One year later: are we clear about the Iberian blackout yet?

Thermal, Mechanical and Electrochemical Energy Storage Workshop (TMCES)
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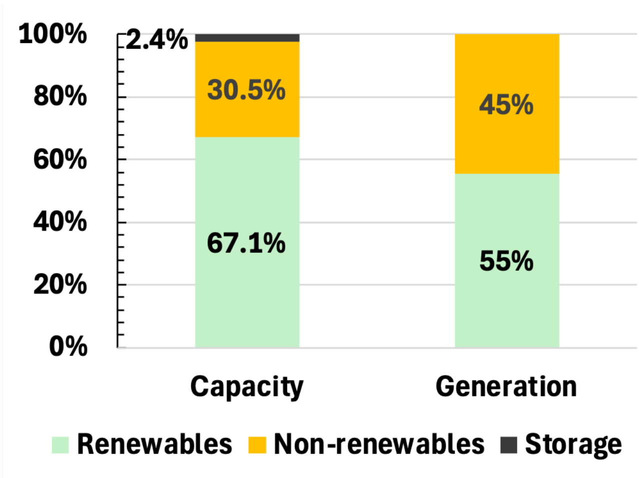
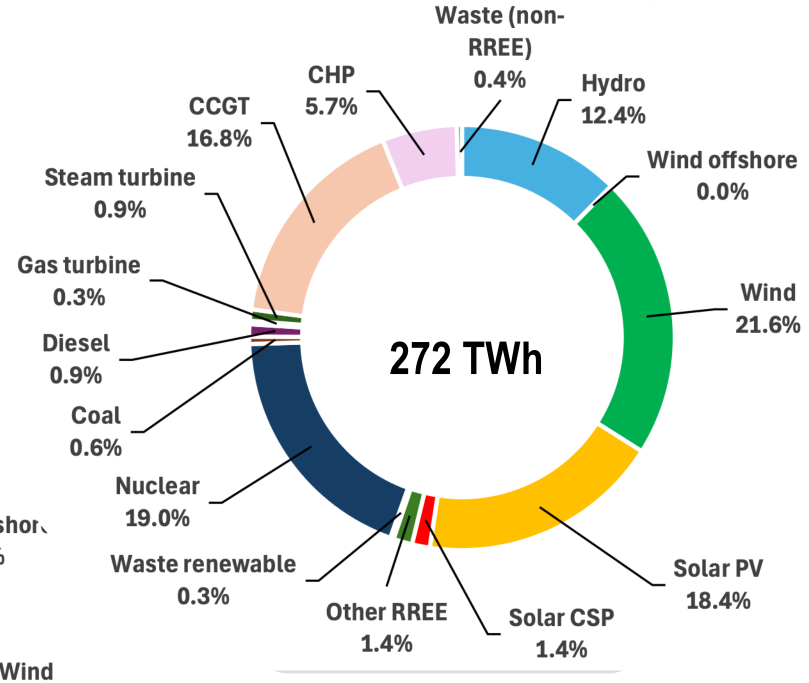
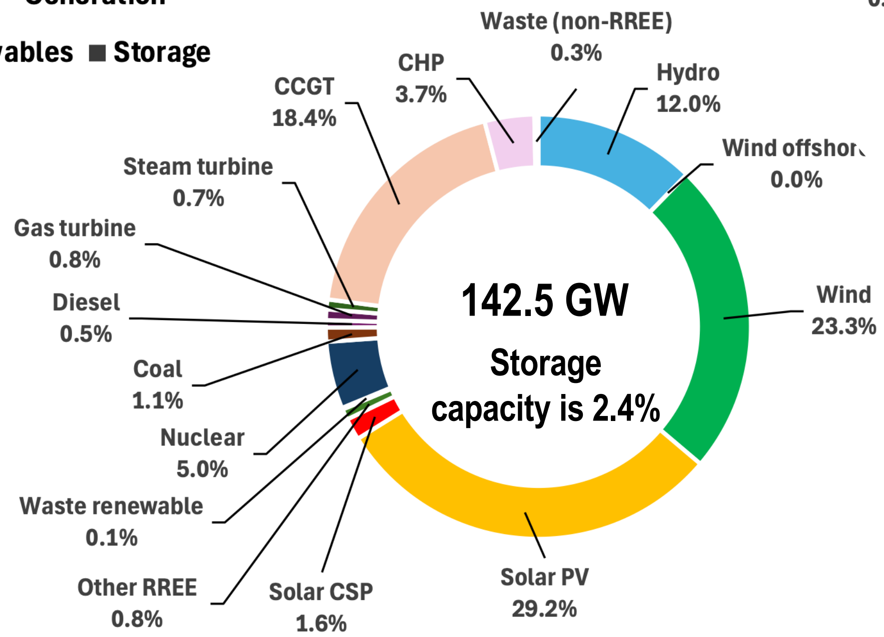
Disclaimer: Except where noted, this presentation is based on documentation made public by the stakeholders involved in the electrical blackout occurring on April 28th 2025

The statements made and opinions expressed in this talk are those of the author and do not represent his employer's (University of Seville)

Spain's electrical system

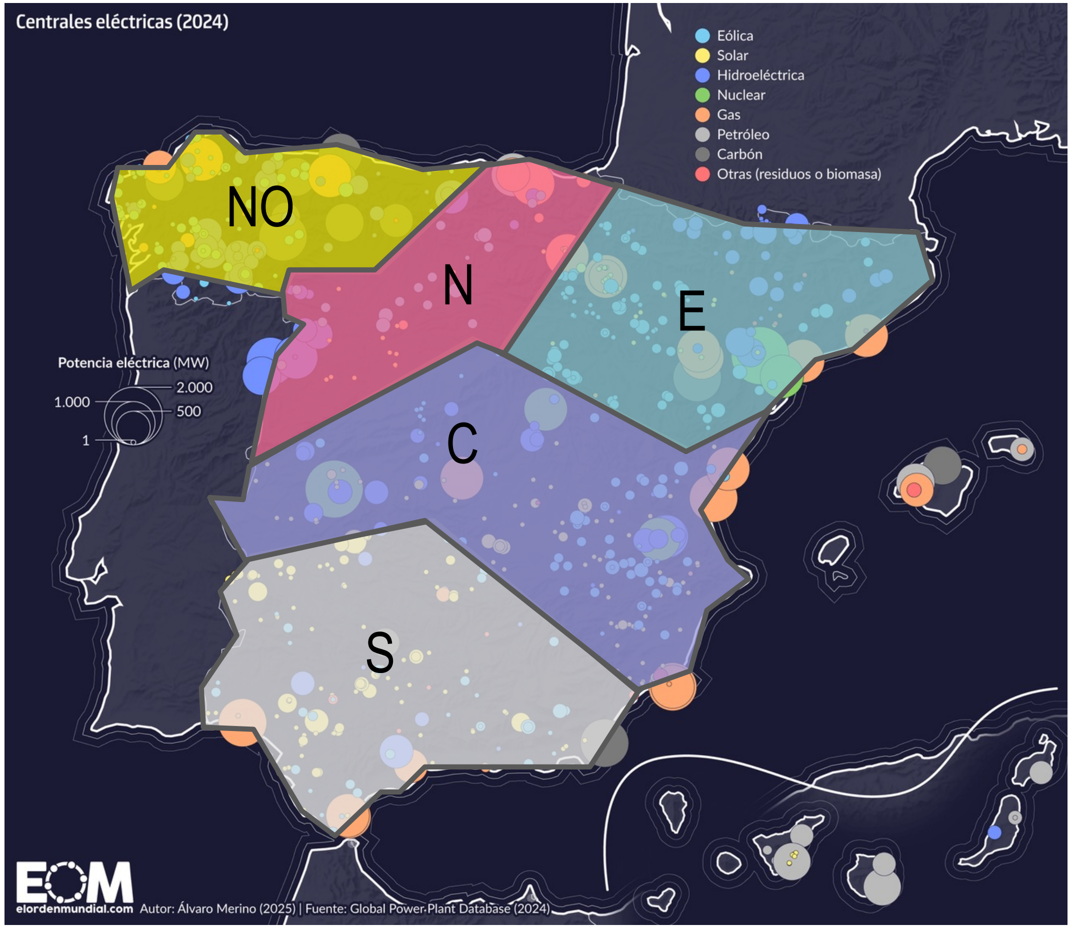


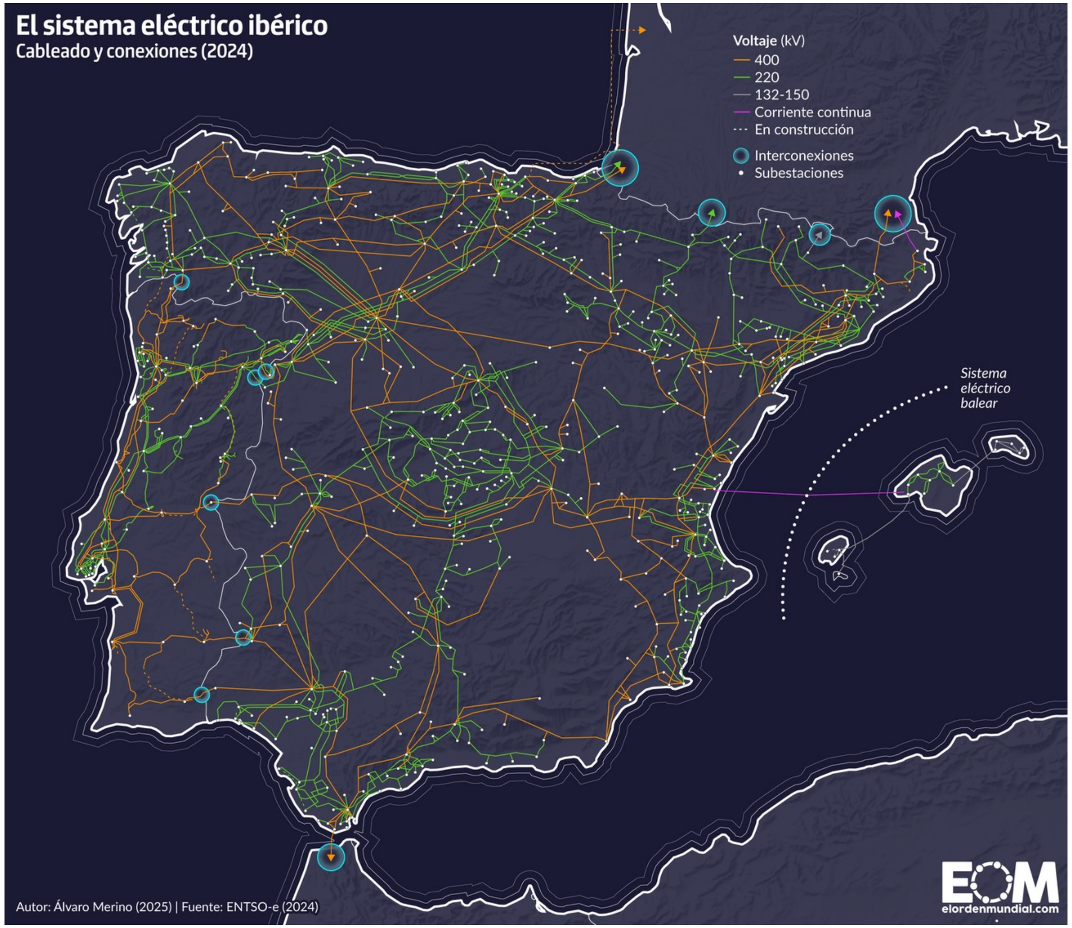




Source: Red Eléctrica de España

Spain’s electrical system

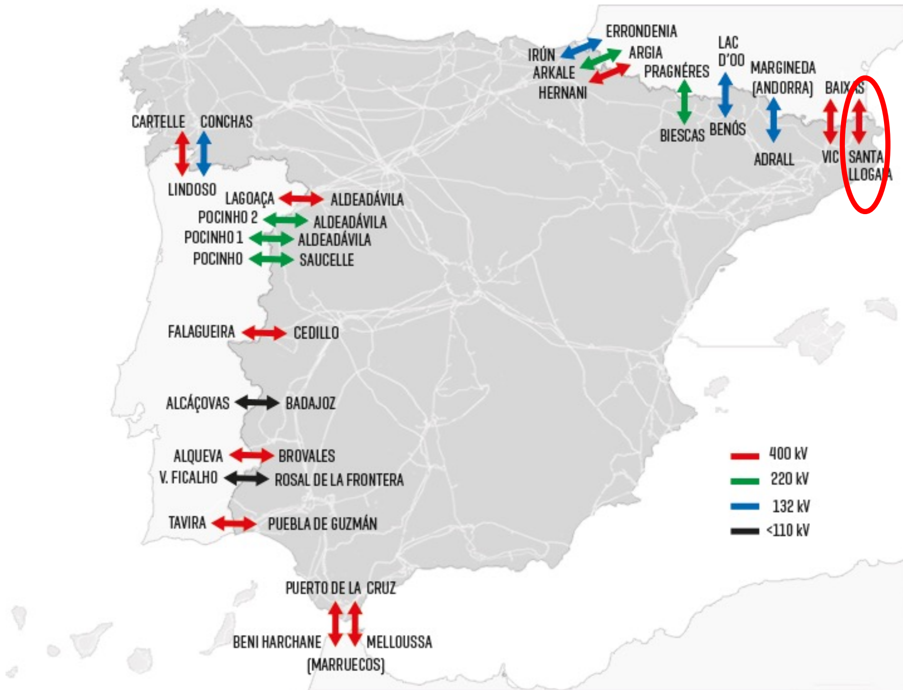




Source: A. Merino, 2025, www.elordenmundial.com, (based on data from the Global Power Plant Database)

Additional considerations

- Historically, **capacity of connections** between Spain and France is (**EU objective for 2030 is 15%**):
    - 5-7% of installed capacity
    - ~8% of peak energy generation
- HVDC operating modes
    - PMODE1: **constant active power** without compensating for frequency/voltage fluctuations
    - PMODE2: adds a control loop to **modify power as a function of frequency deviations**, hence contributing to the damping of transient effects
    - PMODE3: AC emulator. The connection **adapts power to the voltage angle difference between both sides**, helping distribute these inter-region oscillations amongst both sides



Source: N. Hernández-Ranera, 2022, Principios Verdes

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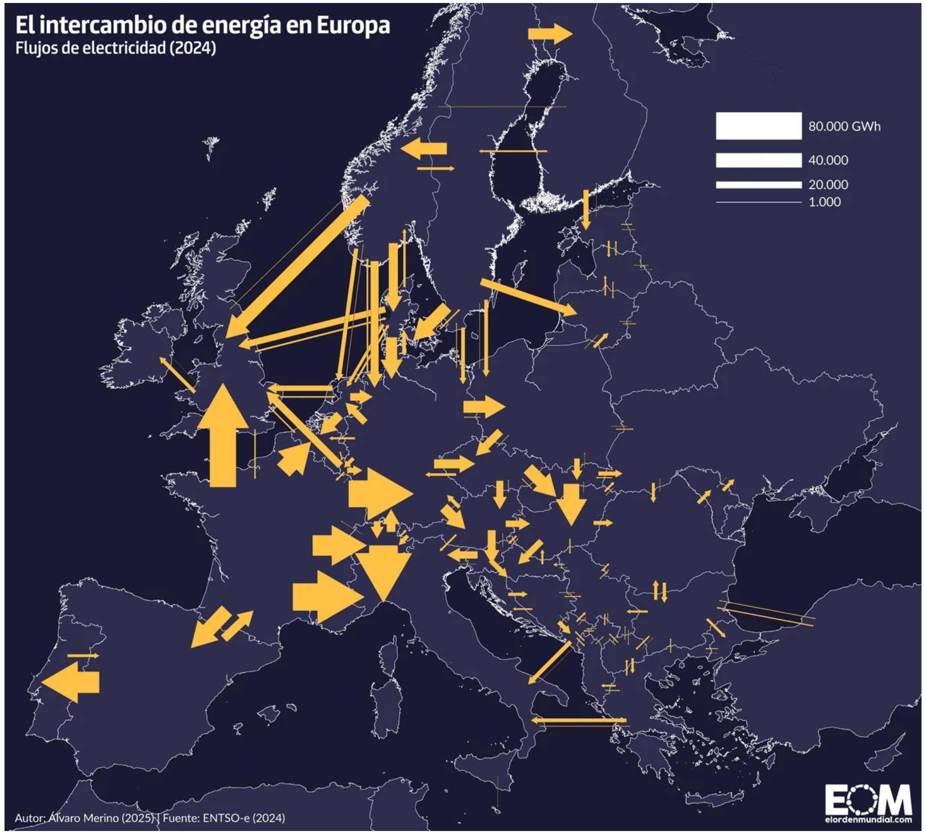
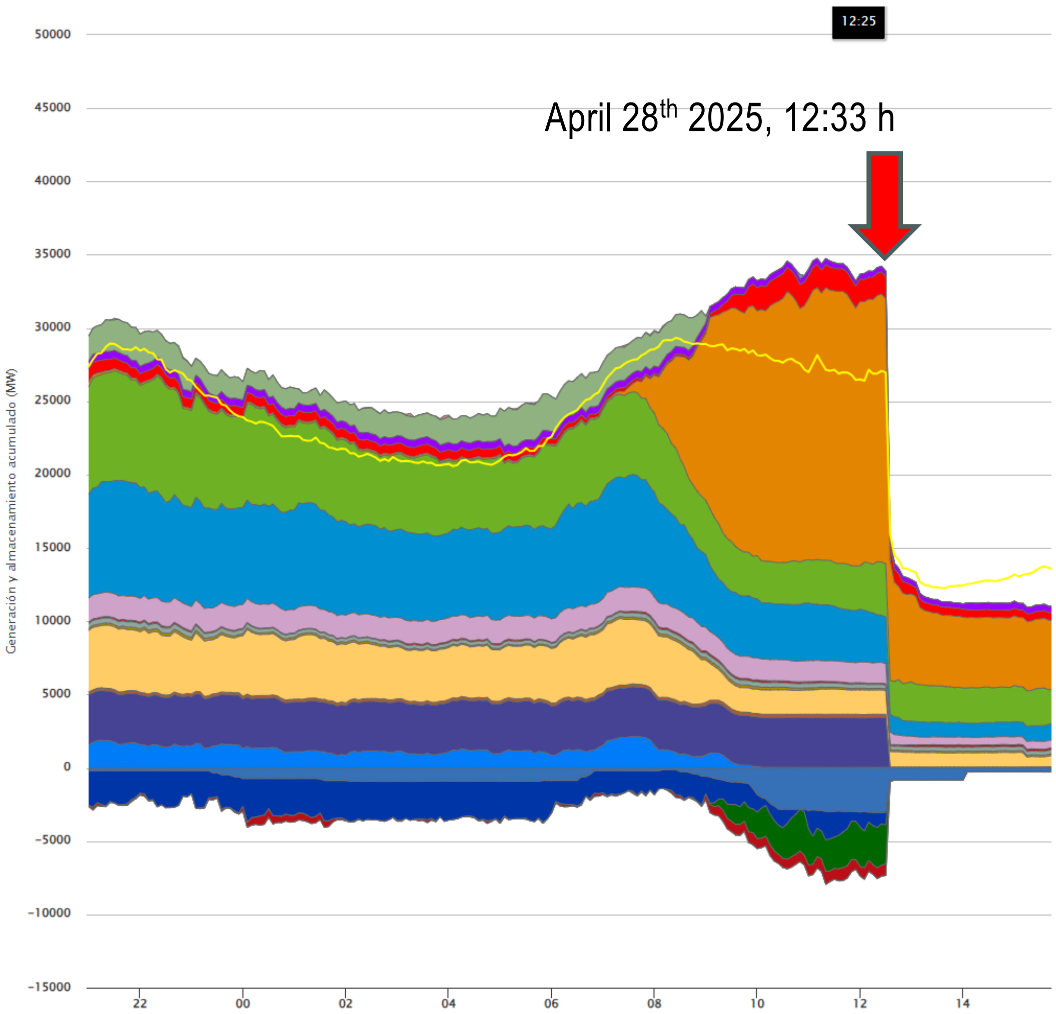
The country is weakly interconnected



Source: A. Merino and J.L. Marín, 2025, *El nuevo orden mundial*

The blackout – Static

	27075	- (%)
Export - Andorra	-8	0 (%)
Export - Morocco	-745	0 (%)
Export - Portugal	-2818	0 (%)
Export - France	-778	0 (%)
Battery storage (+)		(%)
Pumped hydro (+)	29	0,08 (%)
Nuclear	3392	9,92 (%)
Coal	228	0,67 (%)
Combined cycle	1657	4,84 (%)
Steam turbine	116	0,34 (%)
Diesel	262	0,77 (%)
Gas turbine	86	0,25 (%)
CHP / MSW	1424	4,16 (%)
Hydro	3206	9,37 (%)
Wind	3645	10,65 (%)
Solar PV	18283	53,44 (%)
Solar thermal (CSP)	1505	4,4 (%)
RR.EE. Thermal	377	1,1 (%)
Pumped hydro (-)	-3036	0 (%)
Battery (-)	-8	0 (%)
Import - France		(%)
Import - Portugal		(%)
Import - Morocco		(%)



Source: Red Eléctrica de España

<u>Generation</u>

Generation → 34 GWe

PV+W → 21 GWe (64%)

Demand → 27 GWe

<u>Storage</u> (*)

Portugal → 3 GWe

Morocco → 1 GW

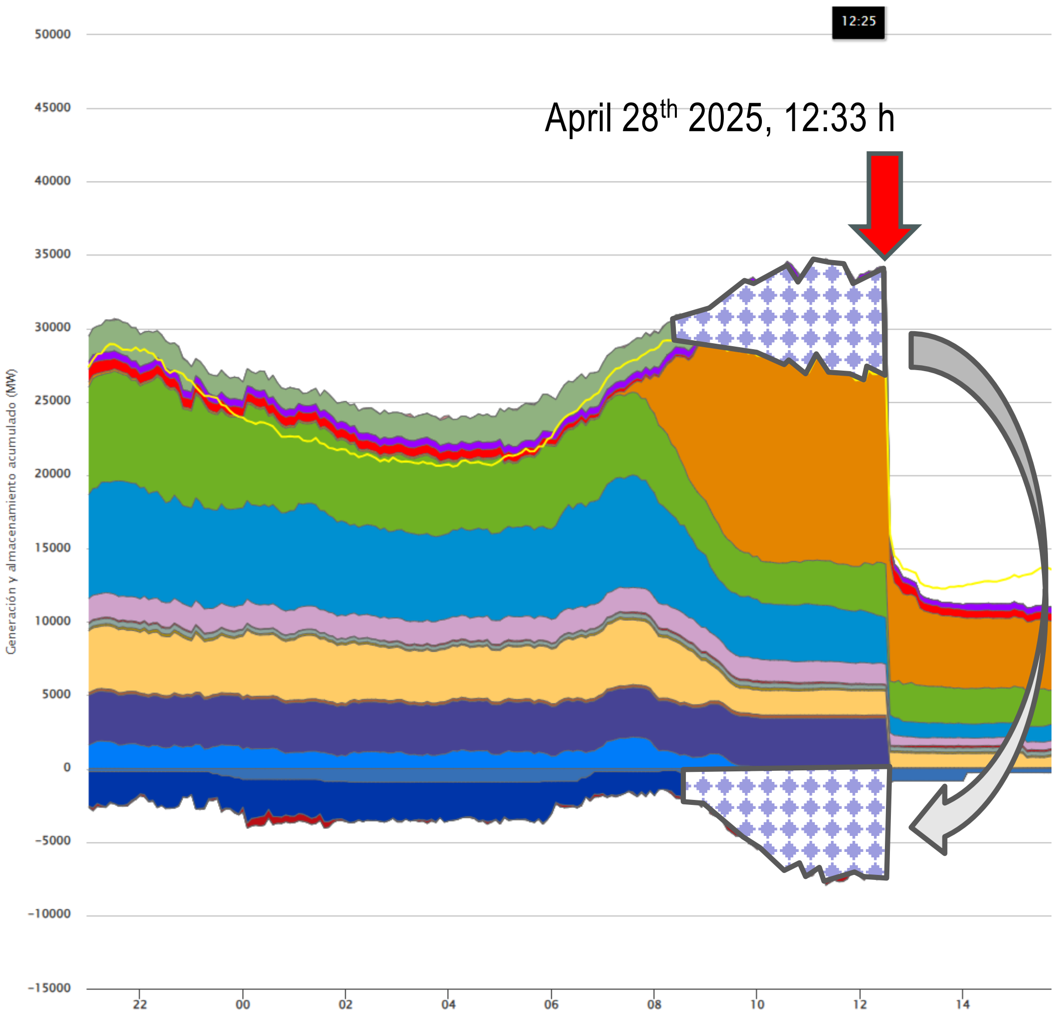
France → 1 GW

Phydro → 3 GWe

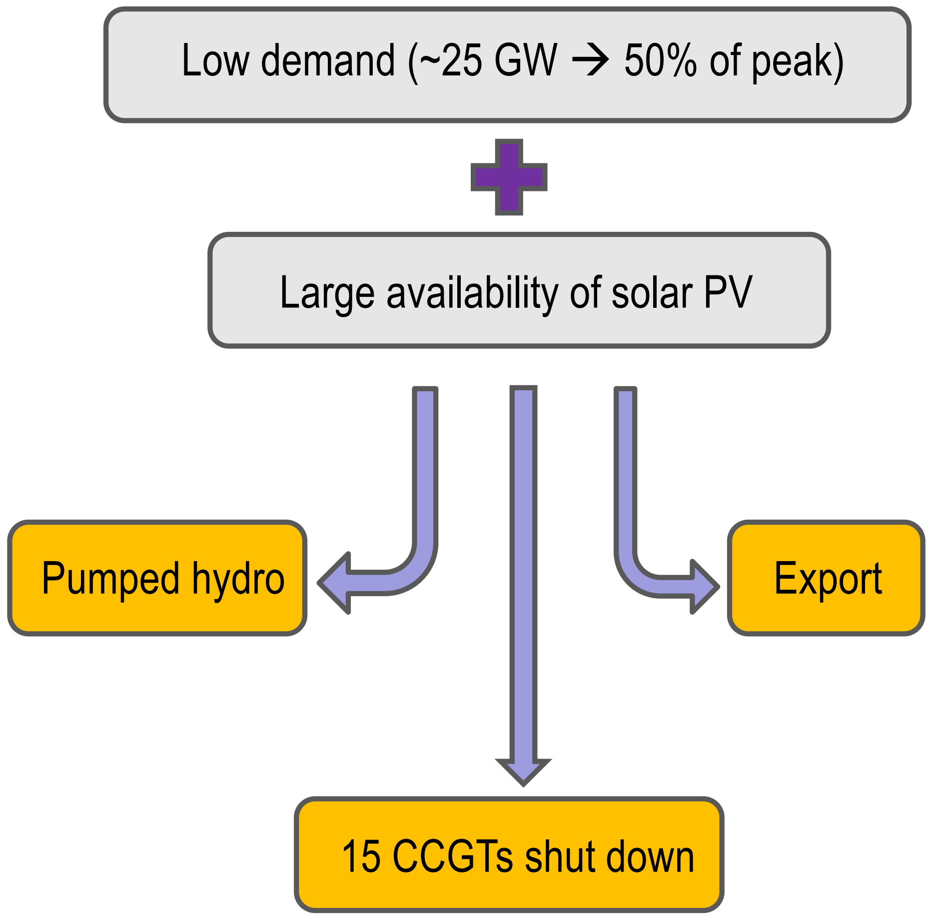
Battery → 0 GWe

82% RREE
64% VRREE

The blackout – Static

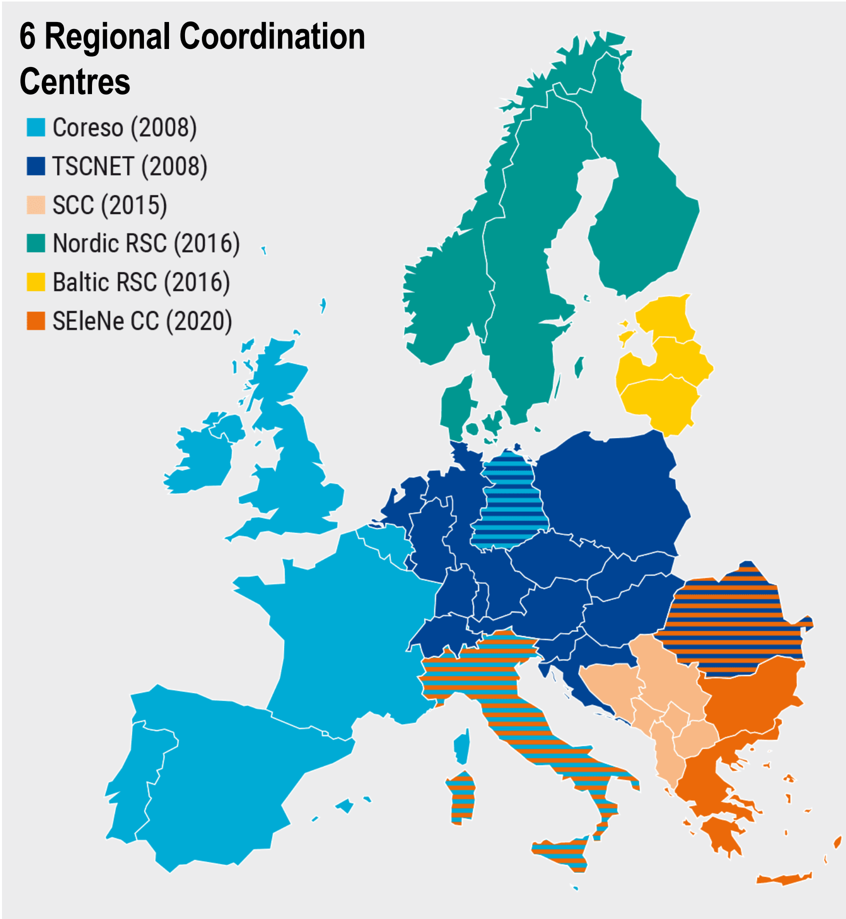


Source: Red Eléctrica de España



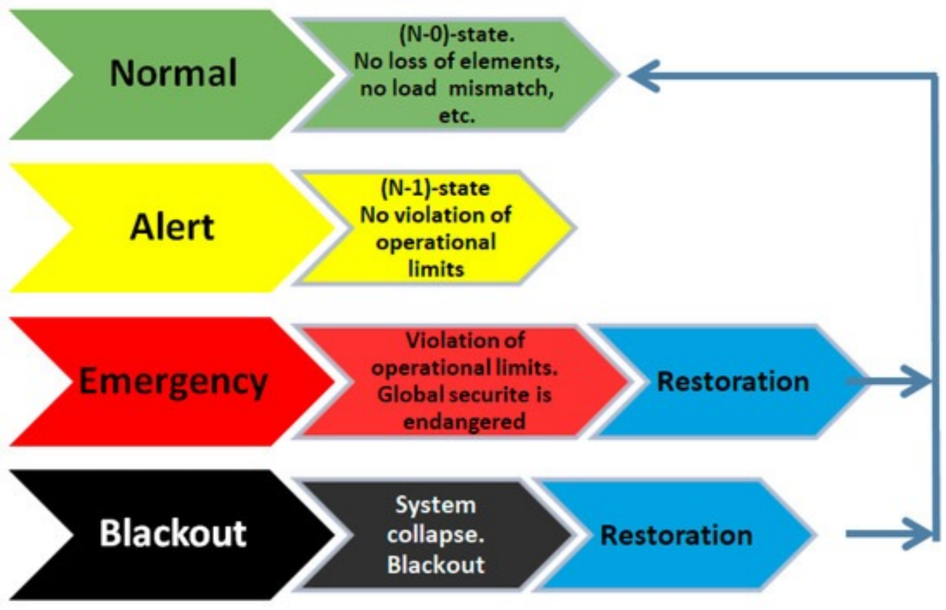
Additional considerations

- ENTSO-E's **European Awareness System (EAS)**
- Surveillance of the synchronous system in Europe, supported by TSOs
- TSOs would share real-time data. Updated every few seconds-minutes
- **<u>Transmission lines are monitored</u>**, mostly statically
- **<u>Distribution grid not monitored</u>**



Additional considerations

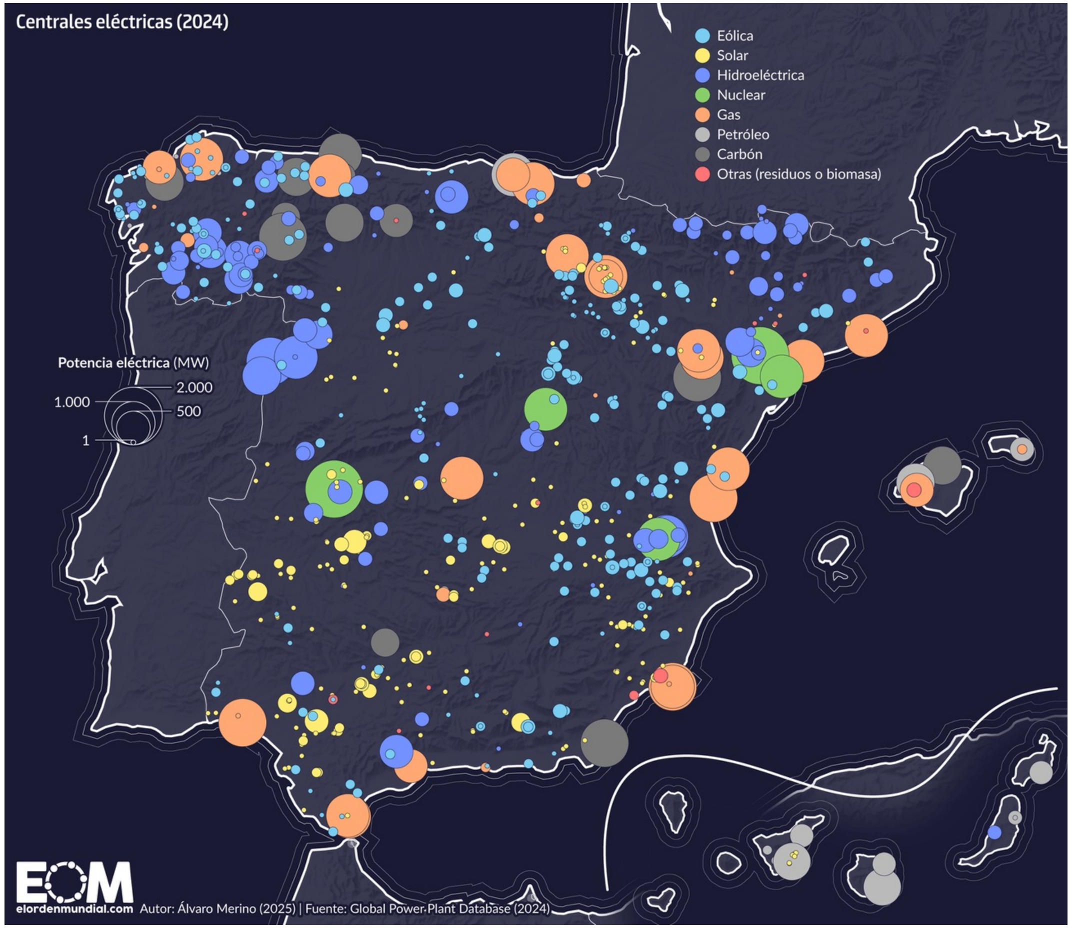
- 5 levels of alert:
  - **Normal:** system runs within the security limits, complying with *N-1*
  - **Alert:** degradation of safety margins — reserves, voltage and frequency—
  - **Emergency:** safety limits are violated (loss of synchronism or activation of *under frequency load shedding* - UFLS)
  - **Blackout:** total loss of voltage in a large part of the control region
  - **Restoration state:** actions for Black Start and reinstatement of topology are implemented



N-1 grid reliability rule:

- N: total number of elements (normally) working in the power system (e.g., all lines running).
- -1: loss of one major element.
- **Rule: If any single element fails, the remaining elements must handle the electrical load automatically**

Getting ready for April 28th

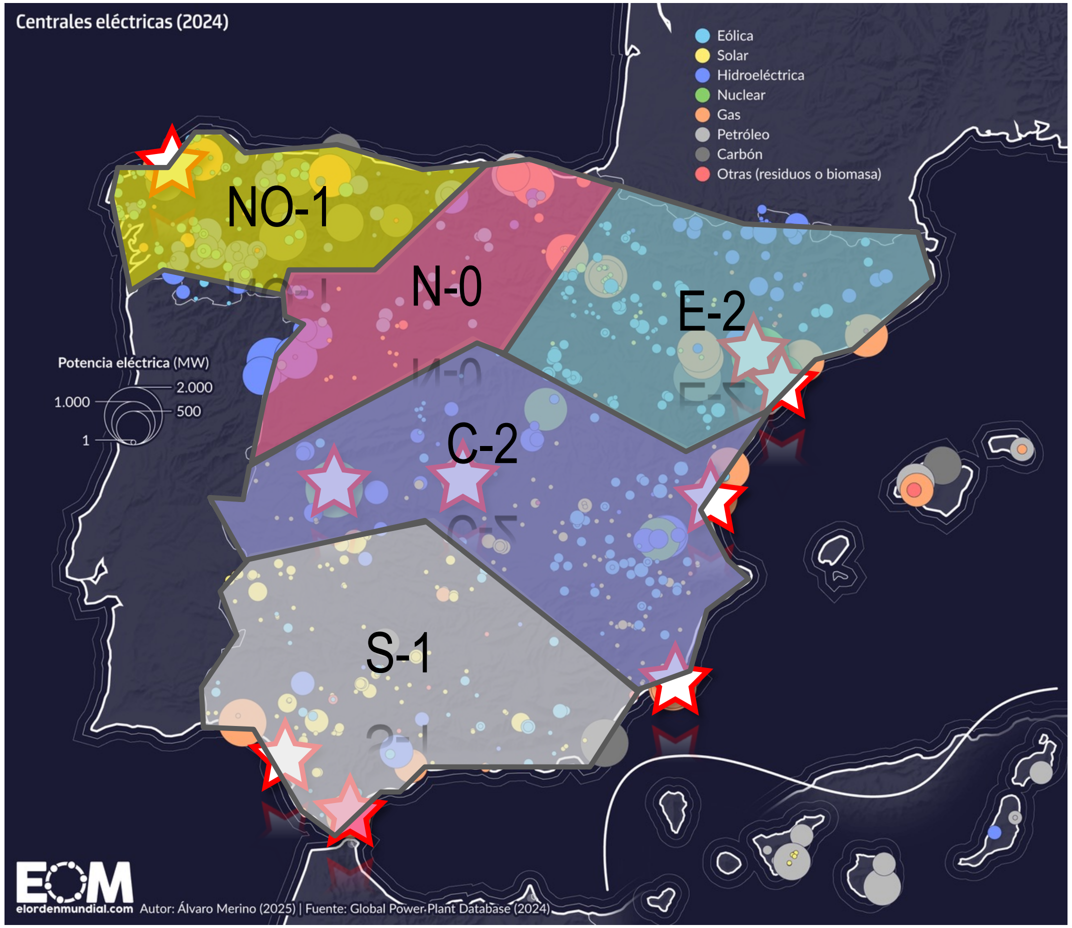


Technology	Unavailable [MW]	Capacity [MW]
Coal	903.5 (49.6%)	1820
CCGT	7426.3 (30.2%)	24562
Fuel-gas	0	8
Nuclear	3078.6 (43.3%)	7117
Pumped hydro	1392.1 (41.8%)	3331

Technical restrictions: unavailable power

Source: Red Eléctrica de España

Getting ready for April 28th



Power station	Type	Output [MW]
Vandellós (1967)	Nuclear	~1100
Ascó (1984)	Nuclear	~2000
Almaraz (1973)	Nuclear	~2000
Cartagena (2004)	CCGT	1200
Arcos de la Frontera (2005)	CCGT	1600
Sagunto (2007)	CCGT	1200
Villaseca de la Sagra (2005)	CCGT	800
As Pontes (2008)	CCGT	800

Planned for voltage control (reportedly)

Source: L. Tecleme,, 2025/7/24, *Los nombres de las centrales involucradas en el apagón (y que el Gobierno ocultó)*, Diario Red

The analysis – Five phases identified

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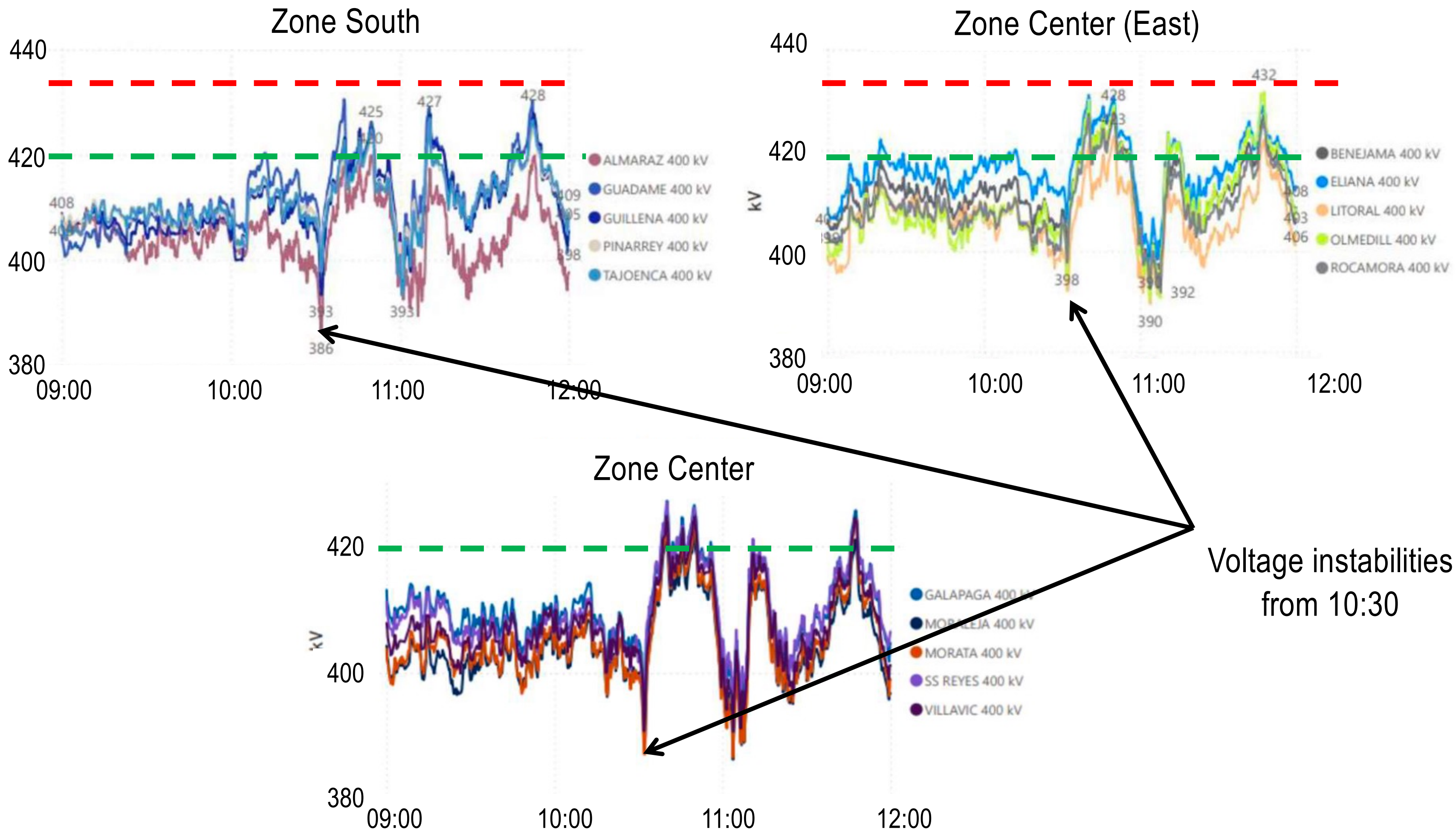
P0 – Voltage instabilities	• Earlier days • Morning of 04/28
P1 – System oscillations	• From: 12:00 (28) • To: 12:30 (28)
P2 – Loss of generation (OV)	• From: 12:32:00 (28) • To: 12:33:18 (28)
P3 – Collapse down to V=0	• From: 12:33:18 (28) • To: 12:33:30 (28)
P4 – Supply restoration	• From: 12:33:30 (28) • To: 14:36 (29)

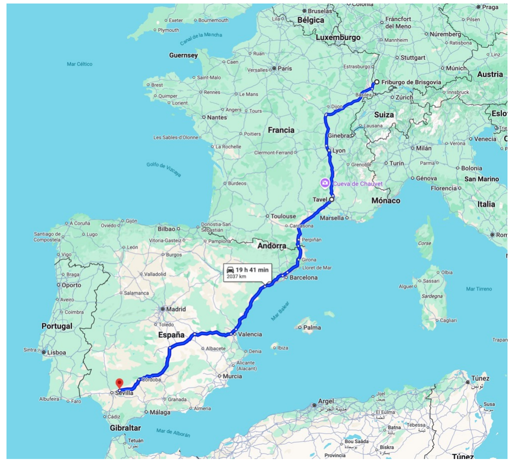
GOBIERNO DE ESPAÑA

Phase 0 – Morning of April 28th (after 10:30 h)



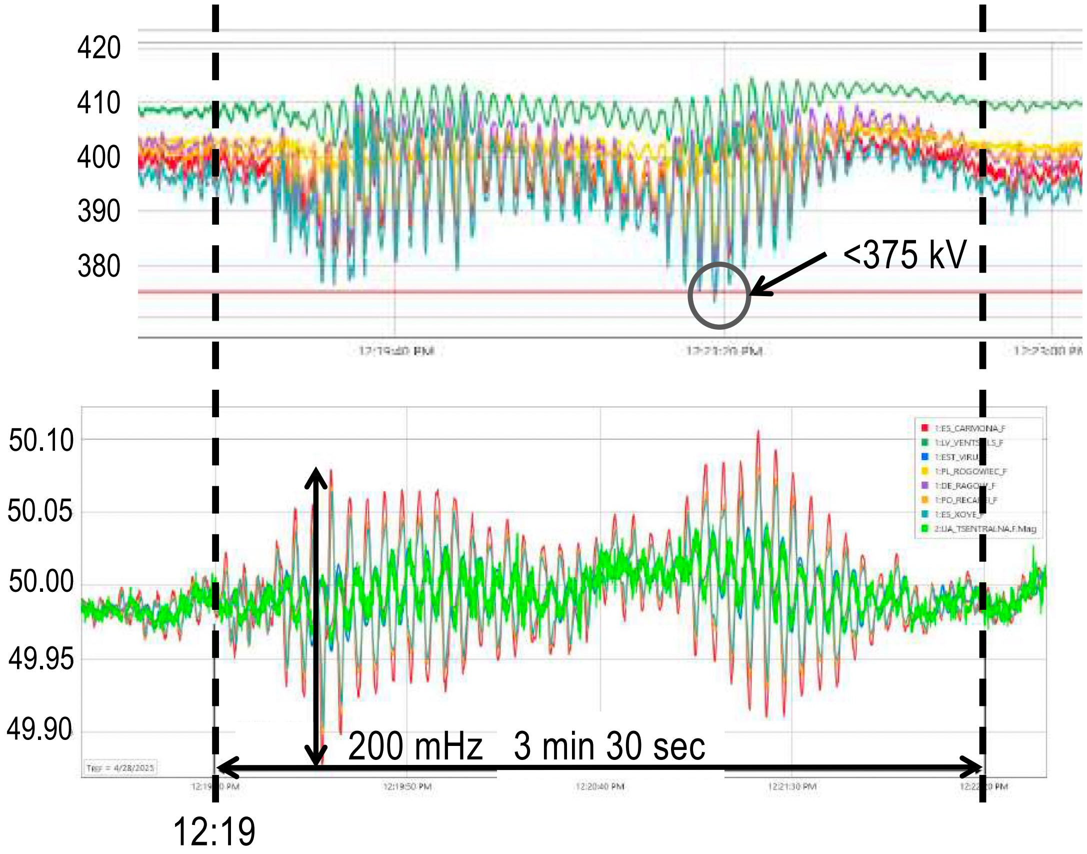
Phase 1 – Morning of April 28th (12:03 h)

12.03 Large oscillations at 0.6 Hz experienced from 12.03



- Power oscillations at 12:03
- ω oscillations amplitude: 70 mHz
- V drops below 380 kV (lower limit)
- Damped in 4 min and 42 sec
- Registered in France and Germany

Phase 1 – Morning of April 28th (12:19 h)



- Frequency and voltage oscillation at 0.2 Hz
- At Almaraz (circle), ΔV is 24 kV (peak-to-peak)
- Pattern is known across Europe

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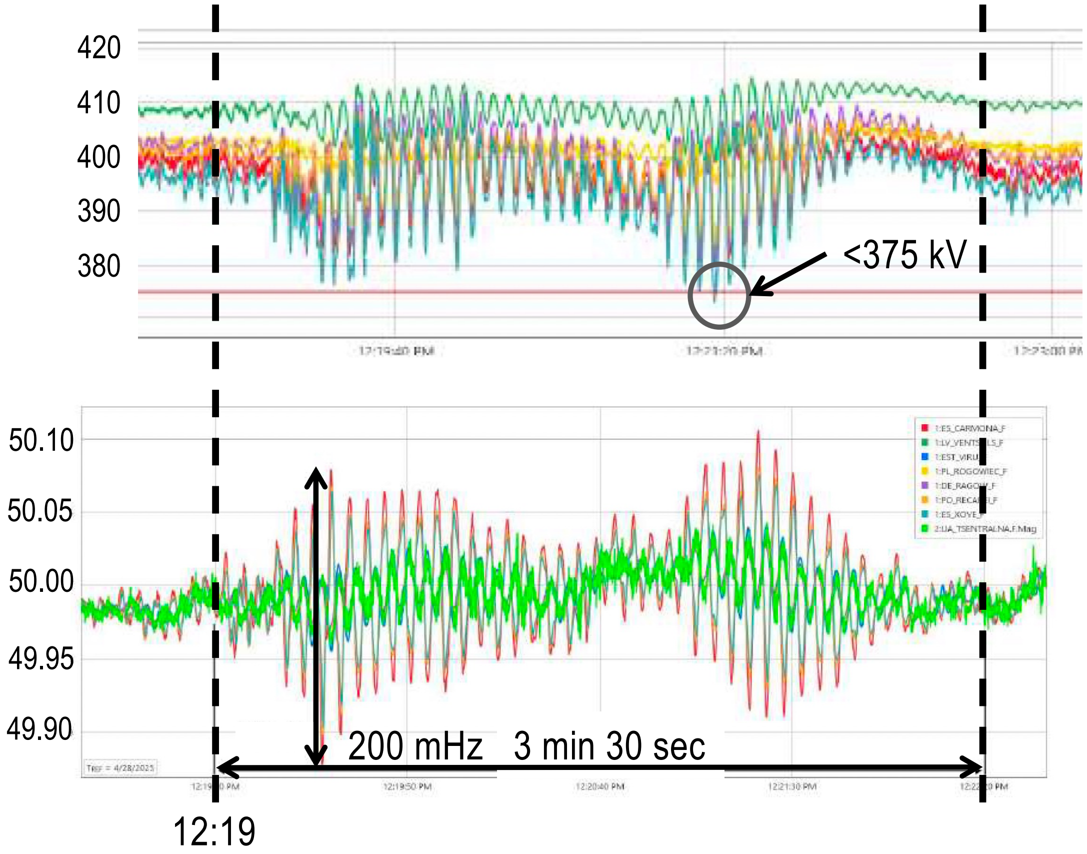
- **12:07 Export to France reduced** to 1000 MW (12:07 – 13:00)
  - Increased damping of Spanish grid (safety margin)
- 12:07 **Three additional 400 kV circuits** online
- 12:11 **Two additional 400 kV circuits** online
- 12:11 **HVDC France-Spain switched to plain DC**, rather than emulated AC
- 12:15 REE asks REN to **reduce export to Portugal**:
  - REE asks REN to reduce to 2000 MW (-1000 MW)
  - Agreed to reduce to 2500 MW until 13:00 and to 2000 MW later

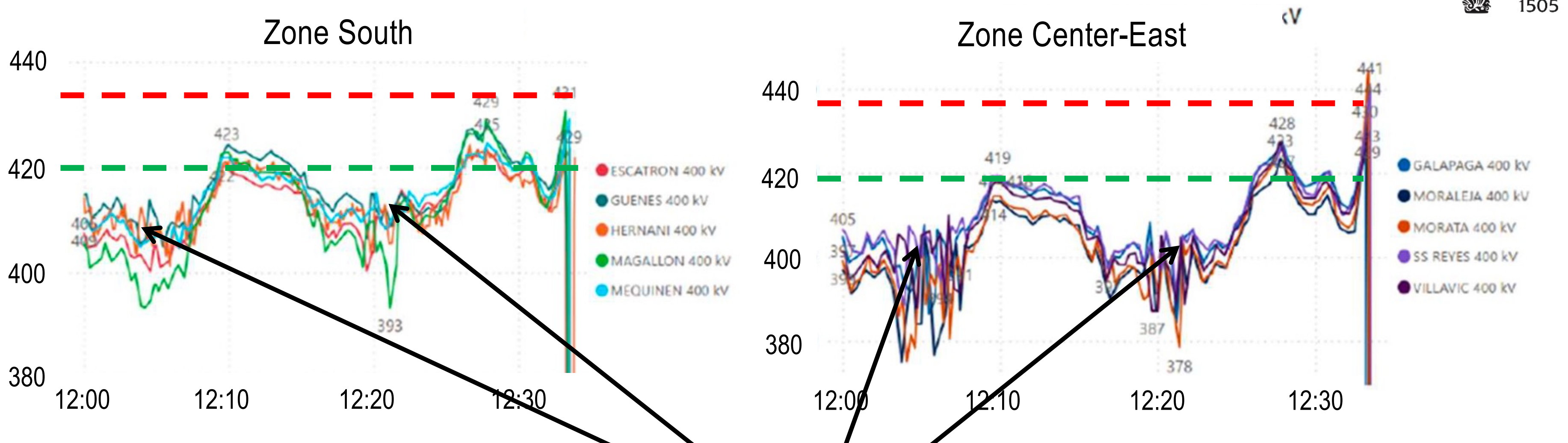
Phase 1 – Morning of April 28th (12:19 h)



- Frequency and voltage oscillation at 0.2 Hz
- At Almaraz (circle), ΔV is 24 kV (peak-to-peak)
- Pattern is known across Europe

- 12:19 Export to France reduced to 1000 MW (12:07 – 14:00)
  - Period extended to 14:00
- 12:19 REE asks REN to reduce export to Portugal:
  - Reduction to 2000 MW to become effective at 12:30
- 12:21 / 12:25 Two additional 400 kV circuits come online
- 12:26 REE seeks Thermal Station in the South → start immediately
  - Faster power plant able to come online in 1h 30 min
  - Agreed to come online at 14:00 (never synchronized)
- **12:XX A plant operator reports (TSO) they might need to go offline due to oscillations**
  - **TSO agrees to have another thermal power station coming online at 15:00 (this never materialized)**

Phase 1 – Morning of April 28th (12:19 h – 12:30 h)



- Strong voltage oscillations at 12:05 and 12:30
- Same time as frequency oscillations

- 12:04 – 12:05 **REE takes 4 shunt reactors OFF at critical nodes with low V** (3x400 kV + 1x220 kV)
- 12:17 – 12:24 **Same action** (since voltage dropped again at 12:16) (3x400 kV + 1x220 kV)
- 12:26 – 12:28 **Generalized trend towards higher voltages → shunt reactors come online again** (3x400 kV + 1x220 kV)

Phase 2 – Morning of April 28th (12:32:00 – 12:33:18 h)

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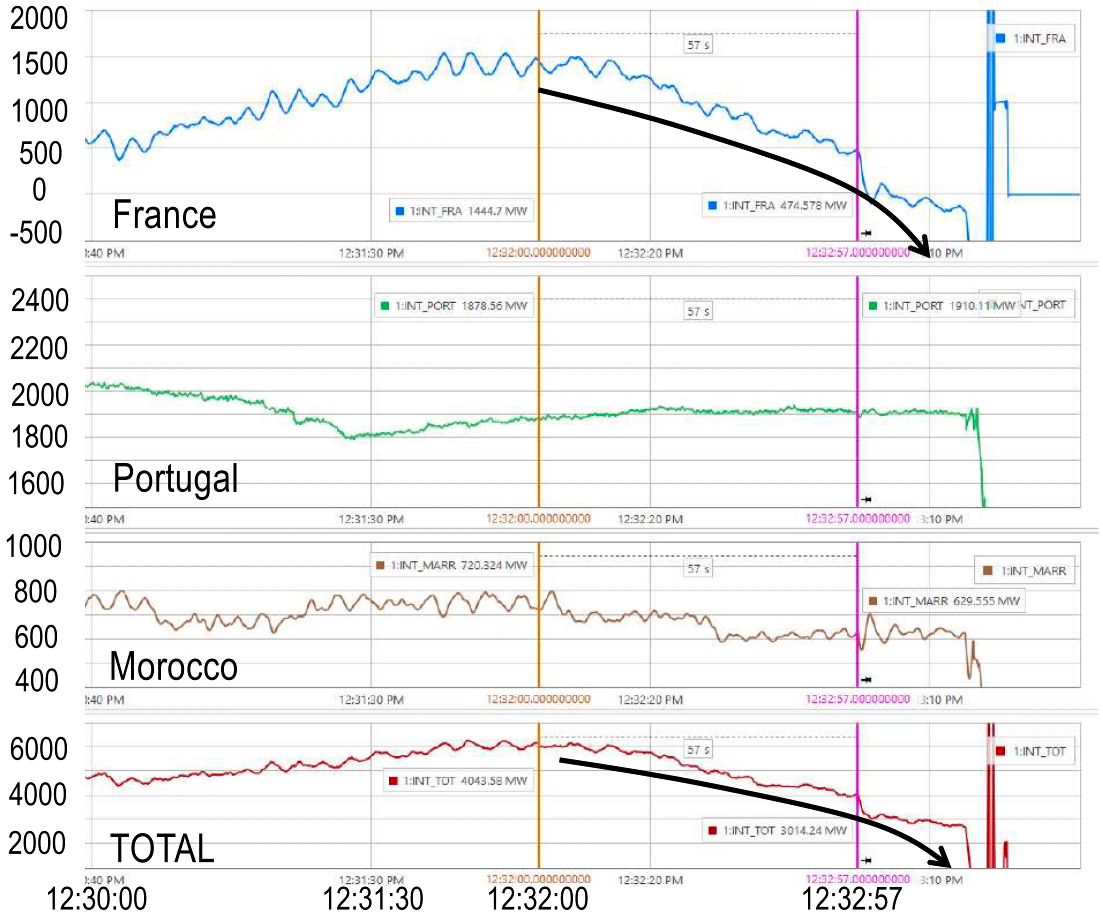

12:32

- Linear and QUICK voltage increase
- Energy exported to France starts to decrease:

Lower load on transmission lines

Voltage increase

Phase 2 – Morning of April 28th (12:32:00 – 12:33:18 h)

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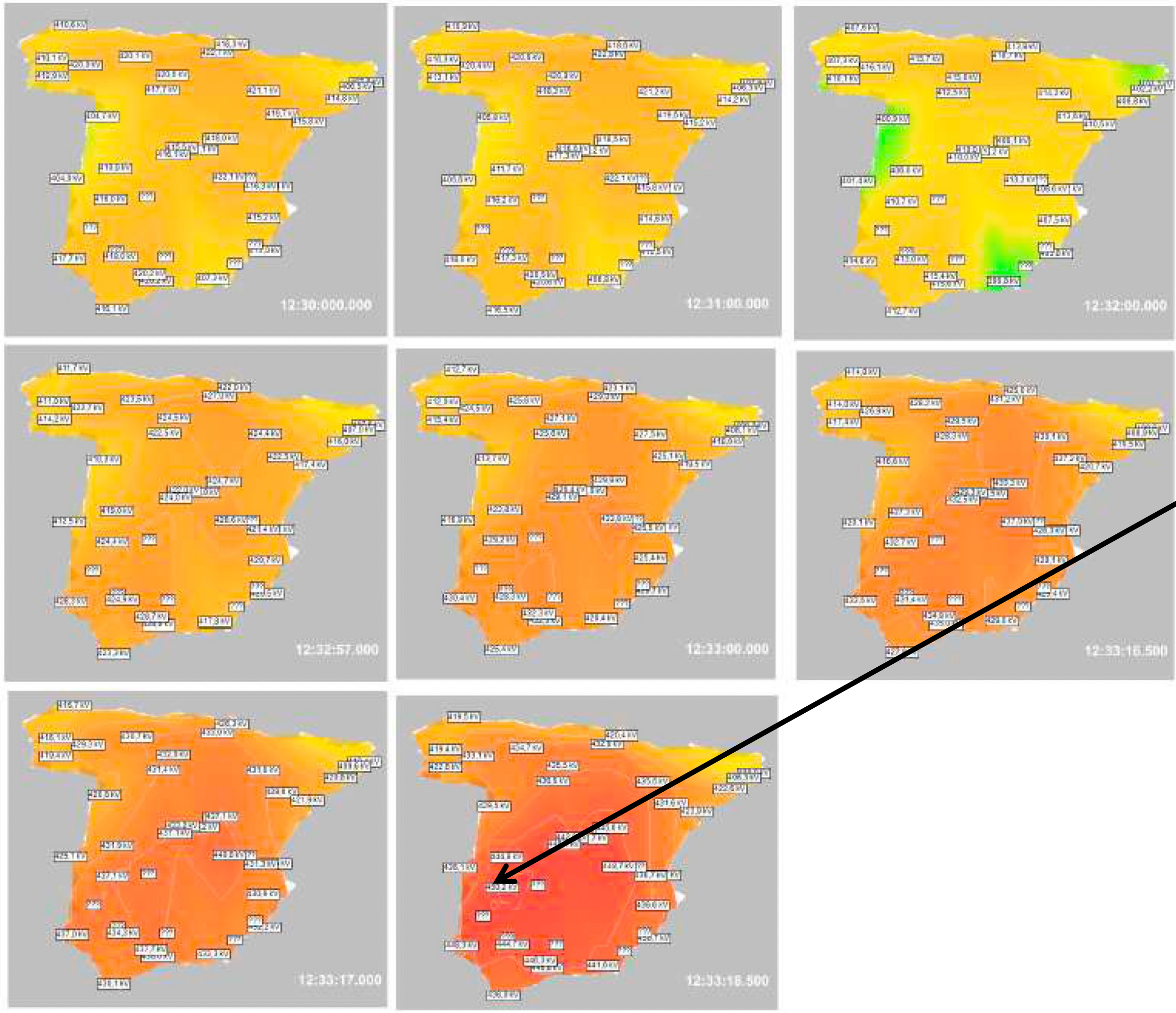

12:32

- Linear and QUICK voltage increase:
  - Almaraz: 413 – 428 kV in 57 s
  - Arroyo: 411– 424 kV in 57 s

Phase 2 – Morning of April 28th (12:32:00 – 12:33:18 h)

Time	MW	Time	MW
12:32:05	2.6	12:32:29	2.3
12:32:09	21.6	12:32:45	0.6
12:32:09	5.9	12:32:49	13.3
12:32:09	4.8	12:32:49	1.1
12:32:09	2.9	12:32:53	11.9
12:32:25	19.2	12:32:53	20.0
12:32:25	3.4	12:32:53	4.8
12:32:29	22.4	12:32:53	10.0
12:32:29	55.6	12:32:53	6.0
525 MW (2%) | 317 MW DG (60%)			

12:32

- Linear and QUICK voltage increase
- Energy exported to France starts to decrease:
- Loss of generation capacity starts

Phase 2 – Morning of April 28th (12:32:00 – 12:33:18 h)

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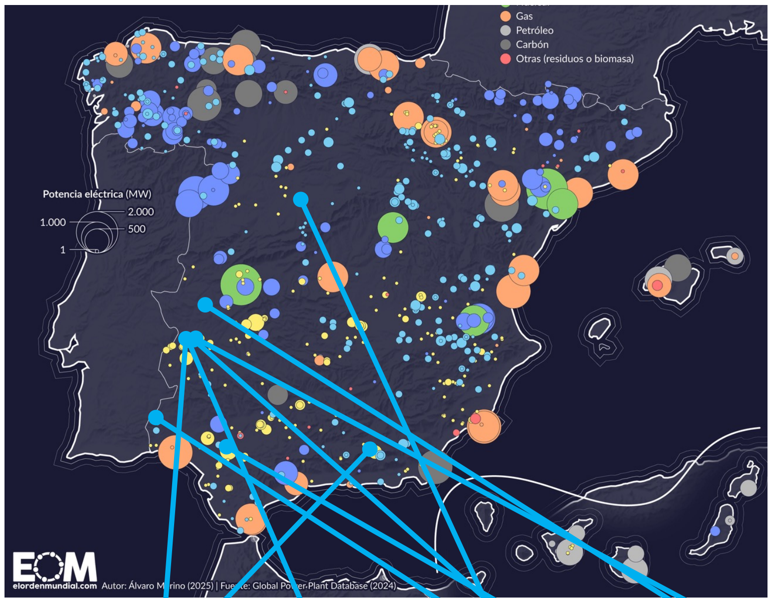

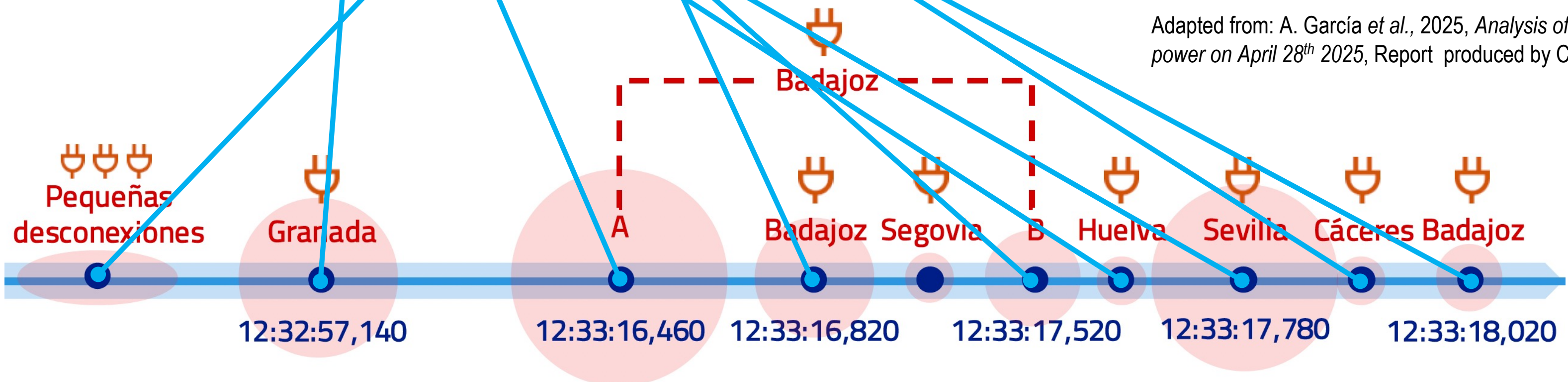

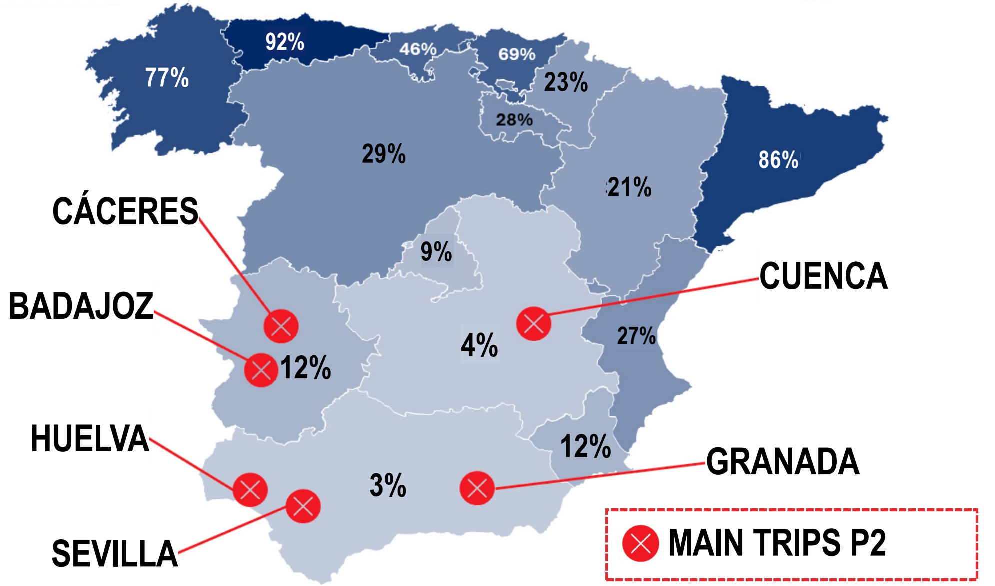

% - Share of synchronous power

Adapted from: A. García *et al.*, 2025, *Analysis of the events leading to the loss of power on April 28th 2025*, Report produced by Compass-Lexecon and INESCTEC

Phase 2 – Morning of April 28th (12:32:00 – 12:33:18 h)

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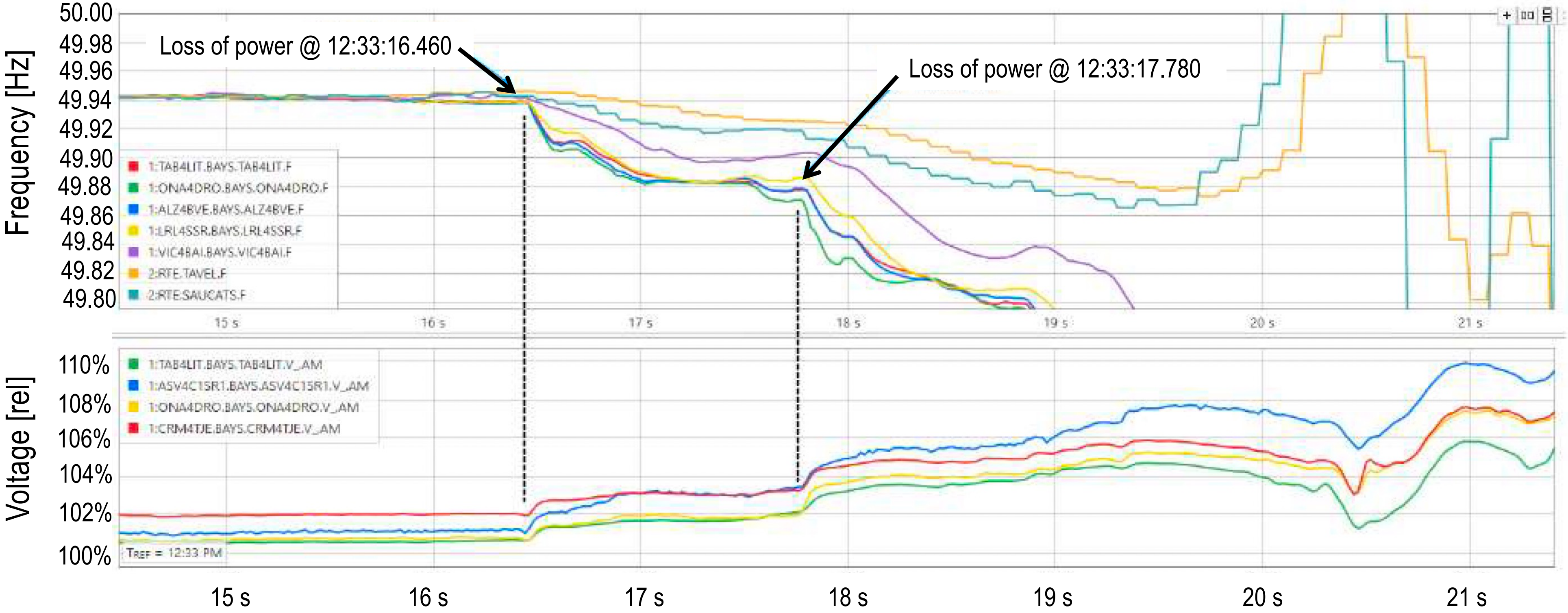
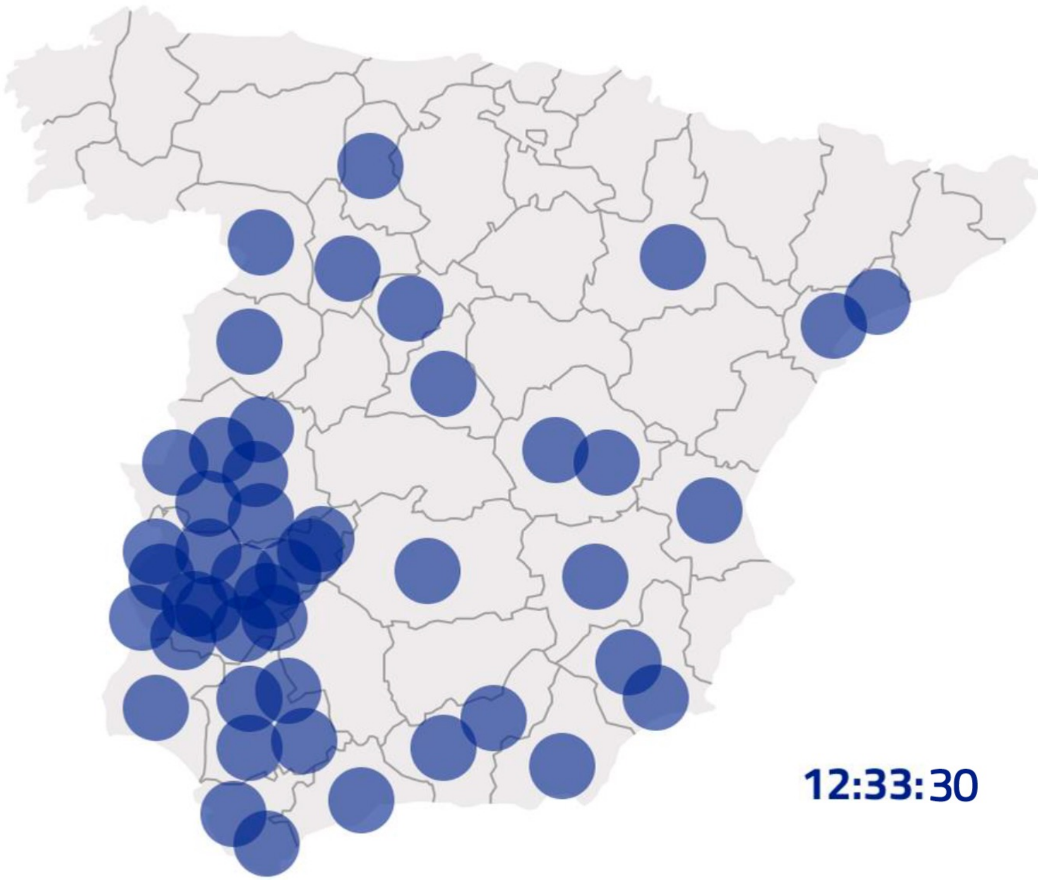
12:33:16.460



Phase 3 – Morning of April 28th (12:33:18 – 12:33:30 h)



12:33:17.780

- From 12:33:18.102, **power plants start to trip due to overvoltage** → voltage registered
  - 12:33:18.102 247.6 kV (+12.5%)
  - 12:33:18.380 443.8 kV (+11%)
- This exceeds the overvoltage that power generators are legally forced to withstand
- **Chain reaction is triggered** (see map on the left)
- 12:33:19.296 Due to loss of power, **frequency drop accelerates** (high negative slope)
- **12:33:19.620 Loss of synchronism Spain-France**
- **12:33:20.240 Pumped hydro stations trip**

Phase 3 – Morning of April 28th (12:33:18 – 12:33:30 h)

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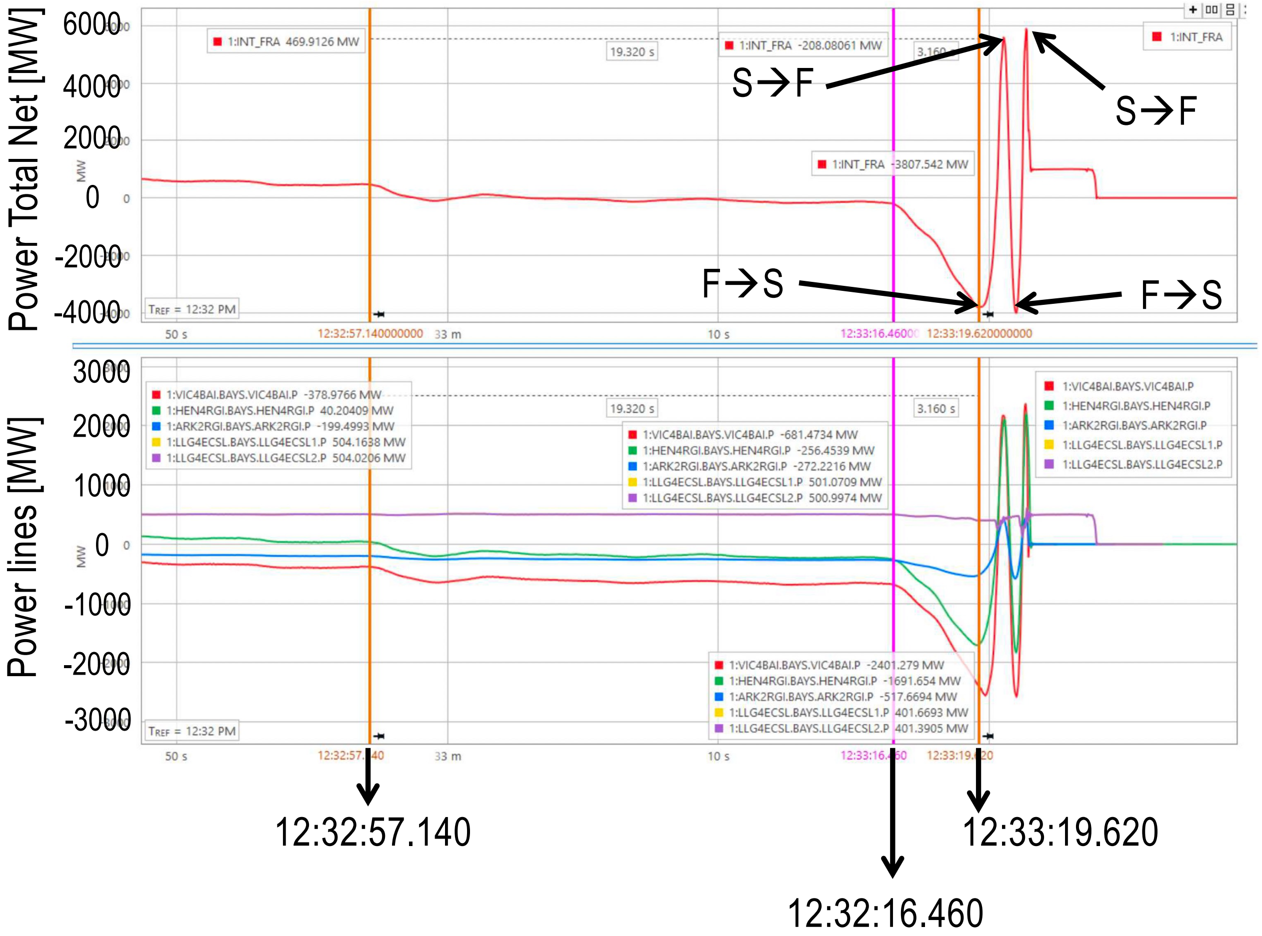
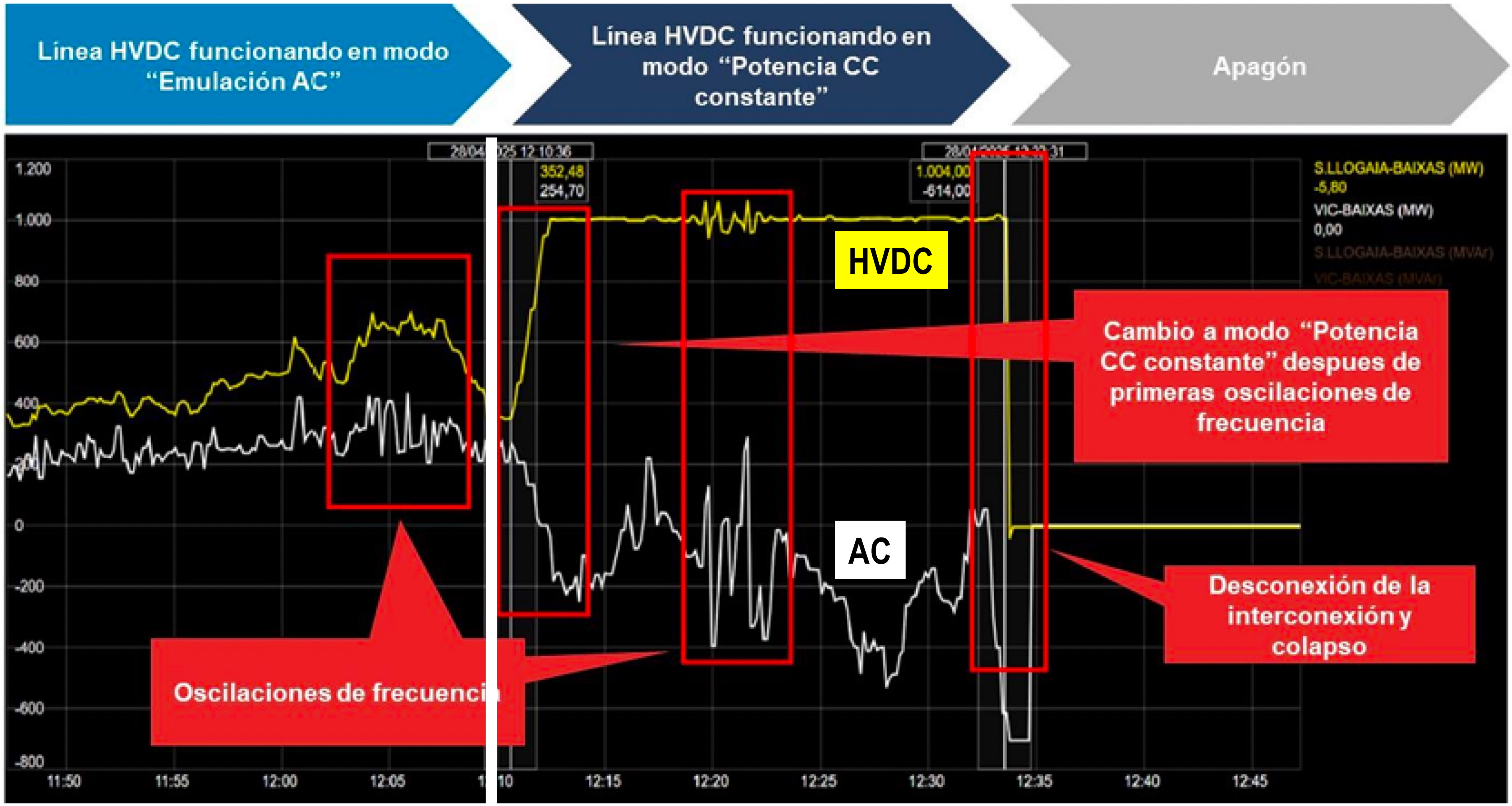


12:33:23.960

- **12:33:19.620 Interconnection Spain - France:**
  - The interconnection is running at full load
    - AC 4609 MW France → Spain
    - HVDC 802 MW Spain → France
  - Large phase shift between France & Spain
  - Loss of synchronism France - Spain
- 12:33:20.520 Maximum energy exported to France (5587 MW)
- 12:33:21.407 **after second wave (export/import shift) AC interconnections trip**
- 12:33:23.960 HVDC connection ceases operation

Phase 3 – Morning of April 28th (12:33:18 – 12:33:30 h)



Phase 3 – Morning of April 28^{th} (12:33:18 – 12:33:30 h)

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- 12:33:20.180 Frequency drops to 49.48 Hz (below 1^{st} pumping load shedding threshold - 49.50 Hz)
- Tripping of power plants due to overvoltage continues (255.3 kV registered in 220 kV lines)
- **12:33:20.500 Frequency falls below 49.30 Hz (2^{nd} pumping load shedding threshold) → 588 MW go offline automatically**
- **12:33:20.600 Frequency falls below 49.00 Hz (1^{st} load shedding threshold –LST–)**
- Some 400 kV lines registered running at 456 kV
- **12:33:20.800 All pumped hydro offline (2037 MW)**
- 12:33:20.760 Frequency falls below 48.8 Hz (2^{nd} LST)
- 12:33:21.000 Frequency falls below 48.6 Hz (3^{rd} LST)
- 12:33:21.380 Frequency falls below 48.40 Hz (4^{th} LST)
- 12:33:21.820 Frequency falls below 48.20 Hz (5^{th} LST)

12:33:20.180

- 12:33:22.040 Frequency falls below 48.00 Hz (6^{th} and last LST)
- Tripping of plants continues: some 400 kV lines registered running at 485 kV
- **12:33:23.400 frequency has fallen below the threshold that power generation systems must legally tolerate**
- 12:33:23.515 Frequency falls to 46.15 Hz
- 12:33:23.590 Frequency falls to 45.89 Hz
- **12:33:29.741 Last group trips → V=0**

Quick notes on active/reactive power and voltage control

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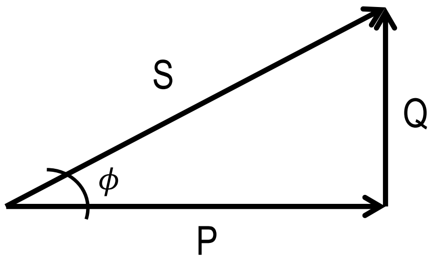
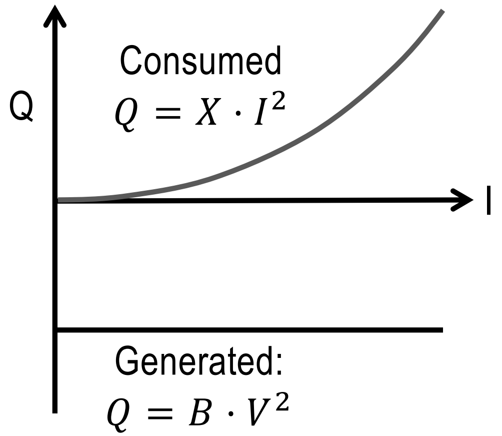
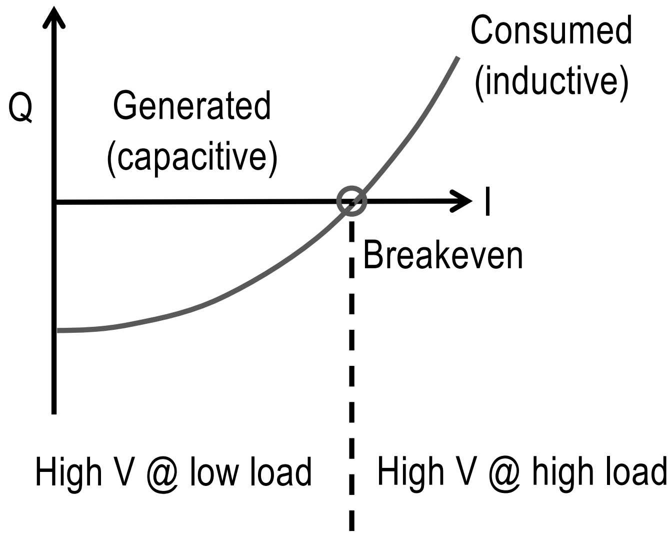


Power factor: $\cos\phi = \frac{P}{S}$

- Motors
- Transformers
- Reactance

- Condensers
- HV lines
- Asynchronous generators





- Highly loaded
  - Consume reactive power
  - Reactance-like
- Lightly loaded
  - Produce reactive power
  - Condenser-like
- Aboveground/underground
  - Underground produce more reactive power (at given V)
- Voltage
  - Higher voltage produce more reactive power (for given length)
- Load
  - Lower voltage produce less reactive power (for given length and load)

LINE / CIRCUIT

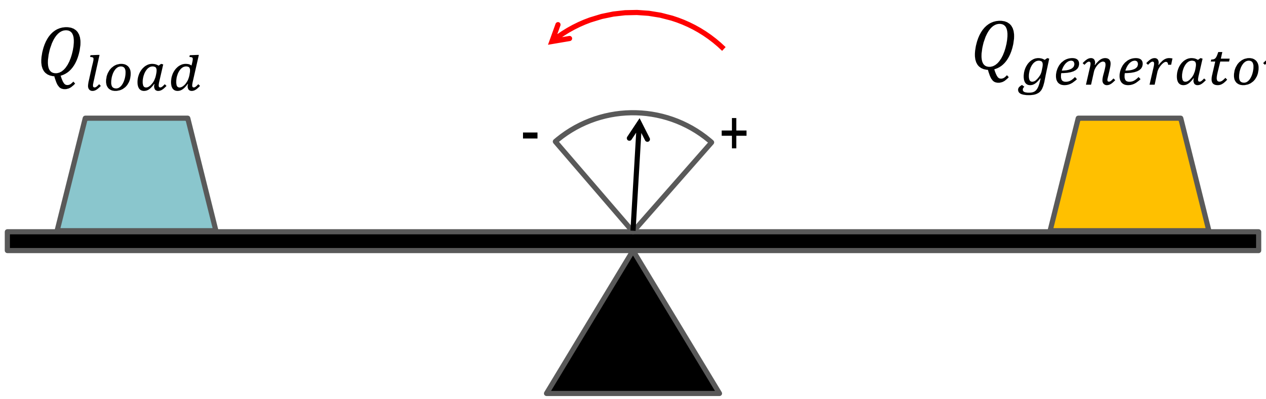
What is known now
(but was still unclear one year ago)

Report released by the Government and group of experts

1

Dynamic voltage control: Thermal stations did not operate as planned, even though they received capacity payment (lack of compliance with OP7.4):

- Should have consumed reactive power to reduce voltage
- Rather, they increased production of reactive power (reduced $\cos\phi$)



$Q_g > Q_l$: $V \uparrow$

$Q_g < Q_l$: $V \downarrow$

Report released by the Government and group of experts

2

Over Voltage trips: Unjustified early trip of installations (OP1.1):

- Installations must withstand 440 kV during 60 mins and 485 kV occasionally
- Several installations tripped at lower voltages
- **HVDC** Spain-France running **in DC shielded France** (avoided cascade effect)

3

Frequency: Oscillations at 0.6 Hz (12:02 h) originated at a large PV facility in Badajoz (South):

- Arguably late reaction of Power/Voltage Control loops of PV Plants
- The power plant amplified (rather than attenuated) oscillations

4

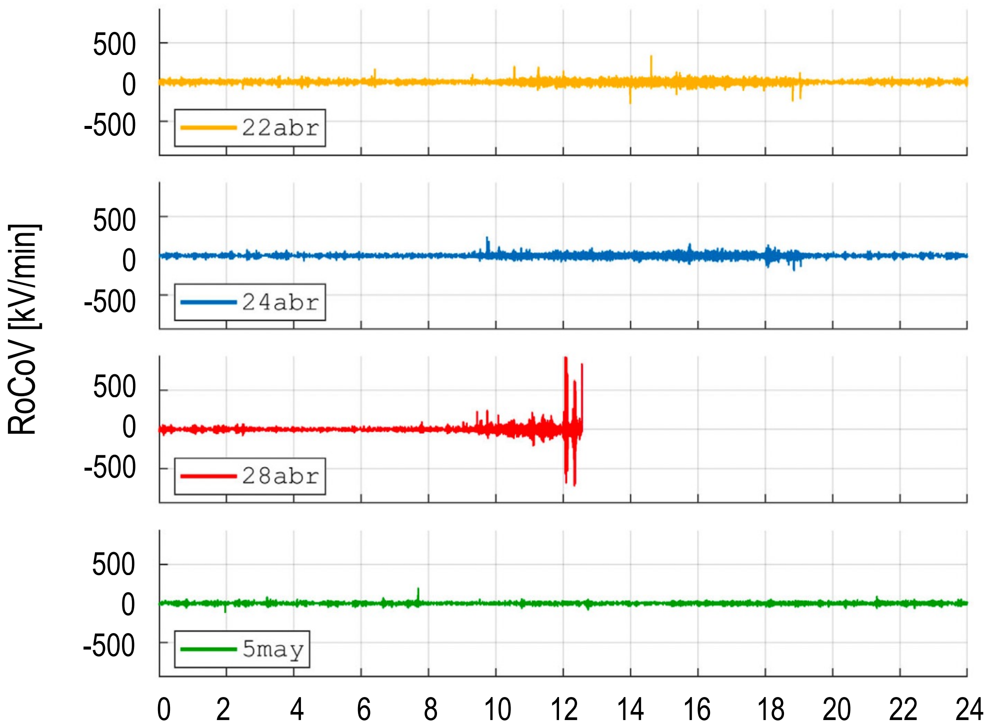
Grid management: 220 and 400 kV lines **were operated correctly**

- Breaking the connection with France and Morocco isolated the problem
- The problem could not be isolated in a meshed grid (overvoltage protection not coordinated)

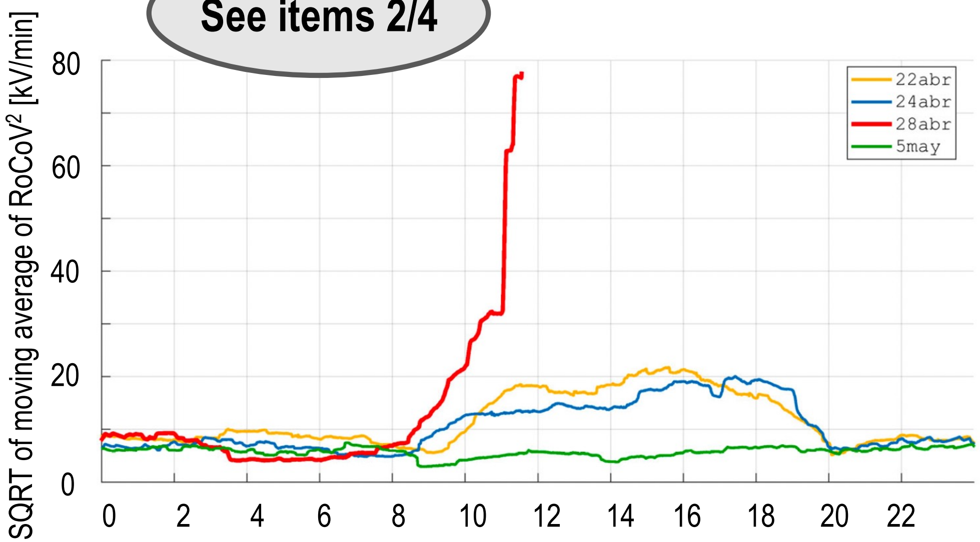
Report released by Iberdrola and Enel (ICAI)

1

Dynamic voltage control: Not only about voltage variation but, most importantly, about rate of change of V (RoCoV):



See items 2/4



- Voltage control systems of the grid not working correctly

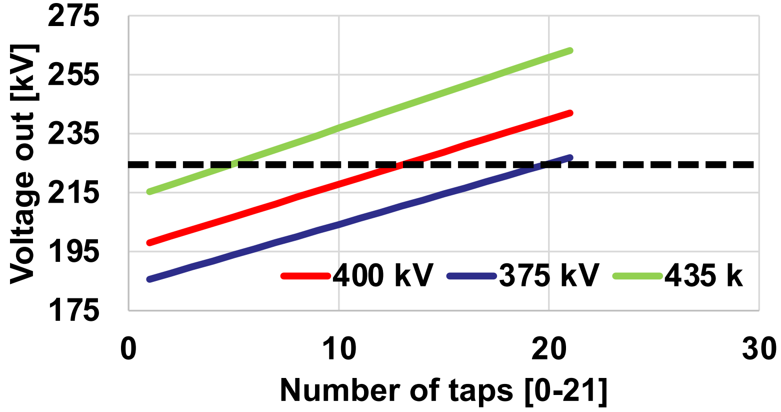
Source: L. Rouco, E. Lobato, F. Echavarren, 2025, *Informe preliminar en relación con el cero de tensión acaecido el 28 de Abril de 2025*, Report produced Universidad Pontificia de Comillas (ICAI)

Report released by Iberdrola and Enel (ICAI)

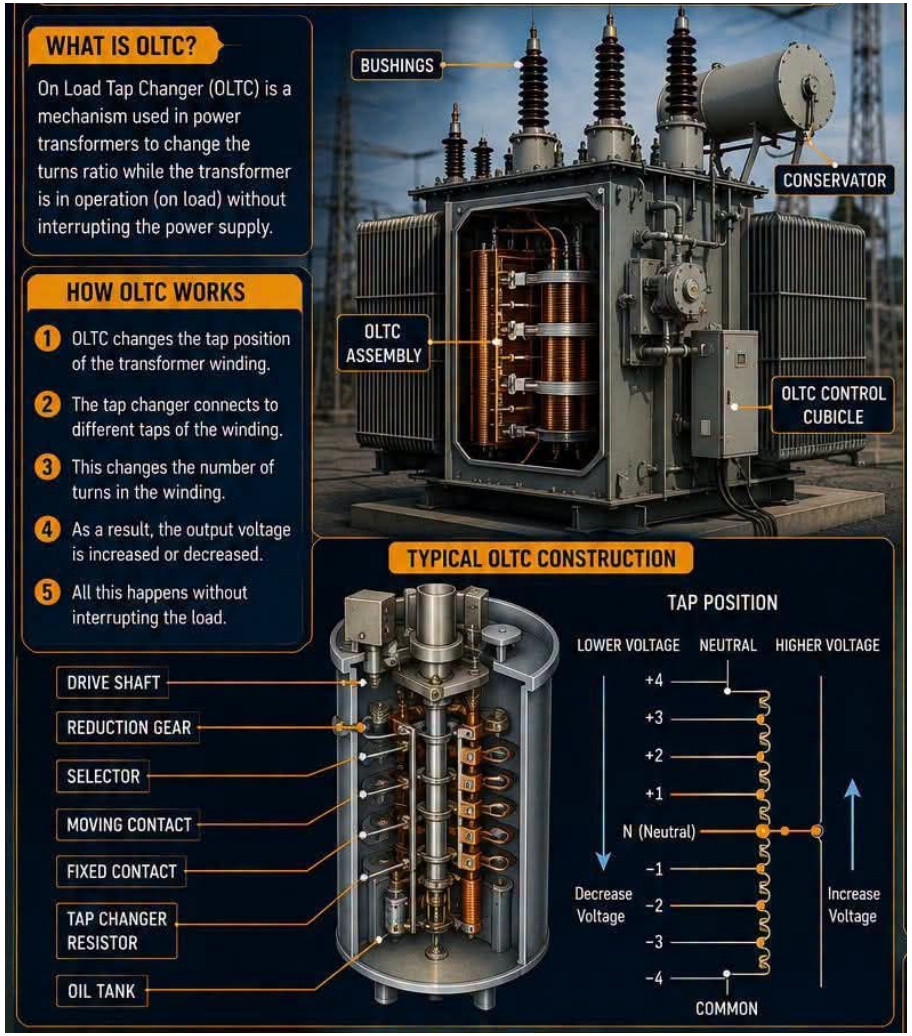
2

Voltage: *tap-lag*

- Tap Changers modify voltage ratio to control output voltage (# of windings)
- Example shows a 400/220 kV OLTC with 21 positions (±10%)



Source: Shahnawaz Hussain, Engineering Portal, Facebook



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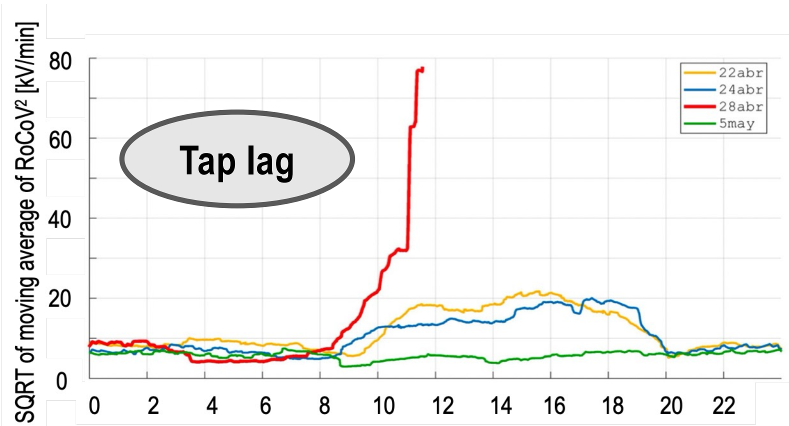
2

Voltage: tap-lag

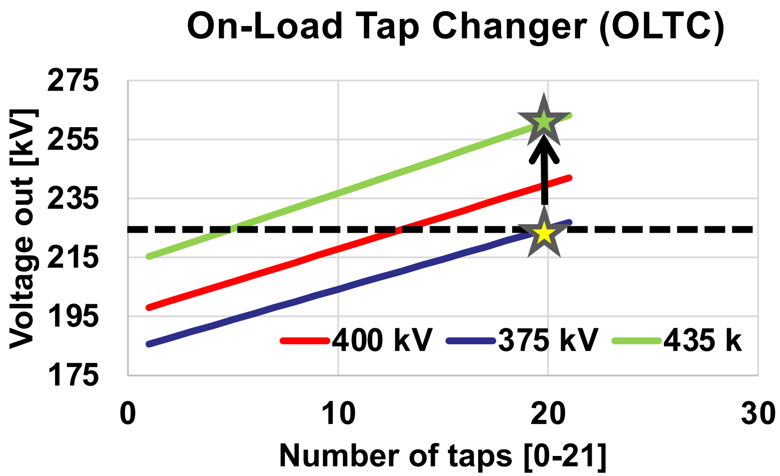
- This is a mechanical device → long response time
- If input voltage increases fast (RoCoV) → SUT is amplifying the problem on the low V end

$$t_{response} = t_{delay\ 1} + t_{tap\ change} + t_{delay\ \geq 2} + t_{tap\ change} \cdots$$

30-60 secs 3-5 secs 5-10 secs 3-5 secs



Source: L. Rouco, E. Lobato, F. Echavarren, 2025, *Informe preliminar en relación con el cero de tensión acaecido el 28 de Abril de 2025*, Report produced Universidad Pontificia de Comillas (ICAI)



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4

Grid management: Weak grid

- 1/3 of the 400 kV lines open in zone S
- Low inertia in Zone S
    - Two CCGTs planned in the South area
    - One of them reporting unavailability to operate not replaced

Strength vs. Damping

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$$\frac{1}{Z_{eq}} = \frac{1}{Z_{L1}} + \frac{1}{Z_{L2}} + \cdots$$

$$\Delta V = \frac{P \cdot R + Q \cdot X}{V}$$

Zone	Nuke	CCGT	Hydro	Total	Demand	Inertia	220 kV	400 kV	220 kV	400 kV
NE	0	3714	6652	12111	3152	3.84		20.7%	2.5%	0.9%
N	0	2995	7843	10837	3585	3.02		14.4%	0.7%	1.6%
E	9642	0	4105	13747	5909	2.33	1.5%	8.5%	2.8%	4.8%
C	2906	8875	4204	15984	8664	1.84	7.0%	26.7%	5.6%	2.2%
S	0	2881	1535	4417	3398	1.30		27.5%		8.3%
Total	**12547**	**18465**	**1746**	**24339**	**25038**	**2.31**	**1.8%**	**18.4%**	**2.3%**	**3.8%**

35.8%

<2 s

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4

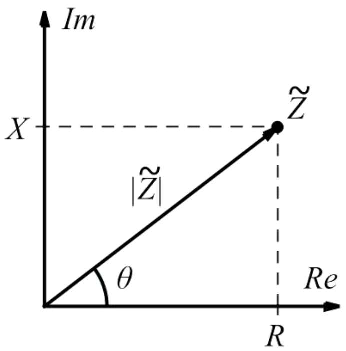
Grid management: Weak grid

- Strong grid: Z_{grid} ↓↓
  - Point of common coupling (PCC): *rigid*

- Weak grid: Z_{grid} ↑↑
  - Point of common coupling (PCC): *sensitive*

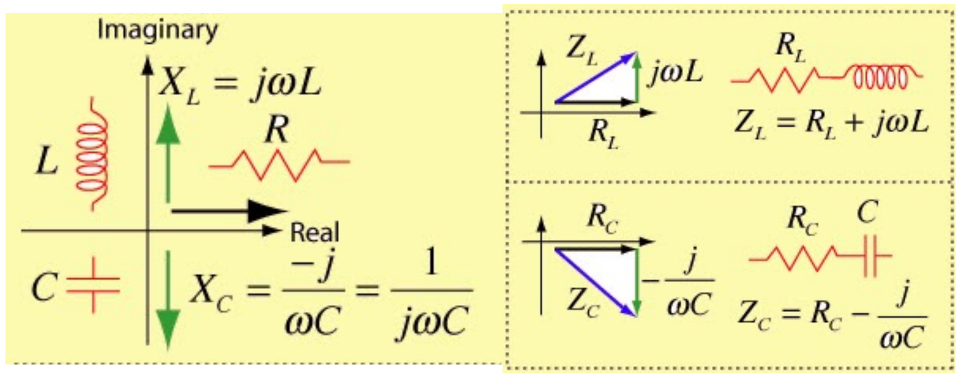
$$\frac{1}{Z_{eq}} = \frac{1}{Z_{L1}} + \frac{1}{Z_{L2}} + \cdots$$

$$\Delta V = \frac{P \cdot R + Q \cdot X}{V}$$



$$Z = R + j \cdot X$$

Z : Impedance
R: Resistance
X: Reactance



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2

Grid management: strength of the grid monitored through SCR

SCR: Short circuit ratio
S_{SC}: Short circuit capacity of system
P_{Gen}: Apparent power generator
V_n: Nominal voltage at node
Z_{Th}: Equivalent impedance

$$SCR = \frac{S_{SC}}{P_{Gen}} \quad \begin{cases} S_{SC,syn} \approx 5 - 7 \\ S_{SC,asyn} \approx 1.2 - 1.4 \end{cases}$$

- Two ways to calculate short-circuit potential at POI (Point of Injection)

$$S_{SC} = \sqrt{3} \cdot V_{SC} \cdot I_{SC}$$

$$S_{SC} = \frac{V_n^2}{Z_{Th}}$$

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2

Grid management: strength of the grid monitored through SCR

Grid class	Z_{Th}	SCR	Comments
Strong	Very low $\|X\| \gg R$	$SCR > 3(10)$	• **Rigid voltage profile.** • **Large number of synchronous generators.** • If a grid fault occurs → large short-circuit current is provided to sustain the system.
Weak	High $\|X\| \approx R$	$2 \leq SCR \leq 3$	• **Sensitive voltage profile.** • **Voltage interacts dynamically with active/reactive power variations: (P/Q coupling).**
Very weak	Very high $\|X\| < R$	$SCR < 2$	• Critical grid stability. • Low short-circuit current available. • High risk of control instability and voltage collapse for conventional inverters

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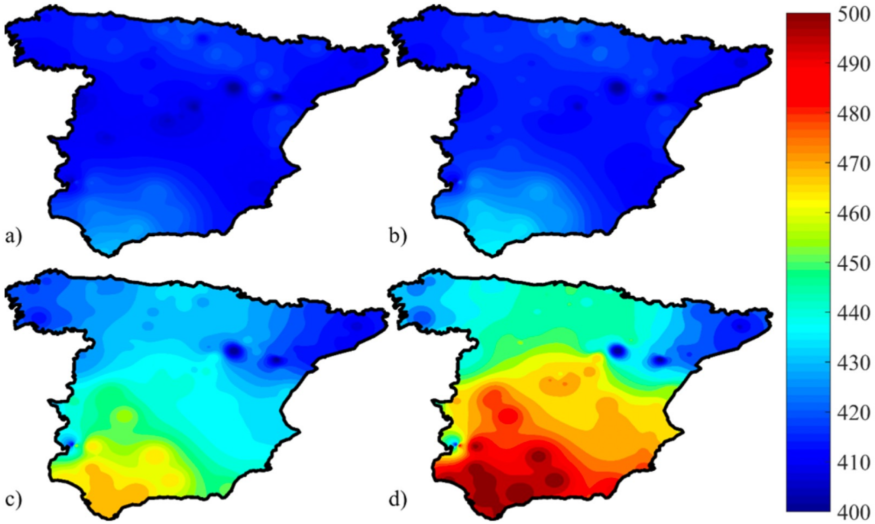
2

Grid management: strength of the grid monitored through SCR



Source: L. Rouco, E. Lobato, F. Echavarren, 2025, *Informe preliminar en relación con el cero de tensión acaecido el 28 de Abril de 2025*, Report produced Universidad Pontificia de Comillas (ICAI)

- In HV lines: $X_{grid} \gg R_{grid}$ (usually) → ΔV controlled by Q
- If $SCR \ll 2$ → Z_{grid} ↑↑ → ΔV controlled by P also
- **Steep ramp-up/down of PV has the capacity to impact ΔV**

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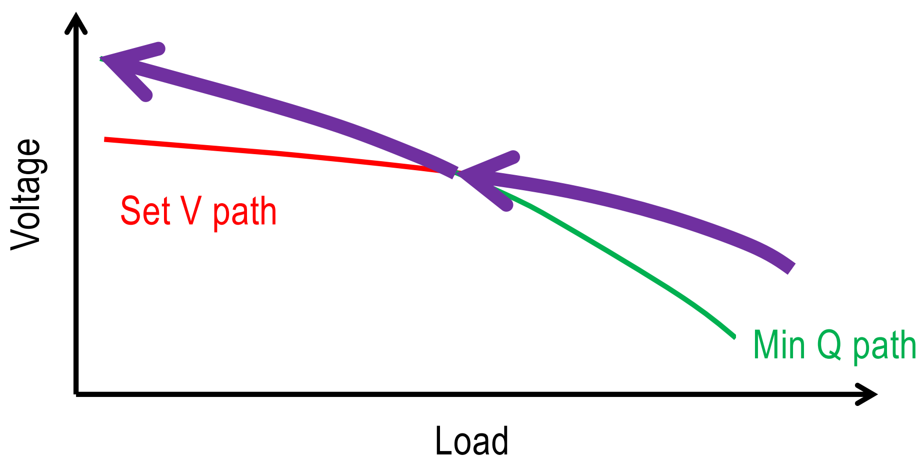
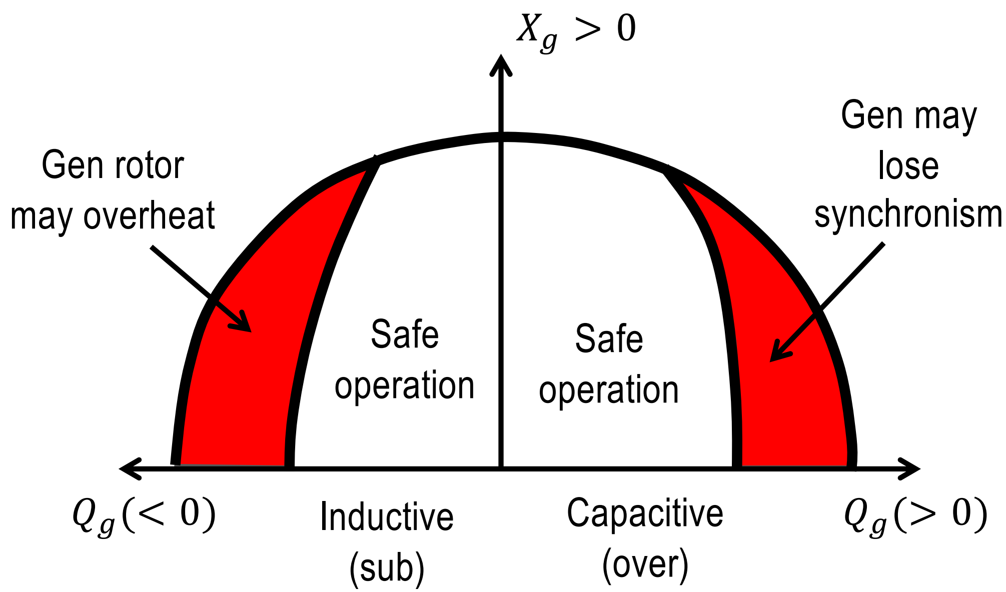
3

Grid management: counterproductive measures to mitigate V oscillations

- 11 lines come online + 13 shunt reactors stop consuming Q (?)
- The cumulative effect is >1000 MVAR added to the grid → V increase reinforced
- Synchronous generators reduce the production of Q to offset V increase





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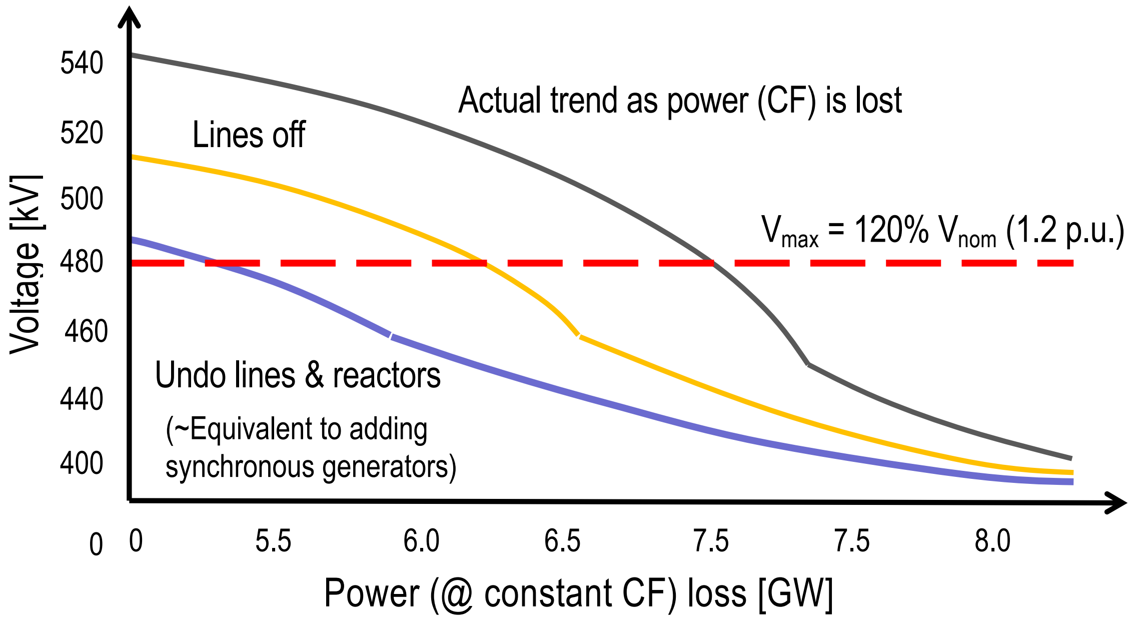
3

Grid management: counterproductive measures to mitigate V oscillations

- 11 lines come online + 13 shunt reactors stop consuming Q (?)
- Synchronous generators reduce Q to offset V increase (until they hit the limit)



Distance to voltage collapse reduced from 2964 MW to 1268 MW

Adapted from: L. Rouco, E. Lobato, F. Echavarren, 2025, *Informe preliminar en relación con el cero de tensión acaecido el 28 de Abril de 2025*, Report produced Universidad Pontificia de Comillas (ICAI)

Report released by Iberdrola and Enel (ICAI)

3

Grid management: counterproductive measures to mitigate V oscillations

- What about asynchronous (inverter-based) generators?
- Can they not consume reactive power?

$$S_{max} = \sqrt{P^2 + Q^2}$$

(S_{max} : Thermal capacity of inverter)

- S_{max} cannot be exceded (overheating)
- When P increases fast → Q must be reduced
- If the grid is weak → reduced consumption of Q → V increases

- Moreover, former OP7.4 (during the blackout) did not allow IBRs to control voltage dynamically through reactive power consumption

Adapted from: L. Rouco, E. Lobato, F. Echavarren, 2025, *Informe preliminar en relación con el cero de tension acaecido el 28 de Abril de 2025*, Report produced Universidad Pontificia de Comillas (ICAI)

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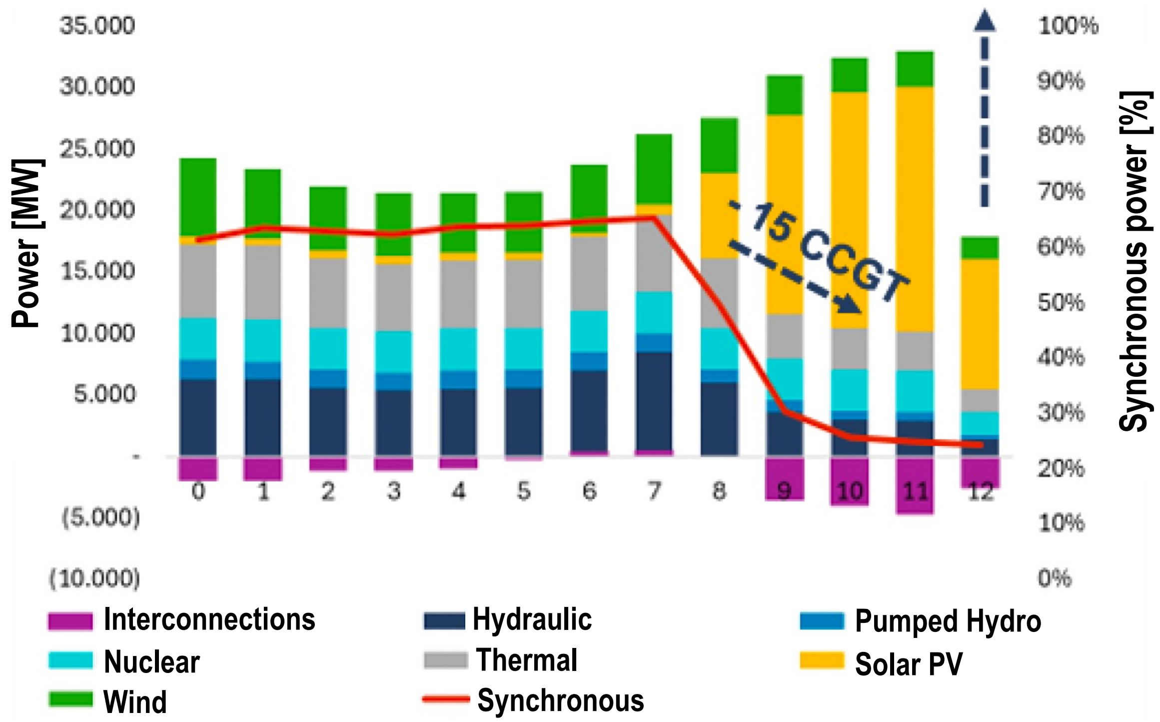
3

Grid management: counterproductive measures to mitigate V oscillations



Adapted from: A. García *et al.*, 2025, *Analysis of the events leading to the loss of power on April 28th 2025*, Report produced by Compass-Lexecon and INESCTEC

Items stakeholders agree on

Item	Technical description	GOV	TSO	UTIL	ENT
Inertia is not a root cause	Grid was running with H=2.3 s (ENTSO > 2.0 s) Higher inertia would have only slowed down Δf	✓	✓	✓	✓
Collapse is due to overvoltage not underfrequency	Blackout was due to imbalance of reactive power, triggering cascaded overvoltage trips Loss of active power or frequency drops not involved	✓	✓	✓	✓
Active power reserve large enough	mFRR > 7000 MW at the time of blackout	✓	✓	✓	✓
UFLS aggravated the problem	Load shedding reinforced the capacitive behavior of the grid → voltage increase accelerated	✓	✓	✓	✓
IBR code (OP7.4) insufficient	OP7.4 / RD 413/2014 prevented IBR from performing dynamic V control → Sinks of reactive power not used	✓	✓	✓	✓
Static N-1 insufficient	EAS classified the system as “safe” throughout the blackout → system unable to detect ultrafast dynamics	✓	✓	✓	✓

Items stakeholders disagree on

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Source of capacitive saturation

- System had wide enough margins
- Saturation was caused by generators that did not absorb the reactive power required by OP7.4
- Meshing was justified in order to damp oscillations

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redeia

- Meshing 11 lines w/o load injected 1.05-2.4 GVAr (Ferranti)
- Distance to voltage collapse in Seville decreased from 3 GW to 1.25 GW
- Voltage collapse was unavoidable even without loss of power

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- No comments on meshing being a causal factor of the collapse
- Supports RCC did not detect capacitive saturation
- Regulatory constraint on IBR is an inherent (organic) primary weakness

entsoe

Items stakeholders disagree on

Nature/origin of the voltage oscillation at 0.6 Hz

- Forced oscillation originating at a PV plant in the west bank (Badajoz)
- **This abnormal behavior actually triggers the series of events leading to the blackout**

- Evidence is **not conclusive**
- Oscillations could as well have been a natural inter-region mode amplified by the very low damping (~1%) of the grid
- This low damping was a consequence of the **lack of combined cycle power plants** (incorporating *power system stabilizers*) in the South region

- Oscillation at 0.6 Hz (detected in Germany also) is **unusual** but the **root cause is not clear**
- The low inertia may have amplified any disturbance at the root node

Items stakeholders disagree on

Justification (legitimacy) of cascaded tips *(tap lag)*

- The first trips (12:32:57-12:33:18) were **inadequate**
- SCADA of TSO logged 418 kV on a 400 kV grid, well **within the limits** of OP 1.1 (<435 kV).

- Trips were correct according to regulations
- **Tap-lag created a blind spot**
- Substations: current collectors at 220 kV were running at **244 kV (>1.1 pu)**
- This was not visible to the SCADA of the TSO

- Does not classify trips as inadequate
- Highlights the **lack of observability** of the underlaying grid by the TSO and RCCs

Items stakeholders disagree on

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Dispatch of electricity in the South region

- Acknowledges one CCGT was reported unavailable in the afternoon of April 27th
- **Not replacing this CCGT is justified by**
  - Voltage stability in the region, on April 27th
  - Other technologies being available

- The South region could only absorb 0.2 GVAr…
- …vs. the 0.7 GVAr injected by the TSO (meshing)
- Not replacing the CCGT was actually **the most critical decision made by the operator**, leading to the blackout

- Does not refer to the dispatch scheme of the TSO…
- …but identifies the **low short circuit capacity** (SCC) as an **organic causal factor** of the blackout

Items stakeholders disagree on

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Ultimate responsible

- Generators did not comply with the obligation to control voltage dynamically
- If the generators had complied with the regulations at the nodes, the system would have absorbed the transient event
- **The blackout was caused by a failure on the (privately-owned and operated) generation side of the grid)**

- Meshing of the grid by the TSO took the system to a **state where collapse was simply unavoidable**,…
- …with insufficient visibility…
- …and inadequate dispatch
- Generators were operated **according to physics and to the regulatory framework** at the connection nodes
- **The blackout was a failure caused by the TSO and the regulator**

- The root cause is closely related to the regulatory framework, **preventing IBRs from controlling voltage dynamically**
- **This failure extends to the national and European regulatory system and cannot be attributed to one stakeholder/agent only**

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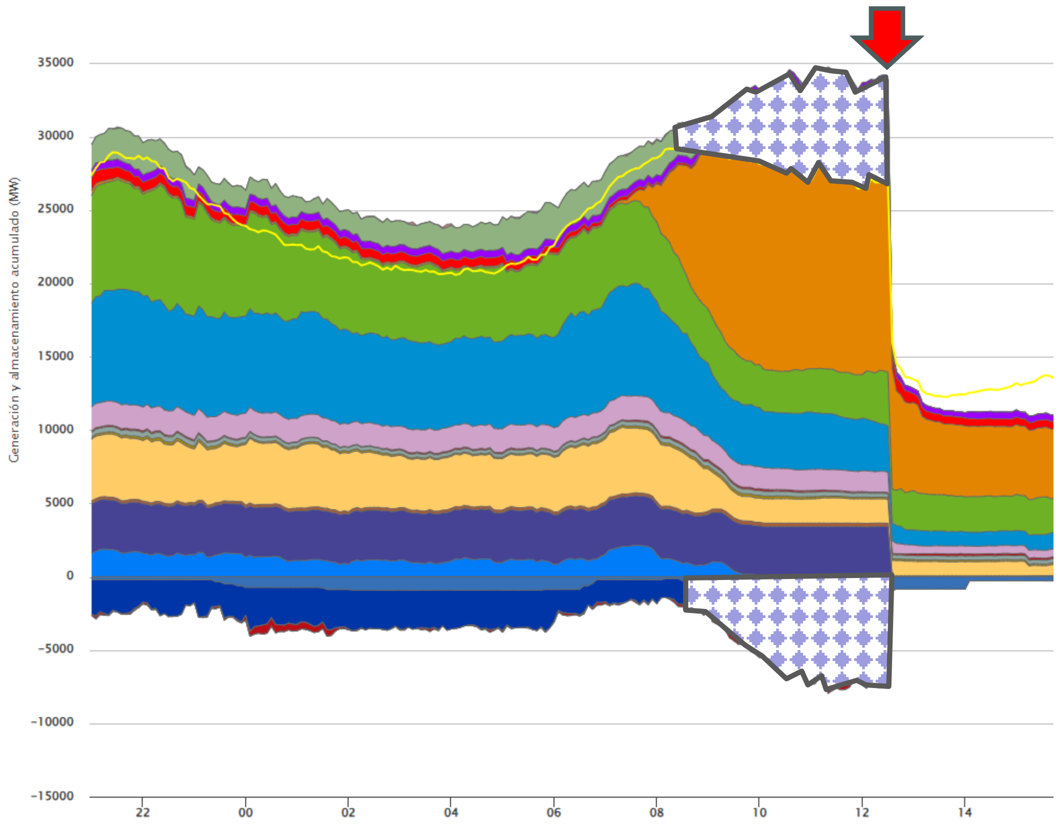
Would have energy storage avoided this?

Questions:

- Would have massive energy storage avoided the situation? Why?



Source: Red Eléctrica de España

Low demand (~25 GW → 50% of peak)

+

Large availability of solar PV

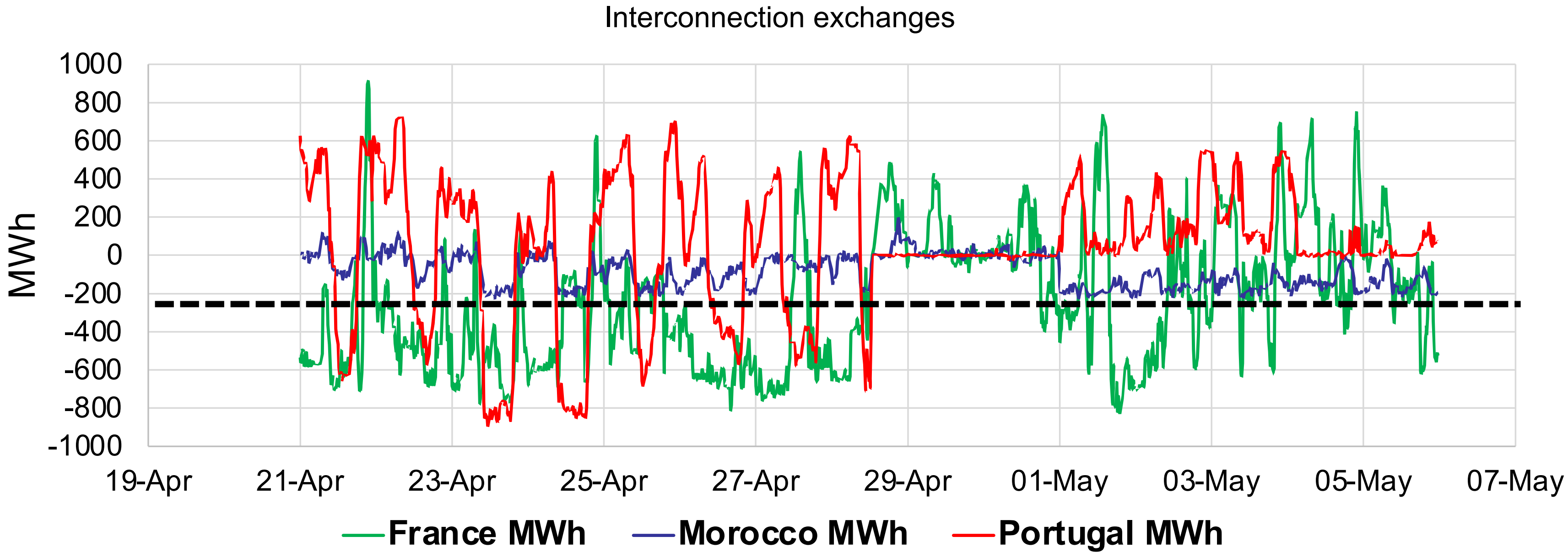
Pumped hydro

15 CCGTs shut down

Export

Questions:

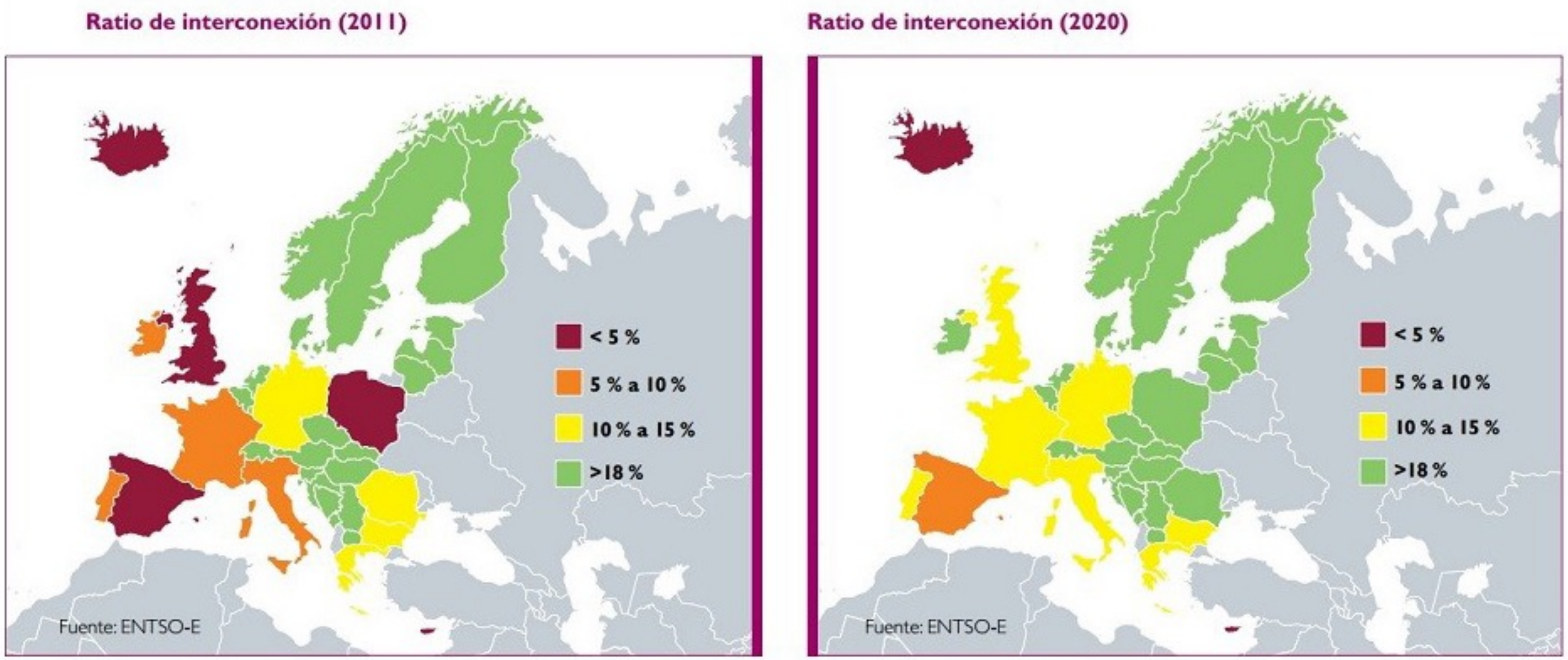
- Would have massive energy storage avoided the situation? Why?
- Are neighboring countries massive energy storage assets?



Source: Red Eléctrica de España

Questions:

- If energy storage is the solution, how much is needed?
- Is an updated market design needed to trigger interest by investors?



Source: ENTSOe

Questions:

- If energy storage is the solution, how much is needed?
  - ENTSO-e's objective for interconnection

15% of installed capacity → ~21 GW

- Is an updated market design needed to trigger interest by investors?
- What storage technologies?

~3 GW

	Capacity 142.5 GW	Generation 272 TWh
Hydro	12.0%	12.4%
Wind offshore	0.0%	0.0%
Wind	23.3%	21.6%
Solar PV	29.2%	18.4%
Solar CSP	1.6%	1.4%
Other RREE	0.8%	1.4%
Waste renewable	0.1%	0.3%
Nuclear	5.0%	19.0%
Coal	1.1%	0.6%
Diesel	0.5%	0.9%
Gas Turbine	0.8%	0.3%
Steam turbine	0.7%	0.9%
Fuel	0.0%	0.0%
CCGT	18.4%	16.8%
CHP	3.7%	5.7%
Waste (non-RREE)	0.3%	0.4%
Pumped hydro	2.3%	
Battery	0.1%	

Source: Red Eléctrica de España

Questions:

- But is it only about storage?
- Synchronous condensers are on its way:
  - 8 condensers already in the pipeline
  - ~100 M€ each
- New / repurposed (10 GW coal)?

$$I_{SC,PV} \approx 2 - 8 \cdot I_n$$

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🇪🇸 New Fleet of Synchronous Capacitors for the Transmission Network.

The operator of the Spanish System will install 8 synchronous capacitors in the peninsular transmission network that will add 2,000 MVAr and 12,000 MW.s of inertia.

🔷 SynCon Cabra 400 kV - 250 MVAr (Andalusia)
🔷 SynCon Brovales 400 kV - 250 MVAr (Extremadura)
🔷 SynCon Litoral 400 kV - 250 MVAr (Andalusia)
🔷 SynCon Belinchón 400 kV - 250 MVAr (Castilla La Mancha)
🔷 SynCon Rocamora 400 kV - 250 MVAr (Valencian Community)
🔷 SynCon Almaraz 400 kV - 250 MVAr (Extremadura)
🔷 SynCon Grado 400 kV - 250 MVAr (Asturias)
🔷 SynCon Beariz 400 kV - 250 MVAr (Beariz)

In the non-peninsular territories, the following have also been approved:

🔷 SynCon Fuencaliente 66 kV - 10 MVAr (La Palma)
🔷 SynCon Haría 66kV - 25 MVAr (Lanzarote)
🔷 SynCon Son Orlandis 220 kV - 100 MVAr (Mallorca)

This equipment, strategically located in sensitive nodes of the transmission grid, will have the functions of short-circuit power supply, voltage regulation and inertial response, helping to improve the strength of the network, participating in the dynamic regulation of zonal reactive power (Voltage Control) and supporting the frequency stability of the system.

By accelerating the bidding and awarding times, we estimate that they can be operational in the 2028-2030 horizon.

Good news for the Spanish electricity system, which in recent years has had to use, via technical restrictions, the coupling of combined cycle plants to gas for regulation and inertial input tasks, in many cases operating at very low power values or at the technical minimum, with the costs for the system that this entails.

One year later: are we clear about the Iberian blackout yet?

Thermal, Mechanical and Electrochemical Energy Storage Workshop (TMCES)
July 29th & 30th 2026 – Charlotte, NC

David Sánchez
University of Seville

Disclaimer: Except where noted, this presentation is based on documentation made public by the stakeholders involved in the electrical blackout occurring on April 28th 2025

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