Analysis of events leading to the peninsular blackout of April 28, 2025

Compass Lexecon and INESC TEC

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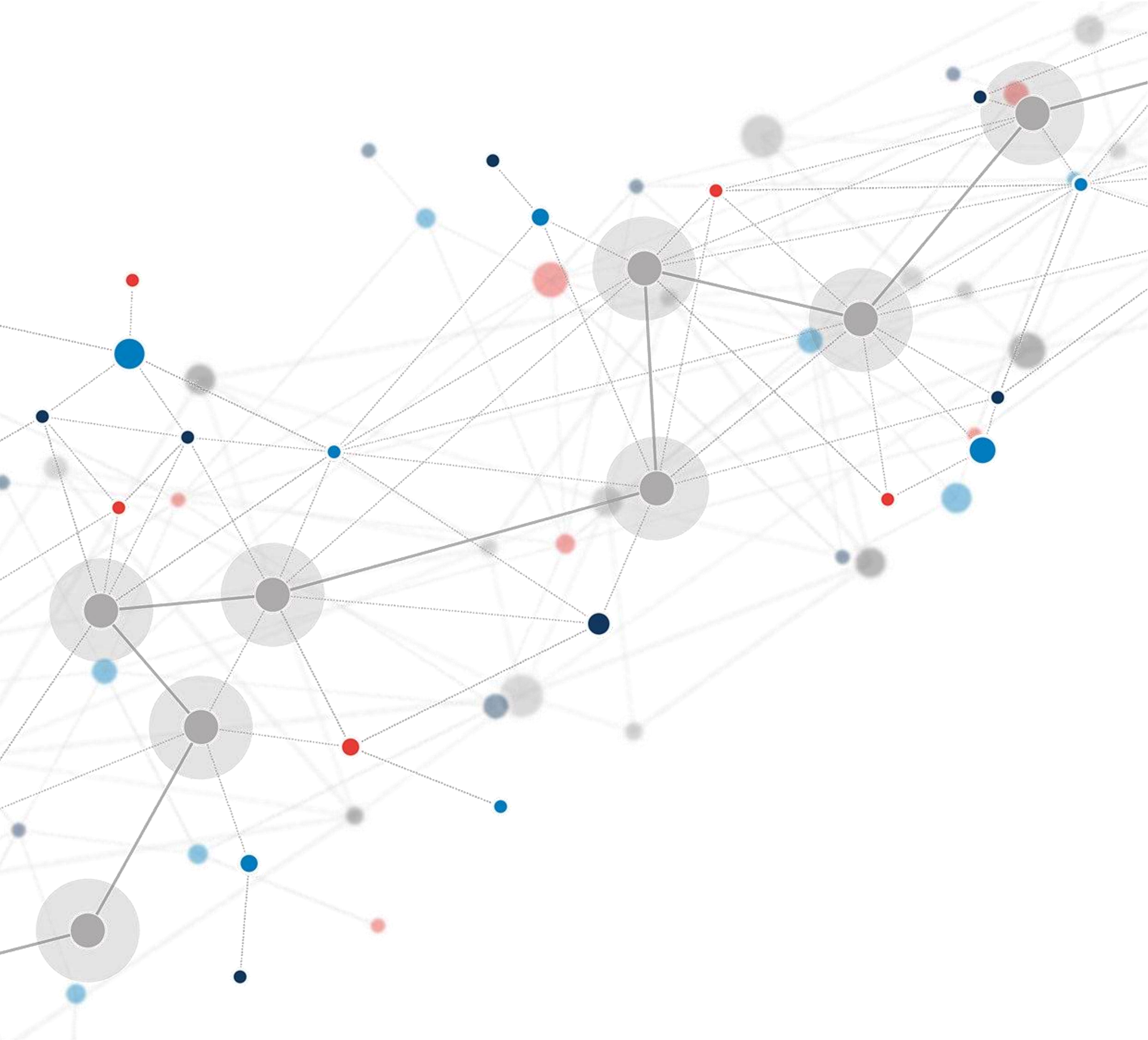

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1 Introduction and main conclusions

1.1 Instruction

1 We have been instructed by Asociación de Empresas de Energía Eléctrica (AELEC), to conduct an analysis of the events leading to the blackout suffered by the Iberian Peninsula's electricity system on April 28, 2025, as well as an evaluation of the factors that may have contributed to the incident. This document presents our findings.

2 The following sources of information were used for this analysis:

a. Information provided by EDP, Endesa and Iberdrola (jointly “AELEC Members”) in their capacity as distributors and generators of electricity. This included: voltage and frequency data from a sample of their substations and generation plants on April 28, as well as for selected days before and after the blackout; records of “High Voltage” warnings received at their control centres; PSS/e simulation outputs; and transcripts of conversations between their control centres and REE’s control centres on April 28 and in the days leading up to the blackout.

b. Simulation results from INESC TEC's proprietary models.

c. Information disclosed by Red Eléctrica de España (REE) and by the "Analysis Committee" established by the Spanish Government,[1] primarily through their respective reports on the events leading up to the blackout (hereinafter referred to as the “REE Blackout Report” and the “Analysis Committee Report”).

3 For a more comprehensive analysis, additional information is required, as the data currently available presents several limitations:

a. It only includes data from EDP’s, Endesa's and Iberdrola's generation plants, which account for approximately 45% of installed capacity in Spain.

b. It only includes data from the distribution networks of EDP, Endesa and Iberdrola, which account for approximately 78% of the distribution networks in Spain.[2]

c. We do not have data that is essential to clarify with more precision the causes of the blackout, such as the individual production of the generation plants, as well as their participation in the different markets and adjustment services, the real-time system conditions or the precise sequence of operational decisions made in the hours leading up to the event. All these data are measured, collected and managed by REE, in its capacity as the Spanish System Operator (SO).

1.2 Main conclusions

4 With the available information, the following preliminary conclusions can be drawn.

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[1] Committee for the Analysis of Circumstances that Concurred in the Electricity Crisis of 28 April 2025.

[2] Estimated based on the regulated remuneration perceived.

In recent years, there have been increasing voltage fluctuations and overvoltage events in the Spanish transmission grid

5 Episodes of voltage fluctuations and overvoltages are increasingly frequent in the Spanish transmission grid. In 2023, REE identified several factors contributing to the increase of frequency of these events, namely: low electricity demand, increase in the installed capacity of renewable generation, decrease in the energy mix of synchronous generation, and high variability in exchanges between Spain and Portugal.

6 The increase in voltage fluctuations and overvoltage events are likely mainly driven by the growing weight of non-synchronous renewable generation without dynamic voltage regulation capacity, due to an obsolete voltage control regulatory framework in Spain. In contrast, in Portugal and France, non-synchronous renewable generation, such as wind and solar PV, participate dynamically in voltage control.

7 In Spain, the regulatory framework governing voltage control in the electricity transmission grid provides a very limited role in voltage control to non-synchronous generators, such as photovoltaic and wind power plants.[3] Under such regulatory regime, these installations operate under a fixed power factor, which means that they absorb reactive power in a fixed proportion with respect to their active production, with no capacity for dynamic adaptation. As a result, only “synchronous” or “conventional” generation (CCGTs, nuclear and hydro plants) can effectively contribute to voltage control in Spain, while wind and solar do not.[4]

8 As of 2022, the SO (REE) informed the regulator (CNMC) that the reliability of the electric system “could not be guaranteed” with the existing regulatory framework on voltage control.

The Spanish System Operator is the entity responsible to maintain voltage control in the transmission grid, and it can employ different tools to do so

9 REE, in its capacity as Spanish System Operator (SO), is the entity responsible to maintain voltage levels in the transmission grid within the ranges stablished by the Operating Procedures. In order to do so, the SO has several tools that it can use. In particular:

- The System Operator (SO) can redispatch generation units through the Technical Restrictions Procedure to address system security and reliability constraints, including those related to voltage control. From the day before up to a few hours prior to delivery, the SO can adjust the dispatch of conventional thermal generation units. In the minutes leading up to delivery, it can also modify the dispatch of hydroelectric power plants, which typically require only a few minutes’ notice to start up.
- It can increase or reduce voltage levels, by opening or closing transmission lines.
- It can use specific elements for voltage control in the transmission network, such as shunt reactors (from now own “reactors”), transformer voltage regulators and STATCOMs.[5]

10 As of January 2024, the System Operator stated that the use of elements in the transmission network for real-time voltage control, such as the use or reactors or uncoupling transmission lines

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[3] Operation Procedure 7.4. - Complementary voltage control services and Royal Decree 413/2014, of June 6, regulating the production of electricity from renewable energy sources, cogeneration, and waste.

[4] Concentrated solar power (CSP), Combined Heat and Power (CHP), and residues power plants are synchronous generators. However, due to current regulations, in terms of voltage control they behave similarly to wind and PV generation, operating with a fixed power factor.

[5] STATCOM stands for STATic synchronous COMpensator. These power electronics-based devices enable real-time voltage regulation.

to control tension had reached their limits, particularly in scenarios where the generation mix included a high share of solar PV and wind technologies. These limitations in real-time voltage control, highlight the critical importance of the SO ensuring that sufficient conventional generation, with effective voltage control capabilities, is coupled.

11 As voltage control is a local phenomenon, the SO must have sufficient resources for voltage regulation distributed across the territory. Ensuring localized voltage control capabilities is therefore essential to maintain system stability under all operating conditions.

In the days prior to the blackout, the system operated under severe voltage fluctuations and overvoltage scenarios

12 The scenario of strong voltage fluctuations and overvoltages that materialized on April 28 was not new. In the days prior to the blackout, particularly on April 16, 22 and 24, the system also experienced severe voltage fluctuations and overvoltage events. Although these fluctuations were more pronounced in certain geographical areas, they affected a substantial part of the Spanish electricity system.

13 According to REE, voltage fluctuations during those previous days were mainly due to: i) abrupt changes in interconnection schedules; ii) steep solar generation gradients; iii) low levels of coupled synchronous generation; or iv) unavailability in the transmission grid and in the interconnection with France.

14 Specifically, on April 22, the overvoltage caused the disconnection of 19 demand and generation sites. These disconnections are the result of the operation of the protections located in the generating plants and customer substations against extreme voltages. These protections are an important element of power system security. Without these protections extreme voltage episodes can damage generation plants and customer substation equipment.

15 With the information provided by AELEC Members, it is not possible to determine the total volume of disconnected generation on April 22. However, it has been possible to identify the disconnection due to overvoltages of two photovoltaic plants in Cáceres and one photovoltaic plant in Cuenca, with a total installed capacity of 739 MW. It is worth noting that these same plants also tripped due to overvoltage protections on April 28, when the initial generation trips occurred (also due to overvoltages). This suggests that these areas experienced inadequate voltage control on April 22, which remained unaddressed by April 28.

The final generation schedule on April 28 exhibited similar features to those that led to voltage fluctuations in the days preceding the blackout and the conventional generation capacity online was at a historical minimum

16 The resulting final generation schedule on the morning of April 28, shaped by the standard sequence of market clearing and subsequent technical adjustments by the SO, shares very similar features to those that led to voltage fluctuations in the days preceding the blackout (i.e., April 16, 22, and 24), that is: steep variations in the renewable generation and interconnection flows; and low levels of conventional generation.

17 On April 28, the day-ahead market cleared without any CCGTs, while the nuclear fleet included 1.7 GW, consisting of one unit at full load and another at partial load. As a result of subsequent adjustments by the SO, aimed at guaranteeing the security and reliability of the electricity system, 3 GW of CCGTs -comprising 19 to 21 units, depending on the hour- were coupled overnight, and nuclear output was increased to 3 GW.

18 However, between 8:00 CET and 10:00 CET, the SO allowed 15 CCGTs to come offline. While we cannot determine the precise reasons that led the SO to adopt this decision, the resulting decrease in conventional generation reduced the voltage control capacity of the Spanish system.

19 At the time of the blackout, only 11 conventional generation units were coupled: 6 CCGTs, 4 nuclear reactors, and 1 coal plant. This represents the lowest number of such units operating in 2025.

20 In addition, the low share of conventional generation with capacity to provide dynamic voltage control was unevenly distributed throughout the different regions of the electricity system, resulting in particularly low shares of conventional generation in the southern region of the electricity system, where overvoltage problems materialized in April 22, and then again in April 28.

21 This limited availability of conventional generation in the South was further compounded by operational decisions taken by REE in the hours before the blackout. REE opted not to replace a CCGT unit in Western Andalusia that had been scheduled for voltage control but was declared unavailable on April 27 at 20:00 CET—despite having seven other capable units in the area.

22 In the final minutes before the blackout, REE attempted to increase the CCGT capacity coupled in the South through the real-time Technical Restrictions Procedure. However, the blackout occurred before the unit that was called on could synchronize. However, hydroelectric plants in Extremadura—available and with faster start-up capabilities—were not requested by REE to come online. The choice to prioritize slower CCGT units over readily available hydro resources has not been explained.

In the hours prior to the blackout on April 28, the system suffered from strong voltage fluctuations

23 From approximately 10:00 CET on April 28, following the removal of 15 CCGT units, strong voltage fluctuations were recorded, both at 400 kV and 220 kV. These fluctuations were not concentrated in a specific area of the electrical system but occurred in a generalized manner. Their magnitude increased over time, repeatedly exceeding the normal operating limits at many boundary nodes of the transmission grid.

24 Although we do not have information on all the actions taken by the SO to stabilize the voltage on the morning of April 28, conversations between the control centers of the distributors and the SO control center reveal that the SO was unable to control the voltage through the use of reactors. The activation and deactivation of these caused strong voltage fluctuations, which further complicated the stabilization of the system. The SO's voltage control difficulties became particularly evident from 12:18 CET, when REE requests the coupling of combined cycles, especially in the South. Finally the coupling of a combined cycle was scheduled for 14:00 CET, which for obvious reasons never arrived on time, since the blackout occurred at 12:33 CET.

Load-shedding was not able to prevent the downward trajectory of frequency and likely exacerbated the voltage control problem

25 At about 12:33:19 CET, following cascading disconnections, the 49.8 Hz frequency threshold was crossed, which activated the first step of pumped storage shedding to contain the reduction of system frequency.

26 Between 12:33:19 CET and 12:33:22 CET, load shedding triggered by under-frequency load shedding relays, took place in both Spain and Portugal, disconnecting more than 5 GW of pumped-

storage and at least another 5 GW of other loads.[6] However, this load shedding was insufficient to stop the downward trajectory of the frequency.

The connection of transmission lines made by REE minutes before the blackout exacerbated the voltage problem

27 From 12:00 CET onwards, REE connected 11 transmission lines, which had been disconnected for days.[7] We understand the reason for this decision was to dampen frequency oscillations. However, the increase of transmission lines in use increased the generation of reactive power, and therefore voltage on the grid. This pushed voltage in already stressed areas higher, further reducing voltage control capability of the system just prior to the blackout.

It is necessary to increase the transparency regarding the technical configuration of HVDC interconnection to assess the impact of the HVDC's mode of operation on the blackout

28 Minutes before the blackout took place, REE changed the mode of operation of the HVDC link with France, from AC line emulation to constant DC power control.[8] This decision is technically justified as a corrective measure to damp low frequency oscillations that were detected after 12:03 CET.

29 The impact of this operational change on the system's responsiveness to unexpected generation losses depends largely on the technical control parameters adopted in the HVDC. However, there is currently no official public information confirming the configuration currently in place.

30 Due to this lack of information, the impact of the HVDC's mode of operation on the blackout cannot be properly assessed.

The capacity margin for control voltage was limited, particularly in southern Spain, and was exhausted by REE's manoeuvres

31 Voltage control in the transmission system depends on the ability to either absorb excess reactive power or generate reactive power. When the system's capacity to absorb reactive power is insufficient, it becomes increasingly vulnerable to overvoltage conditions.

32 On the morning of April 28, the system's capacity to control voltage dynamically was significantly below the annual average, primarily due to insufficient coupled thermal generation. At 12:00 CET, the margin to absorb reactive power dynamically stood at just 3.3 GVAr, nearly half the average margin observed during the first half of the year (5.8 GVAr).

33 In addition, the manoeuvres implemented by REE to dampen oscillations, including the reconnection of transmission lines and the disconnection of reactors, as described by the Analysis Committee, increased reactive power generation by approximately 2.4 GVAr. This additional reactive power effectively exhausted the system's already limited absorption margin.

34 This issue was particularly acute in the southern part of Spain, where the first generation trips were recorded. The capacity to dynamically control reactive power in this region was limited to a single CCGT group, with a reactive absorption capacity of 117 MVAr. REE's maneuvers (reconnecting

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[6] 2,040 MW of pumping in Portugal and 3 GW of pumping in Spain. Based on AELEC Members' information, there were at least, approximately, 2,3 GW of additional load shedding in the Portuguese distribution network and 3,2 GW in Spain.

[7] Between 9:00 CET and 12:00 CET, REE also reconnected 19 transmission lines, some of them located in the southern region.

[8] As ENTSO-E mentioned in its June 6 communication. Available at https://www.entsoe.eu/publications/blackout/9-may-2025-iberian-blackout/

lines and operating rectors) created a regional surplus of reactive power generation of approximately 0.6 GVAr, exceeding the dynamic control capacity of the only available CCGT group.

35 Although enough reactors were installed in the region, capable of providing 1.6 GVAr of reactive absorption capacity, not all were connected to the grid. This was likely due to the speed at which voltage fluctuations developed, that probably left insufficient time to mobilize them.

The initial disconnections evidence a systemic voltage control problem

36 According to the Analysis Committee Report, starting at 12:32:57 CET within a period of 20 seconds three main generation losses occurred —in Granada, Badajoz, and Seville—preceding the cascade of disconnections that ultimately led to the blackout.

37 Regarding the causes of these disconnections, AELEC Members do not have data on the first substations that tripped during these main events. However, they have indicated that their plants did not experience incorrect tripping.

38 Nonetheless, according to REE, the capacity lost during these events—approximately 2,000 MW of renewable generation and a substantial amount of distributed generation (under 1 MW)—was largely the result of protection equipment responses to overvoltage conditions.

39 However, this volume of lost generation implies the near-simultaneous disconnection of dozens of substations and renewable plants, covering various technologies, geographic areas, and owners.

40 Given this diversity, it seems unlikely that all these installations would have failed independently due to isolated malfunctions or local settings. This suggests that a broader, systemic issue was the underlying cause -the lack of sufficient voltage control- rather than isolated faults at the plant level.

The operation in subsequent days with more conventional generation units online has reduced voltage fluctuations

41 Following the blackout the SO has increased the amount of conventional generation on the Spanish system in order to increase voltage control. It has done this by adding conventional generation not initially dispatched in the day-ahead market through the technical restrictions market. As a result, the strong voltage fluctuations, that the system experienced on April 28, have disappeared.

Scheduling additional conventional units on April 28 would have prevented the blackout

42 Our analysis concludes that if the SO had scheduled additional conventional generation on April 28, the blackout could have been prevented. However, the information available does not allow for a precise quantification of how much capacity would have been needed, or where specifically it should have been located.

43 Further, the information available does not allow to analyze whether the conventional generation capacity connected to the system on the morning of April 28 — which provided dynamic voltage control — was sufficient to meet the N-1 criterion established in Operating Procedure 1.1 – Operation and Safety Criteria for the Operation of the Electrical System. In particular, this procedure requires that the system must be operated in such a way that, following the failure of any single network element, the system remains within normal voltage limits and continues to operate securely.

44 Any conclusive analysis would require all the data associated to the operation conditions of the system, such as grid topology, grid electrical parameters, active and reactive loads, active power dispatched in the conventional and renewable generation, or grid and generation technical restrictions. Only the SO has full access to this information.

There are a number of issues that remain to be analyzed

45 While this report provides a preliminary assessment of the April 28 blackout, several key questions remain unresolved. Fully addressing them will require access to more detailed data, which is currently only available to the SO.

46 The following issues, in particular, require further investigation and should be examined in greater depth:

a. What actions did REE take following the overvoltage incidents on April 16, 22, and 24 to prevent recurrence on April 28?

b. Did the April 28 generation schedule comply with the N-1 security criterion, particularly in the southern zone?

c. Why was the CCGT unit in Western Andalusia declared unavailable on the 27th not replaced, despite REE having initially scheduled it for voltage control on the 28th?

d. Can the disconnection of over 2,000 MW across diverse installations in just 20 seconds be explained without systemic cause?

e. Why did REE call on slower-starting CCGT units for voltage control in the final minutes before the blackout instead of available hydro plants in Extremadura?

f. Was the system able to absorb the additional reactive power generated by REE's own maneuvers shortly before the blackout?

g. Why is there no transparent information regarding the technical parameters of the HVDC?

h. What voltage and frequency control capabilities are needed in a system with high renewable penetration?

i. How does the shift to quarter-hourly market resolution affect real-time grid stability?

1.3 Structure of report

47 The remainder of this report is structured in the following sections:

a. Section 2. Voltage control in the Spanish electricity system.

b. Section 3. Voltage fluctuations in the days prior to the blackout.

c. Section 4. State of the electrical system prior to the blackout.

d. Section 5. REE's maneuvers to dampen frequency oscillations.

e. Section 6. Sequence of events leading to the blackout.

f. Section 7. Operation of the system in the days after the blackout.

g. Section 8. Preliminary evaluation on how the blackout could have been prevented.

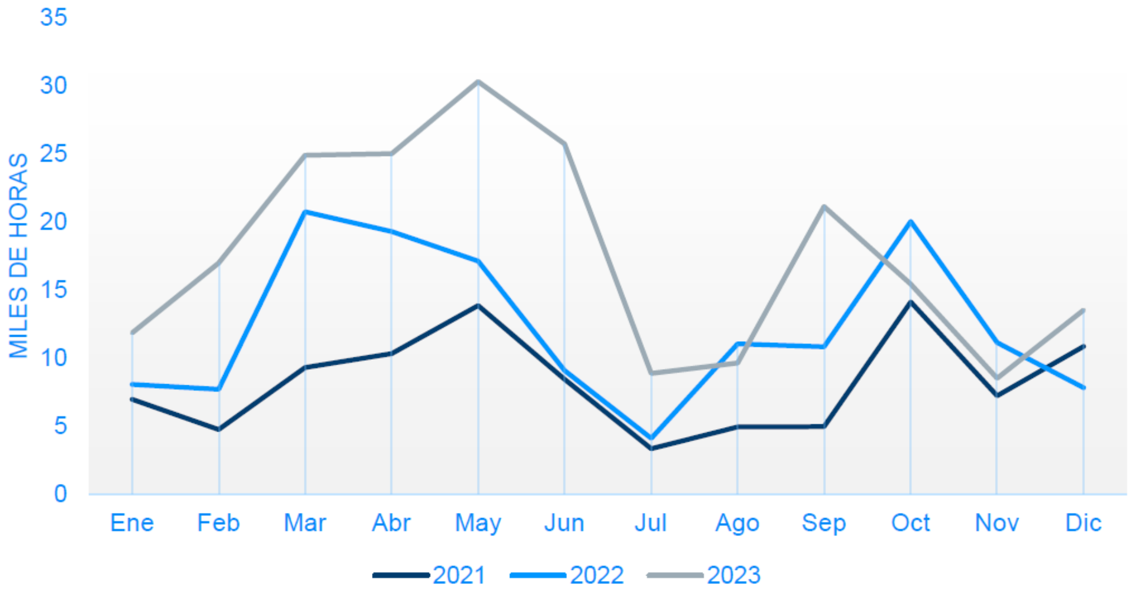
h. Section 9. Issues that remain to be analyzed.

2 Voltage control in the Spanish electricity system

2.1 Increasing voltage fluctuations and overvoltages in the Spanish transmission system

48 In recent years, there has been a sharp increase in the frequency of voltage fluctuations and overvoltages in the Spanish transmission network, as shown in Figure 1.

Figure 1: Number of hours with voltage above 420 kV / 240 kV at transmission network nodes



Source: REE (2024). *Webinar consulta pública control de tensión*. Page 3.

49 As a result of the increase in overvoltages, the number of disconnections triggered by the activation of overvoltage protections at both generation and demand sites has also risen, as illustrated in Figure 2 below. Notably, the majority of these disconnections, approximately 80% are associated with power electronics-based generation, such as wind and solar PV.[9]

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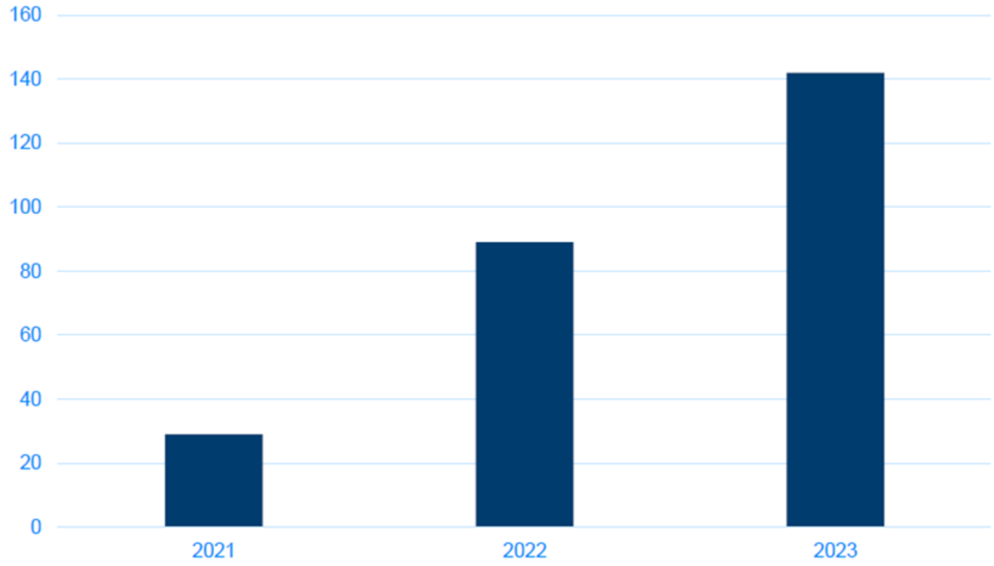
[9] See REE (2024). *Webinar consulta pública control de tensión*. Page 4.

Figure 2: Activation of overvoltage protections on generation and demand sites



Source: REE (2024). *Webinar consulta pública control de tensión*. Page 4.

50 In 2023, REE identified several factors contributing to the increase in the frequency of these events:[10]

a. **Low electricity demand**: In low demand conditions, some lines may operate with a reduced load. This situation causes the lines to increase reactive power injection, which tends to raise the voltage in the grid. In addition, the limited capacity of absorption of reactive power by demand -particularly industrial demand through its inductive loads- increases the likelihood of voltage fluctuations and overvoltages.

b. **Increase in the installed capacity of renewable generation**: Renewable generation such as solar PV, wind and concentrated solar power (CSP), as well as cogeneration and waste to power operate under fixed power factor ranges, which limits their contribution to voltage control. This explains why increases in renewable generation increases the likelihood of voltage fluctuations and overvoltage in the transmission grid. See Figure 3 below.

c. **Decrease in the energy mix of conventional generation**: Conventional units have the capacity to regulate voltage by modifying the reactive power they inject or absorb in response to voltage fluctuations in the grid. Reducing their presence in the generation mix reduces the voltage control capacity. Given that renewable generation has no dynamic participation in voltage control, the increasing presence of renewable generation in the electricity mix, has resulted in a lower capability of the SO to control voltage on the system.

d. **High variability in exchanges with Spain and Portugal**: This variability, derived from market outcomes, introduces fluctuations in the generation and absorption of reactive power, which translates into greater variability in the voltage profile of the transmission grid.

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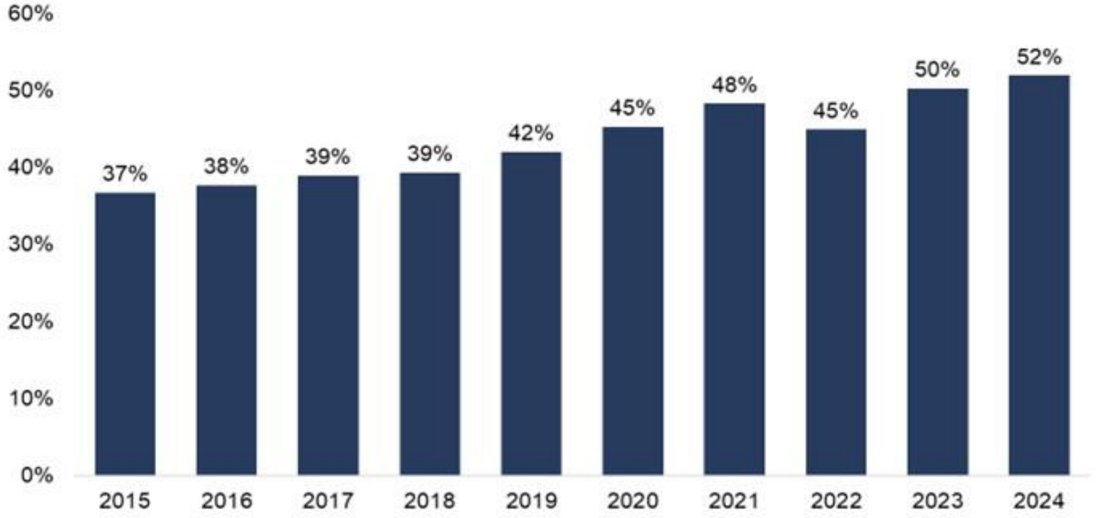
[10] See REE (2023). Technical-Economic Report of the Regulatory Demonstration Project of the new voltage control service. Section 3.

Figure 3: Percentage of non-conventional generation out of total generation



Source: Own analysis based on information from REE.

51 As regards to non-synchronous renewable generation, it should be noted that its lack of voltage control is due to a regulatory issue, and not a technical impossibility.[11] In Spain, voltage control in the transmission grid is governed by Operating Procedure 7.4 – Complementary Voltage Control Service.[12]

52 The Operating Procedure 7.4. was initially designed in the context of an electrical system dominated by conventional synchronous generators, thus giving them a predominant role in voltage control, while non-synchronous generators, such as wind and photovoltaic plants, were effectively excluded from contributing to this function.

53 Royal Decree 413/2014 later introduced some provisions for non-synchronous generators, but these remain limited in scope. Under this regulation, non-synchronous generators operate under a fixed power factor, which means that they absorb reactive power in a fixed proportion with respect to their active production, with no capacity for dynamic adaptation. This condition can only be modified, at most, once a year by instruction from REE. As a result, only conventional generation (CCGTs, nuclear, hydro and coal plants) can effectively contribute to voltage control in Spain, while wind and solar do not.

54 By contrast, in our neighboring countries (Portugal and France) renewables participate in the control of the grid in a dynamic way.

55 It is worth noting that, at least since 2022, both the SO (REE) and the regulator (CNMC) were aware that the reliability of the electric system could not be guaranteed with the existing regulatory framework on tension control. For example, in the report by the CNMC accompanying the September 2022 Resolution on non-frequency services, the CNMC stated:[13]

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[11] In fact, the power electronic converters of most non-synchronous renewable generation can even operate as static compensators helping to manage the voltage profile of the grid.

[12] Royal Decree 413/2014, of June 6, regulating the production of electricity from renewable energy sources, cogeneration, and waste.

[13] CNMC (2022). *Memoria justificativa de la resolución por la que se aprueban las condiciones aplicables a los servicios de no frecuencia y otros servicios para la operación del sistema eléctrico peninsular español*. Page 54. Own translation.

> *"The system operator argues that system security cannot be guaranteed amid the increasing penetration of non-synchronous generation without a voltage control service that ensures the adequate participation of all generation, storage, demand, and self-consumption technologies. This was clearly demonstrated during the incident on July 24, 2021, when, in order to restore voltage, up to 10 reactors had to be manually disconnected within the minute following the loss of the French double circuit. Moreover, power-electronics-based generation not only failed to contribute to voltage control, but 321 installations were disconnected, mostly due to their under/over-voltage protections, resulting in a loss of 2,867 MW of generation capacity, which seriously endangered system security."*

56 Similarly, in its 2023 report on the regulatory pilot project for a new voltage control service, REE stated that:[14]

> *"Currently, RE does not have sufficient tools to prevent voltage levels in the transmission network (RdT) from reaching excessively high values, occasionally exceeding the permissible ranges established by regulations and even causing, at certain moments, the disconnection of generation and consumption facilities due to overvoltage."*

57 Following the April 28 blackout, Operating Procedure 7.4 was updated in June 2025 to address the identified shortcomings in voltage control.[15] The revised procedure enhances the dynamics of voltage regulation and explicitly allows for the participation of electronic converter based generators, such as wind and solar PV. While this marks a regulatory shift, full implementation of the new framework is expected to take between 6 and 18 months.[16]

2.2 The role of the Spanish system operator in voltage control

58 REE, in its capacity as Spanish System Operator, is the entity responsible to maintain voltage control in the transmission grid. In particular, Operating Procedure 1.4 - *Energy delivery conditions at the border points of the grid managed by the system operator* establishes that voltage must remain within the following ranges:

a. Under normal operating conditions, the voltage must be maintained between 205 kV and 245 kV in the 220 kV grid; and between 390 kV and 420 kV in the 400 kV grid.

b. Under N-1 contingency scenarios (i.e. the unexpected loss of a single component such as a transmission line, transformer or generator), the voltage must be maintained between 205 kV and 245 kV in the 220 kV grid; and between 380 kV and 435 kV in the 400 kV grid.

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[14] REE (2023). *Informe técnico-económico del proyecto demostrativo regulatorio del nuevo servicio de control de tensión de septiembre 2023.* Page 3. Own translation.

[15] Resolución de 12 de junio de 2025, de la Comisión Nacional de los Mercados y la Competencia, por la que se modifican los procedimientos de operación para el desarrollo de un servicio de control de tensión en el sistema eléctrico peninsular español.

[16] Resolución de 12 de junio de 2025, de la Comisión Nacional de los Mercados y la Competencia, por la que se modifican los procedimientos de operación para el desarrollo de un servicio de control de tensión en el sistema eléctrico peninsular español. Fundamentos de derecho.

59 The Operating Procedures also establishes that, in addition to maintaining voltage levels within the above ranges, in all cases it must also be guaranteed there are no voltage instability conditions that could lead to a voltage collapse.[17]

60 In order to maintain voltage stability, and voltage levels within the ranges established by the Operational Procedures, the SO has several main tools that it can use. In particular, it can make use of the Technical Restrictions Procedure or operate elements of the transmission network, such as opening or closing lines and connecting or disconnecting reactors.

The Technical Restriction Procedure

61 The Technical Restrictions Procedure enables the System Operator to modify the dispatch—regardless of economic optimality—to address security and reliability constraints in the power system, including voltage control.[18] Specifically:

- From the day before, up to a few hours prior to delivery, the SO can adjust the dispatch of conventional thermal generation units.
- In the minutes leading up to delivery, the SO can also modify the dispatch of hydroelectric power plants, which require only a few minutes notice to start up.

62 Thus, if the technologies that resulted dispatched based on the market outcome do not provide sufficient voltage control (for example because there is a large share of solar PV and wind that do not provide dynamic voltage control) the SO can use the Technical Restrictions Procedure to dispatch additional generation capacity, such as CCGTs or hydro power plants, to provide effective voltage control.

Operations of the transmission network elements

63 During real-time operation, in addition to the voltage control provided by generation plants, as per the existing regulatory framework, if the SO detects that voltage fluctuations or voltage levels pose a risk to the security and reliability of the power system, it has two main tools to directly control voltage levels:

a. Coupling or uncoupling transmission lines to adjust the reactive power flows within transmission grid.[19]

b. Using the available elements of voltage control in the transmission network, such as reactors, FACTs and transformer voltage regulators.[20]

64 Given the rise in overvoltage problems in the Spanish transmission system the SO has been making greater use of these tools and they are close to their limits.

65 In this regard, the SO stated in January 2024 that the resources it had available to control voltage were “exhausting”: reactors were activated around 80% of the time, and the number of uncoupled transmission lines reached levels as of 85 lines during the months of higher solar PV output (i.e. March, April and May), as shown in Figure 4 below. [21]

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[17] Operating Procedure 1.1. - Operational and security criteria for the operation of the electrical system. Section 4.3.2.

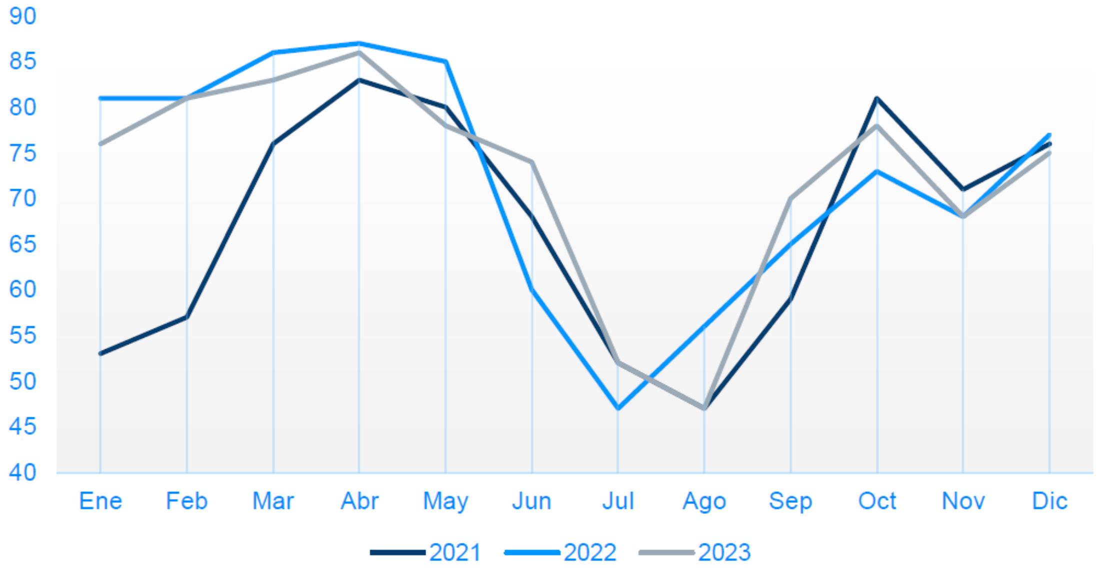
[18] Operating Procedure 3.1. - Generation Scheduling.

[19] Operating Procedure 7.4 - Complementary voltage control service

[20] Operating Procedure 8.1. - Network managed by the system operation.

[21] REE (2024). *Webinar consulta pública nuevo servicio de control de tensión*. Page 3.

Figure 4: Average number of uncoupled transmission lines due to voltage control



Source: REE (2024). *Webinar consulta pública control de tensión*. Page 3.

66 Hence, the ability to reduce voltage levels by uncoupling transmission lines, particularly during periods with high wind and solar PV output, is significantly constrained, as doing so may compromise compliance with the N-1 security criterion on the transmission grid. Unlike thermal generation, renewable generation is widely dispersed throughout the grid, and hence uncoupling lines would result in disconnecting multiple generation units simultaneously and could also lead to demand curtailment, which is generally not allowed.

67 These limitations are also reflected in the recent modification of the 2021–2026 transmission grid development plan, which includes targeted investments to strengthen the system’s voltage control capability.[22] In particular, the revied plan contemplate:

- The installation of 10 new reactors and refurbishment of 6 existing units, to improve discrete voltage control.
- The deployment of 11 synchronous condensers, introduced for the first time in mainland Spain, which provide dynamic voltage regulation.
- The acceleration of a FACTS device in Catalonia (near the French border), originally planned beyond 2026, to help dampen inter-area oscillations in the European interconnected system.

68 This context highlights the critical importance of the Technical Restrictions Procedure in ensuring that sufficient conventional generation, with effective voltage control capabilities, is scheduled for the following day.

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[22] See Resolución de 10 de julio de 2025, de la Secretaría de Estado de Energía, por la que se publica el Acuerdo del Consejo de Ministros de 8 de julio de 2025, por el que se aprueba el listado de actuaciones que se incorporan en el Plan de Desarrollo de la Red de Transporte de Energía Eléctrica 2021-2026 para aumentar la resiliencia de la red de transporte de energía eléctrica.

3 Voltage fluctuations in the days prior to the blackout

69 The blackout of April 28 was preceded by voltage fluctuations recorded in the power grid during the previous days, particularly on April 16, 22 and 24.

70 During those days prior to the blackout, the system operated under severe voltage fluctuations and overvoltage scenarios. Although these fluctuations were more pronounced in certain geographic areas, they significantly affected a substantial part of the Spanish electricity system.

71 According to REE, voltage fluctuations were mainly due to: i) abrupt changes in interconnection schedules; ii) steep solar generation gradients; iii) low coupled conventional generation; or iv) unavailability in the transmission grid and in the interconnection with France.

72 On April 22, the overvoltage caused the disconnection of 19 demand and generation injectors. At least three of the photovoltaic plants that tripped on April 22, with a total installed capacity of 739 MW, were also disconnected on April 28 in the initial moments, when the first overvoltage trips occurred. These plants were located in Cáceres and Cuenca. This may suggest that these areas experienced inadequate voltage control on April 22, which remained unaddressed by April 28.

73 In other words, the events of the preceding days, particularly those of April 22, were early indications of the situation that ultimately unfolded on the morning of April 28.

74 The following is a more detailed description of what happened during those days.

3.1 April 16, 2025

75 A significant stress peak was identified in the Toledo area.

76 In the transcript of a telephone consultation made by a distribution control center to REE's CECORE, REE attributed the overvoltage to reduced conventional generation, in particular to low nuclear generation. In this communication, REE acknowledged that the system was showing anomalous fluctuations and warned about the possibility that similar events could be repeated.[23]

3.2 April 22, 2025

77 During this day, several voltage fluctuations were recorded, being particularly pronounced the voltage peak that took place around 19:02 CET.

78 This voltage spike caused the disconnection of 19 demand and generation positions, including ADIF facilities in Castilla y León (operator of the high-speed rail infrastructure in Spain) and the Repsol refinery in Cartagena. In addition, there were also disconnections of substations in Andalusia,

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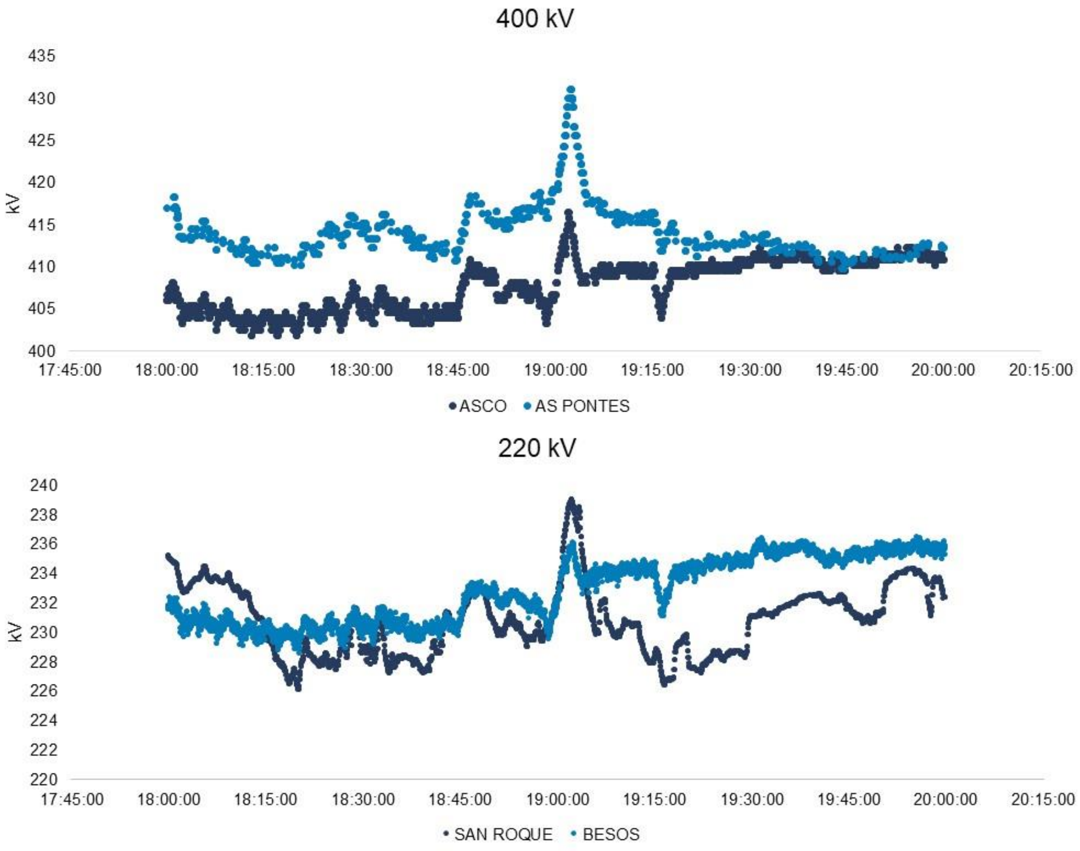
[23] Confidential communications with REE provided by AELEC Members.

Castilla-La Mancha, Extremadura and Madrid.[24] This shows that the fluctuations were not limited to a specific area but affected a significant part of the Spanish electricity system.

79 With the information provided by AELEC Members, it has not been possible to determine the total volume of disconnected generation. However, we have identified the disconnection due to overvoltage protections of two photovoltaic plants in Cáceres and one photovoltaic plant in Cuenca, with a total installed capacity of 717 MW.[25] It is worth noting that these same plants were also disconnected on April 28 at the initial moments, when the first overvoltage trips occurred. This suggests that these areas experienced inadequate voltage control on April 22, which remained unaddressed by April 28.

80 Figure 5 shows the voltage measurements recorded in different generation plants located in Catalonia (Besós and Ascó), Andalusia (San Roque) and Galicia (As Pontes).

Figure 5: Voltage measured at the grid connection of different generation plants on 22/04/2024



Source: Own analysis based on information from AELEC Members.

81 At all measurement points, both in the 400 kV and 220 kV networks, a simultaneous voltage peak was recorded at 19:02 CET. It should be noted that these plants are located far from the points where the disconnections occurred, which shows that the voltage fluctuations were not a localized phenomenon but had a geographically wide scope within the electrical system.

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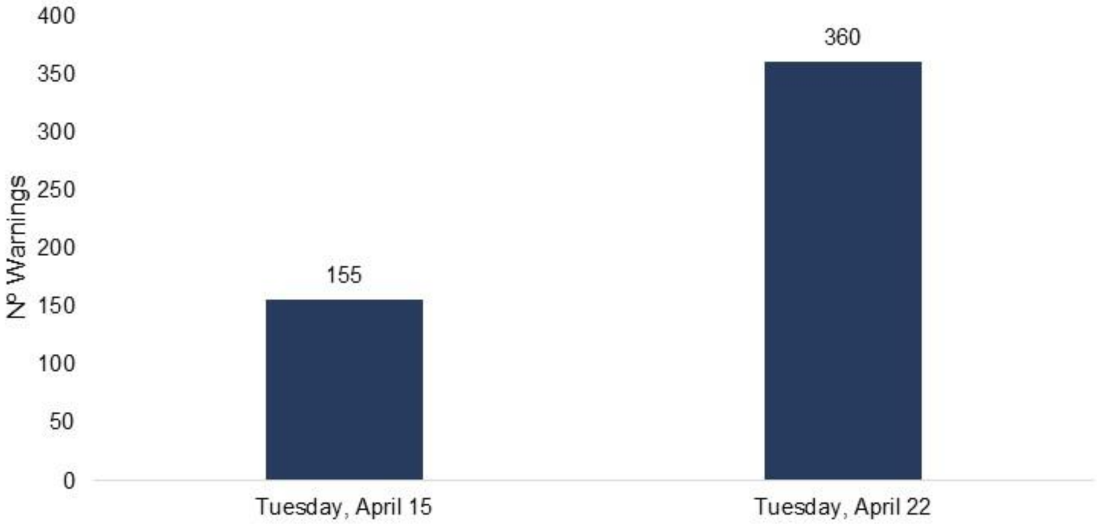
[24] See *REE. Daily report of incidents in the operation. Tuesday, April 22, 2025.*

[25] These plants are connected to renewable generation collector substations with a total installed capacity of 1.3 GW.

82 Voltage fluctuations were also detected by the control centers of distributors, as shown in Figure 6 below. This figure compares the number of "High Voltage" warnings recorded by a control center in the East-Southern region on Tuesday, April 22 versus those recorded the previous Tuesday, April 15.[26] A 200% increase in the number of warnings associated with voltage spikes is observed.

Figure 6: Number of High Voltage warnings recorded by a Control Center on the East-South on April 22, 2025



Notes: The control center receives "High Tension" warnings from its distribution networks in Alicante and Murcia.
Source: Own analysis based on information from AELEC Members.

83 As a result of the impact of the generation and demand disconnections, distributors requested information from REE about the reason for these anomalous operating conditions. REE responded that they were due to three main factors:[27]

a. **Sudden changes in the interconnection schedule with Portugal.** Indeed, at 19:00 CET, there was a very pronounced reversal in the flow of the interconnection with Portugal, with Spain going from having an exporting position of 1.1 GW to an importing position of 1.0 GW. This change of 2.1 GW in the flow represents one of the most significant recorded in the last year**.**

b. **Rapid drop in solar generation**. At 19:00 CET, a 6.5 GW reduction in solar generation was recorded, placing this event among the top largest drops in solar generation observed over the last year.

c. **Disconnection of generation facilities and changes of power flows in the interconnection with France:** Additionally, REE added that the disconnection of generation facilities contributed to further increase voltage levels, as these facilities were absorbing reactive power at the time of their disconnection. In addition, there was a decrease in exports to France, which reduced the absorption of reactive power by the transmission grid.[28]

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[26] The control centers generate a warning each time the voltage exceeds or falls below a certain level.

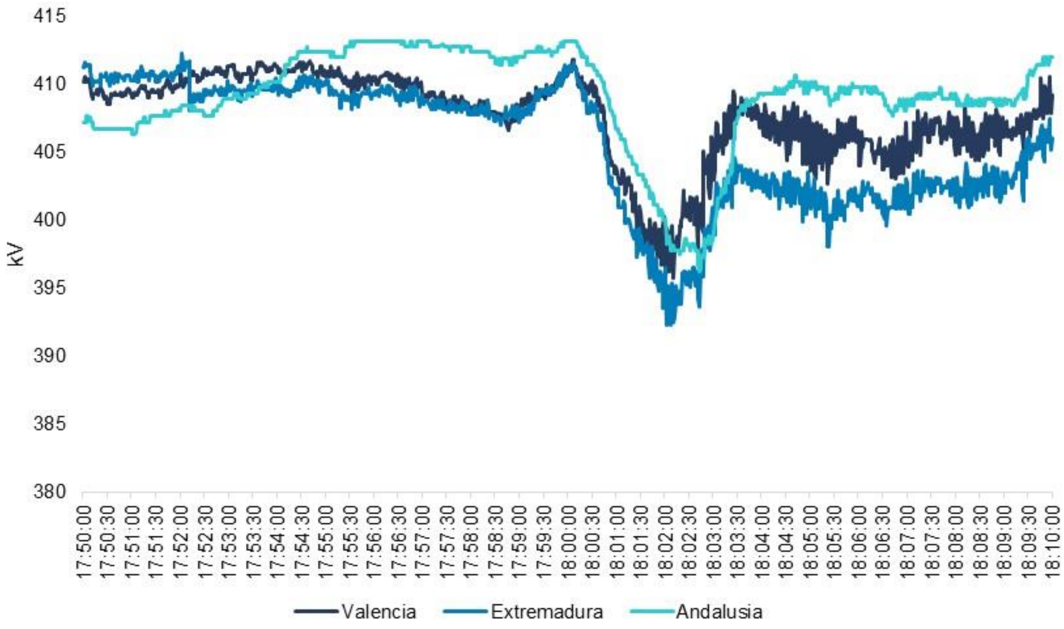
[27] Confidential communications with REE provided by AELEC Members.

[28] Confidential communications with REE provided by AELEC Members.

3.3 April 24, 2025

84 During this day a brief undervoltage is evidenced between 18:00 CET and 18:03 CET, as shown in Figure 7, which presents voltage measurements obtained at various border nodes of the transmission system (Valencia, Western Andalusia, Extremadura).

Figure 7: Voltage and frequency measurements at different points of the high-voltage network on April 24, 2025



Source: Own analysis based on information from AELEC Members

85 As with previous events, this situation was brought to REE's attention. REE explained that these fluctuations were due to the increase in exports to France together with a rapid increase in solar generation, which sharply raised the load on transmission lines and their reactive power consumption, causing a transient voltage drop.[29]

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[29] Confidential communications with REE provided by AELEC Members.

4 State of the electrical system prior to the blackout

86 This section provides an analysis of the state of the Spanish electricity system - focusing on generation schedule, frequency behavior, and voltage conditions- leading up to the blackout.

4.1 Generation schedule

87 The final generation schedule in the Spanish electricity system is determined through a standard sequence, outlined here in illustrative terms. Details on the complete sequence can be found in Annex A.

88 It begins with the day-ahead market, which clears the most cost-efficient dispatch based on demand and generator's bids. The SO then reviews the security of its operation. Following this review, modifications may be introduced by the SO. These modifications include, for example, the dispatch of additional conventional generation capacity to ensure voltage control through the Technical Restrictions Procedure.

89 On April 28, the day-ahead market cleared without any CCGTs, while the nuclear fleet included 1.7 GW, consisting of one unit at full load and another at partial output. As a result of subsequent adjustments by the SO, aimed at guaranteeing the security and reliability of the electricity system (Technical Restrictions Procedure), 3 GW of CCGTs -comprising 19 to 21 units, depending on the hour, were coupled overnight, and nuclear output was increased to 3 GW with an additional unit at full load and another one at partial capacity.

90 However, between 8:00 CET and 10:00 CET, the SO removed 15 CCGT units from the dispatch, no significant adjustments were made to wind generation, and solar remained unchanged from the market outcome.[30] As a result, the number of units that could contribute to voltage control dropped in the South area of Spain from 5 to 1.[31]

91 This limited availability of conventional generation in the South was further compounded by operational decisions taken by REE in the hours before the blackout. A CCGT unit in Western Andalusia, that had been scheduled through the Technical Restrictions Procedure for voltage control on April 28 was declared unavailable to REE on April 27 at 20:00 CET.[32] As a result, it was unable to participate in voltage regulation on April 28. Nevertheless, despite having seven other available units in the area capable of providing this service, REE opted not to replace it.[33] In practice, this means that while REE considered the unit necessary at 14:00 CET on April 27, by 20:00 CET the same day—after its unavailability was declared—it no longer deemed it necessary to secure a replacement.

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[30] See REE Daily Incident Report of April 28.

[31] The units decoupled by REE were Algeciras, Campo de Gibraltar, Palos 1 and San Roque (see REE Daily Incident Report of April 28).

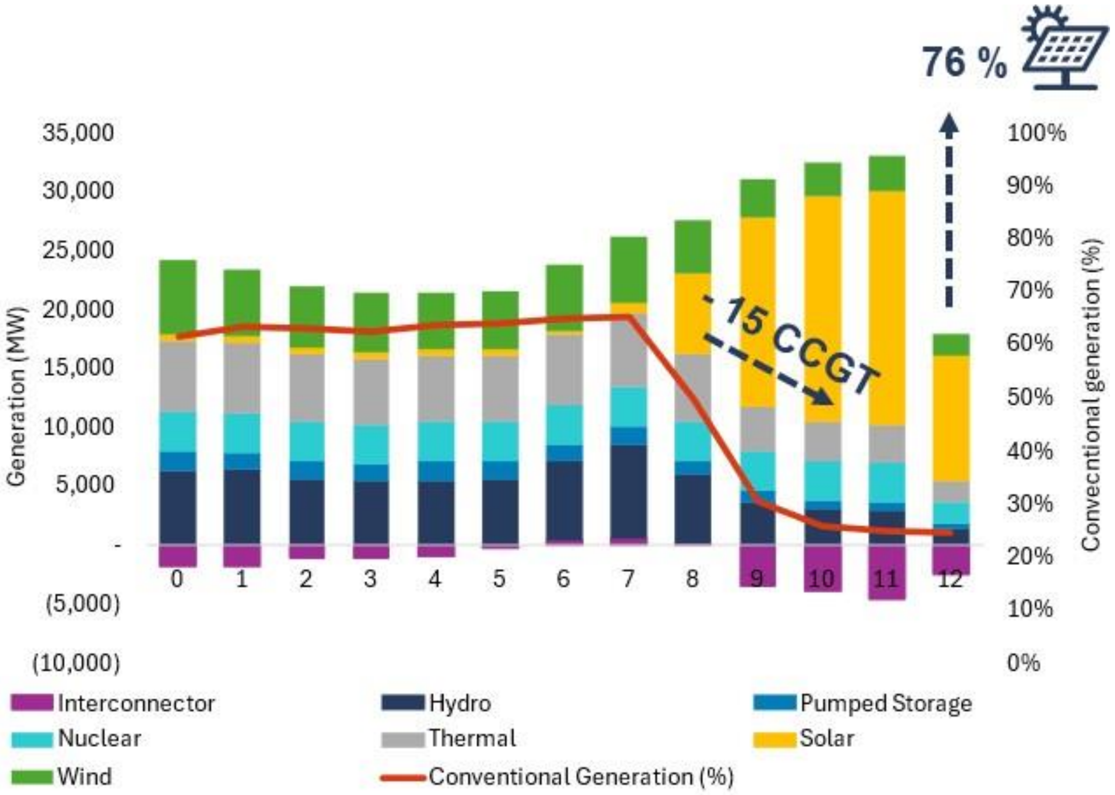
[32] See Analysis Committee Report, page 22.

[33] Information on available units provided by AELEC Members.

92 Additionally, in the final minutes before the blackout, REE called on a CCGT unit to provide voltage control in the south region through the real-time Technical Restrictions Procedure —yet this unit ultimately did not enter into operation, as the blackout occurred before it could be coupled to the system (scheduled for 14:00 CET).[34] This decision was made despite the availability of hydroelectric plants in Extremadura, which have significantly shorter start-up times and could have responded quicker.

93 Figure 8 shows the hourly generation dispatch that took place after all the adjustments until 12:00 CET.

Figure 8: Hourly generation schedule for April 28, 2025 until 12:00 CET



Source: Own analysis based on the "Generación medida" indicator of Red Eléctrica de España.

94 The resulting final generation schedule shares similar features to those that led to voltage fluctuations in the days preceding the blackout (i.e., April 16, 22, and 24), that is: steep variations in the renewable generation schedule and interconnection flows; and low levels of conventional generation.

a. **Pronounced variations in renewable generation.** Between 08:00 CET and 09:00 CET, Spain registered its largest hourly increase in solar output to date, with a 9.1 GW rise. This was accompanied by a sharp decline in wind generation, which fell by 1.2 GW over the same interval.

b. **Abrupt change in interconnection flows.** During that same time window, exports to Portugal surged by 3 GW, representing one of the most significant hour-on-hour changes observed in recent dates.

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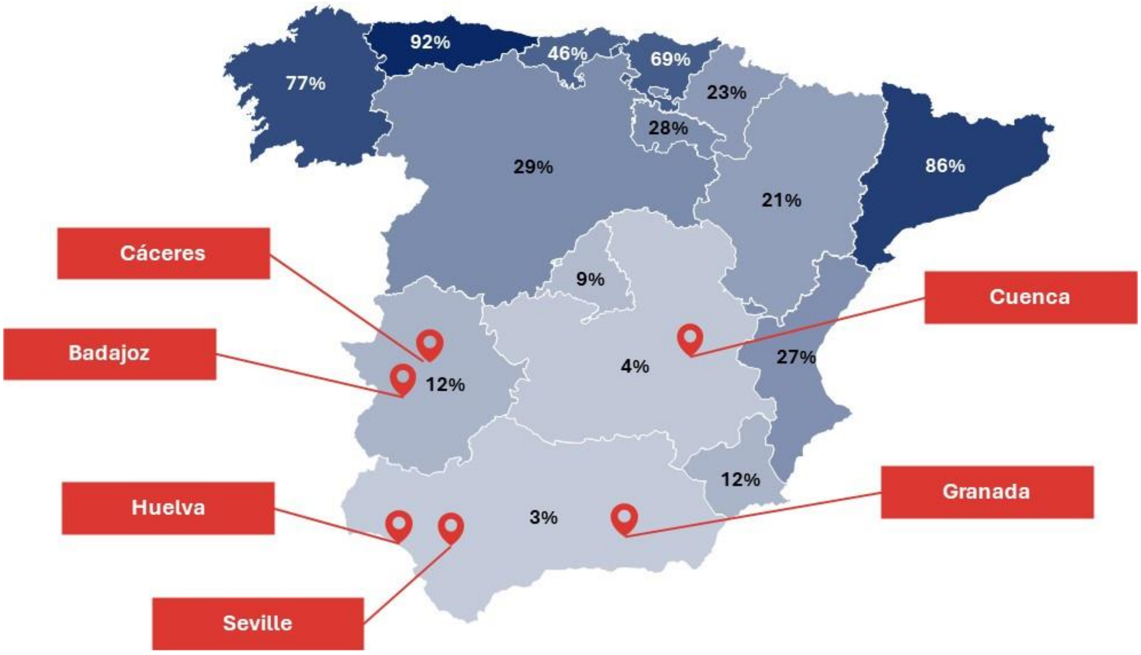
[34] See Analysis Committee Report, page 35.

c. **Low conventional synchronous generation.** At the time these gradients occurred, synchronous generation from CCGTs had been reduced to just 1.2 GW, dropping further to 1.0 GW by 11:00 CET. Only six CCGT units remained online—15 fewer than earlier in the day—and all were operating at or near their technical minimum. Nuclear output stood at 3 GW (with 4 units in operation) out of a total installed capacity of 7 GW. Additionally, one coal unit, out of 5, was running at its minimum stable level. Thus, at the time of the blackout, only 11 conventional generation units were coupled: 6 CCGTs, 4 nuclear reactors, and 1 coal plant. This represented the lowest number of such units operating in 2025.

95 In addition, the low share of conventional generation (CCGTs, nuclear, hydro and coal plants) was unevenly distributed throughout the different regions of the electricity system, resulting in particularly low shares in the southern region of the electricity system. This is illustrated in Figure 9 below, which also highlights — using red markers — the location of the generation for which there is evidence of disconnection during the initial stages of the blackout due to overvoltage.

Figure 9: Share of conventional generation over total generation at 11:00 CET on April 28, at each Autonomous Community (%)



Source: Own analysis based on the "Generación medida" indicator of Red Eléctrica de España.

Note: The locations marked with red dots represent the sites of the first generation trips on April 28 (i.e. within the first 20 seconds of disconnections) that initiated the collapse of the system.

96 It can be observed that the generation disconnections occurred predominantly in regions with a low share of conventional generation capable of providing dynamic voltage control.

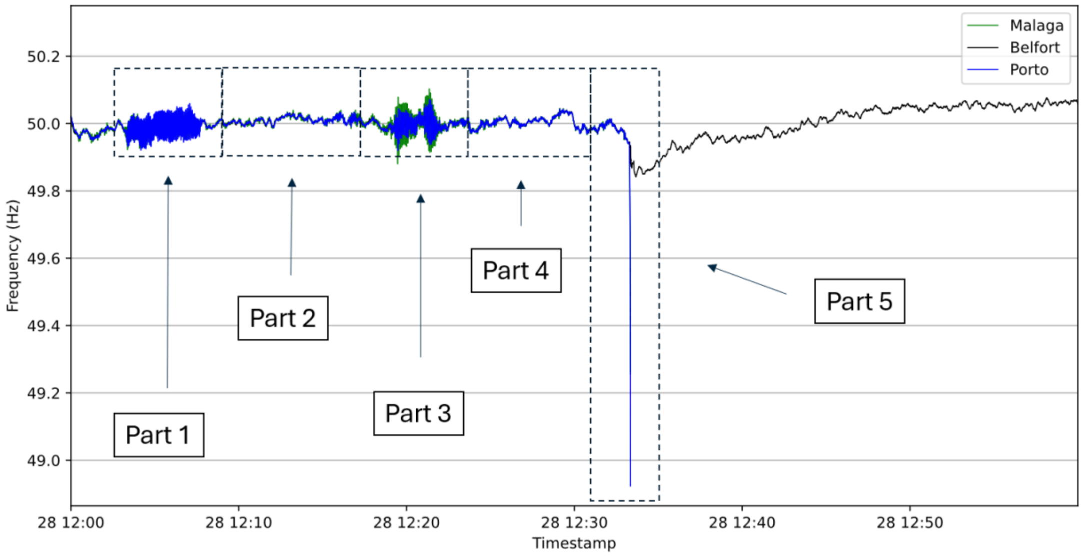
4.2 Frequency status

97 The following is an analysis of the frequency status during April 28. We conclude that minutes before the blackout there were frequency oscillations, which were also reflected in some voltage fluctuations. However, in the seconds prior to the blackout, the frequency was in normal ranges, and there is no evidence that such frequency oscillations could have directly contributed to the blackout.

98 Figure 10 shows the frequency measured on April 28, 2025 at three different locations: Malaga (green line), Porto (blue line) and Belfort in France (black line). The boxes indicate different phases

of the frequency behavior, with box number 5 being the exact time of the blackout, which will be analyzed later. The measurements were performed using phasor measurement units (PMU) at INESC TEC and Grid Radar network.[35]

Figure 10: Frequency evolution on April 28th between 12:00 CET and 13:00 CET



Notes: The X axis shows the time in UTC+2 (i.e. Spanish peninsular time).
Source: INESC TEC

99 At around 12:00 CET, the system frequency was under normal frequency conditions.

100 Between 12:03 CET and 12:07 CET (Part 1), frequency oscillations were recorded in the Iberian system, with an approximate natural frequency of 0.65 Hz. They generated voltage fluctuations, although it has not been possible to verify whether these oscillations had the same frequency.

101 As of 12:10 CET (Part 2), the frequency had already stabilized, and most likely as a precautionary control measure, the operating mode of the direct current ("DC") interconnection between Spain and France was changed from emulation of an alternating current ("AC") line to a fixed DC power flow. This is a common procedure used to damp frequency oscillations, such as those that occurred in the system. Section 5.1 discusses the operation of the interconnection in more detail.

102 Between 12:16 CET and 12:22 CET (Part 3), frequency oscillations reappeared, this time with a natural frequency close to 0.22 Hz. These frequency oscillations correspond, with high probability, to small-signal inter-area oscillations between synchronous generators of Iberia and other ones in the Baltic countries (Grid Radar data shows oscillations in opposition of phase between the Iberian and namely Latvian generators). These oscillations can be damped by means of power systems stabilizers (PSS), usually integrated in the excitation systems of the synchronous generators, provided they are properly calibrated. These oscillations were also reflected in voltage variations. However, it was not possible to verify whether these voltage fluctuations had the same frequency.

103 Finally, at 12:32:55 CET (Part 4), i.e., two seconds before the first power plant trips, the frequency remained in its normal operating range.

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[35] Grid Radar is a company specialized in real-time monitoring of different power system parameters, such as frequency.

104 There is no evidence that these frequency oscillations are responsible for the blackout.

4.3 Voltage status

105 To contextualize the voltage values described in this section, the different voltage limits established by the regulations for both network nodes and generation facilities are reviewed below.

106 Regarding voltage levels at the network nodes:

a. According to Operating Procedure 1.4 (Energy delivery conditions at the border nodes of the grid managed by the system operator), under normal operating conditions, the voltage must be maintained between 205 kV and 245 kV in the 220 kV grid; and between 390 kV and 420 kV in the 400 kV grid.

b. In the agreement signed in 2021 between REE and the distribution grid managers for voltage control in certain reference nodes, two types of thresholds are established:[36]

    i. Limits for activating coordination measures: 205 kV and 235 kV for the 220 kV network; 380 kV and 420 kV for the 400 kV network.

    ii. Limits for activating exceptional measures: 198 kV and 246 kV for the 220 kV network; 375 kV and 435 kV for the 400 kV network.

107 Table 1 below summarizes the above limits.

Table 1: Voltage limits established by the regulations for nodes

	P.O. 1.4 Normal Operating Conditions		Coordination measures		Exceptional measures	
	Lower limit	**Upper limit**	**Lower limit**	**Upper limit**	**Lower limit**	**Upper limit**
Nodes at 220 kV	205	245	205	235	198	246
Nodes at 400 kV	390	420	380	420	375	435

Source: Agreement between REE and distribution grid managers for voltage control at certain reference nodes and P.O. 1.4 Conditions of energy delivery at grid border points managed by the system operator.

108 Regarding the voltage limits applicable to generation facilities, Order TED/749/2020 establishes the maximum and minimum voltage values that must be withstood by such facilities before they proceed to their automatic disconnection to protect their equipment. These thresholds vary according to the power of the installation and the voltage level to which they are connected. Table 2 summarizes the limits applicable to installations of more than 50 MW connected to 220 kV and 400 kV networks.

Table 2: Voltage limits established by regulations for generation facilities with installed capacity above 50 MW

		Order TED/749/2020
	Lower limit	**Upper limit**

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[36] When the limits of coordination measures are exceeded, the automatic regulation of transformers is deactivated, switching to manual tap regulation. When the limits of exceptional measures are exceeded, the distributors stop changing the taps of their transformers.

Table 2: Voltage limits established by regulations for generation facilities with installed capacity above 50 MW

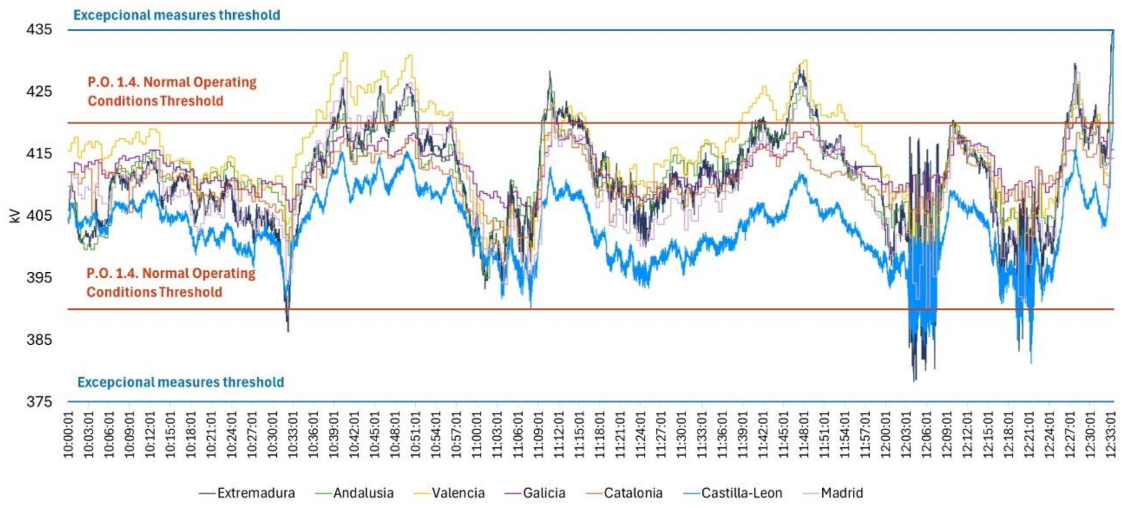
Facilities connected to 220 kV	187	253
Facilities connected to 400 kV	340	440

Source: Order TED 749/2020.

109 The following is an analysis of the voltage status during April 28, in the hours prior to the blackout.

110 Figure 11 shows voltage measurements at 400 kV transmission grid boundary points located in different geographical locations (Extremadura, Andalusia, Catalonia, Madrid, Castilla-Leon, Valencia and Galicia) in the hours leading up to the blackout. [37]

Figure 11: Voltage evolution on April 28th on the 400 kV grid, 10:00 CET to 12:33 CET



Source: Own analysis based on information from AELEC Members.

111 From 10:30 CET onwards, generalized voltage fluctuations were observed in the 400 kV grid throughout the Spanish electrical system, especially pronounced in Extremadura and Andalusia, with minimum values below 390 kV and maximum values close to 430 kV. On several occasions, voltages at various buses in the network was under 390 kV and exceeded the 420 kV, i.e. exceeded the normal operating limits defined by P.O. 1.4.

112 Zooming in on the voltage measurements between 12:29:00 CET and 12:33:18 CET in Andalusia and Extremadura — where fluctuations were most pronounced — it can be observed that, at 12:32 CET, a minute before the blackout, voltage levels in Western Andalusia reached 420 kV and in Extremadura greatly exceeded this level. This value corresponds to the upper limit of the Normal Operating Condition defined by P.O. 1.4 and represents the threshold for Coordination measures.

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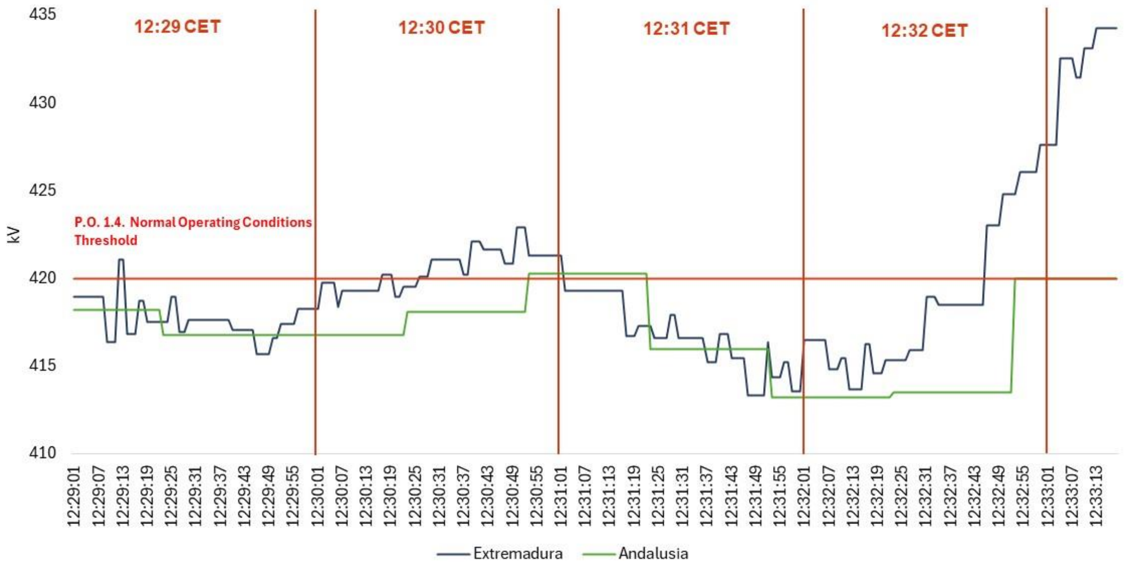
[37] The criterion used for the selection of these points was to have a geographically representative sample of the system. For this purpose, geographically distributed locations were selected both in the periphery and in the center of the peninsula, ensuring adequate coverage of the different areas of the electricity system.

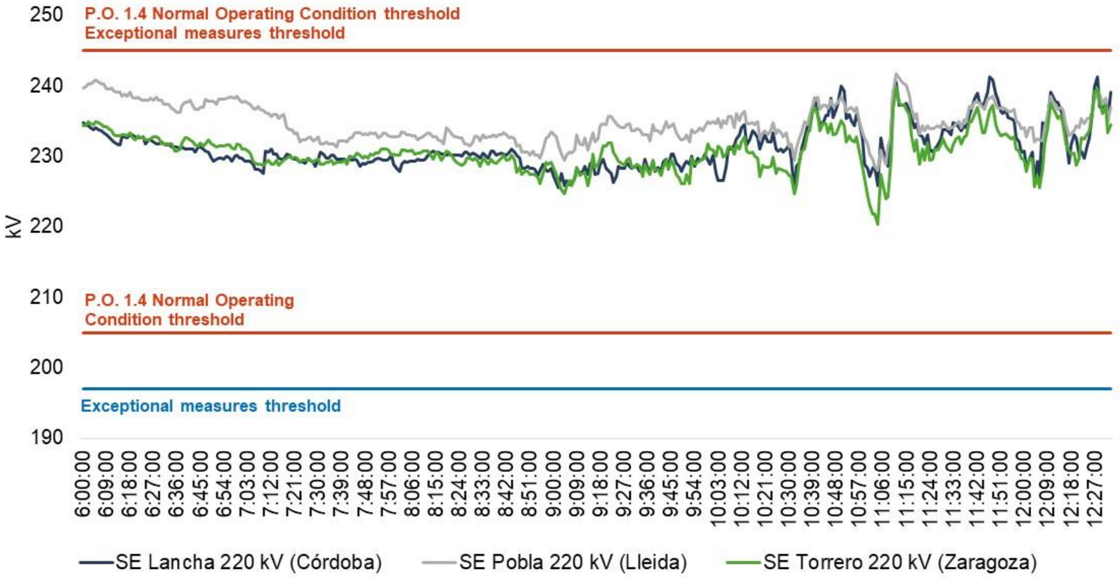
Figure 12: Voltage evolution on April 28th on the 400 kV grid, 12:29 CET to 12:33 CET



Sources: Own analysis based on information from AELEC Members.

113 A similar pattern of voltage fluctuations was also observed in the 220 kV network, with irregularities recorded from 10:00 CET across various locations in Spain. Figure 13 shows voltage measurements at points of the 220 kV network, located in different geographical points (Andalusia, Catalonia and Aragon).[38]

Figure 13: Voltage evolution on April 28th in the 220 kV network



Notas: The upper limit of the P.O.1.4 Normal Condition threshold coincides with the threshold of exceptional measures
Source: Own analysis based on information from AELEC Members.

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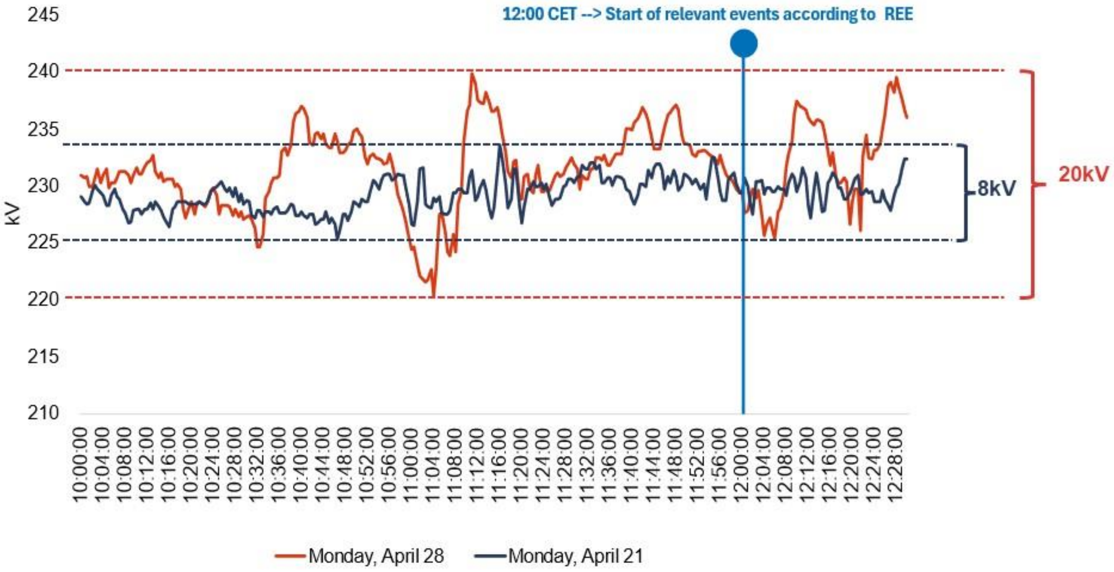
[38] The criterion used for the selection of these points was to have a geographically representative sample of the system. For this purpose, geographically distributed locations were selected both in the periphery and in the center of the peninsula, ensuring adequate coverage of the different areas of the electricity system.

114 Again, from approximately 10:30 CET onwards, generalized voltage fluctuations were observed at all measurement buses, with minimum values of 220 kV and maximum values of 241 kV. In the different points analyzed in this network, it was also observed that on several occasions the voltages exceeded 235 kV, a value considered as the limit for activating coordination measures.

115 To contextualize the magnitude of the voltage fluctuations recorded on the morning of April 28, Figure 14 compares the evolution of the voltage measured that same day (red line) with that recorded the previous Monday (blue line). Monday 21 represents a more stable day in terms of voltage oscillation, with a voltage fluctuation amplitude of 8 kV compared to 20 kV on April 28. The comparison shows a significant difference in voltage behavior between the two days.

Figure 14: Comparison of voltages measured on April 28 and April 21

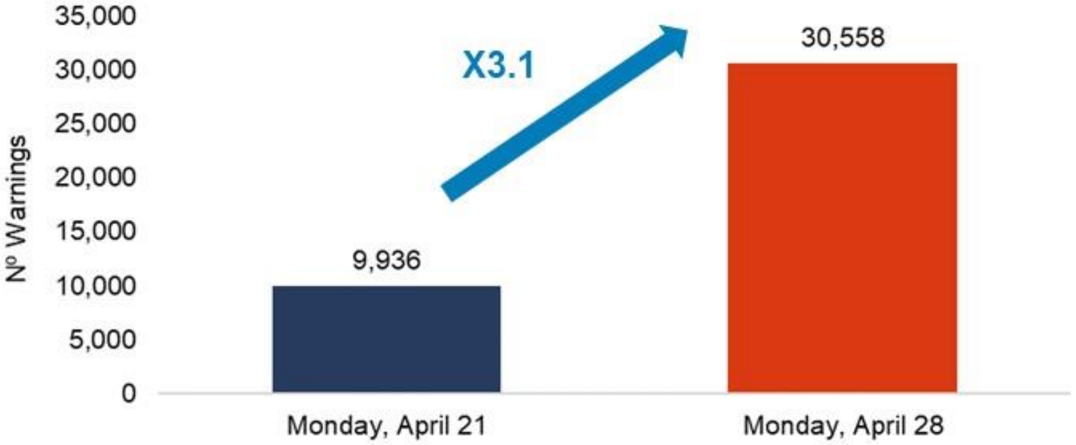


Notes: The measurements correspond to the Torrero 220 kV node.
Source: Own analysis based on information from AELEC Members.

116 Monday April 21 represents a more stable day in terms of voltage oscillation, with a voltage fluctuation amplitude of 8 kV compared to 20 kV on April 28. The comparison shows a significant difference in voltage behavior between the two days.

117 The strong voltage fluctuations on April 28 were also detected by the Control Centers of AELEC Members, as shown in Figure 15. This compares the number of "High Voltage" warnings recorded on Monday, April 28 with those recorded the previous Monday April 21, showing a threefold increase in alerts.

Figure 15: Total "High Voltage" warnings on Monday, April 21 and Monday, April 28

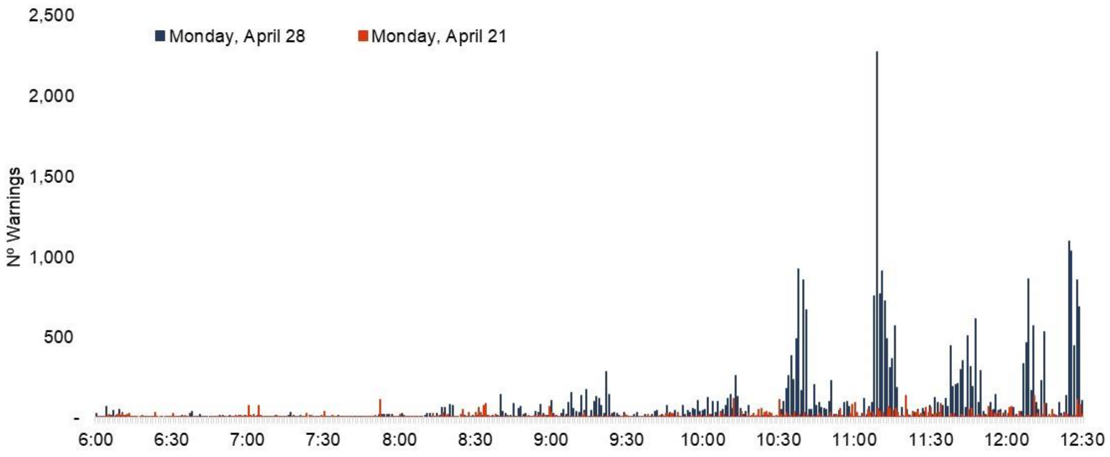


Source: Own analysis based on information from AELEC Members.

118 This increase was not concentrated in a single Control Center, but was observed in all of them, which confirms that the phenomenon of oscillations was systemic. In Annex B we present the breakdown of warnings by geographical area.[39]

119 Additionally, we have analyzed the warnings on a minute-by-minute basis. We present the results in Figure 16 below.

Figure 16: Evolution of "High Voltage" warnings on a minute-by-minute basis on Monday, April 21 and Monday, April 28



Source: Own analysis based on information from AELEC Members.

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[39] These warning were recorded in Control Centres that monitor information from the network in the regions of Basque Country, La Rioja, Navarra, Castilla y León, Madrid, Castilla-La Mancha, Extremadura, Valencia, Catalunya, Aragon and Andalusia.

120 The data show a sharp increase in the number of notifications from approximately 10:00 CET onwards, reaching peaks of more than 2,200 warnings in a single minute— a pronounced contrast to the previous Monday, when the highest count was just 180.

121 On the other hand, the conversations that the different control centers of the distributors held with REE's CECORE on the morning of April 28, provide further evidence that on the morning of April 28, there were severe voltage fluctuations, and that these did not affect a specific area but a wide geographical area.[40]

122 In addition, from these discussions, it also appears that REE encountered significant obstacles to voltage control through the use of reactors. The activation and deactivation of these caused strong voltage fluctuations, which further complicated the stabilization of the system.[41] The SO’s voltage control difficulties became particularly evident when, from 12:18 CET, REE requests the coupling of CCGTs, especially in the south zone. Finally the coupling of a CCGT was scheduled for 14:00 CET, which for obvious reasons never arrived on time, since the blackout occurred at 12:33 CET.

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[40] Confidential communications with REE provided by AELEC Members.

[41] Confidential communications with REE provided by AELEC Members.

5 REE's maneuvers to dampen frequency oscillations

123 As explained in Section 4.2, half an hour before the blackout, the Iberian system experienced two periods of frequency oscillations: the first between 12:03 and 12:07 CET, and the second between 12:16 and 12:22 CET.

124 To dampen these oscillations, REE implemented several measures, mainly:[42]

- A change in the operating mode of the HVDC link on the interconnection with France, and
- the connection of transmission lines.

125 This section analyses the effects of these manoeuvres—specifically, the consequences of changing the interconnection's operating mode on the system's ability to receive external support, and the impact of lines connections on voltage levels.

5.1 Operation of the interconnection with France

126 The interconnection between France and Spain is composed of several alternating current (AC) lines and a high-voltage direct current (HVDC) link. The latter can operate in different modes, with the relevant ones for the analysis of April 28 events being the "AC emulation" mode and the "Constant DC power" mode.

127 In the hours prior to the blackout, the HVDC link was operating in AC emulation mode. However, as highlighted by ENTSO-E, operating a HVDC link in AC emulation mode in parallel with real AC lines may contribute to generate frequency oscillations, particularly in systems with reduced inertia.[43] Indeed, such oscillations were observed in the Spanish system between 12:03 CET and 12:08 CET on April 28, as described in Section 4.3.

128 At approximately 12:10 CET, REE changed the operating mode of the DC link from AC emulation to Constant DC power mode, setting the flow at 1,000 MW of export to France, as shown in Figure 17.

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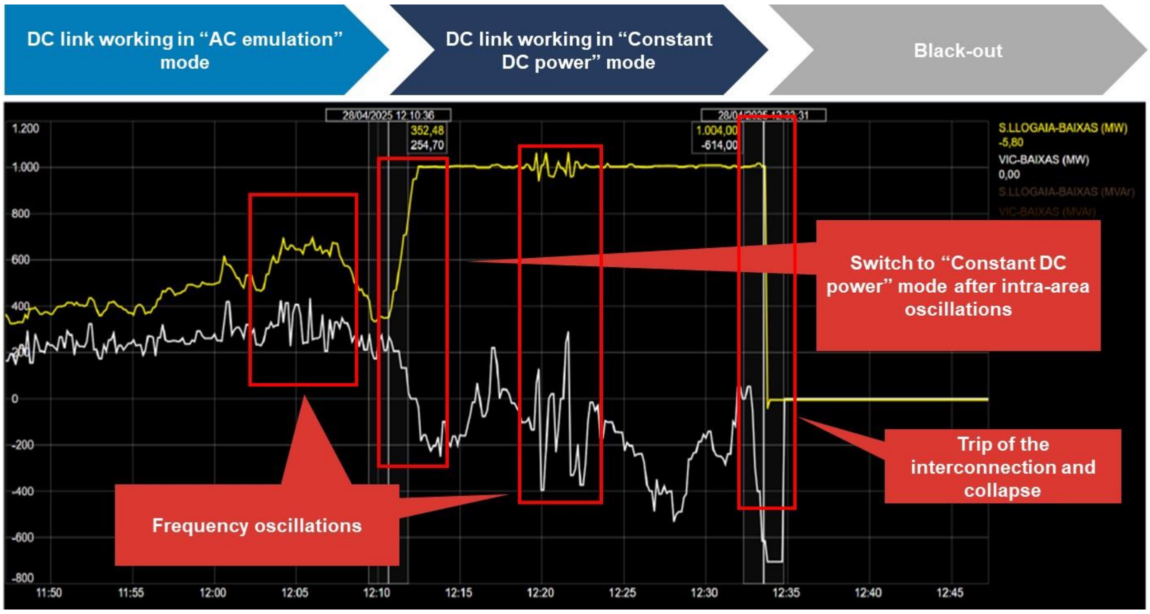
[42] See Analysis Committee Report, pages 29-35. This report also identifies a reduction of the exports to Portugal from 12:30 CET onwards, however this measure is not analyse in this report.

[43] ENTSO-E (2019). HVDC Links in System Operations", Technical paper.

Figure 17: Operation of the interconnection with France on April 28



Notes: The yellow line represent the DC link and the white line represent the AC line.

Source: AELEC Members.

131 According to INESC TEC's preliminary analysis, this operating mode change is technically justified as a response to the frequency oscillations observed since 12:03:30 CET. This type of manoeuvre is referenced in the literature as a preventive or corrective action to damp low-frequency oscillations, such as those that occurred prior to the blackout.

132 However, operating in Constant DC power mode might reduce the degree of synchronization between areas, and therefore the ability of the system to receive help through the interconnection in the event of an unexpected loss of generation. This is particularly relevant regarding the system's initial power response, which becomes less effective.

133 In addition, this might lead to a greater angular difference between areas and, consequently, faster triggering of loss-of-synchronism protections at the interconnection. The extent of this effect depends on: i) the parameterization of the "AC emulation" mode control; and ii) whether, during disturbances, the HVDC link maintains its fixed power control or switches to other modes of operation, such as "AC emulation" control or other support modes better suited to maintain system frequency stability.

134 There is currently no official public information confirming the configuration currently in place. While a 2023 REE publication shared certain aspects of the HVDC's control configuration, there is no assurance that these settings remain unchanged, particularly in light of the evolution of the European power system, such as the integration of the Baltic states in February 2025. [44]

135 This lack of transparency does not imply that the existing configuration is inappropriate, but it does hinder the ability of external stakeholders to conduct informed analyses.

136 In summary, due to the lack of information, the impact of the HVDC's mode of operation on the blackout cannot be properly assessed. However, it is essential to stress the need for increased

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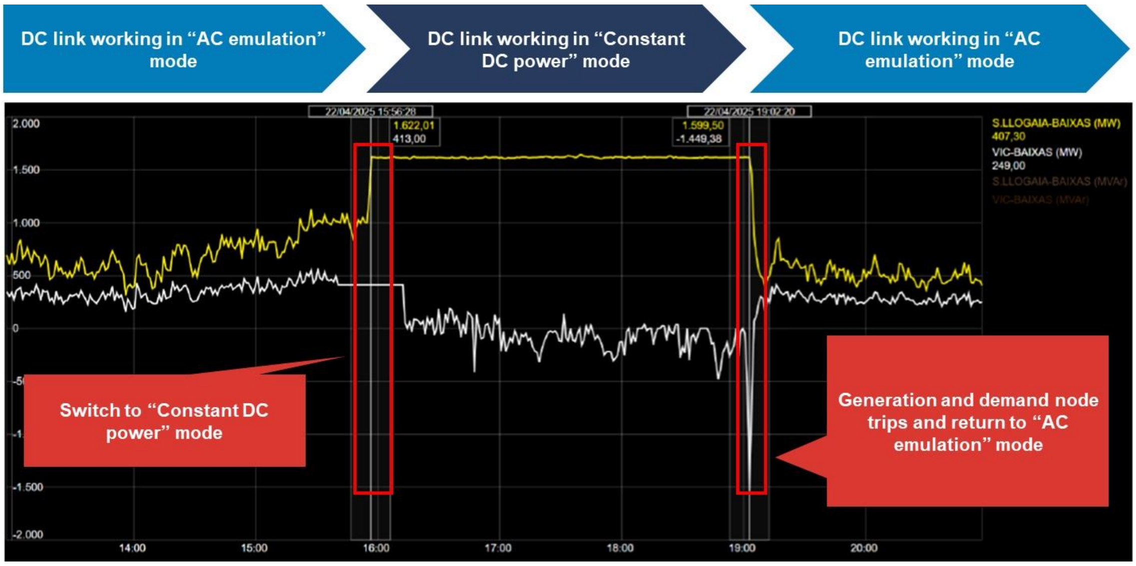
[44] See J. Renedo et al, "Tests on the POD-P controller of INELFE Spain-France VSC-HVDC interconnector," presented at the B4 International SC Meeting and Colloquium, Vienna, Austria, Sep. 2023.

transparency and an independent evaluation of whether the current HVDC parameterization is optimal under existing conditions. This is particularly relevant considering that the forthcoming HVDC interconnection via the Vizcaya Gulf will also be HVDC-based.[45]

137 Additionally, it should be noted that a similar operational change in the interconnection occurred on April 22, 2025. On that day, the DC link operated in "AC emulation" mode until 15:56 CET, when REE switched it to "Constant DC power" mode. However, unlike on April 28, the mode was reverted back to "AC emulation" at 19:02 CET — shortly after generation and demand trips were recorded.[46]

Figure 18: Operation of the interconnection with France on April 22



Notes: The yellow line represent the DC link and the white line represent the AC line.
Source: AELEC Members.

5.2 Connection of transmission lines

138 REE can manoeuvre transmission lines—i.e., connect or disconnect them—to support the stability of the electrical system.

139 On April 28, starting at 12:00 CET, REE connected 11 transmission lines that had been disconnected for several days, or weeks.[47] Figure 19 lists these lines and shows the number of days each had remained disconnected.

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[45] More details about the future interconnection available at https://www.inelfe.eu/es/proyectos/golfo-de-bizkaia

[46] See Section 3.2 for more detail on the generation and demand trips on April 22.

[47] Between 9:00 CET and 12:00 CET, REE also reconnected 19 transmission lines, many of them located in the southern region.

Figure 19: Connection of lines carried out by REE from 12:00 CET

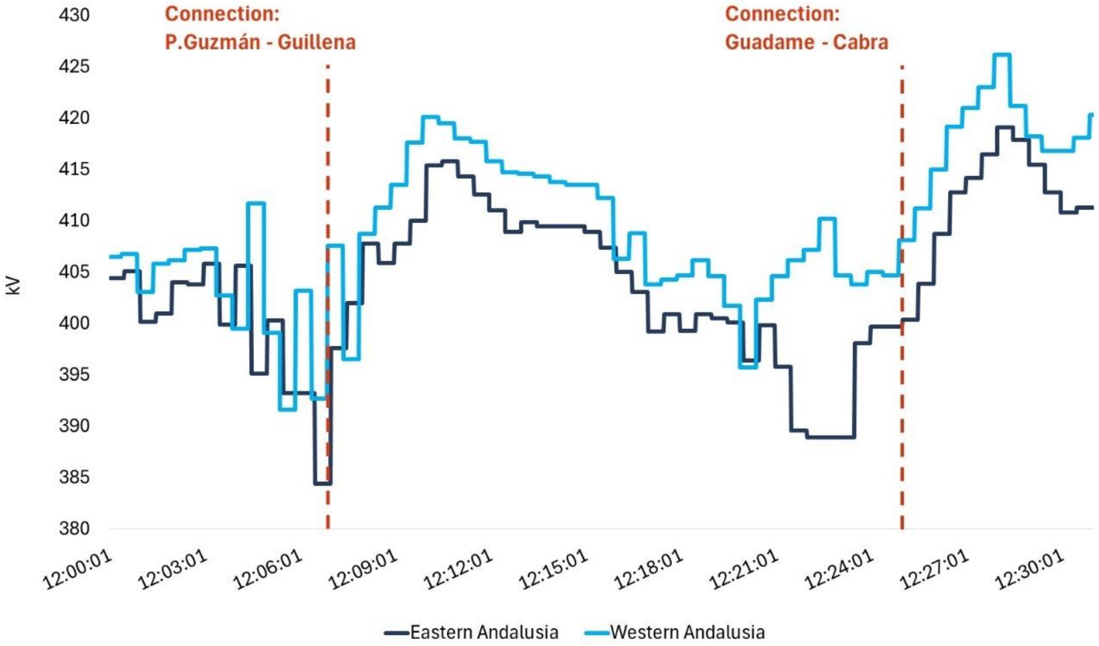
Source: Own analysis based on information from REE, Daily Incident Report of April 28.

140 While connecting transmission lines can help damp oscillations, it can also affect voltage control. In particular, coupling transmission lines increases the grid's overall injection of reactive power, which can raise voltage levels.

141 This is precisely what occurred on April 28. The connection of multiple lines—especially in already stressed regions—further increased voltage levels and exacerbated the overvoltage issues present prior to the blackout.

142 To illustrate this impact, Figure 20 compares the timing of line connections in the South zone of Spain—one of the most affected regions by overvoltages—with voltage readings from the nearest substation for which data is available.

Figure 20: Voltage evolution in the South area, from 12:00 CET



Source: Own analysis based on information from AELEC Members and REE, Daily Incident Report of April 28.

143 As shown in the figure, a marked increase in voltage levels occurs immediately after the connection of the lines, underscoring the relationship between these manoeuvres and the worsening voltage conditions observed in the final moments before the blackout.

144 In summary, the decision to reconnect the transmission lines shortly before the blackout—while possibly justified to dampen frequency oscillations—contributed significantly to the voltage increase that ultimately led to the blackout.

5.3 Impact of the connection of transmission lines and reactors on voltage control

145 In this subsection, we analyse the impact of REE's operational manoeuvres on April 28, particularly the reconnection of transmission lines and the coupling/uncoupling of reactors, on the system's ability to maintain voltage control.

146 Voltage control in the transmission system depends on the ability to either absorb excess reactive power or generate reactive power, in order to maintain voltage levels within acceptable operational ranges. When the system's capacity to absorb reactive power is insufficient, it becomes increasingly vulnerable to overvoltage conditions.

147 For our analysis of voltage control capacity we have requested PSS/e simulations provided by AELEC Members for each hour from January 1 to June 8, 2025.[48] These simulations use as inputs the best available expected system conditions defined by REE and used for REE's day-ahead analysis of Technical Restrictions. As a result, the actual operating points may differ from those

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[48] Red Eléctrica provides PSS/e raw type files. These files contain the structural description of the transmission system at a given hour before conducting the Technical Restriction Procedure, including the network topology, scheduled generation and demand per node, and the status of network elements such as lines and transformers.

represented in the PSS/e files, as the simulations do not reflect any operational adjustments that may have been implemented. A more accurate analysis requires detailed load flow simulations with data from the output of the state estimator (this data is not publicly available and has not been disclosed by REE). Therefore, they are an approximation to real-time conditions in each corresponding hour of the next day.

148 We have separately estimated for each hour reactive power injection, reactive power consumption by non-conventional generation and the reactive power consumption capacity of conventional generation as follows:

- **Reactive power generation**: Derived from the PSS/e solution.
- **Reactive power absorption:**
  - **Demand:** Derived from the PSS/e solution.
  - **Reactors:** Derived from the PSS/e solution.
  - **Non-conventional generation**: Derived from the PSS/e solution.
- **Conventional generation absorption capacity:** For nuclear, CCGTs and coal plants absorption was estimated as 30% of the installed capacity of online units, according to the P48 files which reflect final dispatch after the Technical Restrictions Procedure.[49] For hydro plants, since P48 files do not distinguish between plants that provide voltage control and those that do not, absorption of reactive power is obtained directly from PSS/e simulations. While this method does not account for Technical Restrictions adjustments, the deviation is expected to be limited.

5.3.1 Capacity to consume reactive power of conventional generation and reactors compared

149 First, we have compared the total capacity to consume reactive power of reactors on the transmission system and the capacity of the conventional generation online on the system as of 12:00 CET.

150 Table 3 below presents a breakdown of reactive absorption capacity by region on April 28, based on available data for reactors and conventional generation that was coupled on the system as of 12:00 CET. Hydropower is provided on an aggregate basis as we do not have regional level data.

Table 3: Comparison of reactive power absorption capacity by region at 12:00 CET on April 28

Region	Reactors capacity (MVAr)	Conventional generation capacity (MVAr)
Andalusia	1,850	117
Aragón	1,300	-
Asturias	150	104
Castilla y Leon	1,950	-
Catalonia	1,050	910

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[49] The P48 files are published by REE and contain the final dispatch schedule of generation units for each quarter-hour period of the day. These files reflect the outcome of the full market sequence, including adjustments made through the Technical Restrictions Procedure, and provide an accurate representation of the generation units effectively scheduled to operate in real time.

Table 3: Comparison of reactive power absorption capacity by region at 12:00 CET on April 28

Extremadura	1,250	302
Galicia	450	257
Madrid	2,400	-
Castilla -La Macha	1,050	112
Murcia	150	124
Navarra	150	-
Pais Vasco	400	236
Valencia	1,150	123
Hydropower		2,749
Total	**13,300**	**4,917**

Notes: Conventional generator absorption capacity is estimated as 30% of the total installed capacity of online units.
Source: Own analysis based on information provided by REE in the PSS/e data and ENTSO-E Transparency Platform.

151 We see that the capacity to consume reactive power of reactors, controlled directly by REE, is much larger (more than double) than that of conventional generation that was online as of 12:00 CET. The difference us particularly large in Andalusia, where 1,550 MVAr of reactors were installed but only 117 MVAr of conventional generator absorption capacity was available at 12:30 CET.

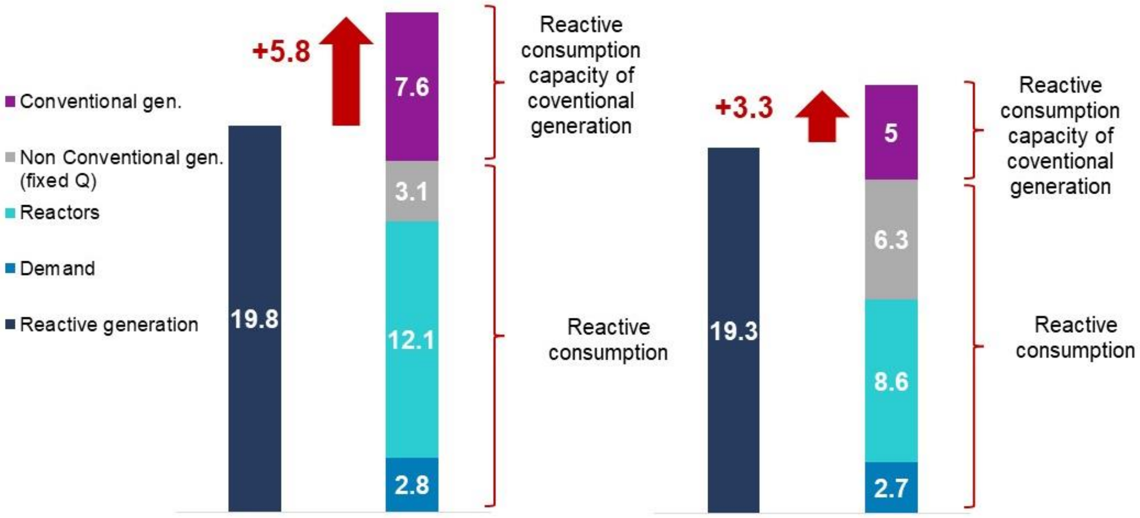
5.3.2 Impact on the system-wide margin to consume reactive power

152 In addition, we have analysed the system’s capacity to control voltage from 12:00 CET onwards on April 28 following the manoeuvres. For this we have:

- Estimated the available margin to absorb reactive power of the system as of 12:00 CET and compared it with the average margin observed on the system over the period from January 1 to June 8, 2025.
- Assessed how REE’s manoeuvres from 12:00 CET onwards affected the reactive power balance and the remaining margin in the system to absorb reactive power.

153 Figure 21 presents these estimates. The two charts compare the average daily balance between January and June 2025 (left chart) with the balance on April 28 at 12:00 CET (right chart). In each chart, the dark blue column represents estimated reactive power generation. The stacked bars to the right represent absorption capacity: from demand (medium blue), reactors (light blue), and renewables (grey), while the final (purple) bar shows the available absorption capacity from conventional generators. The red arrow indicates the overall system margin—the difference between reactive power generated and the system’s capacity to absorb it.

Figure 21: Estimation of reactive balance (GVAr)



Source: Own analysis based on PSS/e simulations provided by AELEC Members and REE's P48 files.

154 As shown above, the system's available margin to absorb reactive power was on average 5.8 GVAr in the first half of 2025 but just 3.3 GVAr at noon on April 28. The reduced margin is primarily driven by two factors: i) a lower absorption by reactors, since they were not all connected to the grid;[50] and ii) a reduction in the reactive consumption capacity of the conventional generation.

155 However, this balance does not yet reflect the additional reactive power introduced by REE's manoeuvres on April 28. To assess the full impact, the following elements must be considered:

- **Reactors manoeuvres:** Beginning at 12:00 CET, REE disconnected eight reactors with a combined capacity of 1,150 MVAr and reconnected five with a total of 750 MVAr, resulting in a net increase of 400 MVAr in reactive power that stop being absorbed.[51] Table 4 summarizes these actions.

Table 4: Reactors manoeuvres carried out by REE from 12:00 CET on April 28

Reactor	Time	Typer of manoeuvres	Reactor capacity (MVAr)
Villaviciosa 400 kV REA 1	12:04	Uncoupling	150
Guadame 220 kV REA 3	12:04	Uncoupling	100
Rueda 400 kV REA 2	12:05	Uncoupling	150
Aragón 400 kV REA 1	12:05	Uncoupling	150
Cabra 400 kV REA 1	12:17	Uncoupling	150
Peñaflor 400 kV REA 1	12:21	Uncoupling	150
Palos 220 kV REA 1	12:24	Uncoupling	100

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[50] According to PSS/e data, total reactors absorption capacity is approximately 13.3 GVAr. See Table 3 for more details on the reactors inventory.

[51] See Analysis Committee Report, page 37, for details on the reactor manoeuvres executed by REE starting at 12:00 CET. The estimation assumes that the buses to which the reactors are connected are operating at their nominal voltage levels.

Table 4: Reactors manoeuvres carried out by REE from 12:00 CET on April 28

Morata 400 kV REA 4	12:24	Uncoupling	150
Vitoria 400 kV REA 2	12:26	Coupling	(150)
Peñaflor 400 kV REA 1	12:27	Coupling	(150)
Guadame 220 kV REA 3	12:27	Coupling	(100)
Guadame 400 kV REA 2	12:27	Coupling	(150)
Morata 400 kV REA 4	12:28	Coupling	(150)
Total			**400**

Source: Own analysis based on Analysis Committee Report, page 37 and the PSS/e data.

- **Transmission lines connections:** At the same time, REE reconnected 11 transmission lines that had previously been disconnected for several days (see Figure 19).[52] To estimate their impact, the raw PSS/e topology was updated to reflect these changes, and the model was re-solved. The results indicate that these reconnections led to an increase of approximately 2 GVAr in reactive power.

156 In total, the above manoeuvres are estimated to have increased reactive power injection from the lines by more than 2.4 GVAr, almost completely eliminating the system's remaining reactive absorption margin of 3.3 GVAr and pushing voltage levels into critical territory.

157 These findings support the conclusion that the limited availability of conventional generation on April 28 was insufficient to contain rising voltage levels. Moreover, REE's real-time actions further aggravated the system's vulnerability in the final moments before the blackout.

5.3.3 Impact on the margin of southern Spain to consume reactive power

158 As previously discussed, voltage control is inherently a local phenomenon. Elevated voltage levels were recorded throughout the morning of April 28 in the southern region of the Spanish transmission system, where the first generation trips took place. It is therefore likely that, following REE's operational manoeuvres, which included the reconnection of transmission lines and changes in reactor operation in this area, the region's margin to absorb reactive power was exhausted.[53]

159 To assess this in more detail, a focused analysis has been carried out for the southern zone of the Spanish grid. The objective was to evaluate the local reactive power balance at 12:00 CET on April 28 and understand the effect of REE's actions on local voltage conditions.

160 The methodology is consistent with the system-wide analysis and is based on PSS/e simulations provided by AELEC Members based on REE inputs.

161 However, given that this regional assessment is limited to a single hour, additional refinements were applied to ensure greater accuracy:

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[52] See Daily Incident Report of April 28.

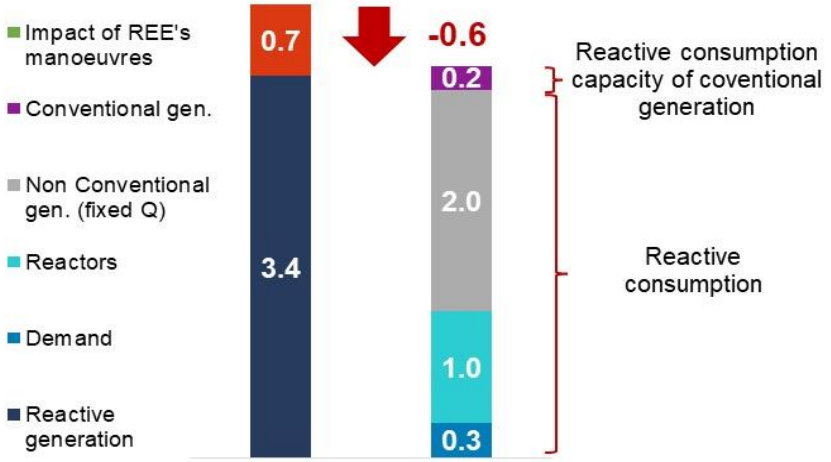
[53] See Analysis Committee Report, page 37 for details on the operation with the reactors and see Daily Incident Report of April 28 for details on the transmission lines connections.

- Pumped storage operation has been approximated using data from the P48 files as opposed to using the PPS/e forecast for each hour.[54]

- Any mismatch in RES generation between the PSS/e simulations and the P48 files has been corrected by linearly scaling renewable generation across the system.

162 Figure 22 presents the resulting reactive power balance in southern Spain on April 28 following REE manoeuvres.

Figure 22: Estimation of reactive balance in the South of Spain (GVAr)



Source: Own analysis based on PSS/e simulations provided by AELEC Members and REE's P48 files.

163 As shown above, the transmission network in the region was generating approximately 4.1 GVAr of reactive power, of which 0.7 GVAr resulted from REE's manoeuvres. Specifically, the impact of REE's actions can be disaggregated as follows:

- The reconnection of transmission lines increased reactive power generation in 0.6 GVAr.

- The net disconnection of one reactor in the south (three disconnected and two reconnected) contributed around 0.1 GVAr.[55]

164 While on the absorption side:

- Grid-connected reactive loads accounted for 0.3 GVAr.

- Reactors were absorbing around 1.0 GVAr.

- Non-conventional generation operating with a fixed power factor absorbed about 1.1 GVAr.

- In terms of conventional generation, only one CCGT unit was coupled in the region, acting as the sole source of dynamic voltage control, with a reactive absorption capacity of approximately

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[54] AELEC Members provided unit level data on the variations of consumption of pumped storage between the PSS/e forecast and the P48 values.

[55] In particular REE disconnected the reactors of Cabra 400 kV REA 1, Guadame 220 kV REA 3 and Palos 220 kV REA 1. And connected the reactors of Guadame 400 kV REA 2 and Guadame 220 kV REA 3.

0.1 GVAr. Additionally, hydro was providing 0.1 GVArs. In total, the conventional capacity was providing 0.2 GVAr reactive power absorption capacity.

165 These findings suggest that the southern region was already experiencing elevated voltage levels due to an already limited margin to absorb reactive power injected by the transmission grid. REE's manoeuvres further aggravated this condition, creating a regional surplus of reactive power generation of approximately 0.6 GVAr, provoking reactive power flows to other areas of the Spanish grid. The dynamic voltage control in southern Spain, provided solely by a single CCGT, was therefore clearly insufficient to absorb the regional reactive power surplus.

166 Although 11 reactors in the region were apparently available, capable of providing approximately 1.6 GVAr of additional reactive absorption capacity, they were not all connected to the grid. It is possible that, given the speed at which voltage fluctuations developed, there was insufficient time to mobilise these resources.

6 Sequence of events leading to the blackout

167 According to the Analysis Committee Report, starting at 12:32:57 CET within a period of 20 seconds three main generation losses occurred, prior to the cascade of disconnections that lead to the blackout:[56]

a. 12:32:57 CET: 355 MW trip in a substation in Granada.[57]

b. 12:33:16 CET: 730 MW trip in two substations in Badajoz.[58]

c. 12.33:17 CET: 550 MW trip in a substation in Seville. [59]

168 This sequence is broadly consistent with the data provided by AELEC Members.

- Regarding the timing and location of the three disconnection events:
  - The information provided by AELEC Members confirms that the first generation trip was in Granada at 12:32:57 CET. The installed capacities of the generation plants that trip in Granada is consistent with a generation loss of 355 MW.
  - The information provided by AELEC Members shows that a substation in the Badajoz region, connecting 831 MW of solar PV and concentrated solar power (CSP) plants, was disconnected at 12:33:16 CET.
  - The information provided by AELEC Members does not allow us to confirm the third generation loss which took place in Seville.
- Regarding the causes of these disconnections, AELEC Members do not have data on the first substations that tripped in the main events according to the Analysis Committee Report. However, AELEC Members have informed us that their plants did not experience incorrect tripping.

169 According to REE, the capacity lost during these events was largely due to improper disconnection by generation plants not justified by voltage conditions. Nevertheless, the widespread and nearly simultaneous disconnection of dozens of geographically dispersed plants—spanning various

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[56] See Analysis Committee Report, pages 41-45. In addition to these three main events, the disconnection of smaller-scale generation units has also been detected, occurring intermittently in time with the main events.

[57] Before the first event, between 12:32:00 and 12:32:55, the Analysis Committee Report identifies small-scale generation losses totalling 525 MW across the territory, of which 317 MW originated from distributed generation and the rest in plants with installed capacity greater than 1 MW.

[58] In the same second, the Analysis Committee Report also identifies two smaller disconnections—one in Segovia (23 MW) and another whose location and capacity are not specified.

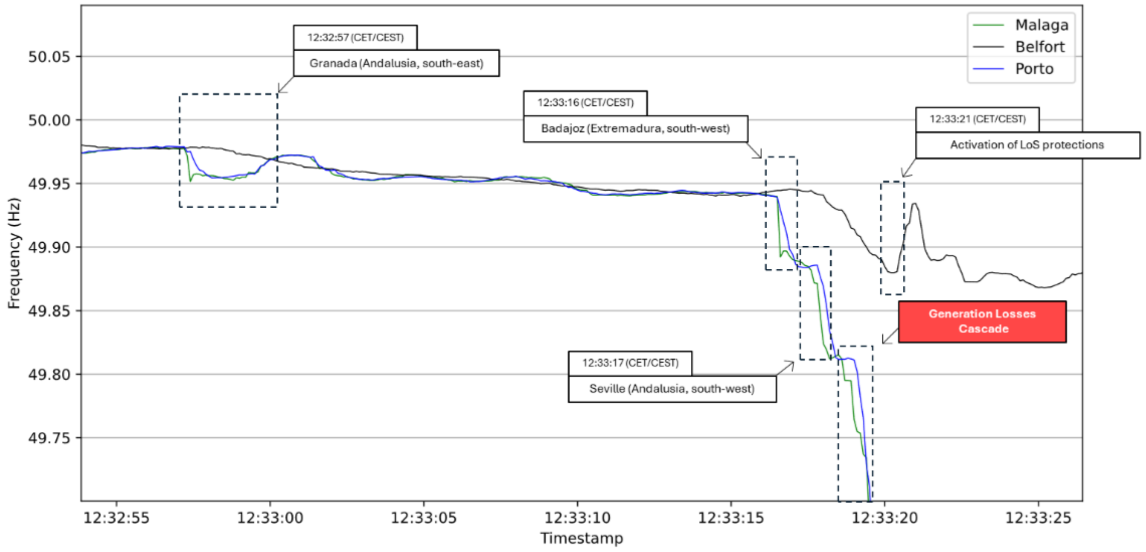
[59] In the same second, the Analysis Committee Report also identifies two smaller disconnections, one in Badajoz and another in Cáceres, although their capacities are not specified.

technologies and owners—suggests that individual failures alone are an insufficient explanation. This pattern instead points to a systemic issue affecting a broader segment of the power system.

170 In what follows we present further details on our findings.

171 Figure 23 shows the frequency measurements taken by the INESC TEC PMUs (Grid Radar), which allows to verify and understand the generation losses that took place at those instants.

Figure 23: Frequency evolution seconds before blackout



Notes: The X axis shows the time in UTC+0; to convert it to Spanish peninsular time, add two hours.
Source: INESC TEC PMU.

172 The above figure shows that there are three frequency decreases (first three boxes in the illustration above) that coincide with the generation trips reported by the Analysis Committee. There is also a very pronounced decrease in frequency (last box, in red) that corresponds to a cascading generation loss and a loss of synchronicity with the rest of the European system.

173 The evolution of the frequency and the progressive disconnection of generation and demand - as a result of the underfrequency load shedding protection - was verified by means of a two-area dynamic model representing the Iberian system interconnected with the Central European grid.

174 The following is an analysis of the sequence of events recorded in the last seconds before the April 28 blackout.

First generation loss (12:32:57 CET)

175 According to the information provided by AELEC Members, we have been able to verify that the system frequency suffers a disturbance compatible with the disconnection of a volume of generation estimated between 300 and 400 MW, as reported by the Analysis Committee. This trip occurs in a substation in the province of Granada.

176 We have identified that the cause of the disconnection was an overvoltage: the substation reached a value of 260 kV, exceeding the operational threshold of 253 kV. After this event, the frequency temporarily recovered.

Second generation loss (12:33:16 CET)

177 Shortly after, a second disconnection occurred with a frequency impact consistent with the loss of between 700 and 800 MW, as reported by the Analysis Committee. This trip occurs in two substations in the province of Badajoz.

178 The information provided by AELEC Members is insufficient to confirm whether the disconnection was caused by overvoltage. Some AELEC Members operate generation plants connected to this substation and reported disconnections due to overfrequency, as the substation tripped first, isolating the plants from demand. However, since the substation is operated by third parties, AELEC Members do not have access to its specific operational data, and thus cannot confirm the cause of its disconnection. Nonetheless, the relatively small frequency drop observed at that time is consistent with a disconnection triggered by overvoltage.

Third generation loss (12:33:17 CET)

179 A second later, a new generation trip was recorded, estimated at about 800 MW in Sevilla, according to Analysis Committee.[60] The small drop of frequency observed at that moment suggests an overvoltage trip.

180 The information provided by AELEC Members does not allow to confirm or refute that this generation loss, or most of this generation loss, took place in Sevilla. However, the data shows disconnections due to overvoltage of solar PV and wind plants within that second (i.e. between 12:33:17 CET and 12:33:18 CET) in other areas of the peninsular system, including Cáceres, Huelva and Cuenca. These plants amount to a combined installed capacity of 1 GW.

181 According to REE in the time frame of these three events, approximately 2,000 MW of renewable generation—along with a substantial amount of distributed generation connected to the distribution network and below 1 MW—was lost.[61] REE attributes a significant portion of these disconnections to improper responses of the equipment to overvoltage conditions.

182 However, this volume of lost generation implies the near-simultaneous disconnection of dozens of substations and renewable plants, involving multiple technologies, dispersed across different geographical areas, and operated by a wide variety of owners.

183 Given this diversity, it is highly unlikely that all of these installations would have independently experienced failures due solely to individual malfunctions or local settings. This strongly suggests that the root cause may lie in a systemic issue affecting a broader segment of the power system, rather than isolated faults at the plant level, such as the lack of sufficient voltage control.

Cascade generation loss due to overvoltage and loss of synchronicity (12:33:18 CET - 12:33:21 CET)

184 The information provided by AELEC Members shows, during this period, disconnections due to overvoltage in the regions of Cáceres and Badajoz.

185 During this period, at 12:33:19 CET, the Iberian Peninsula started to lose synchronism with the European System, and the 49.8 Hz threshold was crossed. This activated the first step of pumped storage shedding (disconnection of pumped storage acting as consumption units) to control the imbalance between generation and demand, but this was insufficient as the frequency continued to fall.

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[60] Besides the smaller disconnections identified by the Analysis Committee Report in Badajoz and Cáceres, we have also identified disconnections in Ávila, Cádiz, Cuenca and Huelva.

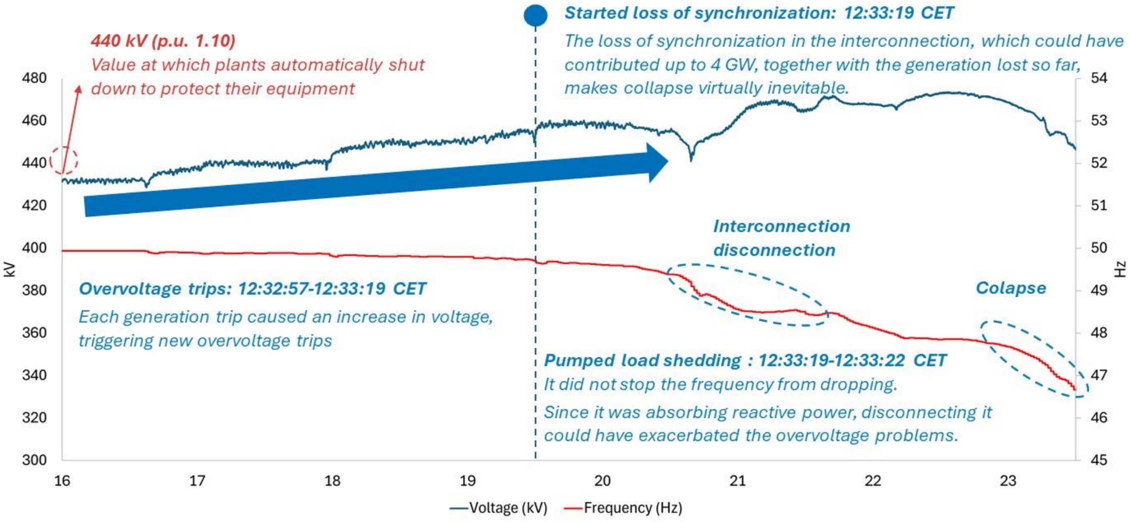
[61] See REE Blackout Report, pages 9-11.

186 Figure 24 shows –the evolution of voltage in a substation in Extremadura from 12:33:16 CET to the collapse of the system. This pattern is consistent with a scenario in which the disconnected plants were absorbing reactive power and, upon disconnection, stopped doing so, contributing to a new voltage escalation. This dynamic would have led to cascading disconnections of additional generation blocks.

187 During this period, at 12:33:19 CET, the Iberian Peninsula started to lose synchronism with the European System, and the 49.8 Hz threshold was crossed. This activated the first step of pumped storage shedding (disconnection of pumped storage acting as consumption units) to control the imbalance between generation and demand, but this was insufficient as the frequency continued to fall.

188 The simulations carried out show that the loss of interconnection, combined with the loss of generation until 12:33:19 CET, makes the collapse of the system practically inevitable from this point onwards.

Figure 24: Voltage and frequency evolution seconds before the blackout



440 kV (p.u. 1.10)
Value at which plants automatically shut down to protect their equipment

Started loss of synchronization: 12:33:19 CET
The loss of synchronization in the interconnection, which could have contributed up to 4 GW, together with the generation lost so far, makes collapse virtually inevitable.

Interconnection disconnection

Colapse

Overvoltage trips: 12:32:57-12:33:19 CET
Each generation trip caused an increase in voltage, triggering new overvoltage trips

Pumped load shedding : 12:33:19-12:33:22 CET
It did not stop the frequency from dropping.
Since it was absorbing reactive power, disconnecting it could have exacerbated the overvoltage problems.

Notes: This automatic disconnection limit applies to generation facilities connected to 400 kV.
Source: Own analysis based on information from AELEC Members.

Disconnection of the interconnection with the Central European System (12:33:21 CET)

189 At this time, the overhead alternating current lines between France and Spain are disconnected due to the operation of the protection systems against loss of synchronism.[62]

Underfrequency cascade generation loss and blackout (12:33:19 CET - 12:33:24 CET)

190 The massive loss of generation, coupled with the disconnection of the interconnection with Central Europe, causes an accelerated drop in frequency. The pumping load shedding mechanism activated its final step at 12:33:22 CET, ultimately disconnecting over 5 GW of pump demand across Spain and Portugal. However, neither of this measure nor other emergency actions were able to stop the deterioration of the frequency, which continued to plummet, producing the blackout at 12:33:24 CET. More than other 5 GW of load was disconnected from the distribution grids of Spain

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[62] See https://www.entsoe.eu/news/2025/05/09/entso-e-expert-panel-initiates-the-investigation-into-the-causes-of-iberian-blackout/

and Portugal during the dropping frequency trajectory, but again this was not sufficient to stop the decrease of frequency that showed RoCoF values larger than 1.5 Hz/s.[63]

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[63] RoCoF stands for Rate of Change of Frequency. It measures how quickly the system frequency changes over time.

7 Operation of the system in the days after the blackout

191 After the blackout of April 28, the operation of the Spanish electricity system underwent notable changes. A significant increase in the amount of conventional capacity — primarily CCGTs — was introduced through the Technical Restrictions Procedure to help mitigate voltage oscillations.

192 Overall, the increased use of conventional resources after the blackout appears to have strengthened the system's ability to regulate voltage. The available evidence indicates that if more conventional capacity would have been coupled on April 28, the blackout would have been prevented.

7.1 Changes in the operation of the system after the blackout

193 The days prior to the blackout, the system was operating with a limited share of conventional generation units capable of contributing dynamically to voltage control. According to REE, this was one of the factors contributing to the voltage oscillations observed on April 16, 22 and 24.[64]

194 Specifically, before April 28, between 10:00 CET and 18:00 CET, the system operated, on average, with 10 CCGT units running at their minimum stable output and four nuclear units operating at full capacity.[65]

195 However, after the blackout it is evident that the number of conventional units coupled to the system have increased considerably. During the same hours, the average number of CCGT units coupled to the system increased from 10 to 20, while the number of nuclear units remain equal.[66]

196 Figure 25 illustrates this shift in dispatch configuration before and after the blackout.

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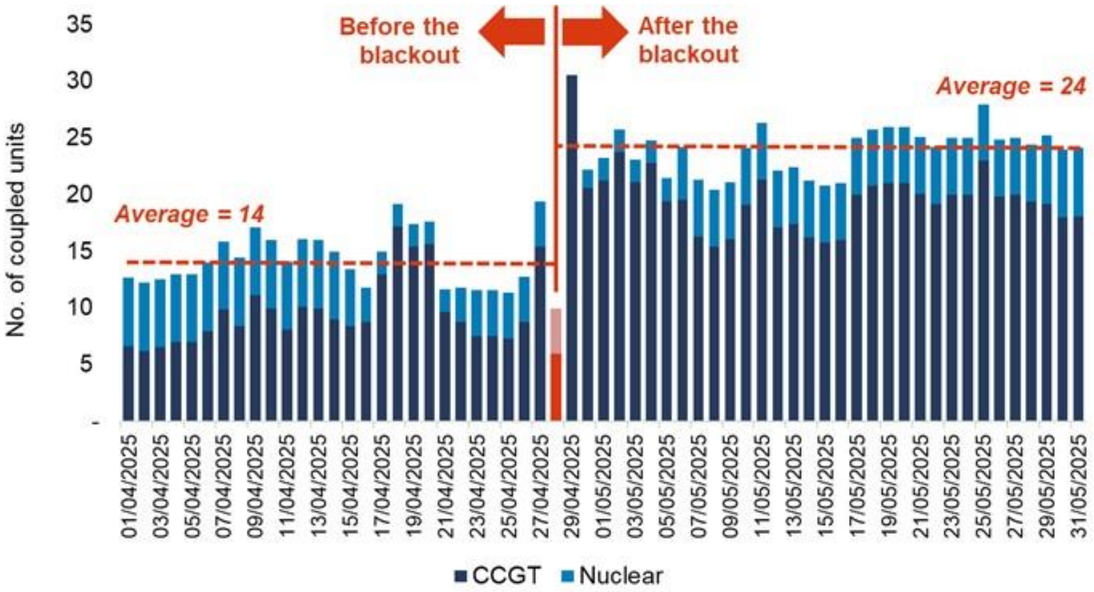
[64] Confidential communications with REE provided by AELEC Members.

[65] Estimation based on the information provided by ENTSO-E in its Transparency Platform between April 1 and April 27. The 10:00 CET – 18:00 CET window is used for the analysis, as it captures the hours of highest solar output, when the system relies more on non-synchronous generation. Outside this period, conventional generation would be needed regardless, making comparisons less informative.

[66] Considers the period from April 29 to May 31.

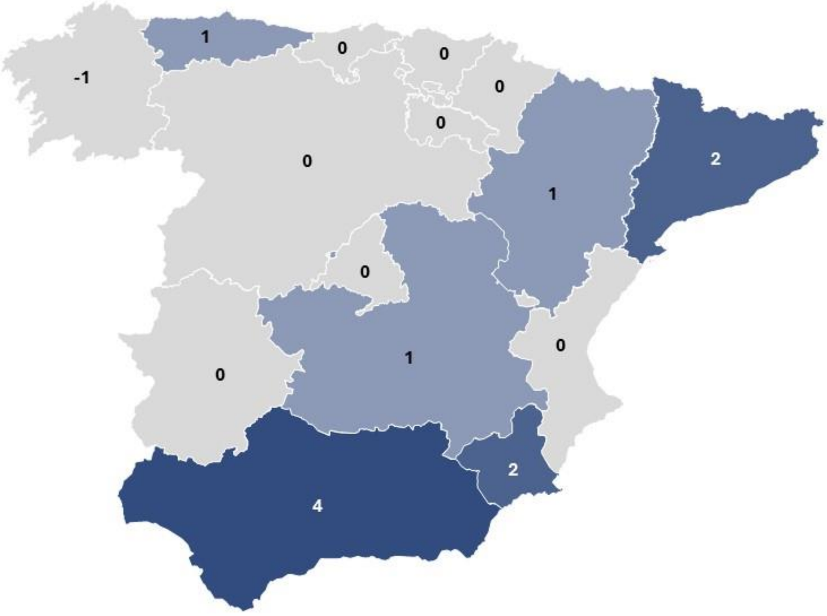
Figure 25: Average number of CCGT and nuclear units coupled between 10:00 CET and 18:00 CET before and after the blackout



Source: Own analysis based on information from ENTSO-E Transparency Platform.

197 This average increase of 10 coupled conventional generation units has not been evenly distributed across the electricity system. Figure 26 breaks down, by region, the additional conventional units scheduled after the blackout.

Figure 26: Increase in the number of CCGT and nuclear units coupled between 10:00 CET and 18:00 CET after the blackout



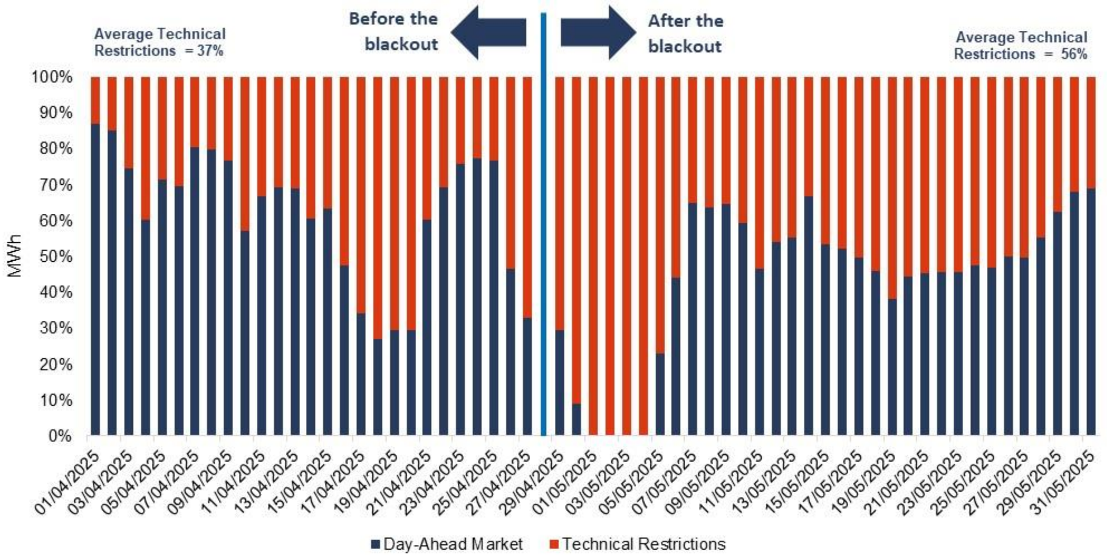
Source: Own analysis based on information from ENTSO-E Transparency Platform.

198 Larger increases are observed in the southern regions, where voltage fluctuations were particularly pronounced, especially in Andalusia, where early generation trips occurred in April 28. In that region, the number of conventional units coupled rose from 2 to 6.

199 It is important to emphasize that this increase was not the result of changes in the day-ahead market. Rather, it reflects adjustments made by REE through the Technical Restrictions Procedure to guarantee the security of the system.

200 The Figure 27 below illustrate the quantity of energy introduced to the system through the day-ahead market via the Technical Restriction Procedure.

Figure 27 : Average CCGT and nuclear energy coupled in day-ahead market and Technical Restriction Procedure between 10:00 CET and 18:00 CET before and after the blackout



Source: Own analysis based on I3DIA files provided by REE.

201 Before the blackout, between 10:00 CET and 18:00 CET, 37% of the energy generated by CCGTs and nuclear units was introduced through the Technical Restrictions Procedure. Whereas after the blackout, this percentage rose to 56%. Notably, all energy generated by CCGTs during this period was dispatched exclusively via the Technical Restrictions Procedure.

202 This indicates that, after the blackout, the System Operator relied more heavily on the Technical Restrictions Procedure to couple additional generation capacity — particularly CCGTs — capable of delivering effective voltage control.

7.2 Impact of more conventional capacity coupled on voltage behavior

203 To assess the impact of increased conventional generation on voltage behavior, we have analysed voltage fluctuations at several geographically dispersed nodes of the transmission network. Specifically, we have compared voltage measurements recorded between April 16 and May 10 — a 12-day window before and after the blackout. For each day, we compute the average voltage variation between consecutive readings within the 10:00 to 12:00 CET interval.[67]

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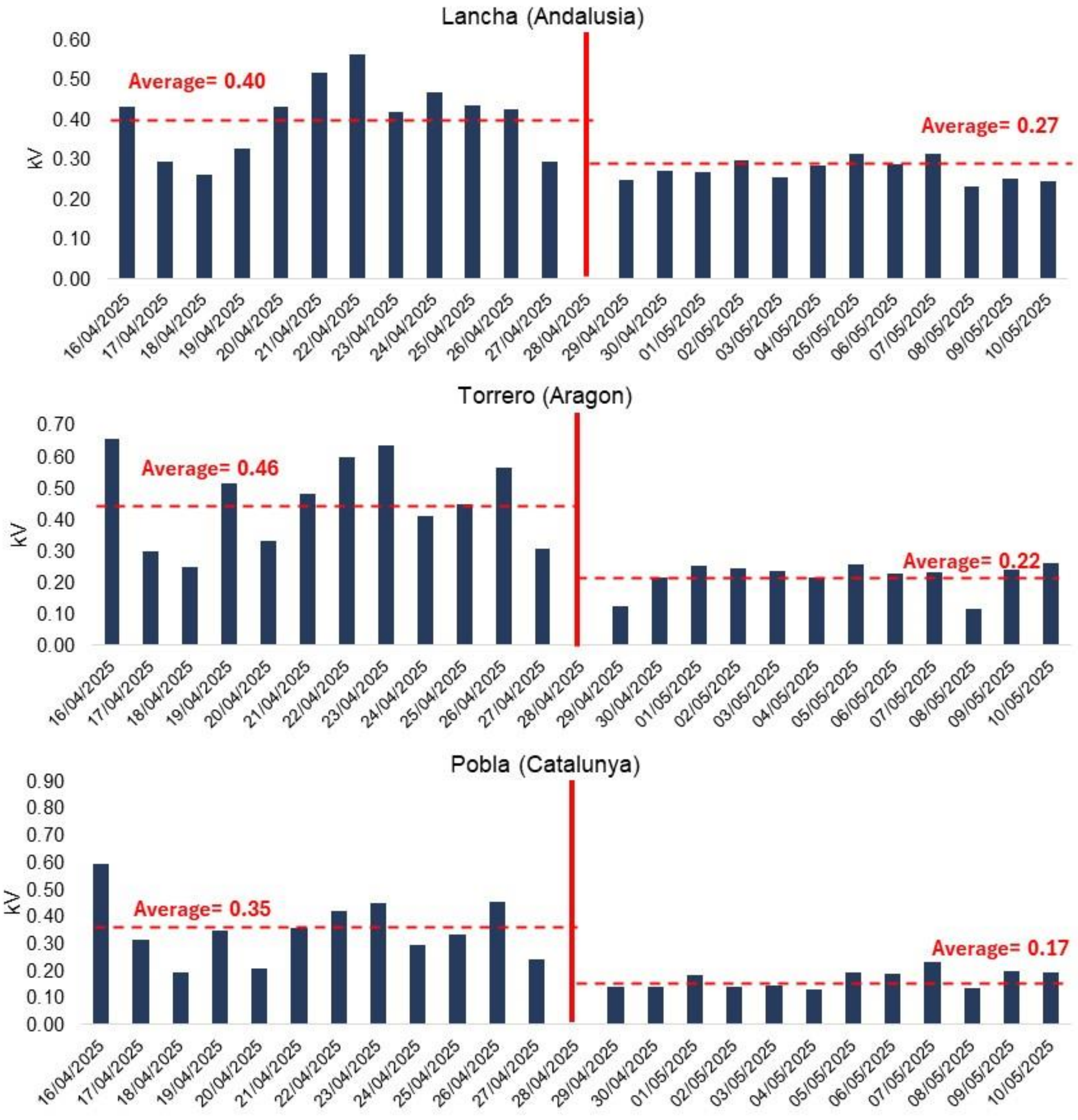
[67] The temporal granularity of the voltage measure available is 30 seconds. The 10:00 CET – 18:00 CET window is used for the analysis, as it captures the hours of highest solar output, when the system relies more on non-synchronous generation. Outside this period, conventional generation would be needed regardless, making comparisons less informative.

204 Figure 28 presents this comparison for three representative substations: Lancha (Andalucía), Pobla (Catalunya), and Torrero (Aragón). It also illustrates the average level of voltage volatility observed before and after the blackout.

Figure 28: Comparison of voltage stability before and after the blackout

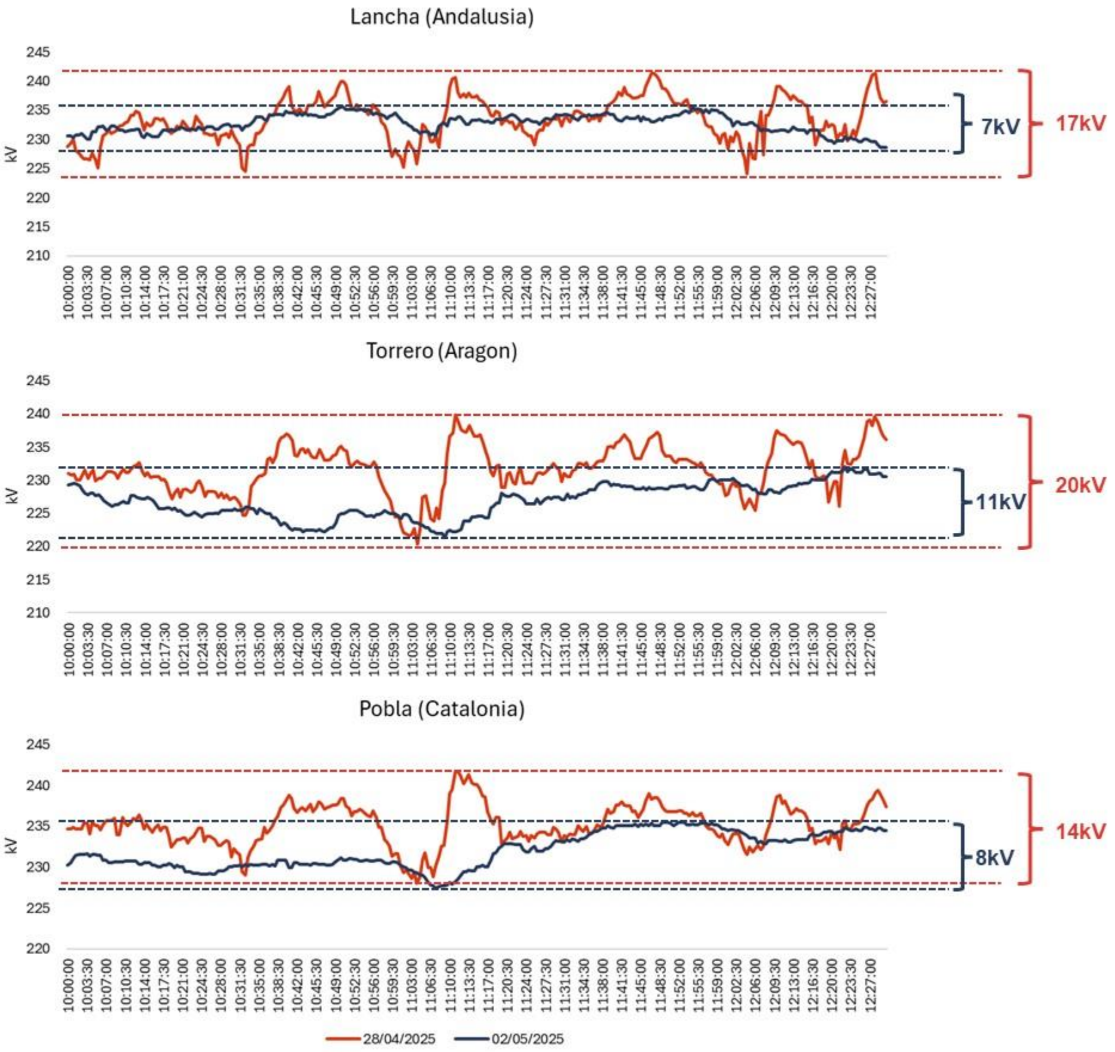


Source: Own analysis based on information from AELEC Members.

205 The results reveal a clear improvement in voltage behavior following the blackout, when a greater volume of conventional capacity was coupled to the system. Specifically, average voltage variation decreased by 37% in Andalucía and by 52% in both Aragon and Catalunya.

206 To further illustrate this pattern, Figure 29 presents a direct comparison of voltage evolution between April 28 and May 2 at the same nodes. May 2 is selected because its level of voltage volatility — measured by average deviation — is the closest to the mean volatility observed across the days following the blackout. As such, it provides a representative example of typical post-blackout voltage behaviour.

Figure 29: Comparison of voltage profiles on April 28 and May 2 at selected nodes



Source: Own analysis based on information from AELEC Members.

8 Preliminary evaluation on how the blackout could have been prevented

207 In this section we present a preliminary evaluation on how the blackout could have been prevented.

208 The information provided by AELEC Members indicates that the sequence of events that led to the blackout was originated by a lack voltage control. While we do not have information on all the actions taken by the SO to stabilize the voltage on the morning of April 28, conversations between the control centers of the distributors and the SO control center reveal that the SO had many difficulties in controlling the voltage using real time voltage control measures, such as the use of reactors.

209 The coupling of additional conventional generation capacity on the morning of April 28, such as CCGTs, capable of providing effective voltage support would have prevented the incident. In this regard, a comparison of voltage evolution between April 28 and May 2 at different boundary buses of the transmission grid, clearly shows that the additional conventional generation capacity coupled after the blackout significantly dampened the voltage fluctuations observed in the morning of April 28 and the previous days.

210 While it is clear that if the SO had scheduled additional conventional generation capacity the blackout would have been prevented, the available information and the lack of data for full power flow simulation studies does not allow for a precise quantification of how much capacity would have been needed, or where specifically it should have been located. Nevertheless, the available evidence suggests that conventional generation capacity was mostly needed in the southern regions of Spain.

211 The information provided by AELEC Members does not allow for an analysis of whether the conventional generation capacity connected to the system on the morning of April 28 — which provided dynamic voltage control — was sufficient to meet the N-1 criterion established in Operating Procedure 1.1 – Operating and Safety Criteria for the Operation of the Electrical System.[68] In particular, this procedure requires that the system must be operated in such a way that, following the failure of any single transmission element, the system remains within normal voltage limits and continues to operate securely.

212 In addition, we do not have information prior to 12:00 CET on the use of reactors by REE on the morning of April 28 in the areas initially most affected by overvoltage. In particular, as illustrated in Table 3 the System Operator had installed in the Andalusia region reactors with a capacity of at least 1,550 MVAr while as of 12:30 CET, the conventional generators operating in the same region provided only 117 MVAr of voltage control capability. In the whole of Andalusia, there was only one unit (a CCGT) providing effective voltage control. The remaining 97% of the generation in the region was produced by plants that do not provide dynamic voltage control.

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[68] We have not assessed the compliance by generation units of reactive power requirements established in Operating Procedure 7.4. We have been informed that different third-party technical experts are analysing this issue.

213 Any conclusive analysis would require all the data associated to the operation conditions of the system, such as grid topology, activation of reactors and FACTS, grid electrical parameters, active and reactive loads, active power dispatched in the conventional and renewable generation, or grid and generation technical restrictions. Only the SO has access to this information.

214 Since the HVDC link operated in AC emulation mode seems to have an ADC controller with a large time constant (50 seconds), operating it in this mode would not have provided clear advantages over constant DC power mode.

9 Issues that remain to be analyzed

215 While this report provides a preliminary assessment of the April 28 blackout, a number of relevant questions remain open. Addressing these questions is required for a comprehensive understanding of the causes of the April 28 blackout and for strengthening the system's resilience moving forward.

216 However, doing so will require access to more detailed information—particularly regarding grid topology, real-time system conditions, voltage and reactive power flows, and the precise sequence of operational decisions made in the hours leading up to the event. Only REE has access to this data.

217 What follows is a set of issues and questions that require further investigation.

a. **Actions taken by REE after the episodes on previous days**: What measures did REE implement to prevent a recurrence of the overvoltage episodes observed in the days prior to April 28—episodes that had already led to the disconnection of both demand and generation nodes?

b. **Compliance with N-1 criterion**: Did the generation schedule for April 28 comply with the N-1 criterion set out in P.O. 1.1? In particular, was the system capable of maintaining voltage control if either of the two conventional generation units in the southern zone had become unavailable?

c. **Justification for not replacing the unavailable CCGT unit:** Why did REE determine at 14:00 on April 27 that it was necessary to dispatch a CCGT unit in Western Andalusia for April 28, and then revise that assessment just six hours later—at 20:00—by deciding not to replace the unit once it was declared unavailable?

d. **Systemic situation and triggering of plants:** Is it plausible that more than 2,000 MW of capacity—spanning numerous installations, technologies, and locations—could disconnect within 20 seconds solely due to incorrect tripping, absent an underlying systemic cause?

e. **REE maneuvers minutes before the blackout:**

    i. Why, in its efforts to control voltage in the minutes before the blackout, did REE call on CCGT units instead of dispatching available hydroelectric plants in Extremadura, which have faster start-up times?

    ii. Given the limited reactive power absorption capacity at 12:00 CET, was the system capable of absorbing the additional reactive power generated by REE's own maneuvers (e.g., line reclosures and reactor disconnections)?

    iii. Why is there no transparent information regarding the technical parameters of the HVDC? This is particularly relevant considering that the forthcoming HVDC interconnection via the Vizcaya Gulf will also be HVDC-based.

f. **Broader issues to consider going forward:**

    i. What are the voltage and frequency control requirements for maintaining stability in a system with high levels of non-synchronous renewable generation?

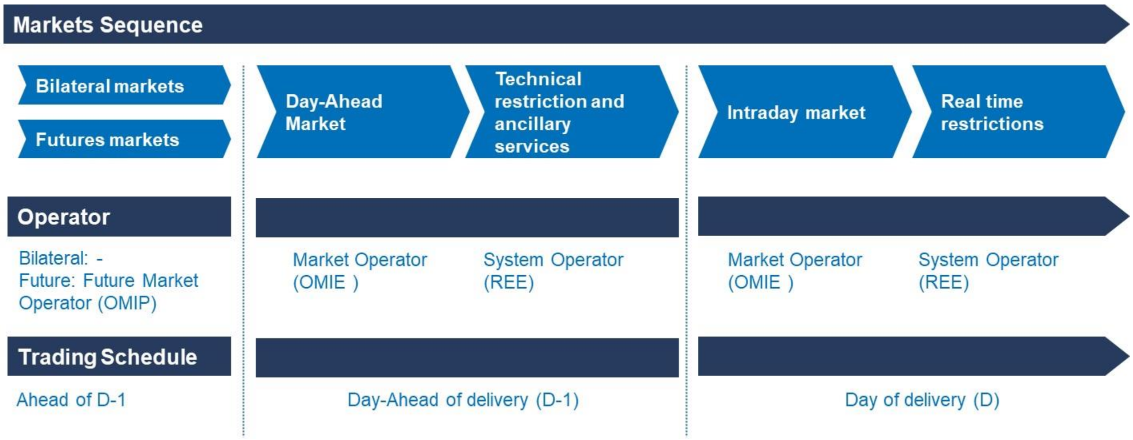
ii. What are the implications of quarter-hourly market resolution for real-time system operations and stability?

A. Annex A: Sequence of markets in the Spanish power system

218 The final generation schedule in the Spanish electricity system is the outcome of a structured sequence of market mechanisms. These include bilateral and forward markets, the day-ahead market, the intraday market, and the balancing and ancillary services markets.

219 Figure 30 summarizes the sequence of markets, indicating the timing of each process and the responsible entities.

Figure 30: Sequence of markets



Source: Own elaboration based on information from OMIE, OMIP and REE.

220 Below, we briefly describe each of these market mechanisms:

- **Bilateral and Futures Markets**: These refer to trading mechanisms that operate outside the centralized spot market. Bilateral markets involve direct contracts between two parties. Futures markets, in contrast, are standardized contracts traded on organized platforms such as OMIP. Both serve to hedge price risks and secure supply conditions over longer time horizons.
- **Day-Ahead Market**: Conducted on the day before delivery (D–1), this market determines the hourly dispatch schedule for the next day. Generators submit their offers, which are matched against demand bids. The last accepted offer sets the hourly price under a pay-as-clear mechanism. The Market Operator, OMIE, is responsible for managing this process using the Euphemia algorithm.
- **Technical Restrictions and Ancillary Services**: Following the clearance of the day-ahead market, the SO conducts an initial round of adjustments to resolve technical constraints that may compromise system security and operability. This involves modifying production, demand, or storage schedules as needed. In parallel, ancillary services markets are used to procure the reserve capacity required to maintain frequency stability and manage unexpected imbalances.

- **Intraday Market**: On the day of delivery (D), several intraday sessions are held to allow participants to revise their positions in light of updated forecasts for demand and renewable output. Like the day-ahead market, the intraday market is also managed by OMIE.

- **Real-Time restriction**: Finally, the results of the intraday sessions are submitted to REE, which supervises real-time system conditions and activates constraint-resolution mechanisms as necessary. These are executed through upward and downward energy bids to ensure the secure and continuous operation of the grid.

B. Annex B: High Voltage warning geographical disaggregation

221 This annex presents a geographic breakdown of the “High Voltage” warnings registered by the Control Centres of AELEC Members. It compares the number of warnings recorded on Monday, April 28, with those recorded on the previous Monday, April 21.

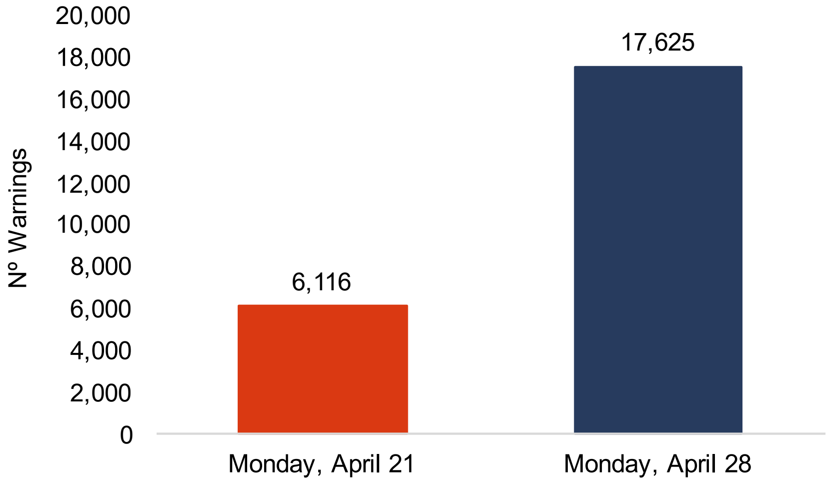
222 The data is grouped into five geographical areas, each aggregating alerts from different regions of the transmission network. The regional composition of each area is as follows:

- **North**: Basque Country, La Rioja, Navarra, Aragón.
- **West**: Castile and Leon.
- **Center**: Madrid, Castilla-La Mancha, Extremadura.
- **East**: Valencia, Catalonia and Murcia.
- **South**: Andalusia.

223 The data is presented in two parts: first, a summary of total daily warnings by area; and second, the minute-by-minute warnings by area.

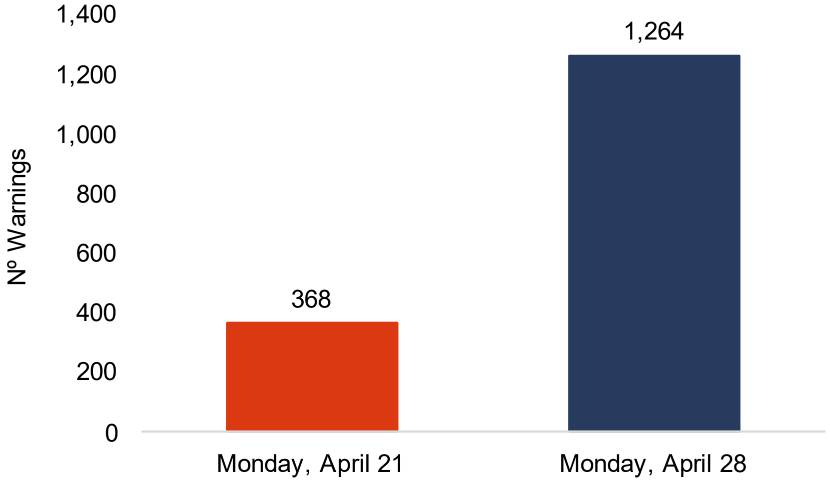
B.1 Daily “High Voltage” warning by geographical area

Figure 31: Evolution of "High Voltage" warnings, North



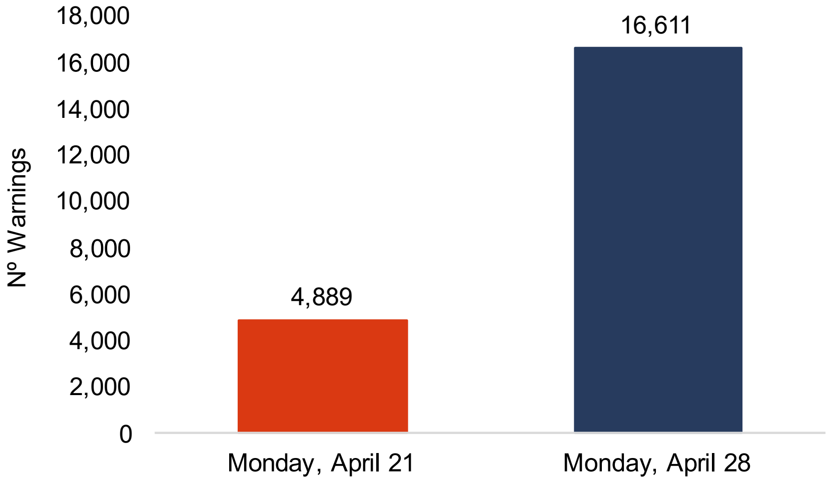
Source: Own analysis based on information from AELEC Members.

Figure 32: Evolution of "High Voltage" warnings, West



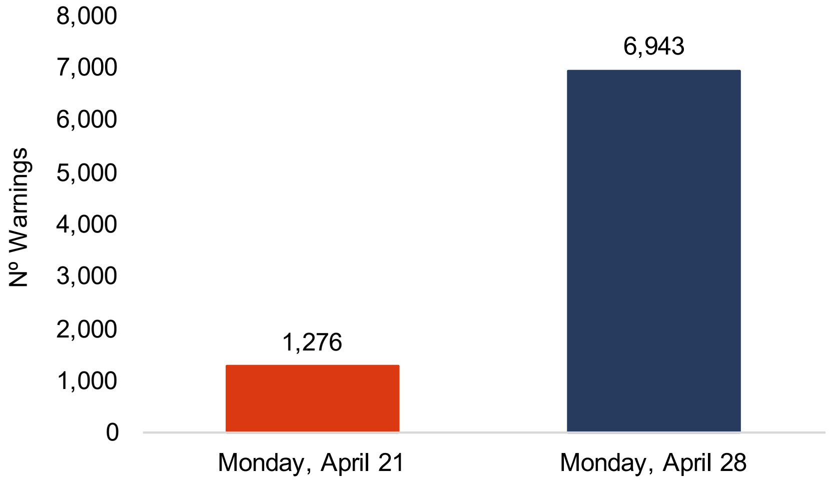
Source: Own analysis based on information from AELEC Members.

Figure 33: Evolution of "High Voltage" warnings, Center



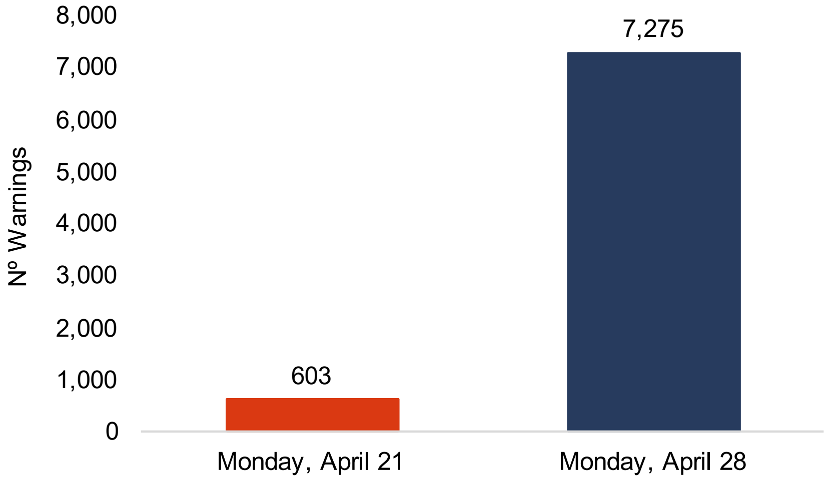
Source: Own analysis based on information from AELEC Members.

Figure 34: Evolution of "High Voltage" warnings, East



Source: Own analysis based on information from AELEC Members.

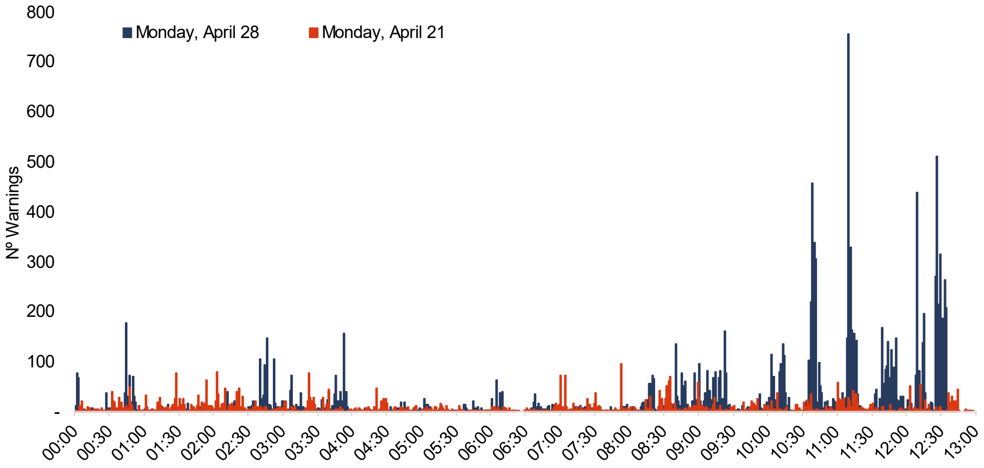
Figure 35: Evolution of "High Voltage" warnings, South



Source: Own analysis based on information from AELEC Members.

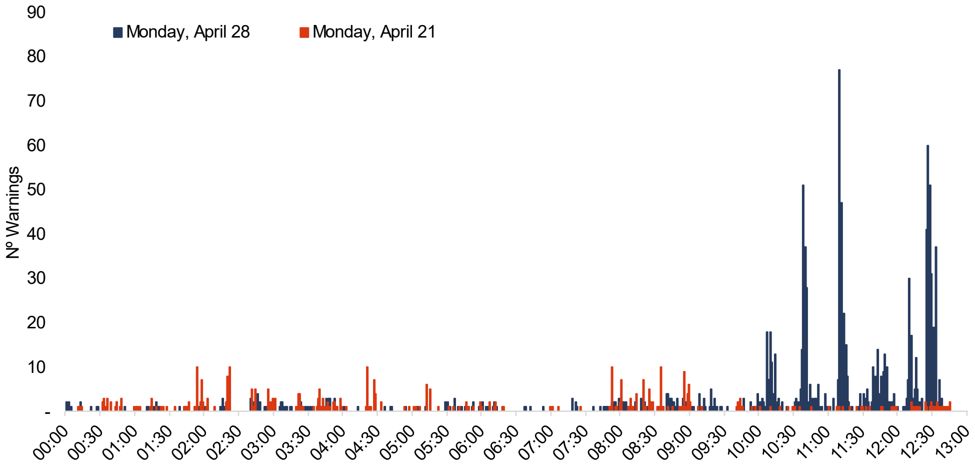
B.2 Minute-by-minute comparison of “High Voltage” by geographical area

Figure 36: Minute-by-minute comparison of “High Voltage” warnings, North



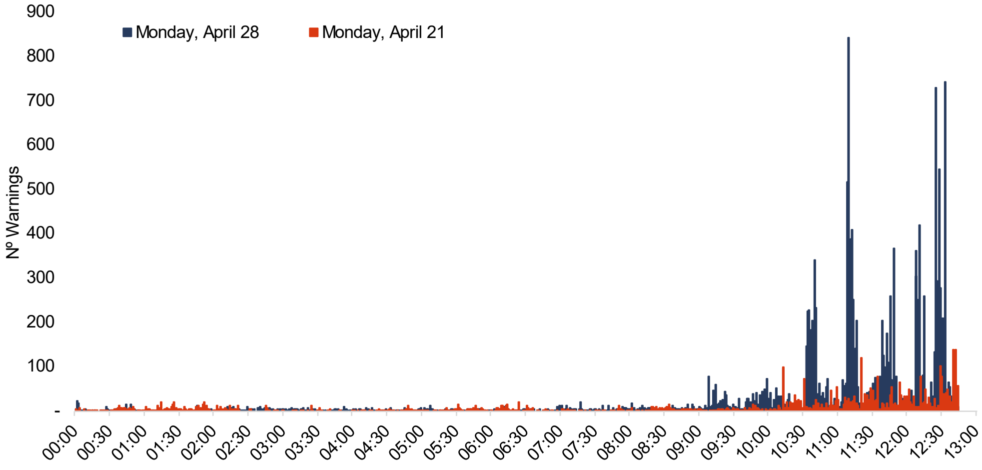
Source: Own analysis based on information from AELEC Members.

Figure 37: Minute-by-minute comparison of “High Voltage” warnings, West



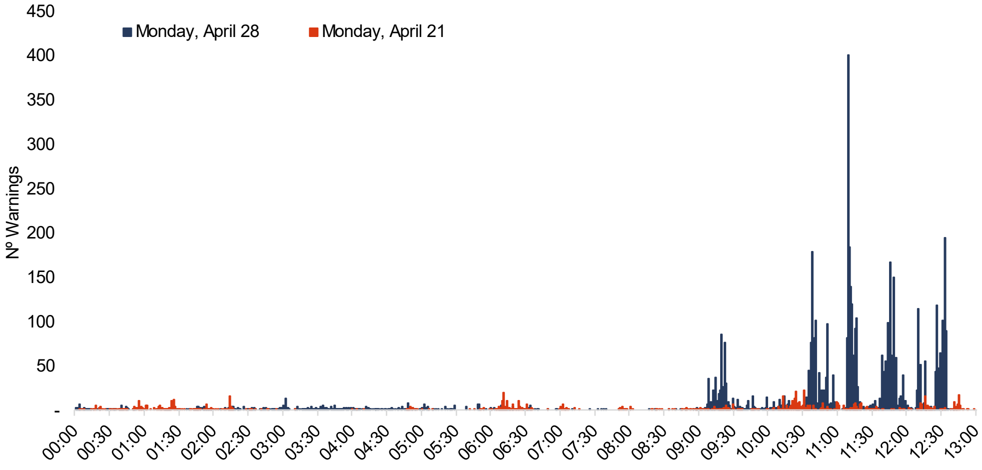
Source: Own analysis based on information from AELEC Members.

Figure 38: Minute-by-minute comparison of “High Voltage” warnings, Center



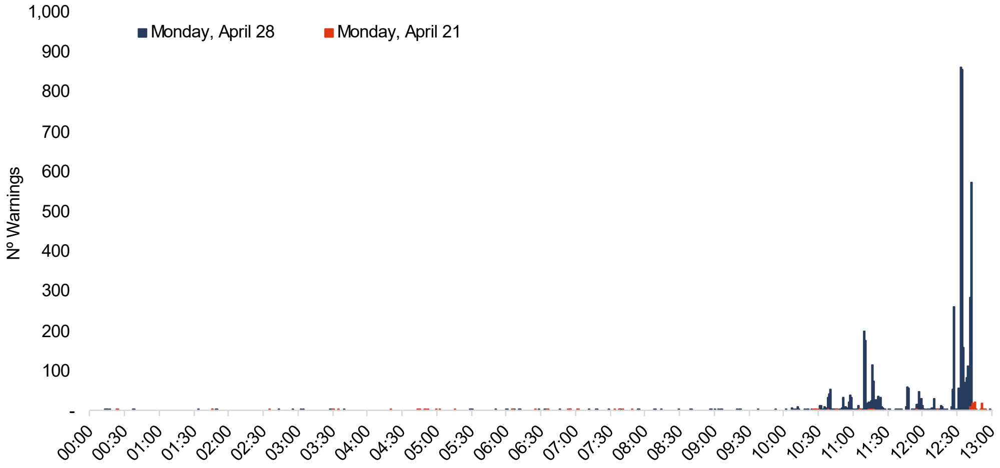
Source: Own analysis based on information from AELEC Members.

Figure 39: Minute-by-minute comparison of “High Voltage” warnings, East



Source: Own analysis based on information from AELEC Members.

Figure 40: Minute-by-minute comparison of “High Voltage” warnings, South



Source: Own analysis based on information from AELEC Members.