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Blackout and System Restoration on the Iberian Peninsula on April 28 and 29, 2025

Factual analysis based on publicly available data and information

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Erlangen, May 16, 2025

Preamble

On April 28th, 2025, one of the most severe disruptions to date occurred in the continental European transmission grid, leading to a large-scale power outage on the Iberian Peninsula. The causes of this major disruption, the detailed sequence of events, and the subsequent restoration of the grid are currently being investigated in detail by both the transmission system operators involved and the *European Network of Transmission System Operators* (ENTSO-E).

This report was first published in German on May 12th, 2025. It summarizes the information currently available and provides a systemic analysis of the sequence of events and consequences of the disruption. All information has been carefully researched, verified, and documented with relevant sources. Nevertheless, it cannot be ruled out that some of the information published so far may prove to be inaccurate as the investigation progresses.

The final conclusion summarizes key aspects and measures aimed at ensuring future supply and system security in the European transmission grid and at sustainably increasing the resilience of the systems.

Recommended Citation:
S. Linnert, I. Burlakin, G. Kordowich, G. Mehlmann, M. Luther, *„Blackout and system restoration on the Iberian Peninsula on April 28 and 29, 2025 - factual analysis based on publicly available data and information“,* Report, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), May 12, 2025

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1 Introduction

On April 28th, 2025, at 12:33 CEST, a major disturbance occurred in the power system of the Iberian Peninsula. Approximately 60 million people were affected by the power outage. Spanish Prime Minister Sánchez reported a loss of 15 GW of generation capacity within five seconds, corresponding to around 60% of the demand at that time [1]. Published data from the Spanish transmission system operator (TSO) Red Eléctrica de España (REE) show a scheduled demand of approximately 25 GW at 12:30 CEST, while actual generation at 12:35 CEST was 12.7 GW [2]. At 12:38 CEST, the Iberian grid was disconnected from the Continental European power system [3]. By April 29th at 07:00 CEST, power supply had been nearly fully restored, with gas and hydro power plants, as well as the interconnectors between France, Spain, and Morocco, playing a crucial role in the grid restoration [3–5].

The reports available so far indicate that the grid collapse was triggered by sudden and massive generation losses. This led to a frequency drop on the Iberian Peninsula and separation from the Continental European synchronous area. Currently, no information is available regarding automated load shedding. The frequency gradient was too steep for successful primary frequency control. According to the European Network Codes, primary frequency control must activate within 2 seconds, although full deployment may take up to 30 seconds [6]. The exact causes of the generation loss remain unknown. The Portuguese TSO Redes Energéticas Nacionais (REN) cited significant voltage fluctuations in Spain as the reason for generator trips in Portugal [4]. Furthermore, inter-area oscillations are reported in [7].

The Spanish and Portuguese authorities, as well as REN, strongly rejected media claims that an atmospheric phenomenon caused the outage. REE likewise ruled out a cyberattack [8]. On April 29th, 2025, the Central Investigating Court No. 4 of the Audiencia Nacional opened a case to determine whether the nationwide blackout was caused by a cyberattack on critical infrastructure. Such an event could be classified as a terrorist act under Article 573 of the Spanish Penal Code. The judge ordered both the National Cryptologic Center (CCN) and Red Eléctrica to submit technical reports on the causes of the outage within ten days. However, investigators emphasize that, at this stage, there is no evidence supporting such a scenario [9–11].

2 Statements of Transmission System Operators

The TSOs of Spain (REE), Portugal (REN), and France (RTE), which were directly and indirectly affected, and the European Network of Transmission System Operators for Electricity (ENTSO-E) commented on the events on the same day as the blackout. An overview of these initial statements is provided below.

2.1 European Network of Transmission System Operators for Electricity (ENTSO-E)

ENTSO-E announced on April 28th, 2025, that "soon after 12:30 CEST, a major incident occurred in the power systems of Spain and Portugal". This led to power outages in both countries and briefly in the nearby French border areas. According to ENTSO-E, the protocols for restoring the voltage of the electricity system were initiated immediately. The Spanish and Portuguese TSOs coordinated the restoration of the energy supply utilizing hydroelectric power plants and support from neighboring France and Morocco [12].

2.2 Red Eléctrica de España (REE)

At around 16:00 CEST, Spain's TSO announced a national "cero energético," the complete collapse of the electrical energy supply system. At around 17:00 CEST, REE announced via social media that the power supply had already been restored in Catalonia, Aragon, the Basque Country, Galicia, La Rioja, Asturias, Navarre, Castilla y León, Extremadura, and Andalusia. About an hour later, the REE reported that further areas in Madrid, Valencia, Murcia, and Castilla-La Mancha had been added. At around 04:00 CEST the following day, 100% of the substations in the transmission grid were resupplied. At 07:00 CEST, 99.95 % of consumption was covered [13].

2.3 Redes Energéticas Nacionais (REN)

Shortly after the incident occurred, the Portuguese TSO confirmed the "corte maciço," the complete collapse of the Iberian Peninsula's electricity supply from 12:33 CEST. At the same time, REN announced the activation of all grid restoration plans in cooperation with power plant operators and European stakeholders and started investigating the causes [14].

The communicated grid restoration measures included the black start of the 990 MW "Tapada do Outeiro" gas-fired power plant to restore supply in northern Portugal. Additionally, REN utilized the 159 MW "Castelo de Bode" hydropower plant and Spanish-Portuguese interconnectors to restore supply in the south [4, 5, 15].

Over the course of the day, REN also announced initial findings on the technical cause of the fault. A "significant oscillation" in the Spanish grid triggered the protection systems of Portuguese power plants. This led to their disconnection and ultimately to a complete blackout [4]. Furthermore, REN clarified that it was not involved in speculation that the blackout had been triggered by an atmospheric phenomenon [8].

2.4 Réseau de Transport d'Electricité (RTE)

The French transmission system operator RTE supported the Spanish grid by providing up to 2 GW via the cross-border interconnectors. After the Iberian grid disconnected from the continental European grid at 12:38 CEST, the 400 kV connection between France and Catalonia was put back into operation at 13:30 CEST. These interconnectors supported the gradual restoration of power to the Iberian Peninsula. Supply interruptions in parts of southwestern France and the Basque Country were limited to a few minutes [3].

3 Data Basis

In chapters 4-6, publicly available data from the ENTSO-E Transparency Platform was utilized [16]. These data are shown in Figures 1, 2, and 6-9, which comprise values reported by transmission system operators at 1-hour intervals. Additionally, transits to Morocco are not included in [16], as Morocco is not an ENTSO-E member and therefore not required to provide data in accordance with EU Regulation No. 543/2013. Consequently, this data may deviate from actual performance data, particularly during disruptions. Nevertheless, it provides valuable insights, particularly regarding grid restoration.

High-resolution measurement data are currently not available. Therefore, all subsequent illustrations should be regarded as a preliminary snapshot.

4 Pre-Incident Situation: Generation Portfolio and Cross-Border Power Flow

Spain's installed generation capacities reflect the ongoing transition toward increased reliance on renewable energy sources. In addition to conventional power plants such as gas, coal, and nuclear energy, wind and photovoltaic systems play an increasingly prominent role. As shown in Figure 1, by 2025, 65.9% of installed generation capacity is already attributed to solar, onshore wind, and hydropower.

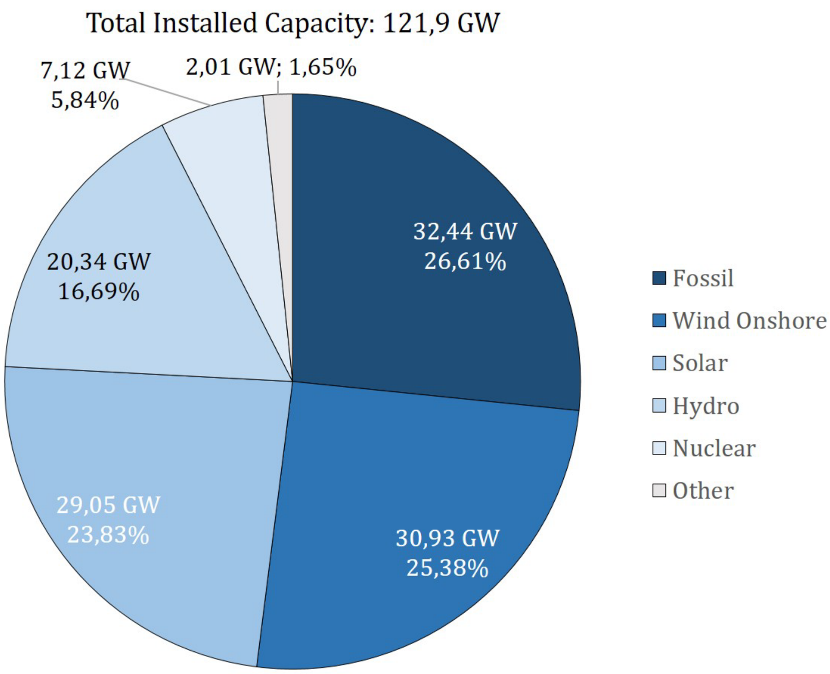


Figure 1: Installed generation capacity in Spain (April 2025)

Prior to the disturbance, electricity generation in Spain was predominantly based on renewable energy sources. According to REE, at the time of the event, 59.8% of the load was covered by photovoltaic generation, 10.6% by wind power, and 10.5% by nuclear power [17]. Four out of seven nuclear power plants were in operation at that time [18]. Figure 2 shows the cross-border physical power flows between Spain (ES) and its neighboring countries France (FR) and Portugal (PT). A significant export can be observed prior to the disturbance, driven by high photovoltaic generation.

The very high share of renewable energy led to low system inertia in the Spanish power system. This is due to the low share of conventional generators with synchronous machines, which provide the rotating mass essential for inertia.

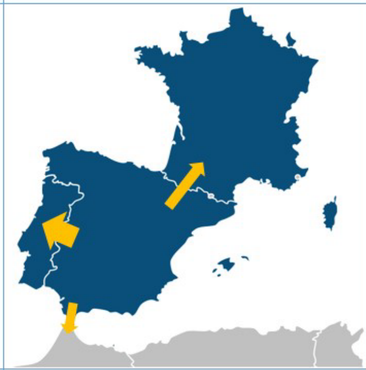
Date	28.04.2025	
Time	11:00 – 12:00 (CEST)	18:00 – 19:00 (CEST)
		
ES-FR	1303,7 MW	
FR-ES		1637,5 MW
ES-PT	2308,1 MW	
PT-ES		0,43 MW
ES-MAR	769,84 MW	
MAR-ES		17,92 MW

Figure 2: Cross-border physical current flows

5 Emergence and Impact of the System Failure

Figure 3 shows the frequency profile in Continental Europe, based on measurements from Spain, Portugal, Latvia, and Germany. The data from Spain, Portugal, and Latvia were kindly provided by GRIDRADAR, while the data for Germany were obtained from the measurement station of the Chair of Electrical Power Systems. Oscillations are already visible prior to the generation loss, initially limited to Spain and Portugal. Between 12:18 and 12:22 CEST, inter-area oscillations - regional power and frequency swings - can be observed. The oscillations in Erlangen and Riga are in opposite phase to those in Porto and Málaga.

However, the frequency drop did not occur until 12:33 CEST and was triggered by a generation loss. According to REE, this was caused by the near-simultaneous failure of two generation units in southwestern Spain, presumably photovoltaic plants, with a time gap of approximately 1.5 seconds [19, 20]. Figure 4 shows the frequency values at the moment of system collapse. Based on the available measurement data, no inter-area oscillations are visible at that time, leaving the exact cause unclear. Reference [21] reports an additional "event" 19 seconds prior to the grid collapse. This is confirmed by Figure 5.

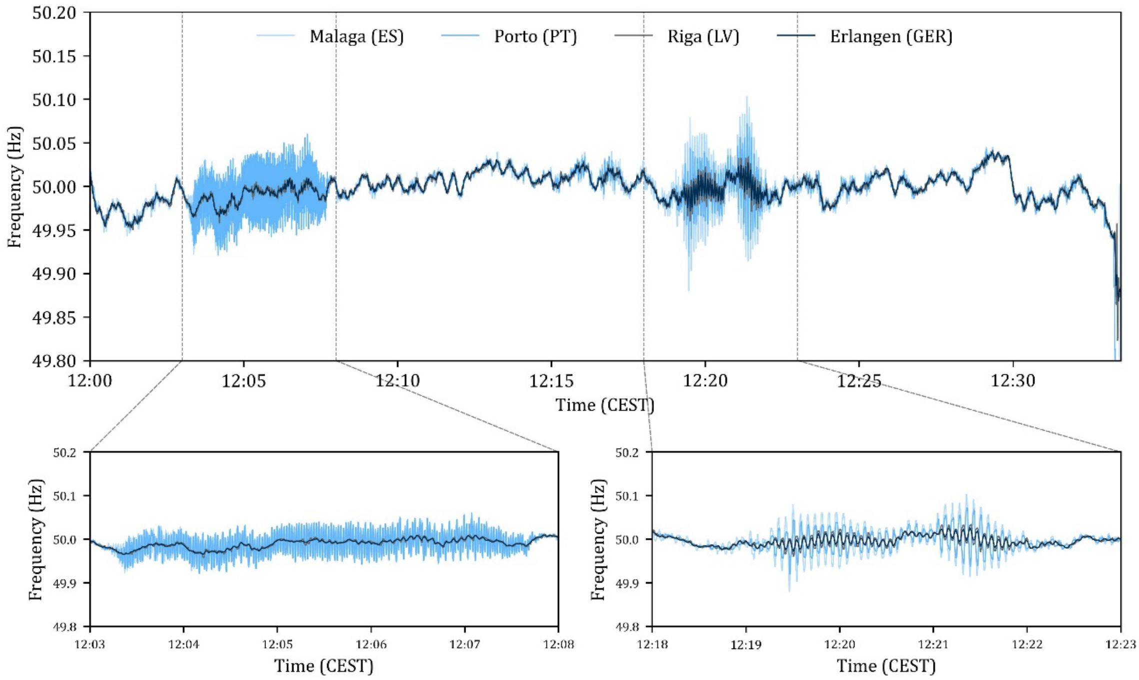


Figure 3: Oscillations in grid frequency prior to the disturbance

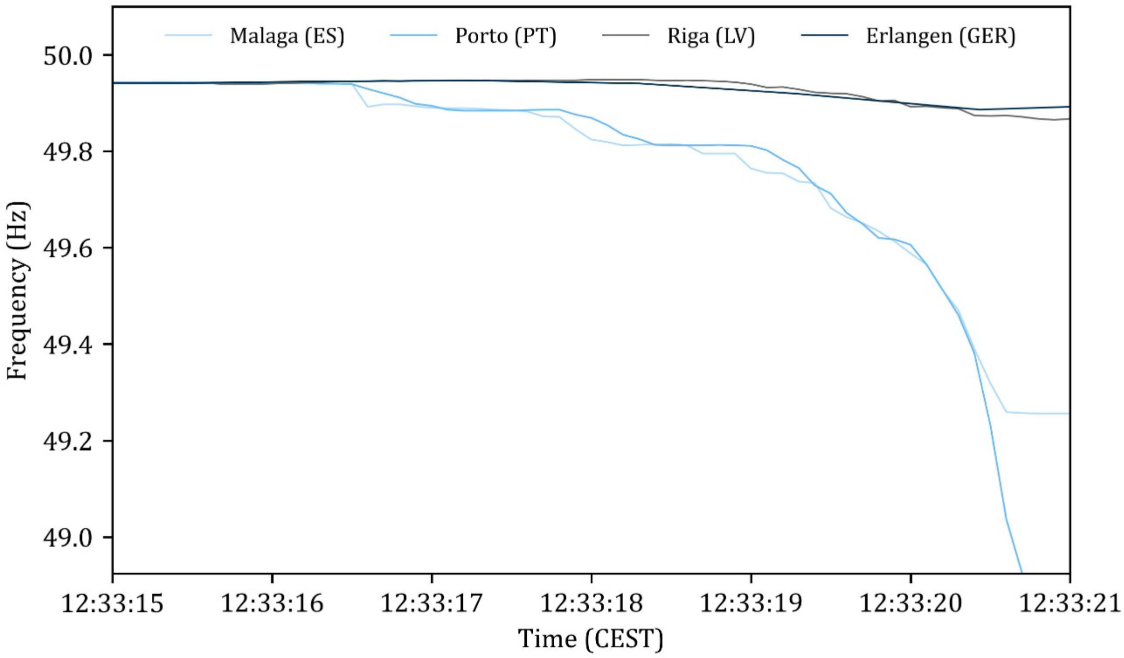


Figure 4: Frequency measurements during the disturbance

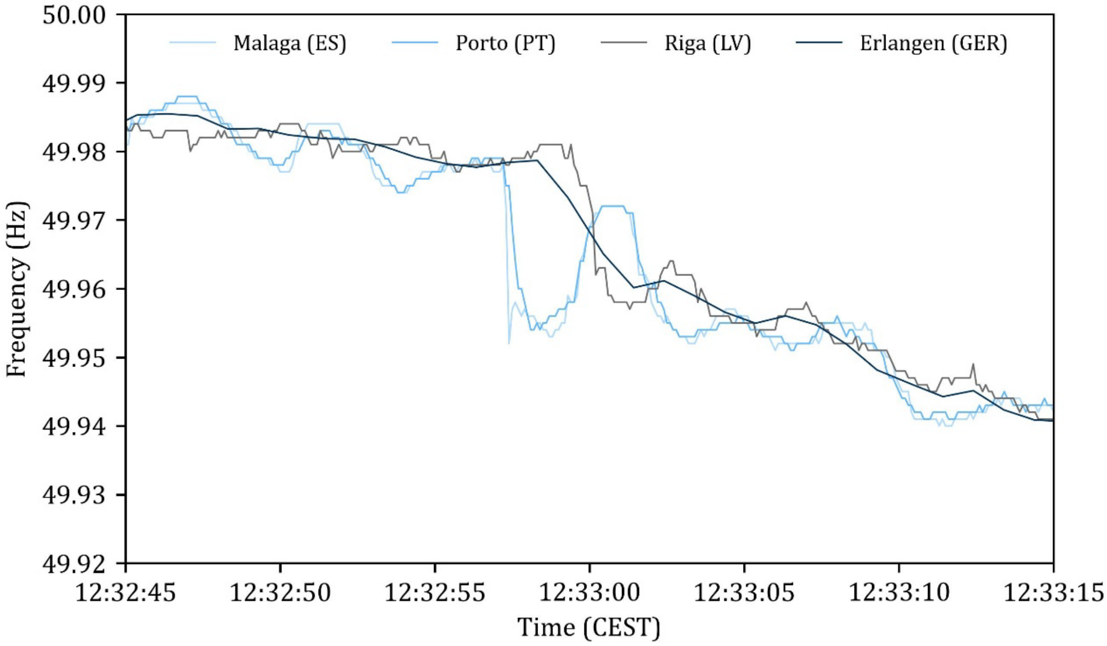


Figure 5: Frequency measurements 30 seconds before the disturbance

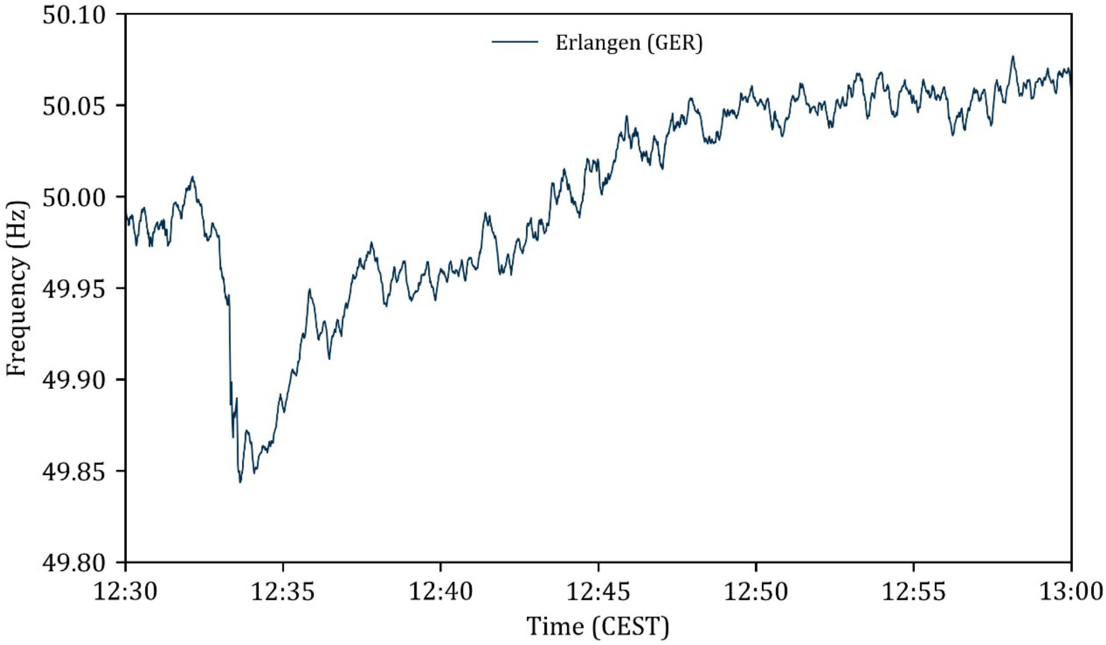


Figure 6: Frequency measurements in Germany after the disturbance

According to REE and REN, all cross-border power flows were suspended as a result of the grid separation. The interconnections with France (several 400 kV three-phase AC lines, including two eastern corridors near Catalonia, western links via the Basque grid, and the HVDC link Baixas - Santa Llogaia) and the AC interconnection Ceuta–Algeciras between Spain and Morocco were immediately disconnected. The remainder of the Continental European grid remained largely unaffected by the disturbance.

Generation units in France were also impacted. At 12:33 CEST, the Montézic pumped-storage units 2 and 3, with a combined capacity of 454 MW, disconnected [22, 23]. Following the collapse of the Iberian grid, at 12:40 CEST, Unit 1 of the Golfech nuclear power plant, with a capacity of 1,310 MW, also disconnected unexpectedly from the grid [24]. Outage notifications from the operator Électricité de France (EDF) were logged to the minute, making it unclear whether the Montézic units contributed to the Iberian blackout or, like Golfech 1, were a consequence of it. On May 9th, 2025, ENTSO-E published a similar timeline of events accompanied by the appointment of an expert panel [25].

Figure 6 presents the forecasted (day-ahead, intraday, current) and measured (actual) PV generation values, summarized as follows [16]:

- *Day-Ahead Forecast*: Generation forecast for the following day, published at 18:00 CEST on the previous day and not updated retrospectively.
- *Intraday Forecast*: The forecast is published at 8:00 CEST on the delivery day and is not subsequently updated.
- *Current Forecast:* Represents the current available forecast and is updated regularly.

- *Actual Values:* Actual measured feed-in of wind and solar power, which is published after the delivery period.

Before the incident, measured PV generation closely matched the forecasts. Shortly after the disturbance, however, a 15 GW drop in PV generation was recorded. Even on the day after the blackout, April 29th, 2025, at 12:00 CEST, only about 50% of the forecasted day-ahead PV capacity was being delivered.

Figure 8 shows a total generation deficit of approximately 15 GW. Despite the blackout, a load of around 10 GW was reported in the Spanish grid area, for which a conclusive explanation has not yet been established. According to Figure 8, full restoration of supply to end consumers took approximately 18 hours. The statements made by REE [13] are consistent with the collected data.

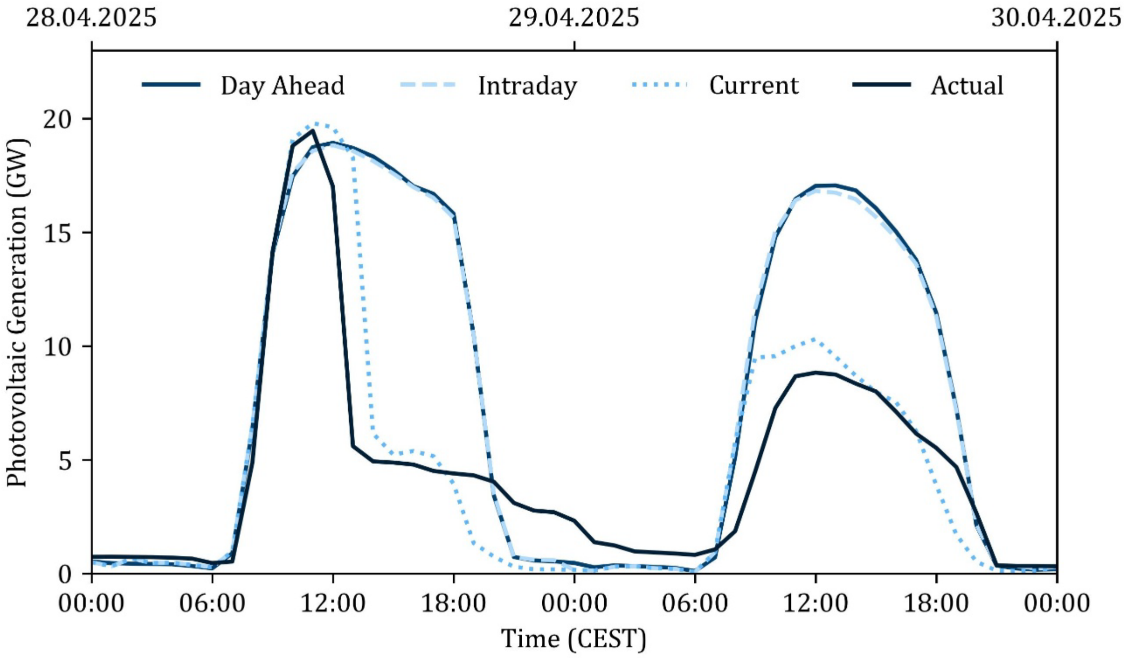


Figure 7: Forecast and actual generation of photovoltaic generation in Spain

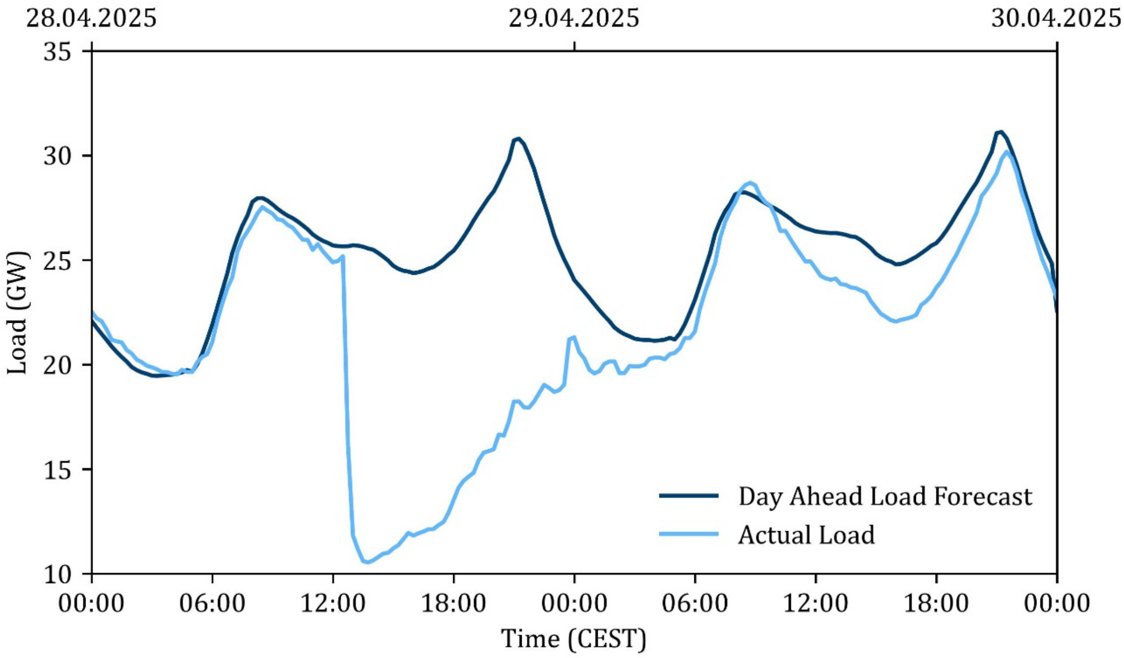


Figure 8: Load forecast and actual load in Spain

6 Grid and Supply Restoration

Black-start procedures were initiated to restore the grid and power supply. These primarily involved the activation of black-start capable power plants, support from neighboring transmission networks, and emergency power supply for critical infrastructure, coordinated by REE and REN. Initially, gas and hydro power plants were restarted, and external assistance was requested.

Figure 9 shows that nuclear power plants did not participate in the grid restoration. All four Spanish nuclear units that were online at the time of the disturbance—providing a combined output of nearly 3.4 GW—were safely shut down. The operation of their cooling systems was ensured by emergency generators [2].

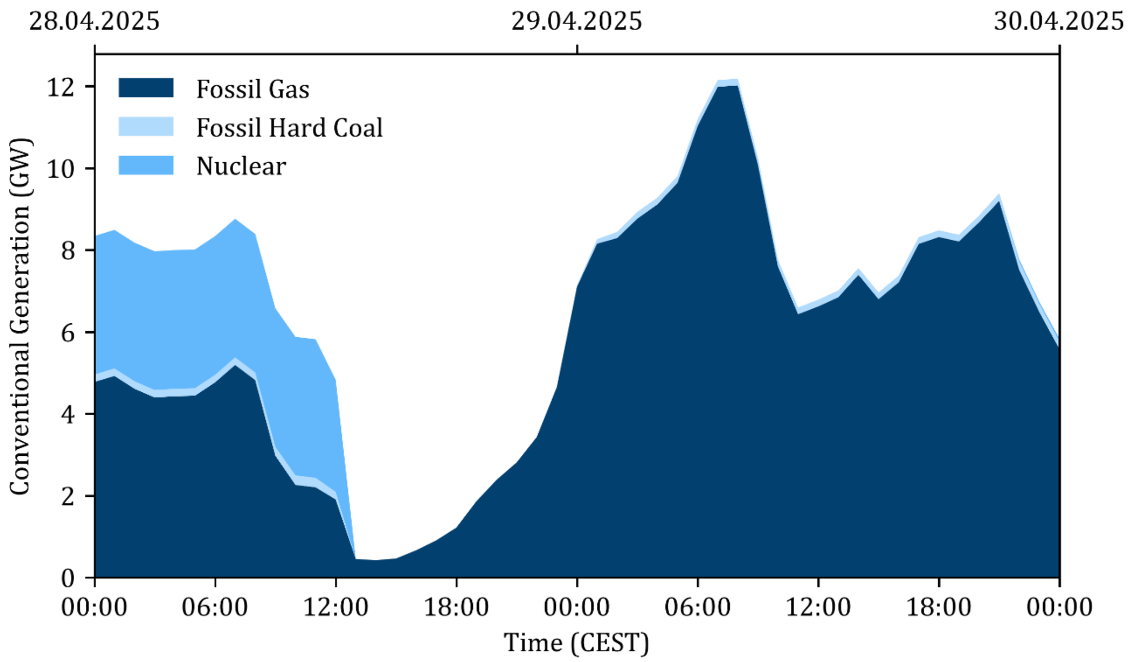


Figure 9: Fossil and nuclear generation in Spain

Since nuclear power plants could not be used for grid restoration, gas-fired power generation was increased from around 5 GW before the disturbance to approximately 12 GW. Gas power plants thus served as the primary fossil-based generation source actively contributing to the restoration process.

Hydropower also played a key role in the grid restoration. The generation profile of Spanish hydropower plants in Figure 10 shows that specifically pumped-storage and reservoir-type plants were utilized for grid restoration. In contrast, generation from run-of-river plants remained largely constant due to technological constraints.

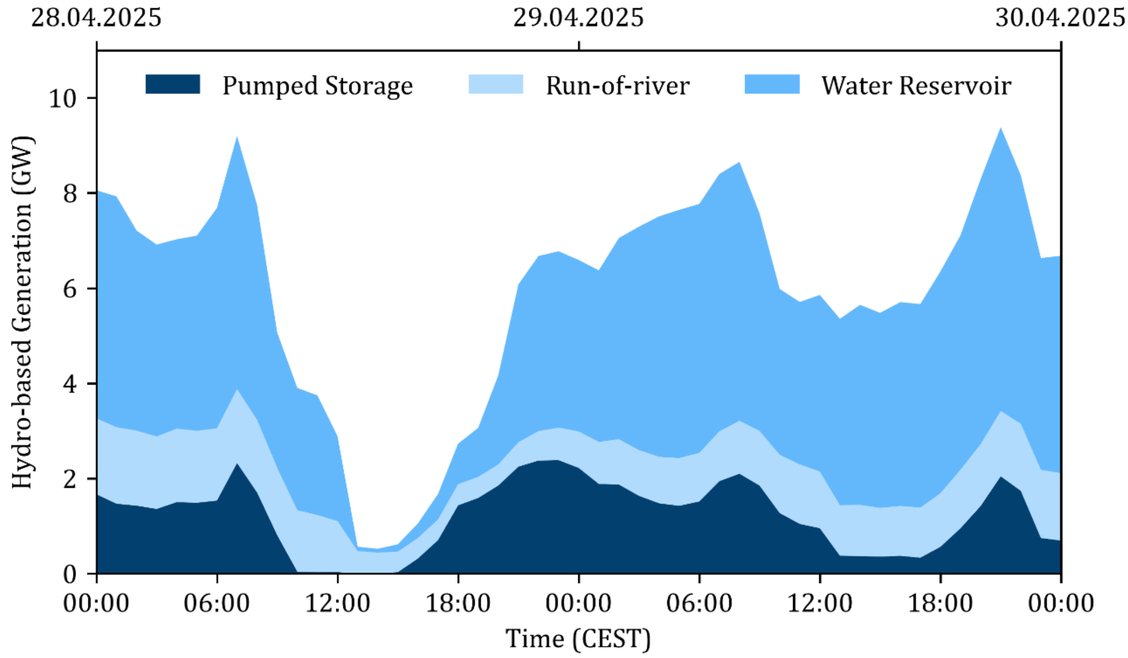


Figure 10: Hydro-based generation in Spain

In addition to gas and hydropower plants, the restoration of the Spanish grid also benefited from significant external support. Morocco supplied 900 MW via the 400 kV AC interconnection Tarifa - Fardioua, and France supported the restoration of power supply in Spain through interconnectors. Starting at 13:30 CEST, interconnections were gradually re-energized, initially between France and Catalonia. Within minutes, RTE was able to supply 700 MW via the interconnectors, increasing the transmission to up to 2 GW [3, 26]. The exact times of individual interconnector reactivations have not been published yet.

By around 23:00 CEST, approximately 51% of Spain's demand (12.8 GW) was covered, and 70% of the transmission substations were energized. At 07:00 on April 29th, REE reported that 99.95% of the supply (25,794 MW) had been restored and all 680 transmission substations were back in service [2].

REN had previously reported that the Portuguese grid had been "fully stabilized" by 23:30 local time (00:30 CEST) [27]. In Portugal, the restoration was carried out exclusively using gas and hydropower plants. A key element was the successful black start of the Tapada do Outeiro gas power plant (990 MW), which was used to restore supply to northern Portugal. The Tapada do Outeiro plant operates without commercial market participation and serves solely as a reserve facility. For supplying southern Portugal, the Castelo de Bode hydropower plant (159 MW, a reservoir plant with flow operation), along with an interconnector to Spain, played a critical role [4, 5].

7 Conclusion and Lessons Learned

This report provides an overview of the currently known facts regarding the major disturbance in the Continental European transmission system on April 28th, 2025, and the subsequent grid restoration. A detailed root cause analysis and technical investigation is the responsibility of the affected transmission system operators and ENTSO-E.

Although the exact causes and sequence of events have not yet been fully clarified, preliminary investigations suggest a chain of unplanned events. The resulting system behavior reveals an overlap of various stability phenomena, which ultimately led to the separation of the Iberian Peninsula's transmission network from the rest of the European synchronous grid. Based on these findings, a number of recommendations can be derived to safeguard future security of supply in Europe.

The integration of renewable energy sources at all voltage levels is increasingly replacing conventional thermal power plants. This results in a growing demand for system services, which were previously provided primarily by synchronous generators in conventional power plants. Additionally, the ability to control renewable energy systems in transmission and distribution networks must be significantly improved.

The events clearly underline the importance of system stability in power systems that are increasingly based on photovoltaic and wind power. The following aspects - addressing interoperability and system-wide coordination - must be considered both individually and in combination, and implemented with significantly greater urgency than before:

Expansion of Transmission Infrastructure
Grid expansion - particularly targeted reinforcement of interconnectors, both AC and HVDC - contributes significantly to system stability. Additionally, the development of an HVDC overlay grid in Europe can provide system services such as controlled power flow and support in critical grid situations.

Increasing Inertia through Rotating Masses and Grid-Forming Inverters
PV and wind power plants are grid-connected via inverters. The replacement of synchronous generators with inverter-dominated generation initially reduces system inertia. Lower inertia increases the rate of change of frequency (RoCoF) during sudden imbalances between generation and load, making countermeasures such as primary frequency control and load shedding more difficult.

Grid-forming inverters in combination with storage systems can provide synthetic inertia and thus significantly enhance system stability. Additionally, synchronous condensers can supply physical inertia and contribute to voltage stability through reactive power control.

System Damping

Oscillations in grid frequency were repeatedly observed before the network separation. Further investigations are required to assess whether associated power oscillations contributed to the disturbance.

Conventional power plants typically use Power System Stabilizers (PSS) to dampen local and inter-area oscillations. These devices are integrated into voltage regulators and can be tuned and placed to optimize damping. Oscillations in the 0.1–1 Hz range typically require specific extensions to turbine governors.

However, because power plant dispatch is based on the merit-order market logic, these damping capabilities are not always available or may be limited. To define future requirements for adaptive damping systems, comprehensive system studies at the European level are necessary.

Inverter-based generation systems can also contribute to oscillation damping through appropriate control functions. These capabilities require system modifications and are associated with higher investment costs. Unlike wind turbines, PV systems cannot provide active power during faults due to the lack of a rotating mass. Therefore, large PV plants should be expanded with storage systems to form hybrid plants capable of providing active power for damping.

Extended Control Capabilities of HVDC and FACTS Systems

HVDC systems based on self-commutated inverters must be equipped with advanced, vendor-independent control strategies. These include Power Oscillation Damping (POD), frequency support, and grid-forming control modes. Flexible AC Transmission Systems (FACTS) devices such as Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM) can provide fast voltage regulation and damping of oscillations. As eSTATCOMs, they can also supply synthetic inertia.

Dynamic Security Assessment (DSA)

The increasing share of renewables, greater asset utilization, and the shift toward curative system operation necessitate dynamic security assessments. To date, most European TSOs rely primarily on steady-state security assessments based on load-flow calculations. DSA tools are rarely used in operational practice. Improved coordination between steady-state and dynamic grid modeling and analysis is essential going forward.

Inclusion of Protection Concepts in Dynamic Studies

Protection schemes must be considered for all system modifications, both at the relay and system level. In particular, for stability studies, protection modeling is recommended to prevent unintended trips, lack of selectivity, or cascading failures. The dynamic feed-in behavior of inverters - largely determined by their control systems - must be accounted for to ensure reliable and selective protection operation. Protection Security Assessment (PSA) tools can support this evaluation.

Development of Modal Analysis Tools for Large-Scale Networks

For assessing the oscillatory behavior of the Continental European transmission grid - particularly in inverter-dominated systems - comprehensive modal analysis tools must be developed. These tools allow for targeted identification of critical modes and corresponding damping strategies. Modal analysis thus provides system-specific insights into the placement and tuning of effective mitigation measures such as PSS or POD to dampen inter-area oscillations.

The sequence of events before and during the major disturbance illustrates the complexity of modern power systems and highlights the critical role of system stability for Europe’s security of supply. Achieving ambitious climate targets and transitioning to a renewable-based power system will require extensive research and action - more urgently than ever - to be harmonized and implemented at the European level.

Acknowledgment

The authors of the report would like to extend their gratitude to Professor Dr. Tobias Veith of GRIDRADAR for promptly providing the measured frequency curves. Additionally, they would like to express their appreciation to Professor Dr.-Ing. Johann Jäger and Dr.-Ing. Dieter Braisch for their expert guidance and advice.

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