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

Compass Lexecon and INESC TEC

Compass Lexecon: Antón García, Albert Riera, Alberto Martín
INESCTEC: João Peças Lopes, Francisco Fernandes, Rui Sousa

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INESCTEC

COMPASS LEXECON

Compass Lexecon and INESC-TEC analysis

- This analysis is a joint work of:

COMPASS LEXECON

Multinational economic consultancy with a long track record in regulation and analysis of electricity markets

INESCTEC

Research and development institute of the Faculty of Engineering of the University of Porto, with more than 30 years of experience in the analysis and simulation of electrical systems

- The analysis is based on the following sources of information:
  - Information provided by AELEC Members, in their capacity as distributors and generators, encompassing approximately 45% of the installed capacity and 78% of the distribution networks.
  - Information disclosed by Red Eléctrica de España ("REE") and the "Analysis Committee" set up by the Spanish Government.(1)
  - Transcripts of conversations between AELEC Members' control centres and REE.
  - Simulation results with INESC TEC's proprietary models.
- For a more comprehensive analysis, additional information is required that is only available to REE.
- The conclusions of this document are preliminary, as there are matters that are still under analysis.

Source: NASA

(1) Committee for the Analysis of Circumstances that Concurred in the Electricity Crisis of 28 April 2025

The Analysis Committee's and REE's view of the facts is different

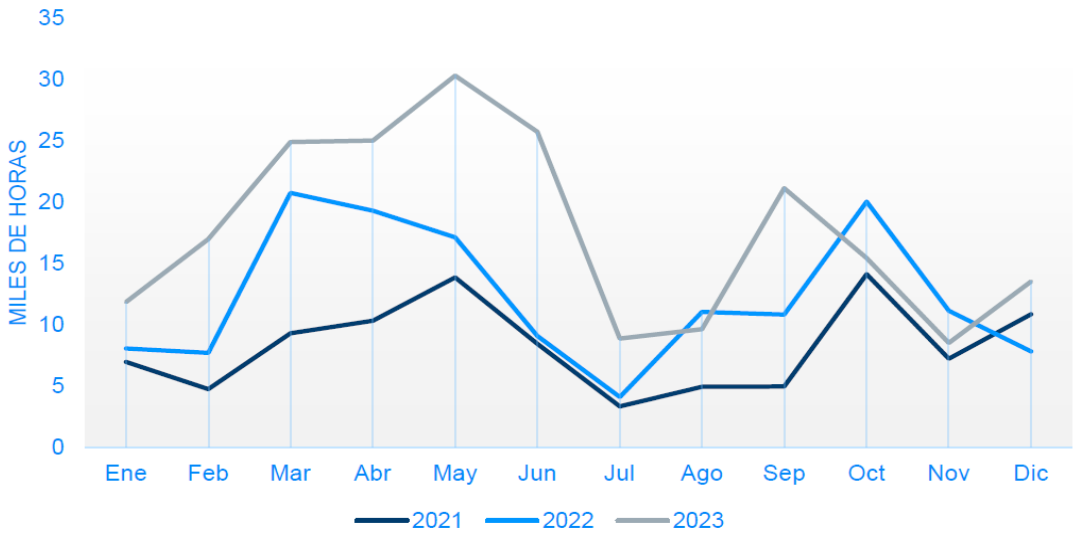
	1 Overvoltage in previous years	2 Voltage fluctuations in previous days	3 D-1 generation schedule	4 Voltage fluctuations between 10:00-12:00	5 Manoeuvres to dampen oscillations	6 Conventional generation voltage control	7 Reason for the tripping of the first plants	8 Operation in subsequent days
GOBIERNO DE ESPAÑA	Not analysed	There were significant fluctuations	Lowest number of coupled thermal power groups of the year	There were significant fluctuations	The change of interconnection to constant DC mode aggravated the situation	Failed to comply with regulations	Vicious circle of overvoltage and some incorrect tripping	Not analysed
RED ELÉCTRICA DE ESPAÑA	Not analysed	Not analysed	It was adequate	The situation was stable	The change of interconnection to constant DC mode did NOT aggravate the situation	Failed to comply with regulations	Incorrect tripping	Not analysed
COMPASS LEXECON INESCTEC	They have increased in recent years	There were significant fluctuations	The lowest capacity to control voltage in the year, lowest in the south	There were significant fluctuations	Pending analysis	There was not enough conventional generation to control voltage	Simultaneous failures without a systemic cause seem unlikely	Decrease in fluctuations

Our conclusions are largely in line with those of the Analysis Committee

Differences with Compass Lexecon and INESC TEC analysis

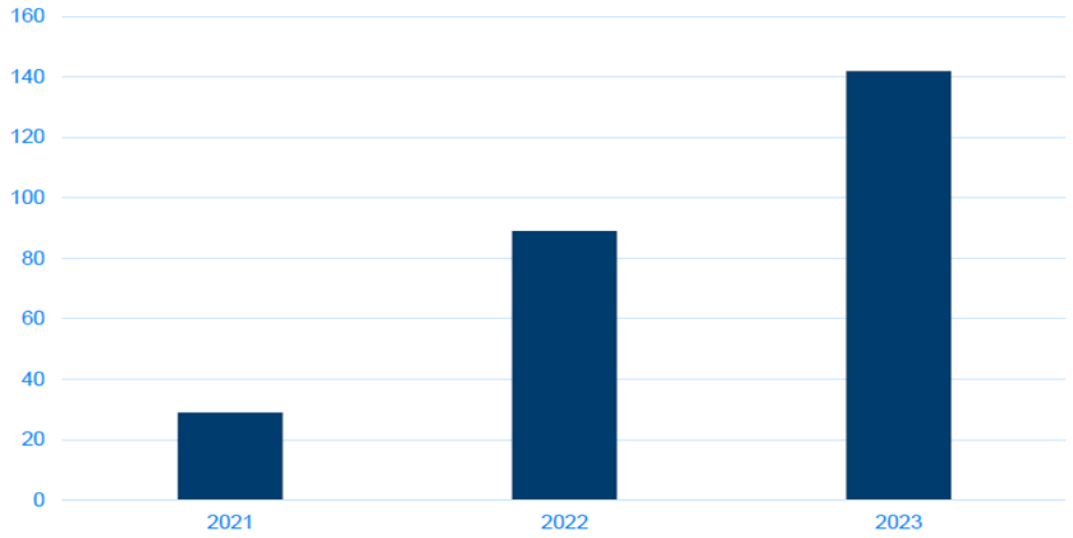
Overvoltage episodes in the transmission grid have increased in recent years

Number of hours with above-normal voltage at transmission grid nodes



Source: REE

Number of overvoltage disconnections at generation and demand sites



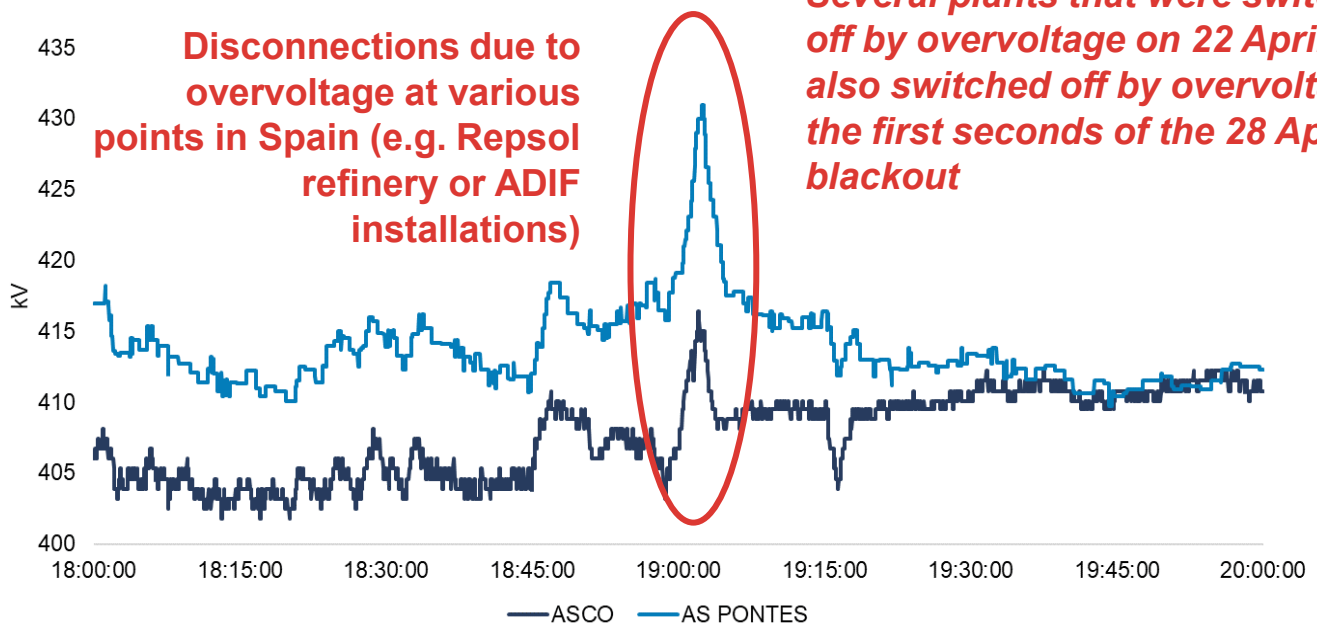
Source: REE

REE (2023): "At present, REE does not have sufficient tools to prevent voltages in the transmission grid from reaching very high levels, sometimes exceeding the admissible ranges established in the regulations"(1)

Source (1): REE (2023). Technical-economic report on the regulatory demonstration project for the new voltage control service of September 2023. Page 3. Own translation

On 16, 22 and 24 April, there were significant overvoltage episodes in the transmission grid

Measured voltage at Ascó (Catalonia) and As Pontes (Galicia) plants on 22/04/2024



The Analysis Committee identifies the reasons for these overvoltages

1. Low conventional generation coupled
2. Steep gradients of solar generation
3. Abrupt changes in interconnection flows

The events of 22 April suggest that voltage control was insufficient in some areas, and that this situation was not corrected on 28 April

Source: Own elaboration with data from AELEC Members and Report of the Analysis Committee on the causes of the blackout

REE is responsible for controlling voltage in the transmission grid and has several tools at its disposal for this purpose

D - 1 / Previous hours

Increasing conventional thermal generation (e.g. CCGTs) through Technical Constraints

REE has the capacity to schedule the conventional generation necessary to guarantee the security of the system

Real time

Increasing generation by real-time Technical Constraints

CCGTs may need hours of advance notice, hydro only a few minutes

REE specific equipment for voltage control (e.g. reactors)

Opening or closing transmission lines

Given the growing voltage problems, REE has been making greater use of these resources

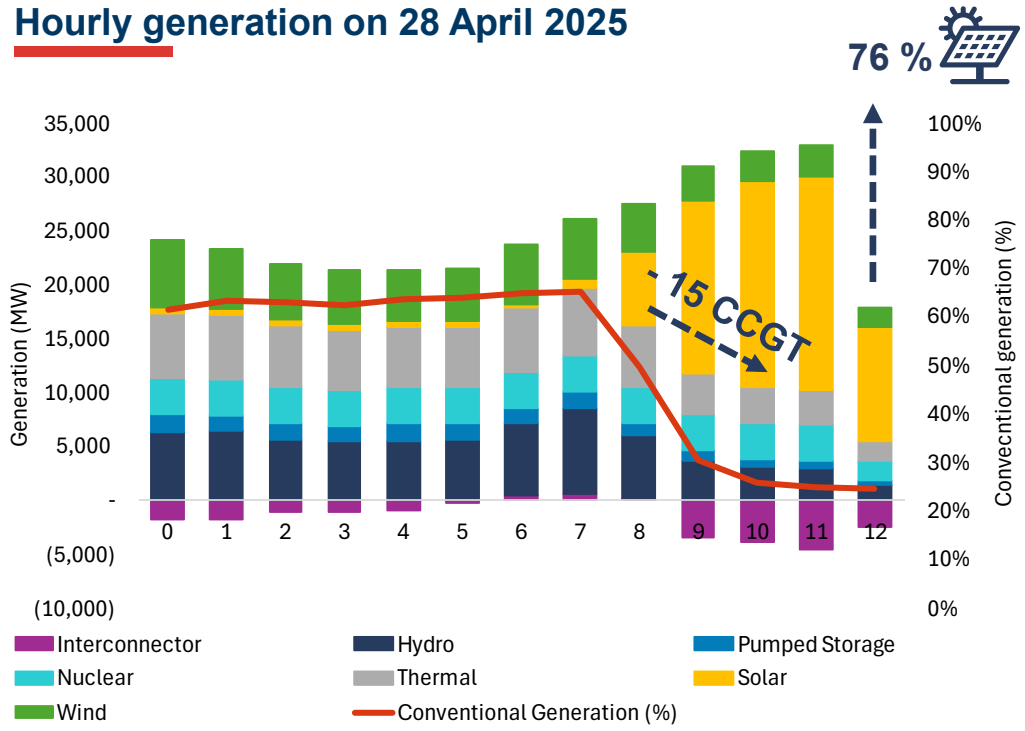
REE declared in January 2024 that these resources were being “exhausted”(1)

This makes it even more important to schedule sufficient conventional generation

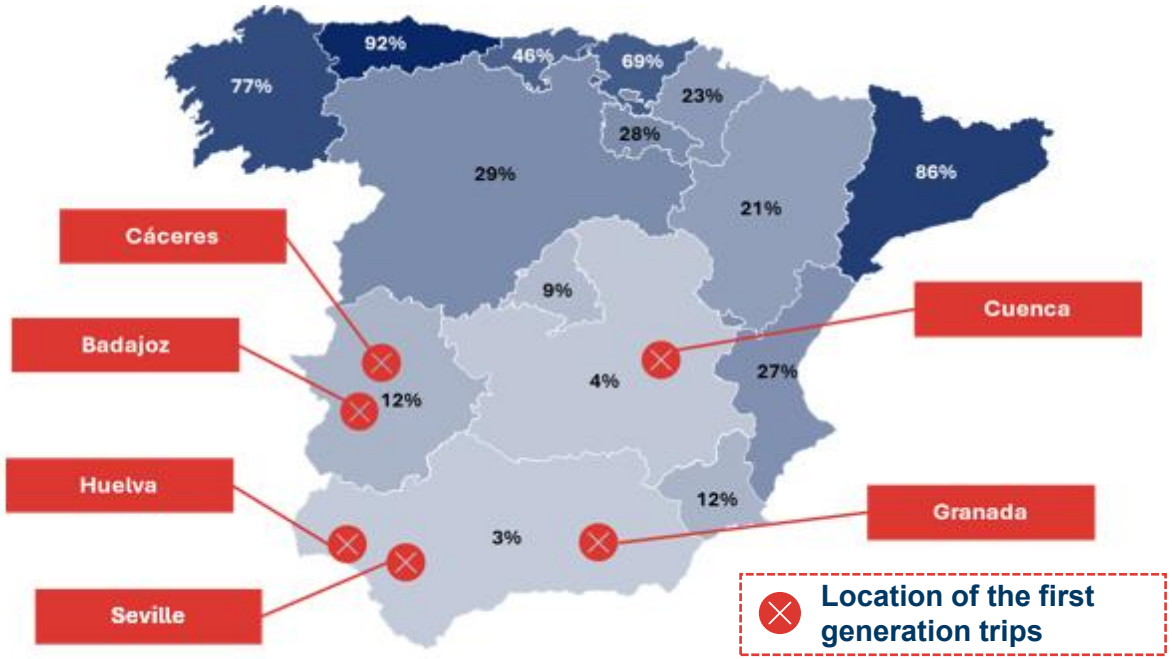
Source (1): REE (2024). Webinar public consultation on voltage control

The number of coupled thermal groups was the lowest of the year, and they were concentrated in the north

Hourly generation on 28 April 2025



Share of conventional generation at 11:00 CET on 28 April, by Autonomous Community (%)



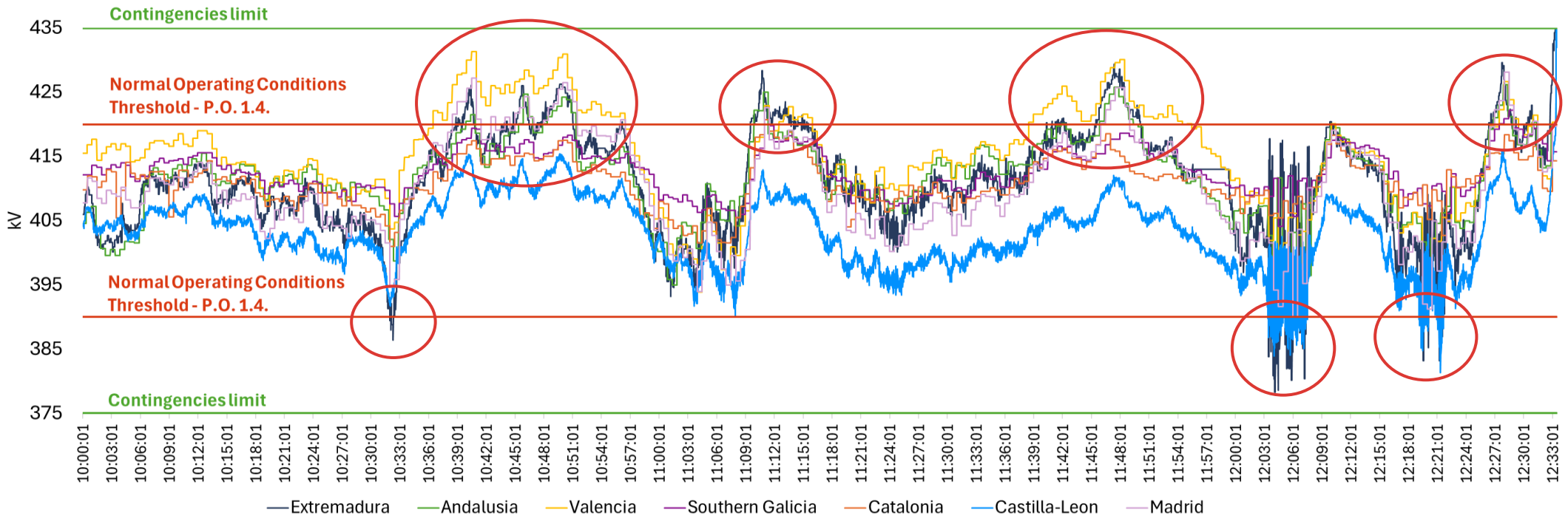
The generation schedule shares similarities with previous days, where there were instances of voltage fluctuations. REE decided not to replace a CCGT scheduled for the 28th in the southern area that was declared unavailable on the afternoon of the 27th due to a fire

Source: Own elaboration with data from REE and AELEC Members

Note: Generation trips observed between 12:32:57 and 12:33:17

Voltage fluctuations between 10:00-12:00

From 10:00, when the coupled CCGTs decrease, there are strong voltage fluctuations that repeatedly exceed the limits of normal operating conditions



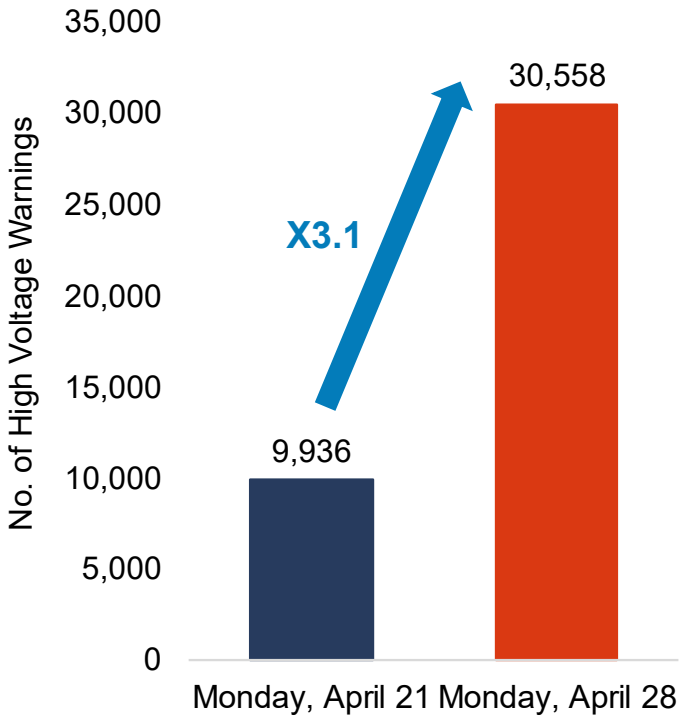
AELEC Members' conversations with REE's control centre reveal that REE was aware of the strong voltage fluctuations and the existing concerns

Source: Own elaboration with data from AELEC Members

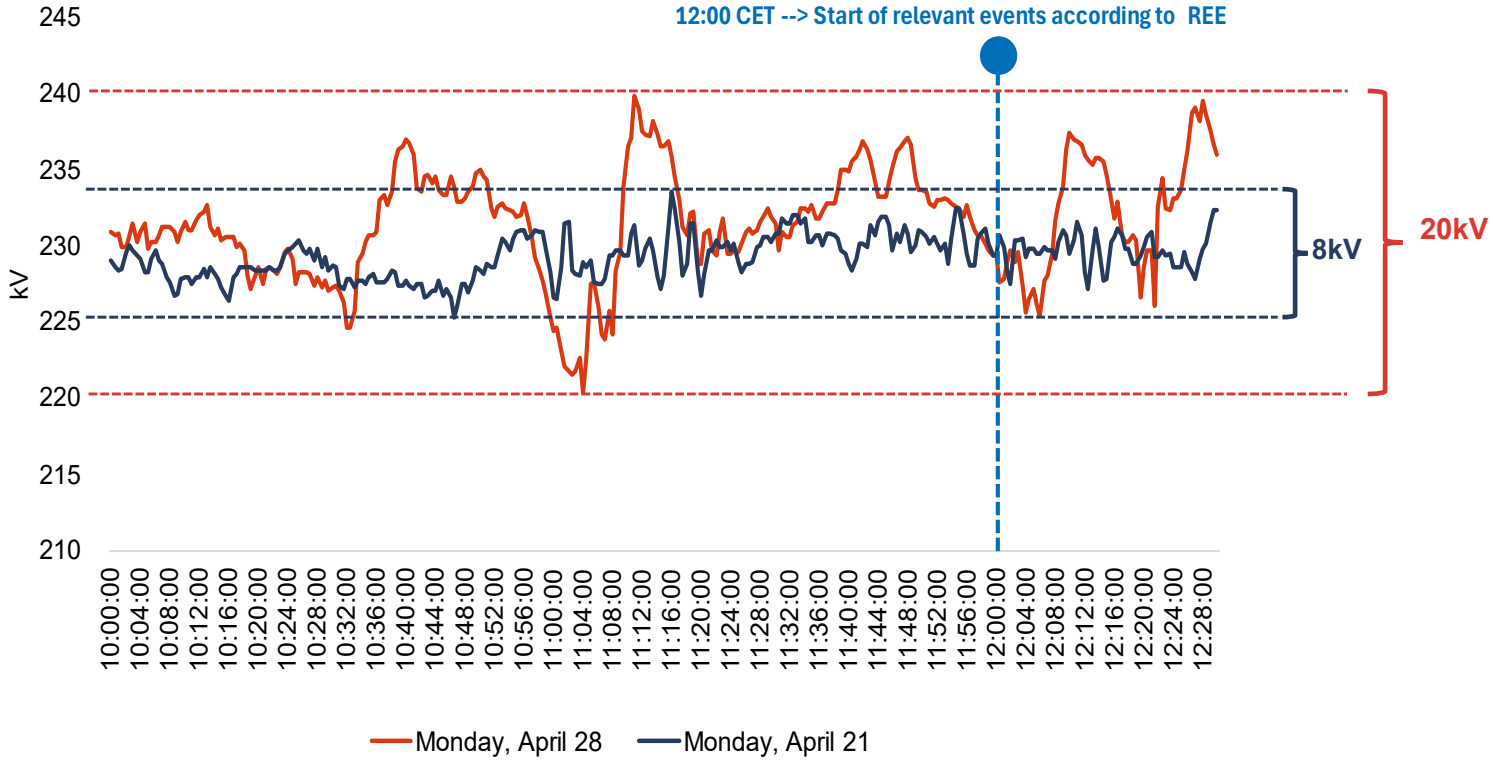
Voltage fluctuations between 10:00-12:00

The voltage fluctuations on 28 April were not normal

No. of High Voltage Warnings registered at the Control Centres (up to 12:00 CET)



Voltage recorded at border points of the 220 kV grid (Zaragoza)



The number of High Voltage warnings received at the control centres was more than 3 times higher than the observed on any other comparable day

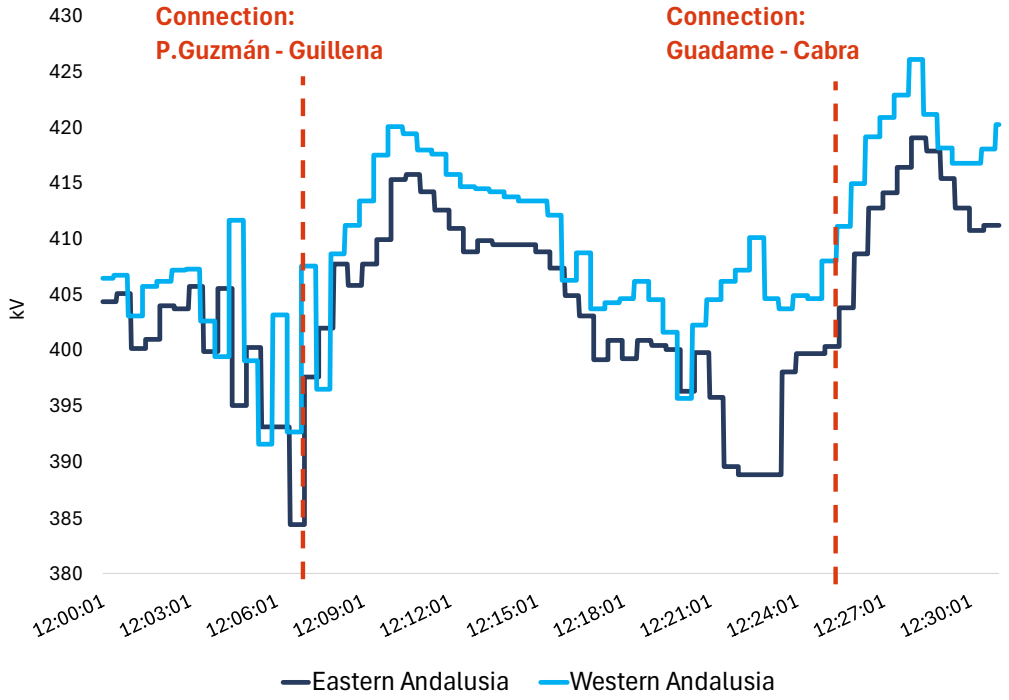
Source: Own elaboration with data from AELEC Members

REE's manoeuvres on transmission lines weakened the system

Connection of lines carried out by REE from 12:00 CET for oscillation control

(# days since they were disconnected)

Line connection impact on voltage in the South zone

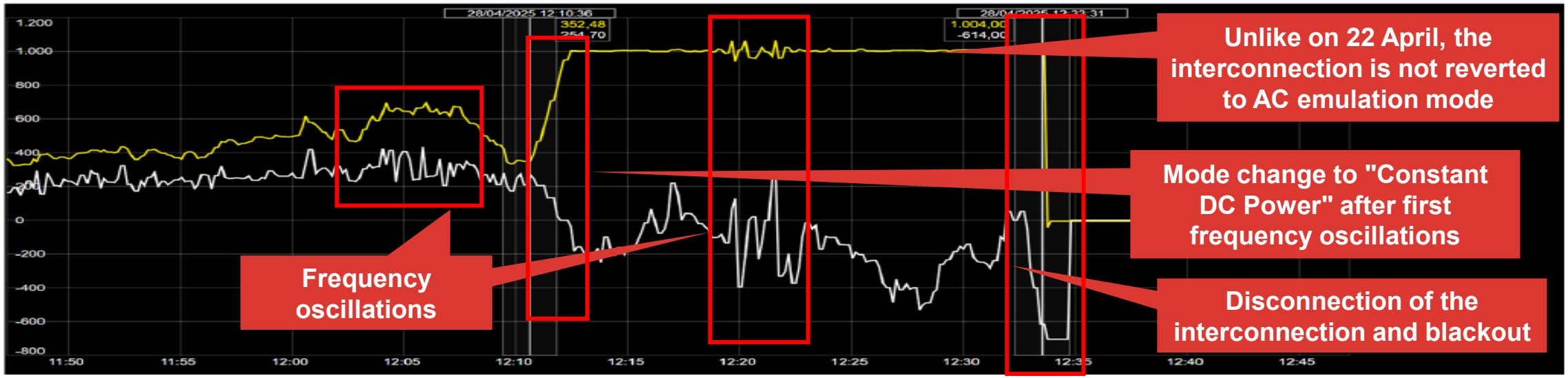


The connection of lines, which had been disconnected for several days, aggravated the overvoltage situation that existed minutes before the blackout

Source: Own elaboration with REE data

Minutes before the blackout, REE switches the interconnection with France to "Constant DC power" mode

DC line operating in "AC Emulation" mode → DC line operating in "Constant DC power" mode → Blackout



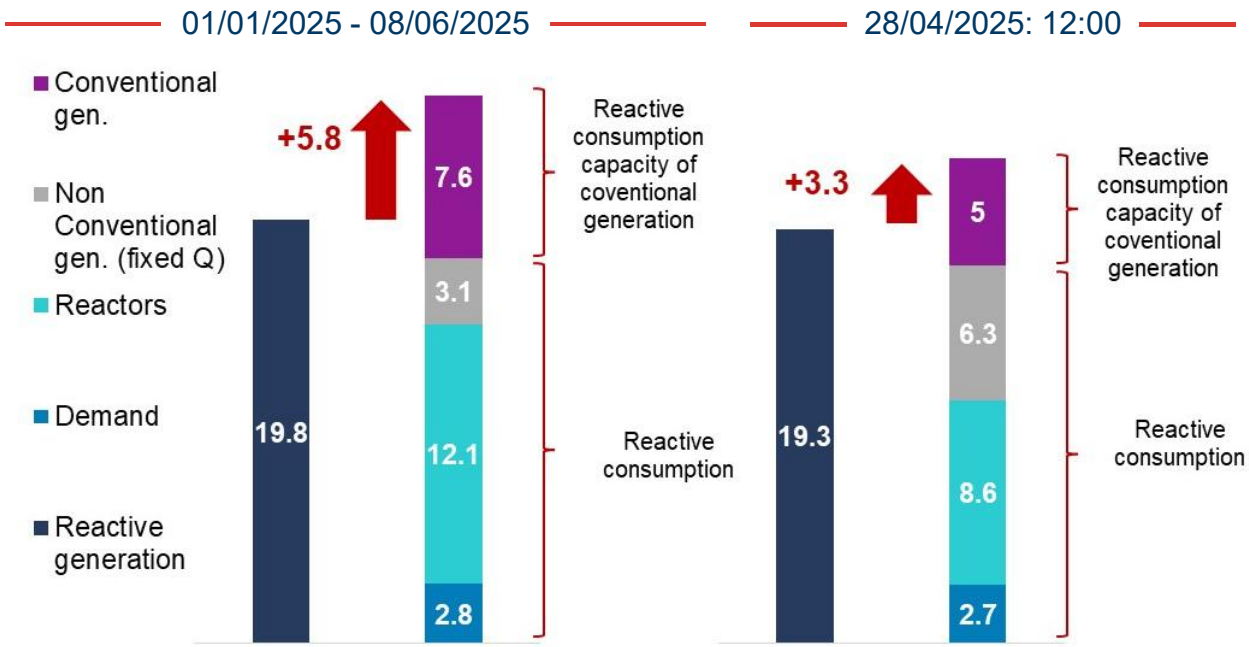
With the available information it is not possible to determine how this mode of operation affected the blackout. An analysis is required for which the necessary data is only available to REE

Source: Own elaboration
Note: AC: Alternating Current, DC: Direct Current

Coupled thermal generation was low and REE's manoeuvres exhausted voltage control capacity

- The capacity to control voltage on the morning of 28 April was very limited compared to the average for the year due to insufficient coupled thermal generation.
- The manoeuvres to dampen oscillations (line closures and disconnection of reactors, described by the Analysis Committee) increased reactive generation by approximately, 2.4 GVAr, exhausting the existing margin. This margin was, in all probability, lower in the South of Spain.

Estimation of reactive balance (GVAr)



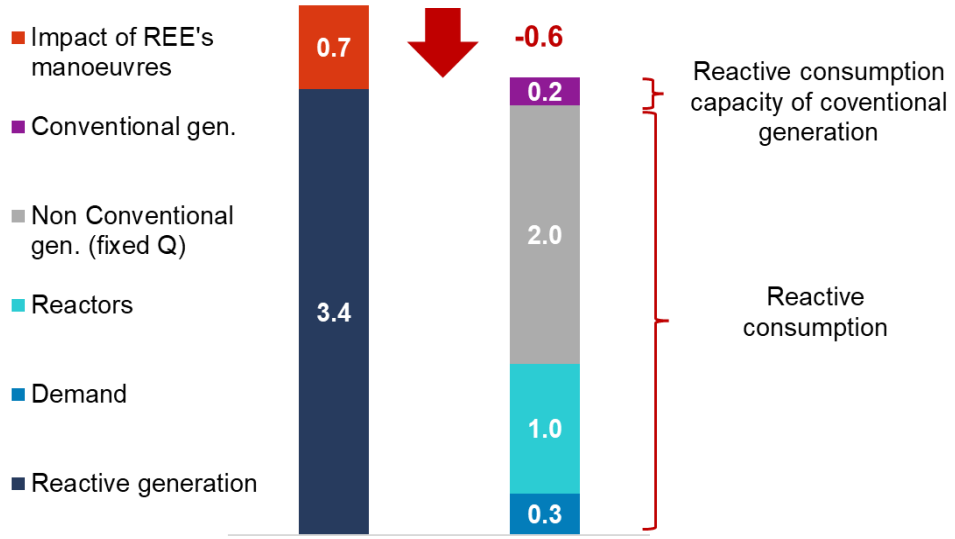
Everything indicates that the low level of coupled conventional generation, particularly in the south, was not enough to contain the voltage increases, which were aggravated by REE's manoeuvres

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

The situation was particularly critical in the south, there was only one CCGT coupled and REE's manoeuvres created a surplus of reactive power

- At 12:00 CET, in southern Spain, the margin for absorbing reactive power was very limited.
- Following REE's manoeuvres, which included reconnecting lines and disconnecting reactors in the south, there was a surplus of reactive power in this region of approximately 0.6 GVAr.
- In this area, there was only one plant with dynamic voltage control capability, a CCGT, which was unable to absorb the surplus of reactive power.

Estimation of reactive balance in the south at 12:00 CET (GVAr)



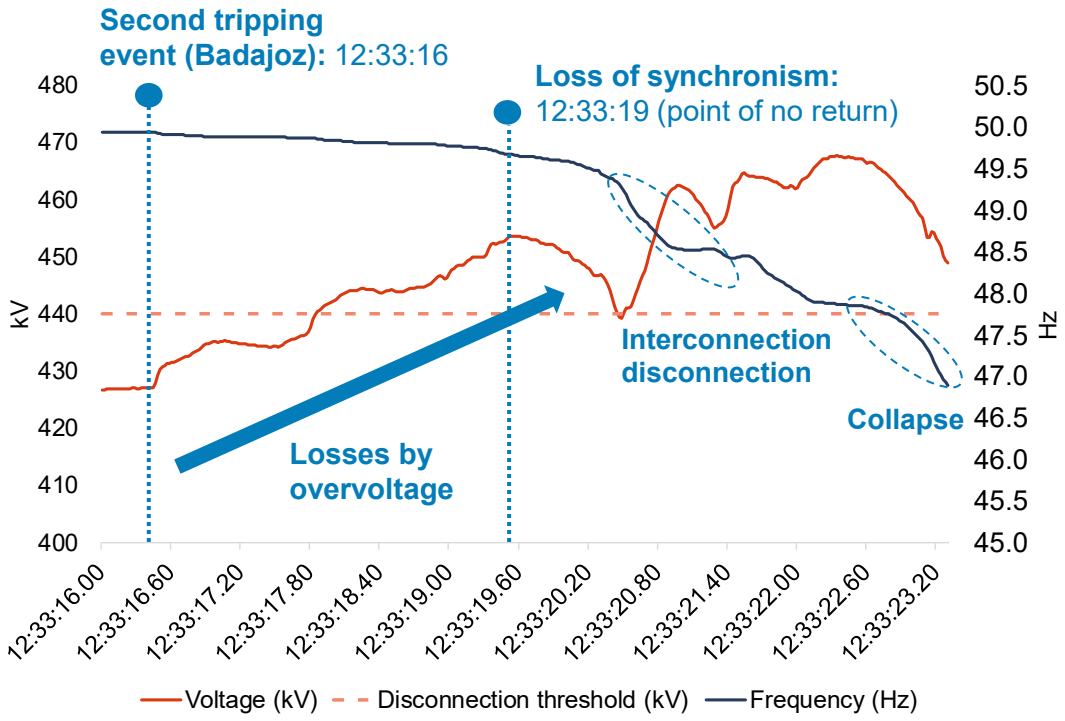
Dynamic voltage control in southern Spain, provided solely by a CCGT, proved insufficient to absorb the regional surplus of reactive power

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

The initial disconnections evidence a systemic voltage control problem

- AELEC partners do not have data on the first substations that tripped according to the Analysis Committee Report. AELEC Members have informed us that their plants did not have incorrect tripping.
- With the second overvoltage trip event, with a total cumulative disconnection of 1,610 MW, a vicious cycle of disconnection/overvoltage starts.[1]
- REE claims that, in 20 seconds, 2,000 MW of renewable generation and a substantial amount of generation connected to the distribution grid, of less than 1 MW, are lost, and that a large part of these disconnections are caused by an incorrect response to overvoltage situations.
- In any case, these 2,000 MW would represent dozens of substations and renewable plants, of different technologies, in different geographical locations and of several different owners.

Frequency and voltage evolution before the blackout

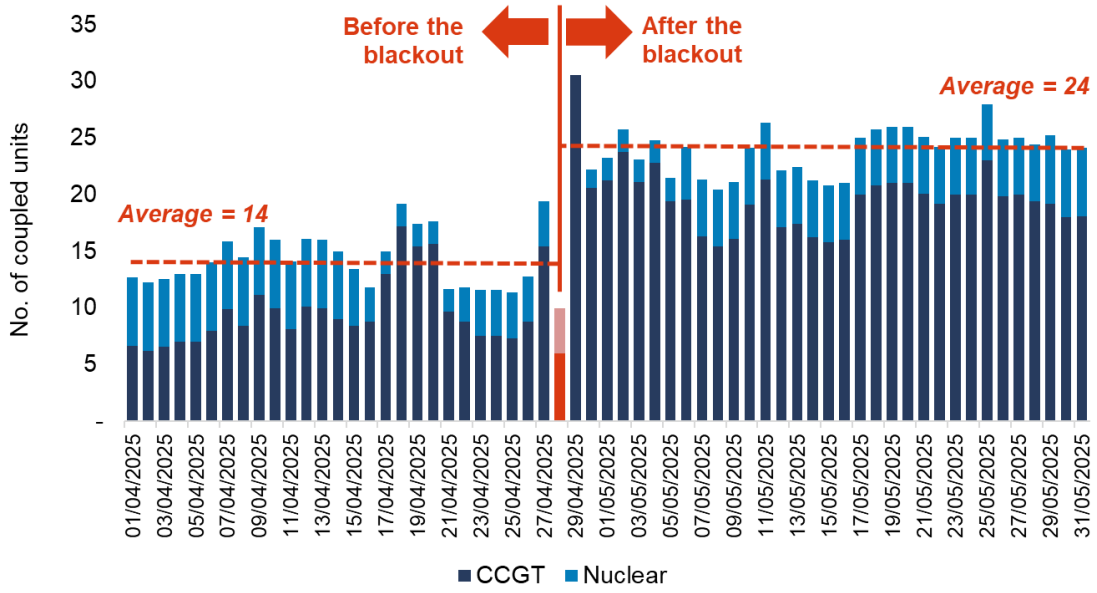


It seems unlikely that all these facilities had simultaneous failures without a systemic cause

Source: Own elaboration with estimation of AELEC Members
Note (1): According to the Analysis Committee Report, they are composed of: (i) losses before Event 1 (525 MW); (ii) Event 1 losses (355 MW); and (iii) Event 2 losses (730 MW)

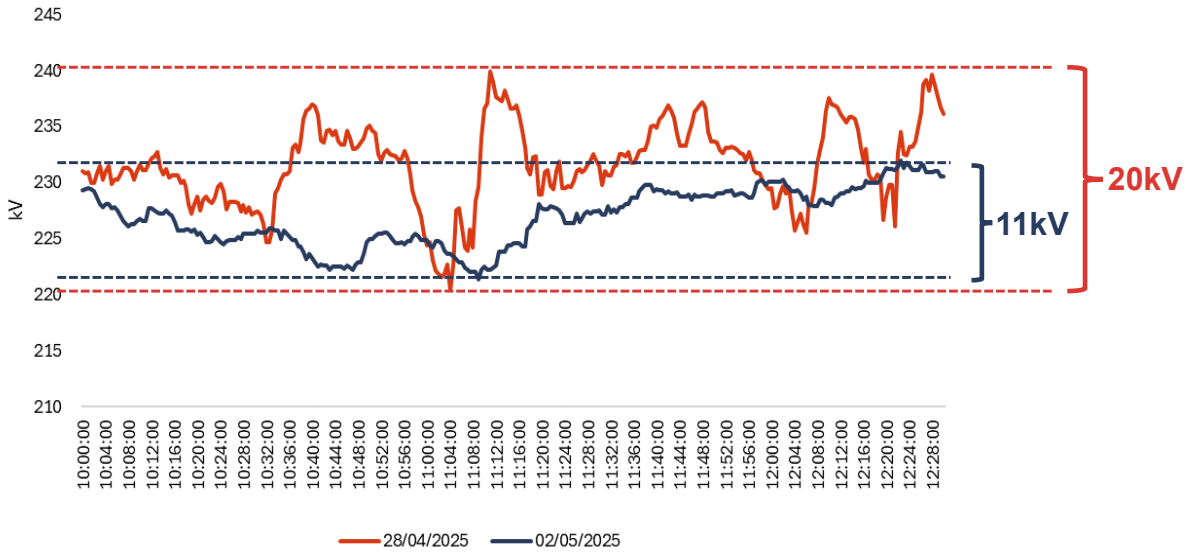
The operation in subsequent days with more conventional generation has reduced voltage fluctuations

CCGT and nuclear coupled by REE before and after the blackout in the central hours of the day (10:00 - 18:00 CET)



Note: The figure for the 28th refers to groups coupled at 12:30 CET

Coupled conventional generation impact on voltage in the 220 kV grid (Zaragoza)



After the blackout, 10 additional groups have been connected, which has reduced voltage fluctuations by between 37% and 52%

Source: Own elaboration with REE data

Issues to analyse

1 Actions taken by REE after the episodes on previous days

- What actions did REE carry out to avoid, on 28 April, the overvoltage episodes of the previous days, which caused the disconnection of demand and generation nodes?

2 Compliance with criterion N-1

- Did the 28 April generation schedule meet the N-1 criterion set out in P.O. 1.1.? Could this schedule guarantee voltage control if either of the only two conventional generation units in the southern zone were lost?

3 Reason for non-replacement of the CCGT declared unavailable

- Why did REE consider at 14:00 on 27 April that it was necessary to connect a CCGT unit in Western Andalusia for 28 April, and at 20:00 on 27 April it no longer considered it necessary?

4 Systemic situation and triggering of plants

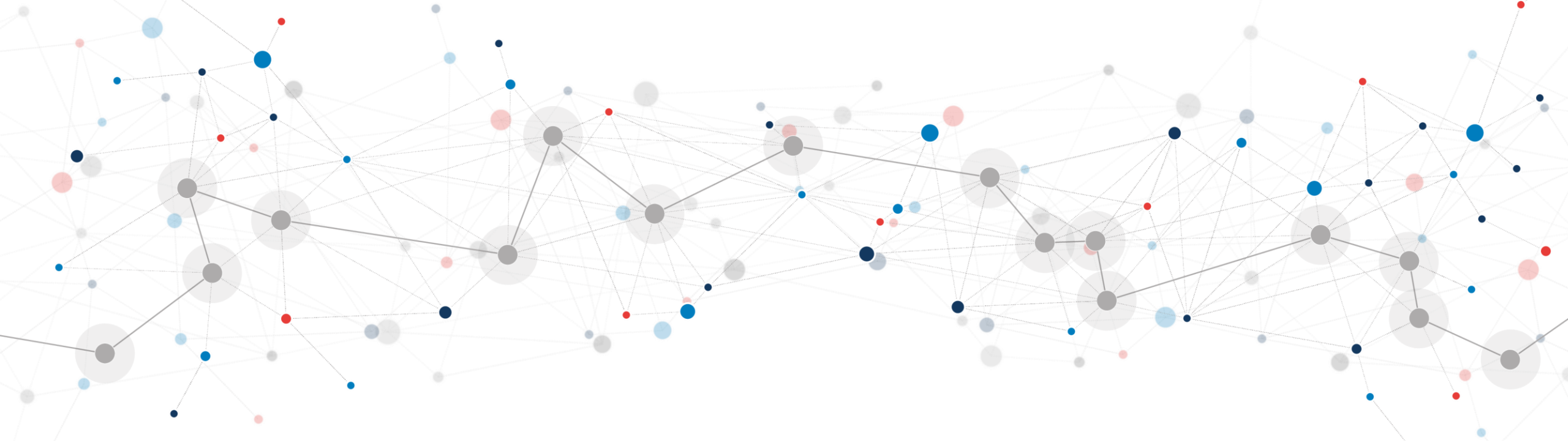
- Is it possible that more than 2,000 MW from a multitude of installations can be lost within 20 seconds due to incorrect tripping, without a systemic cause?

5 REE manoeuvres minutes before the blackout

- Why, in the minutes before the blackout, in order to try to control the voltage, did REE call on CCGTs to produce instead of the hydroelectric plants available in Extremadura, which have shorter start-up times?
- Given the small reactive power absorption capacity of the system at 12:00, could the system absorb the additional reactive power generated by REE's manoeuvres (disconnection of reactors and connection of lines)?
- What was the influence of the interconnection's mode of operation on the blackout? Had the mode of operation been changed earlier, could the blackout have been delayed?

6 Issues to consider for the future

- Voltage and frequency control requirements in a system with a high degree of renewable penetration.
- Implications of the quarter-hourly market for system operation
- Operation of direct current interconnections (HVDC).



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