12:32:00 voltages were back below 420 kV and oscillation amplitudes below 20 mHz: conditions *appeared* stable



Mechanism as explained in the note.

Sequence of actions

At 12:33:00 the south was at its reactive absorption ceiling

2,315

MVar absorbed by P.O. 7.4 generators in south Spain, against **1,002 MVar** of remaining capacity

185

MVar of absorption from the 332 renewable generators operating under fixed power factor

2,700

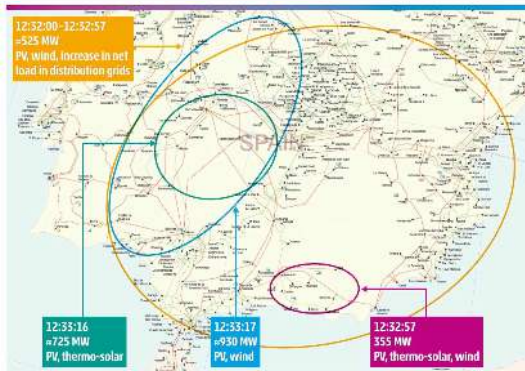
MVar of south Spain shunt reactor capacity disconnected: **67.5%** of the installed total

The system was at its reactive absorption ceiling before the cascade began

- An **overvoltage-driven** blackout: exhaustion of reactive power *absorption* capacity, not a shortage of reactive supply; load flow shows the safety margin at 12:30 was insufficient (Rouco et al. 2026)

Figures: ENTSO-E (2026), as reported in the note.

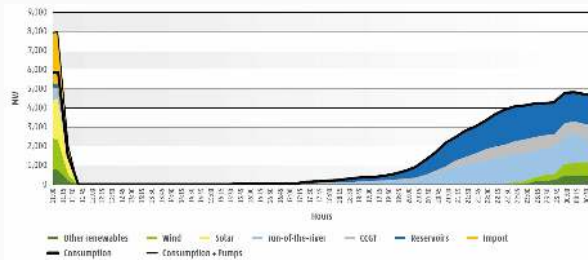
Overvoltage in shared infrastructure tripped generation in clusters



Notes: Areas of major generation disconnection in Spain, 12:32:00–12:33:18; labels as printed in the figure (approximate). Source: ENTSO-E (2026) and Spanish committee (2025), as in the note.

- Before 12:32:57: about **525 MW** of PV and wind disconnections, plus net-load increases in distribution grids
- **12:32:57**, Granada: a transformer trip disconnects **355 MW** (PV, wind, thermo-solar) that was consuming 165 MVar
- **12:33:16**, Badajoz region: about 725 MW (PV, thermo-solar)
- **12:33:17**: about 930 MW (PV, wind) in the blue cluster
- Each cluster: several facilities sharing a **common evacuation infrastructure**
- Voltage above 1.1 pu for 16 s, under the 30 s threshold for ICS violation classification

Voltage was gone by 12:33:30; restoration relied on black-start hydro



Notes: Generation and load in the Portuguese system, 28–29 April 2025. Source: REN via ENTSO-E (2026), as in the note. The time axis is Portuguese time: the collapse at 12:33 CEST appears at 11:33.

- Remaining generation disconnected over **12 seconds**; pump trips and load shedding were insufficient
- Spain lost **25,638 MW** of demand and Portugal **5,900 MW**: 100% of connected load in both
- Black-start plants (Castelo de Bode and Tapada do Outeiro) created islands that gradually absorbed load and generation
- **Portugal** restored by 00:22 on 29 April; **Spain** 99.95% of demand by 04:00; technical work continued until 14:36

Pumping load

Portugal's voltage framework held, yet Portugal still went dark

- Portugal gives **real-time voltage or reactive setpoints** directly from the TSO to synchronous generators and to renewables above 1 MW
- **No generation trips** were observed in Portugal or France during 12:32:00–12:33:18 (ENTSO-E 2026)
- Portugal collapsed when **frequency fell below protection thresholds** after the large Spanish generation losses, at rates above 1.5 Hz/s (INESC TEC 2025)

The note's reading

A voltage-control framework works within its domain, but cannot stop a frequency collapse that starts with generation losses elsewhere in a coupled system. Synchronous areas need **harmonized frameworks** across all connected systems.

The counterfactual

Institutional failures

Failure 1, control authority: the TSO could not steer renewables in real time

Spain

- Royal Decree 413/2014: facilities of 5 MW or more must follow TSO power factor instructions
- Instructions arrived **by email**, with implementation timelines of “a few days”
- No framework required or compensated **real-time controllability**

- As a result **24 GW** of renewable voltage-control capability could not be coordinated by the TSO
- **Policy:** mandatory SCADA integration above a capacity threshold, with TSO authority to send setpoints in real time. A control-rights problem, not an equipment problem

Portugal

- Synchronous generators and renewables above 1 MW receive setpoints **directly from the TSO**
- Solar plants respond in real time through SCADA
- Shows direct control authority is technically and institutionally feasible

Sources: ENTSO-E (2026), as relayed in the note.

Failure 2, incentives: hourly compliance, second-by-second needs

- Royal Decree 413/2014: power factor between **0.98 inductive and 0.98 capacitive**, on an hourly basis, checked after the fact from hourly settlement data, with penalties for violations
- The band limits reactive power to **20%** of active output; on 28 April renewable plants operated near unity power factor rather than at absorption limits
- Hourly averaging **hides** second-by-second performance, and sub-hourly voltage support earns **no compensation**
- Even static compliance was weak: nearly **22%** of the 850 highest-generating plants did not meet their power factor obligations on 28 April (Government of Spain 2025)

Policy implication

Move from hourly power factor compliance to **continuous voltage-control service**, with 5-minute monitoring and explicit compensation. An incentive-design problem.

Failure 3, enforcement: contracted thermal units absorbed too little

- Thermal units programmed and paid for voltage control showed **insufficient reactive absorption** in practically all connected units for at least one period that morning; some even generated reactive power (Government of Spain 2025)
- Under P.O. 7.4 the service counts as adequate if **75% of hourly samples** meet the voltage or reactive power criteria: no obligation to respond in real time (ENTSO-E 2026)
- The penalty scheme was prescribed but **never developed**; the framework had **not been updated since 2000**, and a revision was pending for four years

Policy implication

Enhanced supervision, real-time compliance monitoring and credible penalties, for thermal and renewable units alike. An enforcement problem, distinct from the renewable utilization gap.

Market structure contributed by compressing time, not by direct causation

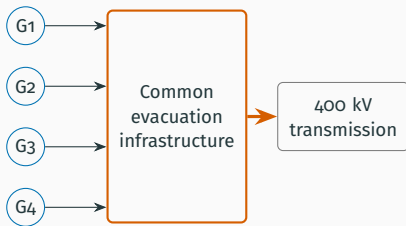
1. **More transitions:** 96 daily program changes under quarter-hourly clearing against 24 under hourly
 2. **Coincidence at 12:30:** the Portuguese export reduction (12:27–12:30) and the quarter-hourly transition arrived just as damping had left the system at high voltage. Between 12:32:00 and 12:32:57 French exports fell by 1,030 MW, 480 MW of it from observable renewable changes
 3. **Little analysis time:** about **11 minutes** between damping (12:22) and the cascade (12:32:57)
- The investigation warns that markets closer to real time may **constrain security analysis**, especially in less interconnected systems like Iberia
 - The planned 30-minute intraday gate closure compares with 15–30 minutes typically needed for security assessment
 - Even so, the other vulnerabilities **would have persisted**

The note's counterfactual: hourly clearing would have given about 38 more minutes to assess

Morning deviations

Operator incentives

Shared evacuation infrastructure hid a common-mode vulnerability



Schematic: many owners behind one private link to the grid.

- Dozens of facilities with different owners connect through shared private infrastructure; operation and maintenance is often subcontracted
- **Generators** lacked visibility of conditions in the infrastructure they connect through
- The **TSO** lacked real-time telemetry, so it treated facilities as independent and missed the common-mode risk
- Fragmented governance also **delayed the investigation**
- All three Phase 2 event clusters came from overvoltage in common evacuation infrastructure

The note stresses these barriers matter **ex ante**: a cascade of about 20 seconds leaves no room for human intervention.

Governance reforms

Lessons and policy

Beyond N-1 screening: stressed base cases and common-mode failures

- The N-1 criterion remains **conceptually sound**; the **standard implementation** proved insufficient
- The Granada initiating event could be studied within N-1, but typical screening overlooked:
 - stressed pre-contingency conditions with elevated voltages
 - correlated responses of facilities sharing evacuation infrastructure
 - inverter-based resource dynamics and protection settings
 - rapid market-driven power flow changes
- Operators need **dynamic simulation** of inverter-based resources and protections, **stressed base cases**, explicit **common-mode failures**, and the collective response of distributed renewables

The note's warning

Without better modeling and wider scenario coverage, assessments may systematically underestimate vulnerability to novel failure modes.

European coordination and recurrence risks

Coordination

- EU RfG 2016/631 requires voltage-control capability in renewables, yet national frameworks often **do not use it**
- Portugal's SCADA-integrated setpoints contrast with Spain's email instructions
- The investigation recommends a review of the cost-benefit analysis of quarter-hourly markets, weighing security as well as efficiency

Recurrence risks (without comprehensive reform)

- **Regulatory:** barriers to renewable voltage control persist as conventional generation retires
- **System evolution:** new inter-area modes as the Continental European system widens (Ukraine and Moldova 2022, the Baltics 2025); peripheral systems exposed to amplified oscillations
- **Governance:** ownership of shared infrastructure blocks ex-ante identification of common-mode risks

Similar events could occur in other regions with high renewable penetration, peripheral interconnection and fast market evolution.

Reforms match the failures; quick regulatory fixes come first

Failure	Reform in the note
Control authority	Mandatory SCADA integration; TSO real-time setpoints
Incentives	Continuous service, 5-minute monitoring, explicit compensation
Enforcement	Real-time compliance monitoring and credible penalties
Shared infrastructure	Technical capacity, telemetry into TSO SCADA, clear responsibilities

- **Immediate:** regulatory changes enabling renewable voltage-control services; enhanced compliance supervision
- **Medium term:** infrastructure (synchronous compensators, FACTS, interconnection capacity) and market reforms; long-term measures in parallel
- The note: recurrence risk falls **substantially** with five areas (mandatory renewable participation, real-time SCADA, compensation, monitoring, coordinated control); co-benefits: lower service costs, less curtailment, lower CO₂

Conclusion

Limits: what the note can and cannot say

- A **synthesis of public reports**: no estimates of its own; the numbers are the investigation's, and Phase 2 magnitudes are approximate
- Quarter-hourly clearing contributed **not through direct causation**; the counterfactual of hourly clearing suggests more flexibility, but the other vulnerabilities would have persisted
- Portugal's framework addresses voltage, not a frequency collapse; the Spanish counterfactual is stated as what "could have" happened
- The cascade lasted about 20 seconds: governance reforms act **ex ante**, not as faster crisis response
- The counterfactuals and reform effects are phrased as what "suggests" or "could" follow, not as results

Conclusion

- An **overvoltage cascade**, traced to three institutional failures: **control authority gaps, incentive misalignment, enforcement failures**
- 24 GW of renewable voltage control left unutilized; market timing and fragmented governance compounded the failures
- Reforms: SCADA integration, continuous compensated service, monitoring with credible penalties
- Restoration (99.95% of Spanish demand by 04:00 on 29 April) shows the value of robust emergency procedures

The transition needs institutional evolution beyond technology and markets

Thank you! hmorao@phd.iseg.ulisboa.pt

Backup

Backup: earlier warning signs and the morning of 28 April

- Voltage instability episodes had been recorded earlier in 2025, on 31 January, 19 March, and 22 and 24 April; the last two are the most relevant to 28 April (Government of Spain 2025)
- 06:00–09:00 on 28 April: voltage stable, with variability below 5 kV. From about 09:00 greater variability, with significant excursions after 10:30
- 10:30–11:10: voltage rises coincided with solar generation drops, as export programs shifted from export to import from France
- Five minor oscillations (05:49, 08:52, 10:30, 11:06, 11:23), all around 0.2 Hz, were damped without operator intervention
- The 12:00–12:30 oscillations were more pronounced and fell in a 15-minute market interval transition

Source: the note's chronology, citing Spanish committee (2025).

Backup: the operator's damping actions, step by step

After	Actions reported in the note
First oscillation (12:03–12:07)	Reduced French exports from 1,500 MW; HVDC changed from AC-emulation to constant power mode (12:11); five 400 kV circuits connected
Second oscillation (12:19–12:22)	French exports cut further, to a 1,000 MW target; Portuguese export reduction requested, from 2,545 MW to 2,000 MW (scheduled for 12:30); additional circuits connected; thermal generation ordered online (90-minute start-up)

- The committee notes the measures “inadvertently” raised voltage by increasing network meshing (Government of Spain 2025)

Source: ENTSO-E (2026), as relayed in the note.

Backup: why Portugal's lost load is 5,900 MW

- The 5,900 MW is consumer load connected at the instant of collapse, **excluding pumping load** already disconnected
- Peak pre-blackout demand including pumping reached about **8,000 MW** earlier in the day
- Pumping load (about 2,100 MW) was disconnected progressively by automatic frequency defense schemes between 12:33:20 and the final collapse at 12:33:30

Source: the note's footnote and the figure's caption; REN via ENTSO-E (2026).

Backup: the note's Portugal counterfactual

- The initial Granada event removed only **165 MVar** of reactive absorption
- The note argues that coordinated absorption of about **2,000 MVar**, from partial deployment of the 24 GW of renewable capability under Portugal-style real-time control, *could have* prevented the overvoltage cascade
- An order of magnitude more than the Granada loss, it says; “Portugal’s experience validates” frameworks that enable renewable voltage control
- But failures **propagate through physics** regardless of local institutional advantages, hence harmonization

Caveat

This is the note’s reasoning, not a simulation.

Backup: thermal plant evidence

- P.O. 7.4 defines compliance as meeting the reactive reference in at least **75% of hourly samples**
- The entity responsible for the penalty scheme had never developed it: no enforceable consequences on the day
- One southern plant: the TSO had sent advance instructions to absorb more on comparable past days but did not on 28 April; the plant defaulted to a lower absorption setting
- A second plant ramped toward the TSO reference, but too slowly to track the fast voltage changes
- ENTSO-E Expert Panel: an ambiguous response-speed requirement, tolerance for hourly non-fulfilment and no enforceable penalties could not ensure real-time voltage support (ENTSO-E 2026)

Backup: deviations on the French interconnection that morning

- At 10:00 and 11:00 significant power flow deviations occurred on the French interconnection
- 10:00: a **900 MW** shortfall in the programmed solar increase (about 1,100 MW actual against about 2,000 MW programmed), attributed to market price signals triggering curtailment
- 11:00: an “anomalous” **1,200 MW** demand increase, compatible with temporary distributed generation reduction
- Program changes have an adjustment window of -5 to $+5$ minutes around the nominal time, causing transient flow fluctuations

Source: Spanish committee (2025), as relayed in the note.

Backup: why the unavailable unit was not replaced

- One unit declared unavailability on the evening of 27 April; the operator chose not to replace it in real time, as voltage seemed adequate (Government of Spain 2025)
- The framework carried an incentive tied to the **volume** of energy contracted for voltage control, not to reliability (Batlle et al. 2026)
- Each MWh scheduled for this purpose displaces a MWh of renewable generation, attracting political pressure to contract less
- Constraint management cost rose from €240 million in 2019 to €1.2 billion in 2024
- In renewable-dominated systems day-ahead prices understate operating costs: ancillary service costs in Spain rise by about €0.045/MWh per euro of lower day-ahead price (Davi-Arderius and Jamasb 2026)

The note's reading: this makes the decision rationally explicable, even if operationally consequential in hindsight.

Backup: governance reforms for shared infrastructure

- **Technical capacity:** minimum capabilities for operators of common evacuation infrastructure (data, analysis, coordination with the TSO)
- **Telemetry:** voltage and power flow measurements integrated into TSO SCADA
- **Responsibilities:** clear allocation among generators for protection coordination, data provision and emergency planning
- **Information protocols:** timely data for the operator and investigators, without consent delays
- Ex-ante aims: **coordinated or staggered overvoltage protection settings** among facilities on one infrastructure, and security assessments that capture common-mode risk

The committee recommended specific regulation for shared infrastructure (Government of Spain 2025).

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