Who turned off the light?
Storyboard of the total blackout in Spain

7th Thermal, Mechanical and Chemical Energy Storage Workshop
July 30th & 31st 2025 – San Antonio, TX

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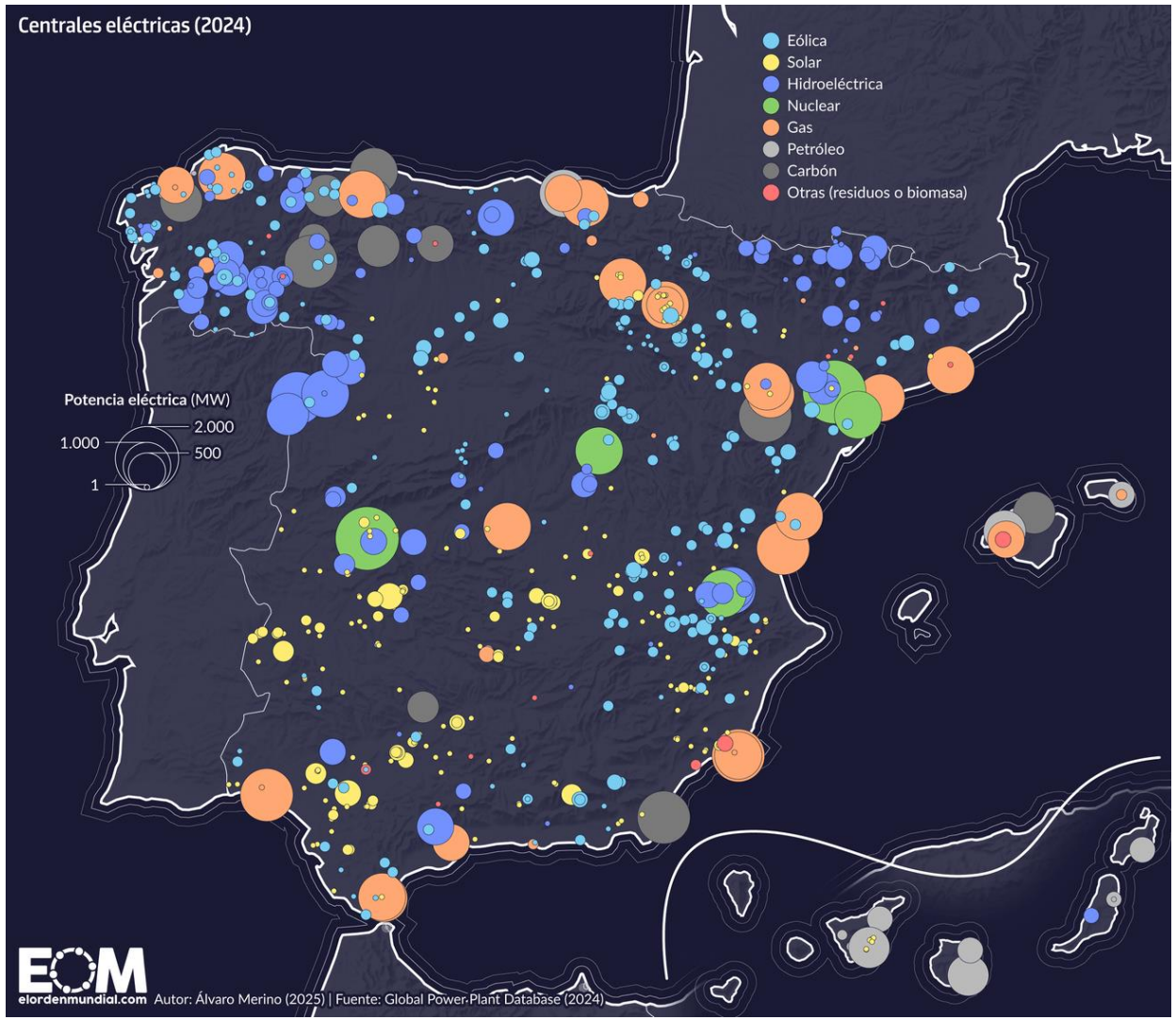
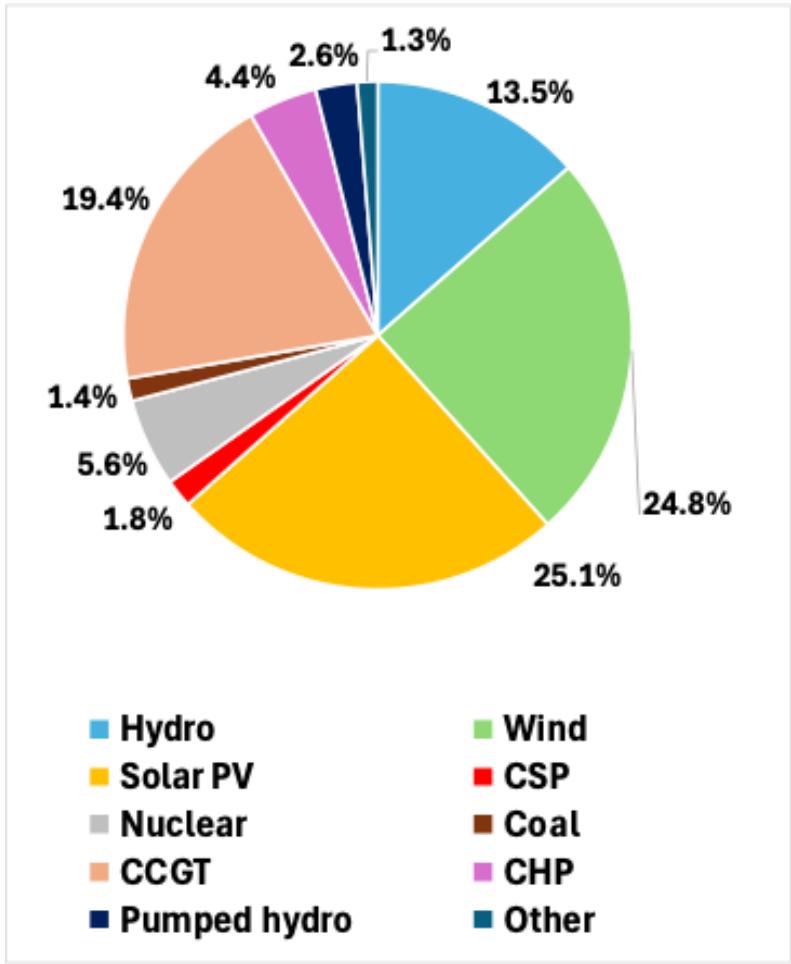
Disclaimer: Except where noted, this presentation is based on the non-confidential version of the report on the causes leading to the blackout on April 28th 2025, issued by the Government of Spain: *Versión no confidencial del informe del comité para el análisis de las circunstancias que concurrieron en la crisis de electricidad del 28 de abril de 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)

The stage – Spain's electrical system





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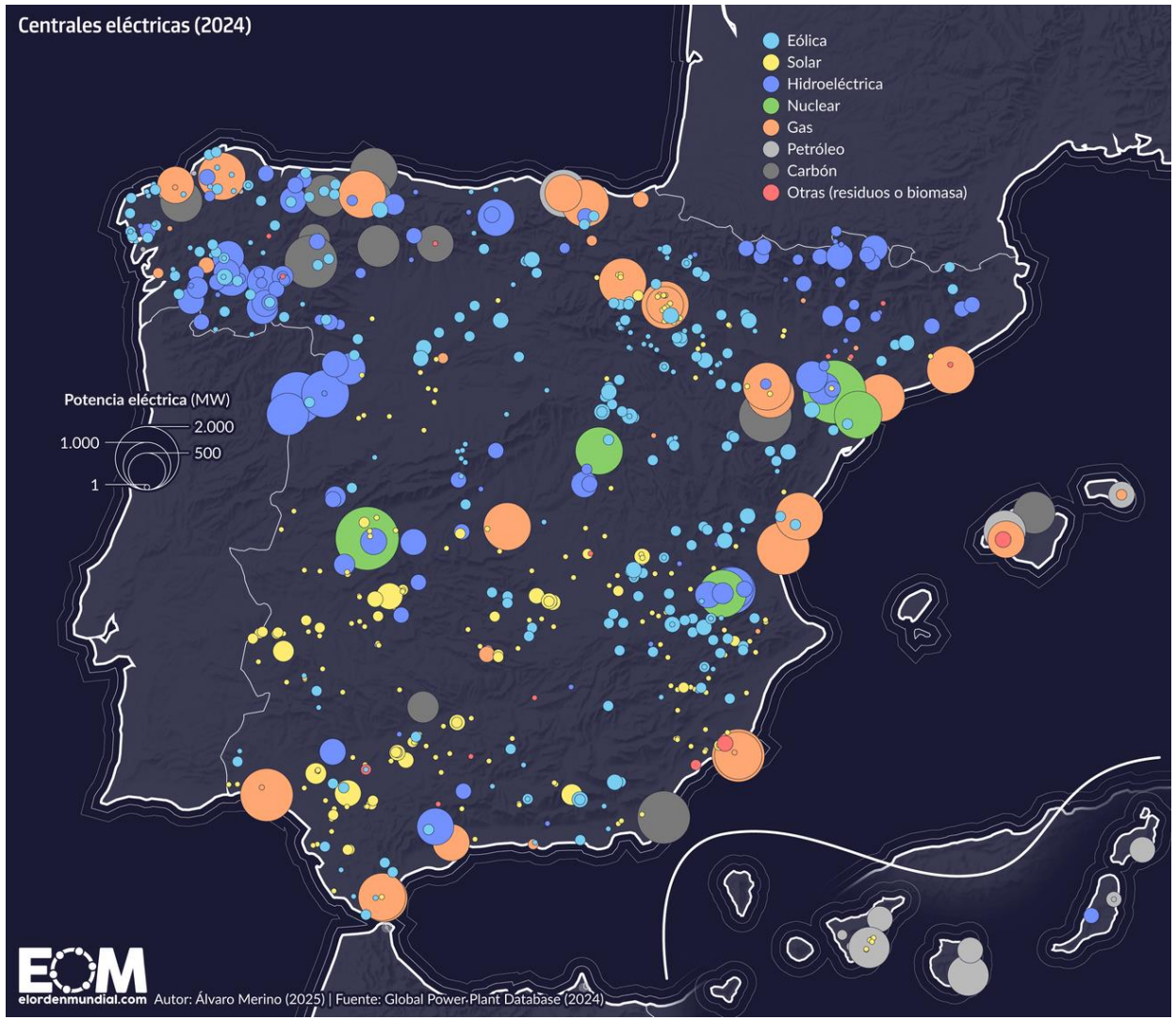
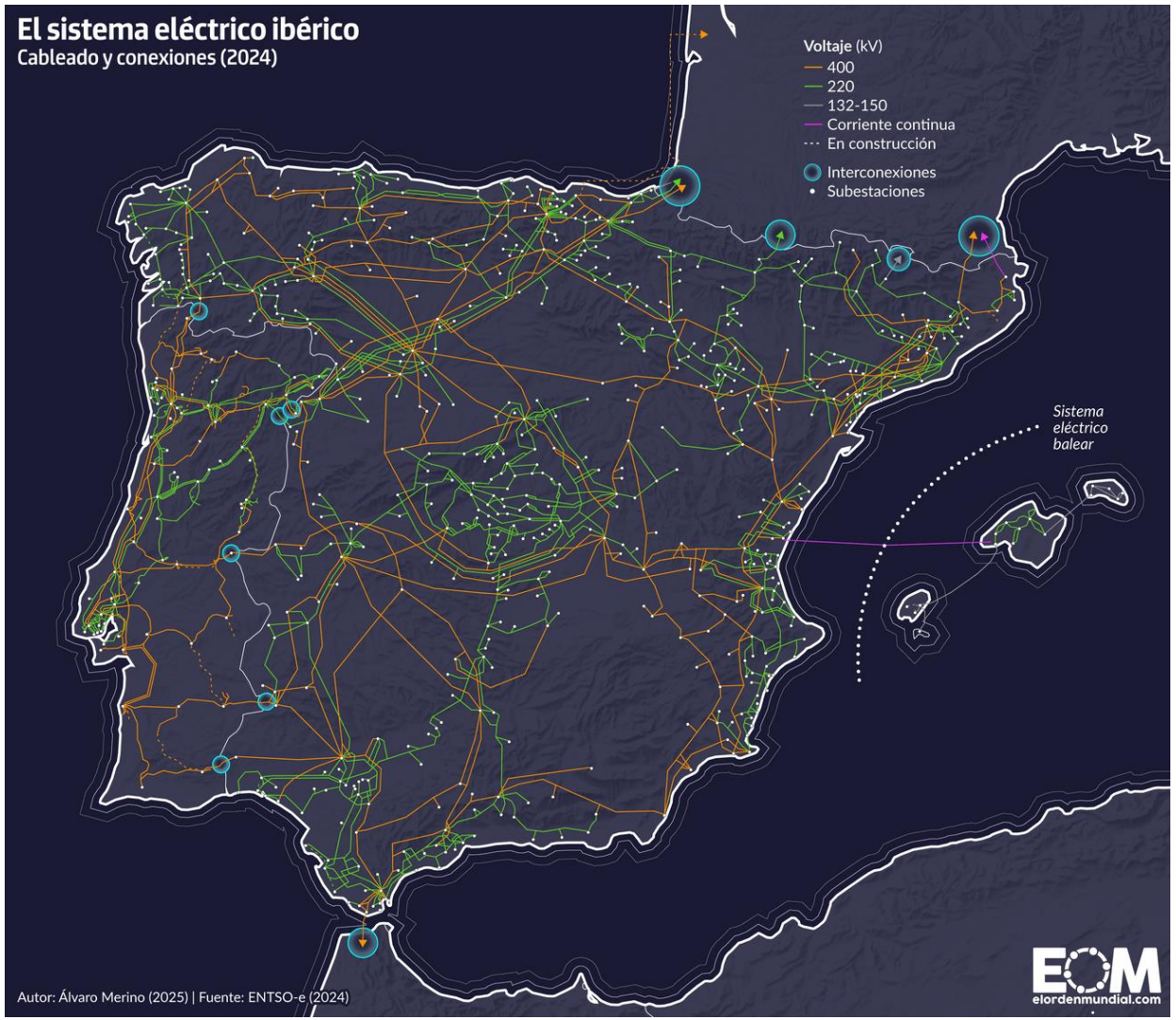
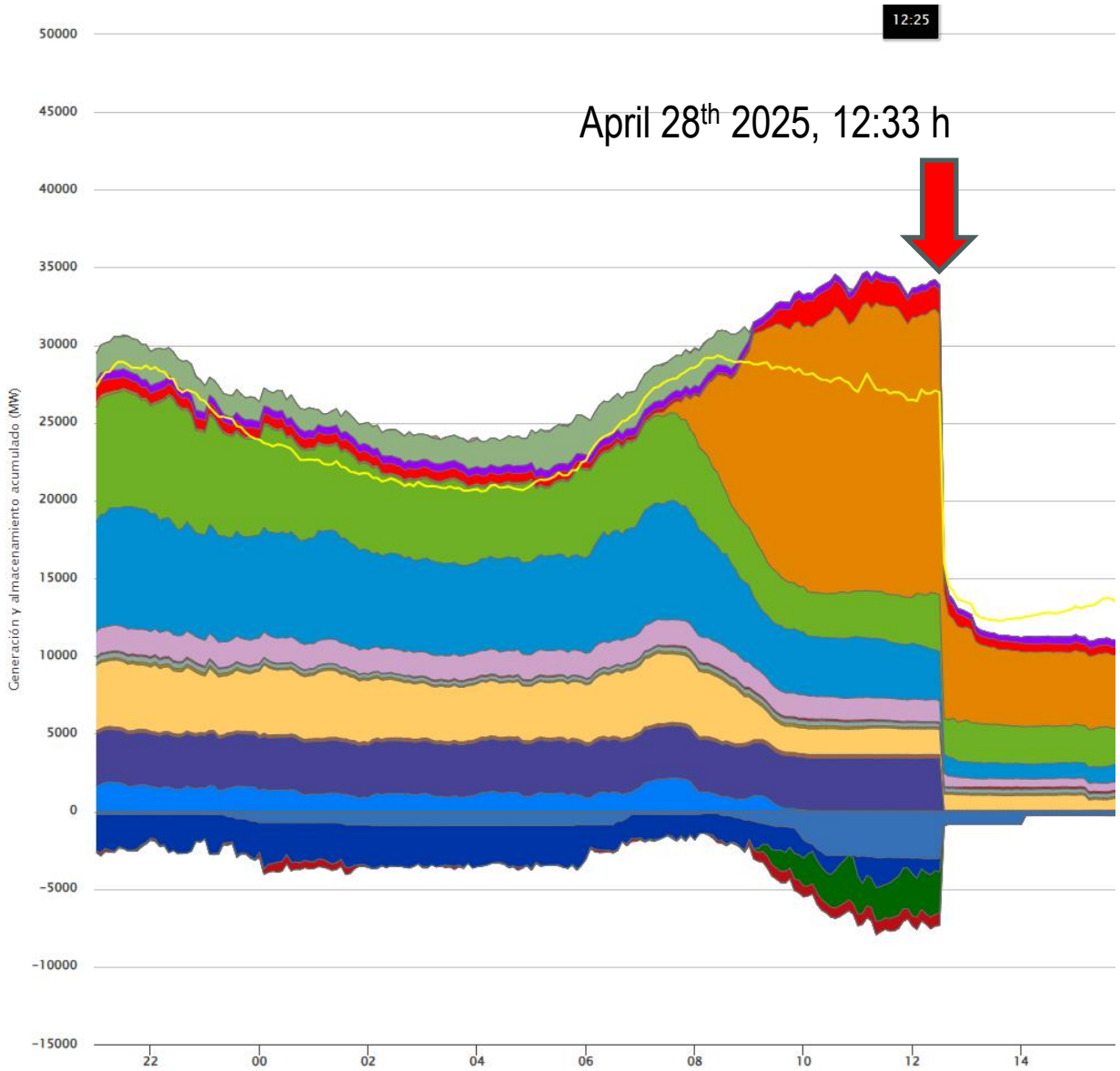




The crime scene – a total loss of power

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

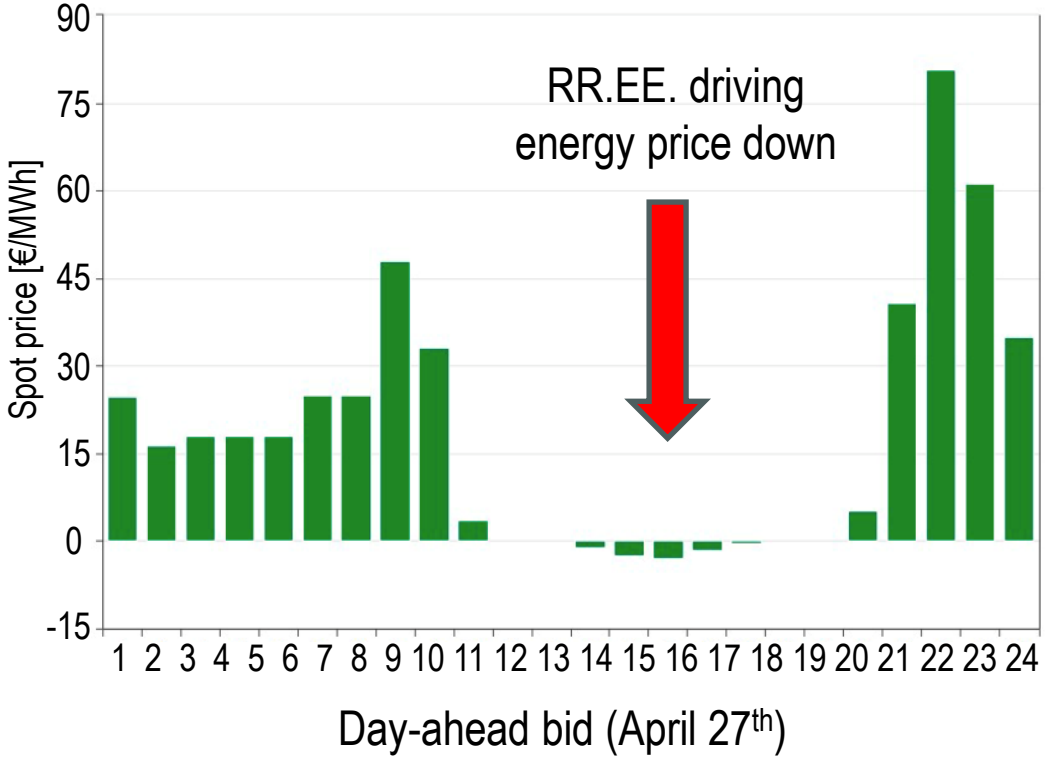


Source: Red Eléctrica Española

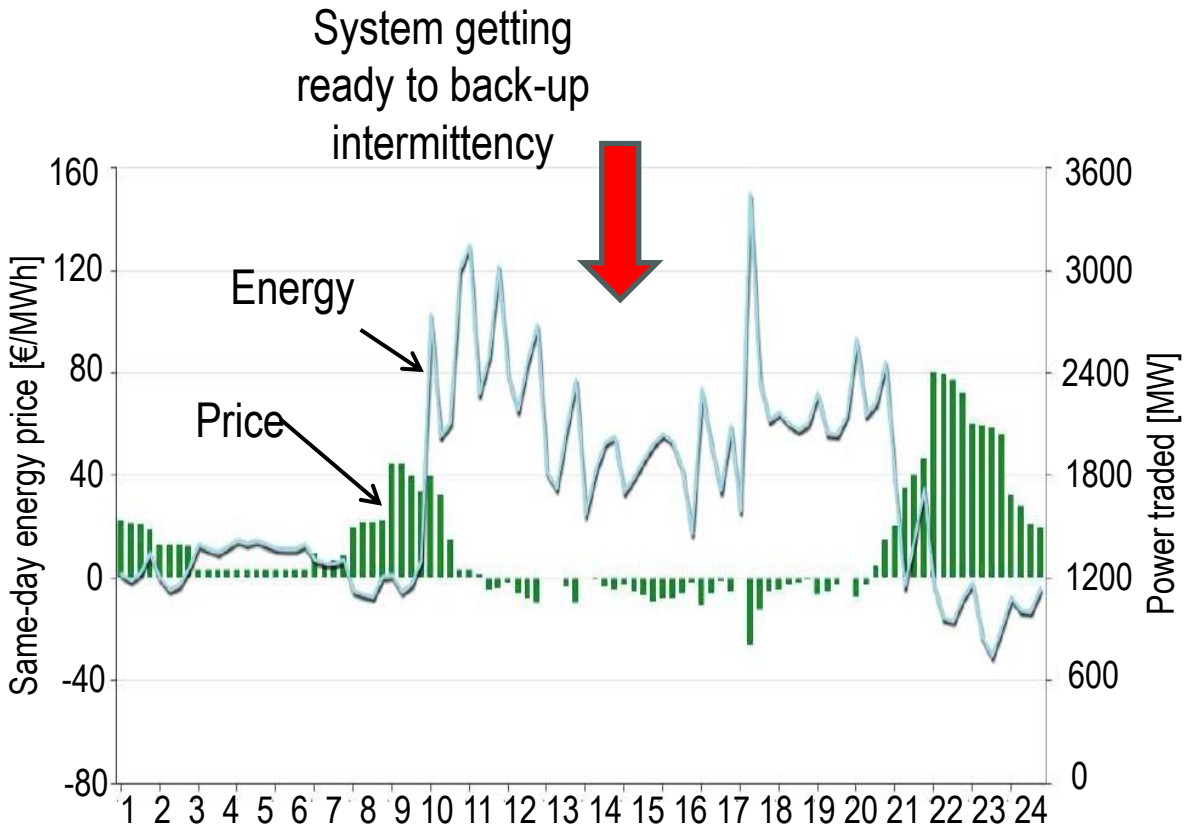
INTRO

Just another day at the office

The calm before the storm



Day-ahead bid (April 27th)



Same-day bid - price and energy (April 27th)

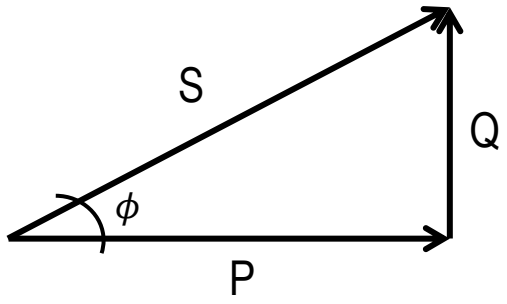
The calm before the storm

Power station	Type	Output [MW]
Vandellós (1967)	Nuclear	1087
Ascó (1984)	Nuclear	2060
Almaraz (1973)	Nuclear	2095
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 dynamic voltage control (technical restrictions)

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

Quick notes on active/reactive power and voltage control

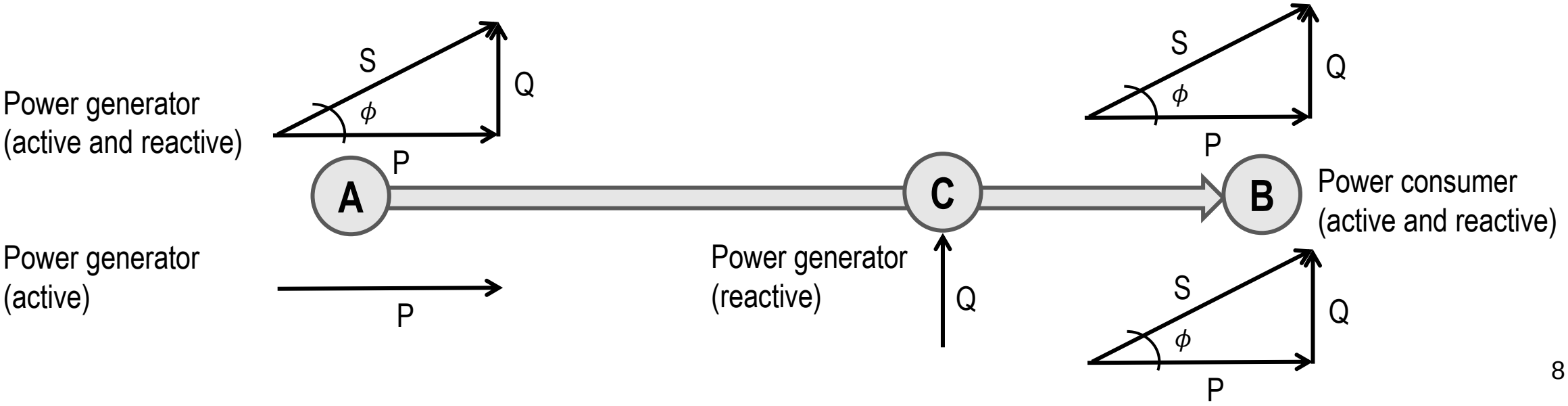


Power factor: $\cos\phi = \frac{P}{S}$

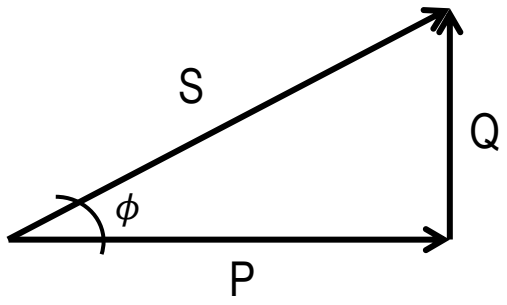
- Motors
- Transformers
- Reactance

- Condensers
- HV lines

- Reactive power is needed by consumers
- It must be generated
  - Power generator overload
- It increases transmission losses
  - Overload of transmission lines
- It makes an impact on voltage



Quick notes on active/reactive power and voltage control



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

- Motors
- Transformers
- Reactance

- Condensers
- HV lines

- Synchronous
  - Produce/consume reactive power
  - Can control voltage actively
- Asynchronous
  - Consume reactive power
  - Cannot control voltage

GENERATOR

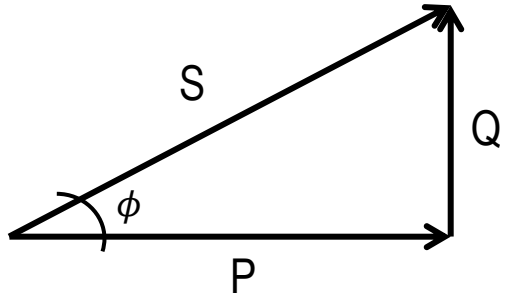
- Condenser
  - Produces reactive power
  - Increases voltage (static)
- Reactance
  - Consumes reactive power
  - Decreases voltage (static)

CONDENSER/REACTANCE

- Features
  - Consume reactive power (proportional to I^2)
  - Active voltage control

TRANSFORMERS

Quick notes on active/reactive power and voltage control



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

- Motors
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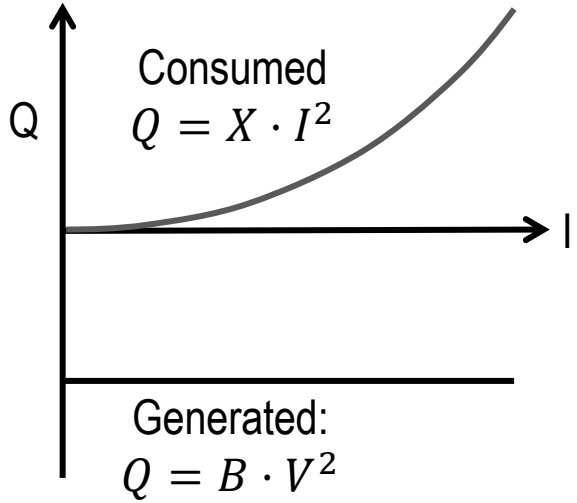
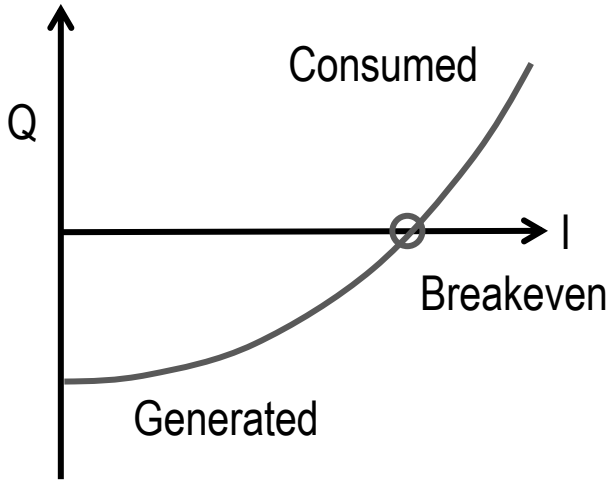




- Highly loaded
  - Consume reactive power
  - Reactance-like
- Lightly loaded
  - Produce reactive power
  - Condenser-like
- Aboveground/underground
  - Underground produce more reactive power (at given V)
- Voltage
  - Higher voltage produce more reactive power (for given length)
- Load
  - Lower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

LINE / CIRCUIT

The analysis – Five phases identified

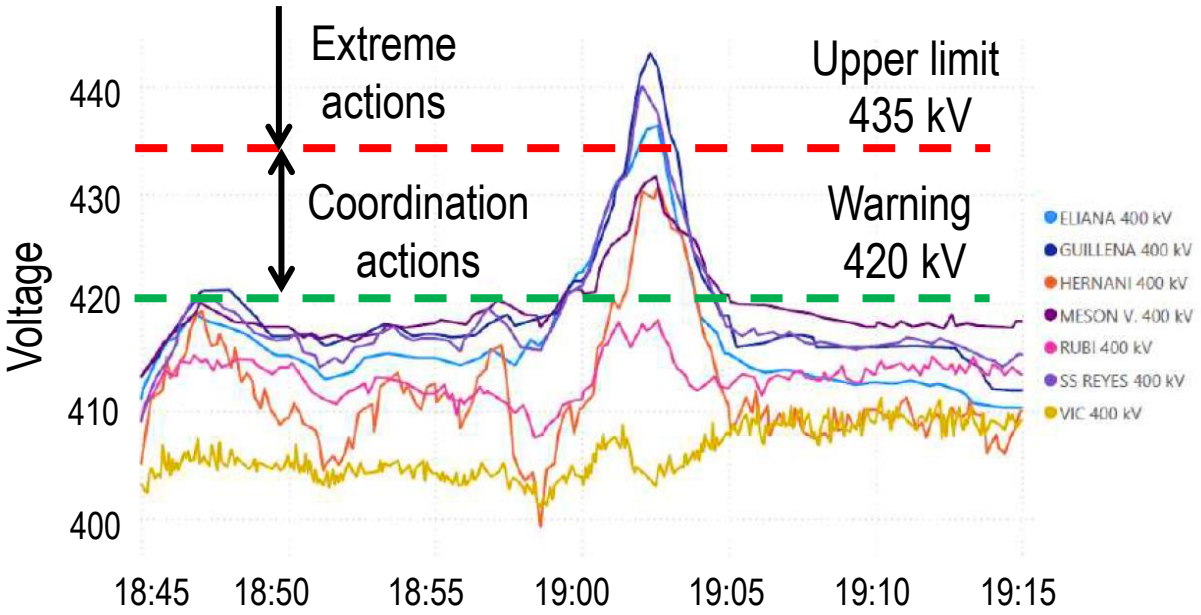
COVERED TODAY

- **P0 – Voltage instabilities**
  - Previous 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 recovered**
  - From: 12:33:30 (28)
  - To: 14:36 (29)

PHASE 0

That which is seen, and that which is not seen (Frederic Bastiat)

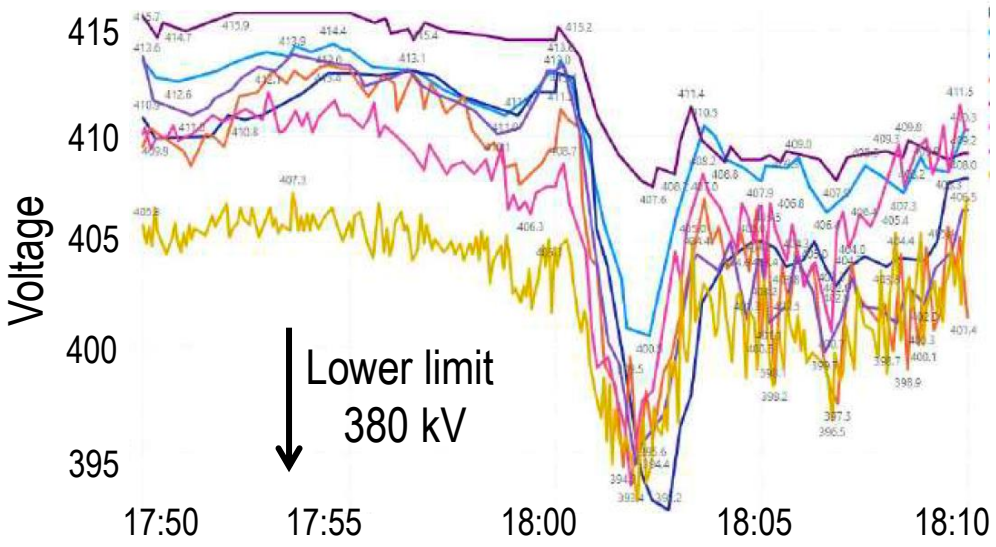
Phase 0 – Previous days



Voltage at selected nodes (April 22nd)

- Export to Portugal (1650 MW) ceased
- PV ramp-down:
  - It is usually ~500 MW/min at that time of the day
  - Grid balance control triggers additional 750 MW down at 19:00.
- Large plants unavailable in the center of the country
- In 1 minute, several transmission lines in this region come online:
  - From overloaded and consuming reactive power
  - To underloaded, acting as condensers
- Small share of synchronous power providing continuous (dynamic) voltage control
- PV + Wind amounts to 59.2%

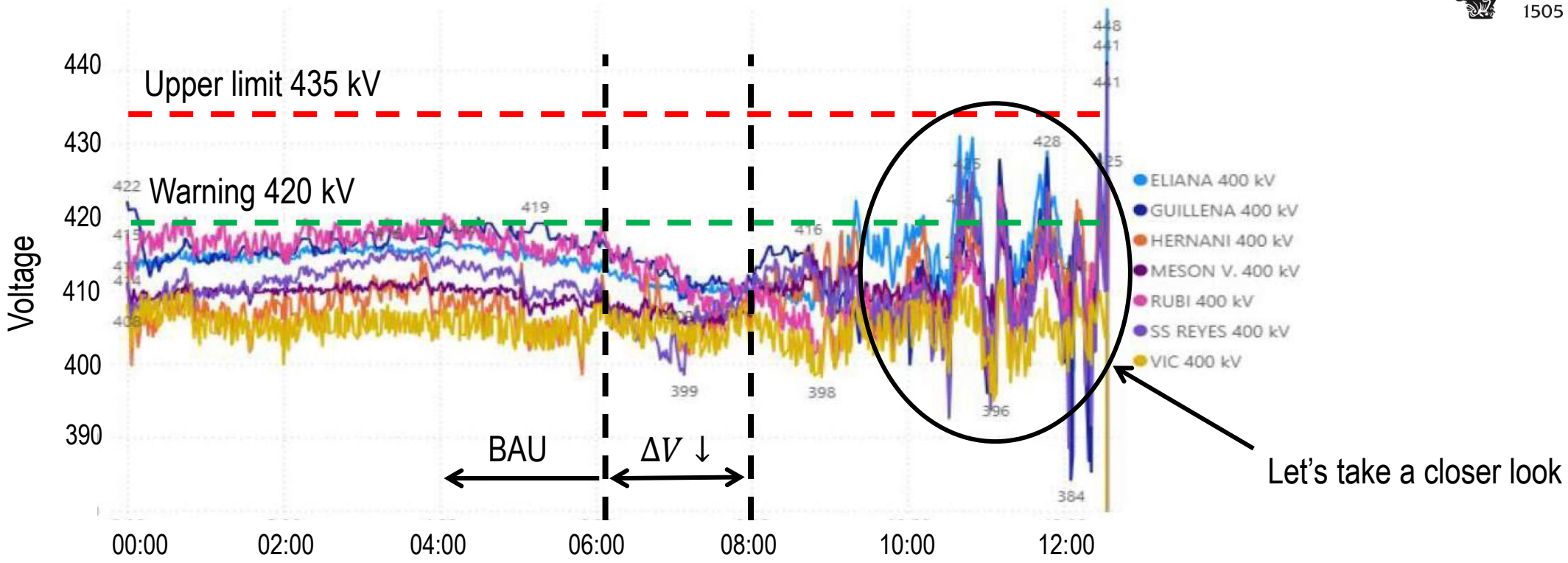
Phase 0 – Previous days



Voltage at selected nodes (April 24th)

- Series of events take place at 18:00:
  - Total export power increases to 1675 MW
  - Energy exported to France is raised to 1220 MW
  - PV generation is 900 MW…
  - … against 340 MW planned for that time of the day
  - Much larger load on the grid → lower voltage

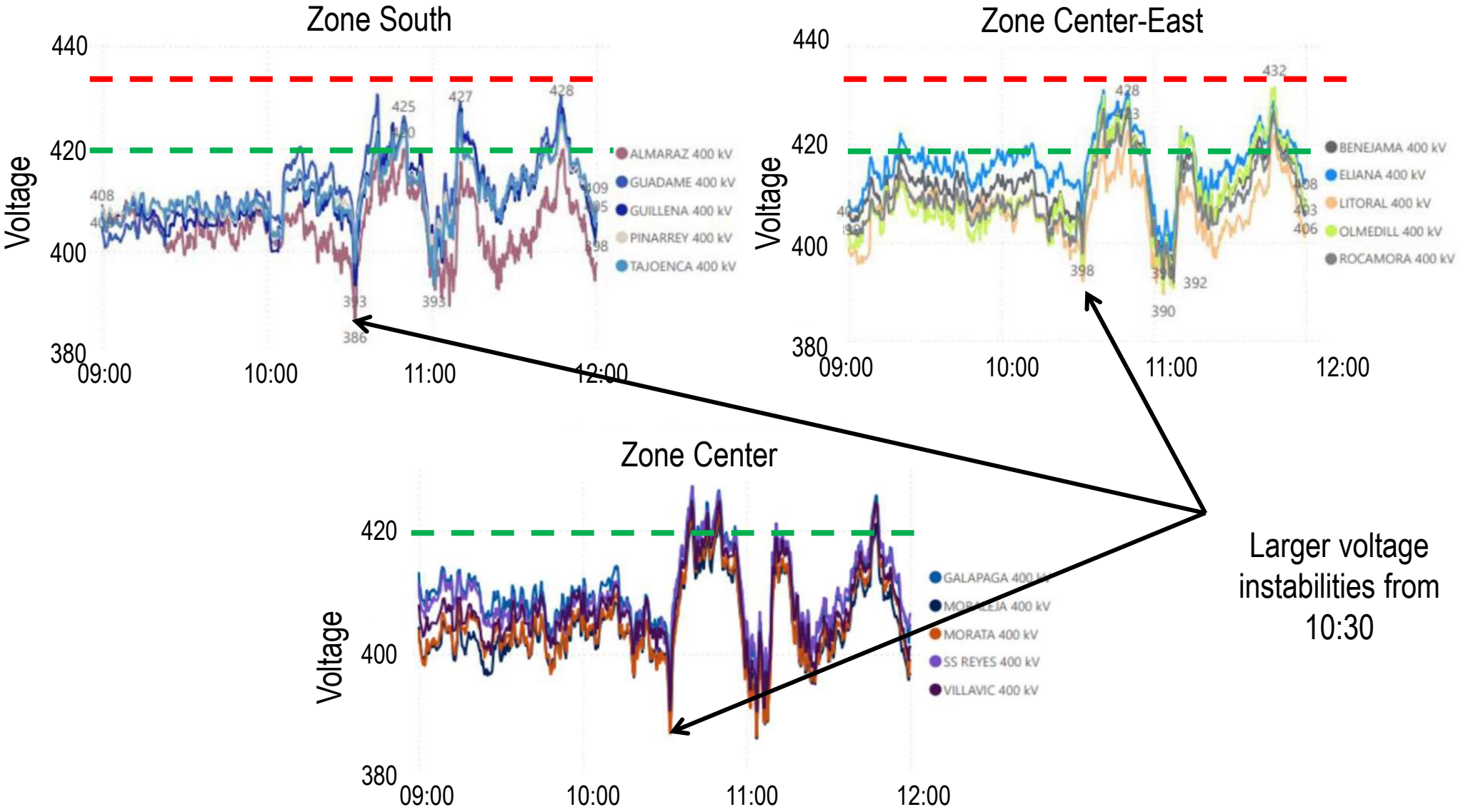
Phase 0 – Morning of April 28th (before 10:30 h)



Voltage at selected nodes in the morning of April 28th

- Voltage instabilities start at 06:00
- Export of electricity to France drops by 1000 MW (planned)
- 06.00 – 08:00 Voltage drop due to demand increase → increased load of grid (planned)

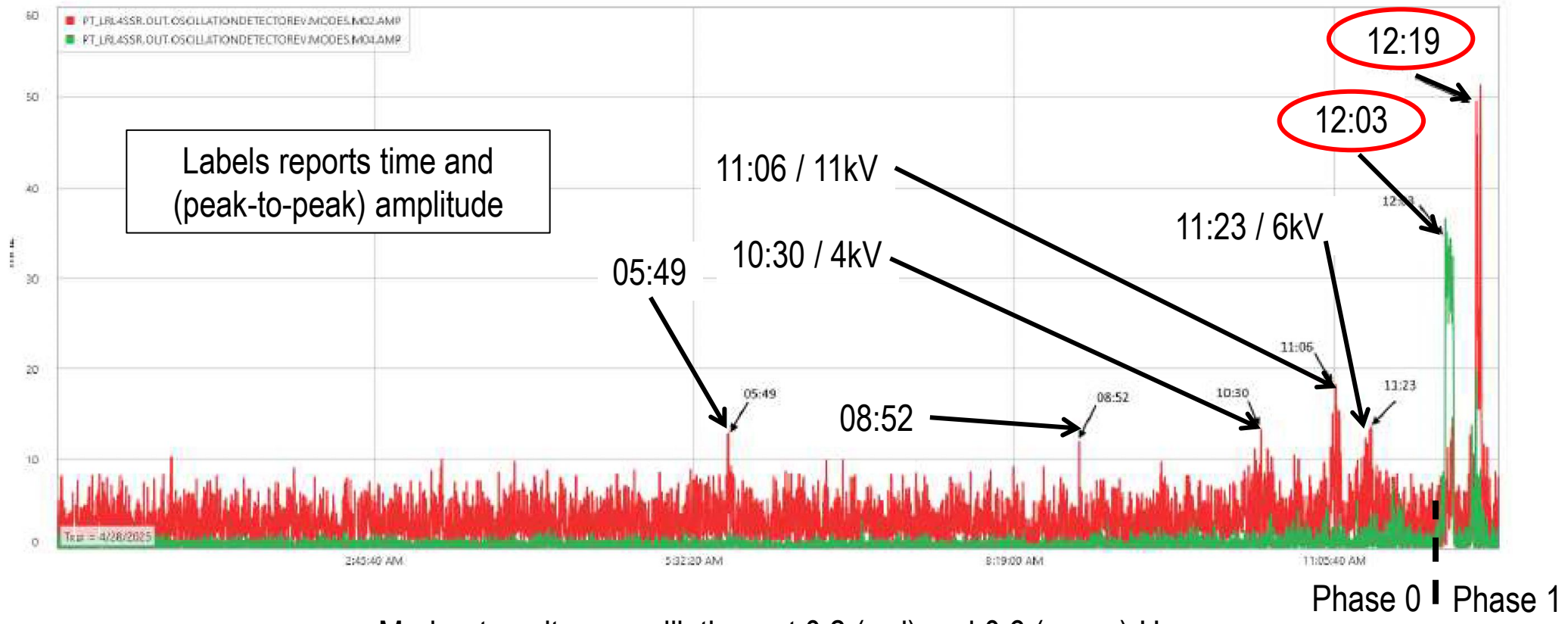
Phase 0 – Morning of April 28th (after 10:30 h)



PHASE 1

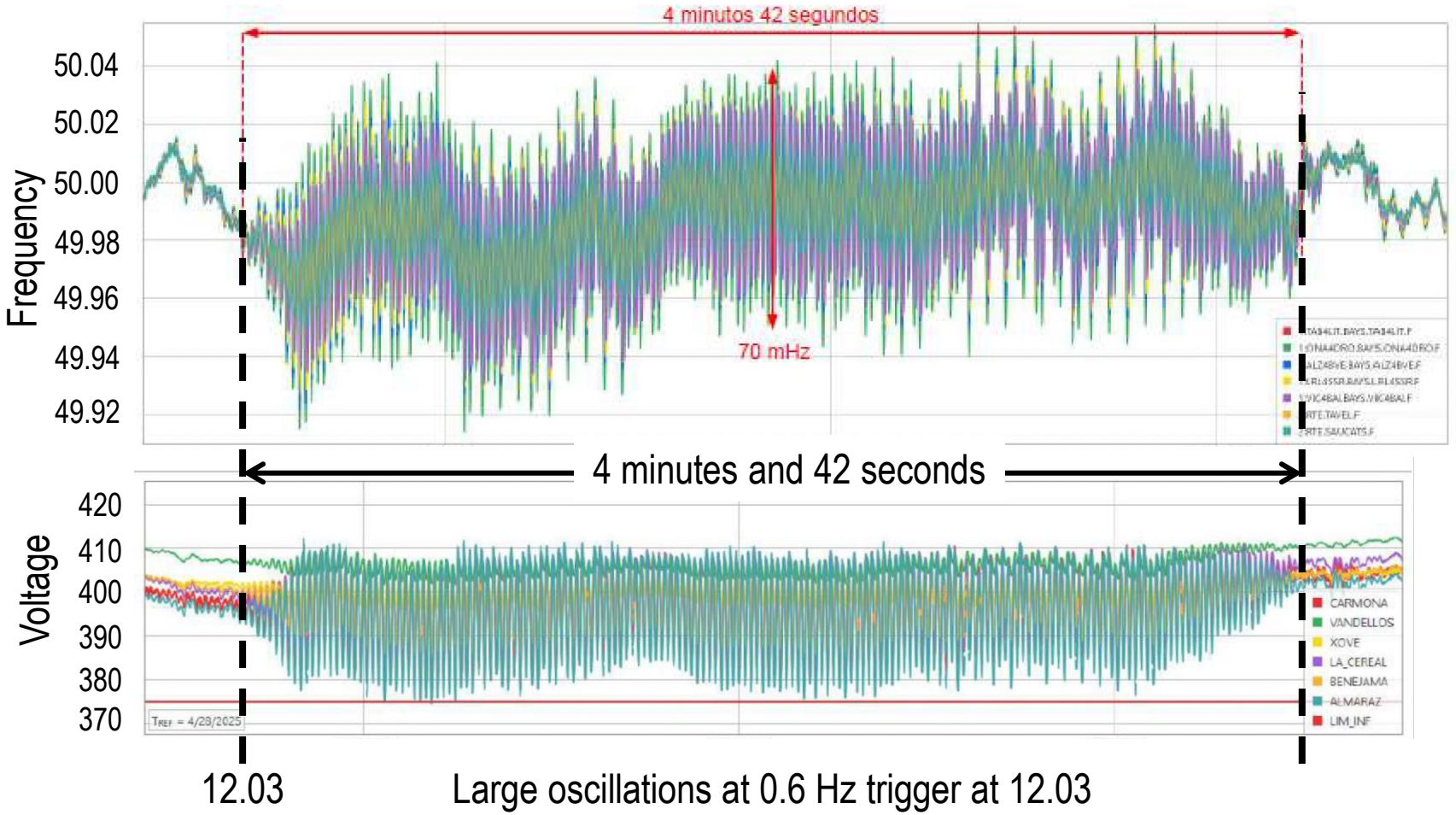
Not just another day at the office

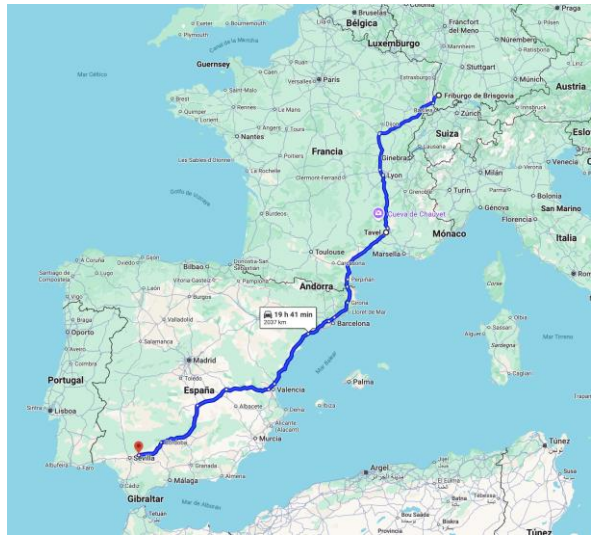
Phase 1 – Morning of April 28th (10:30 – 12:00 h)



Moderate voltage oscillations at 0.2 (red) and 0.6 (green) Herzs

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





- 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 (12:03 h)

ACTIONS

- 12:07 Energy exported to France decreased to 1000 MW (12:07 – 13:00)
  - Increased damping capacity of Spanish grid (safety margin)
- 12:07 Three additional 400 kV circuits come online
  - Enhanced reliability and increased damping capacity
- 12:11 Two additional 400 kV circuits come online
  - Enhanced reliability and increased damping capacity
- 12:11 HVDC connection France-Spain starts to work as plain DC, rather than emulated AC
- 12:15 REE asks REN to reduce energy exported to Portugal:
  - REE asks REN to reduce this to 2000 MW (-1000 MW)
  - After negotiation, it is agreed to reduce to 2500 MW until 13:00 and to 2000 MW later

Voltage oscillations mitigated

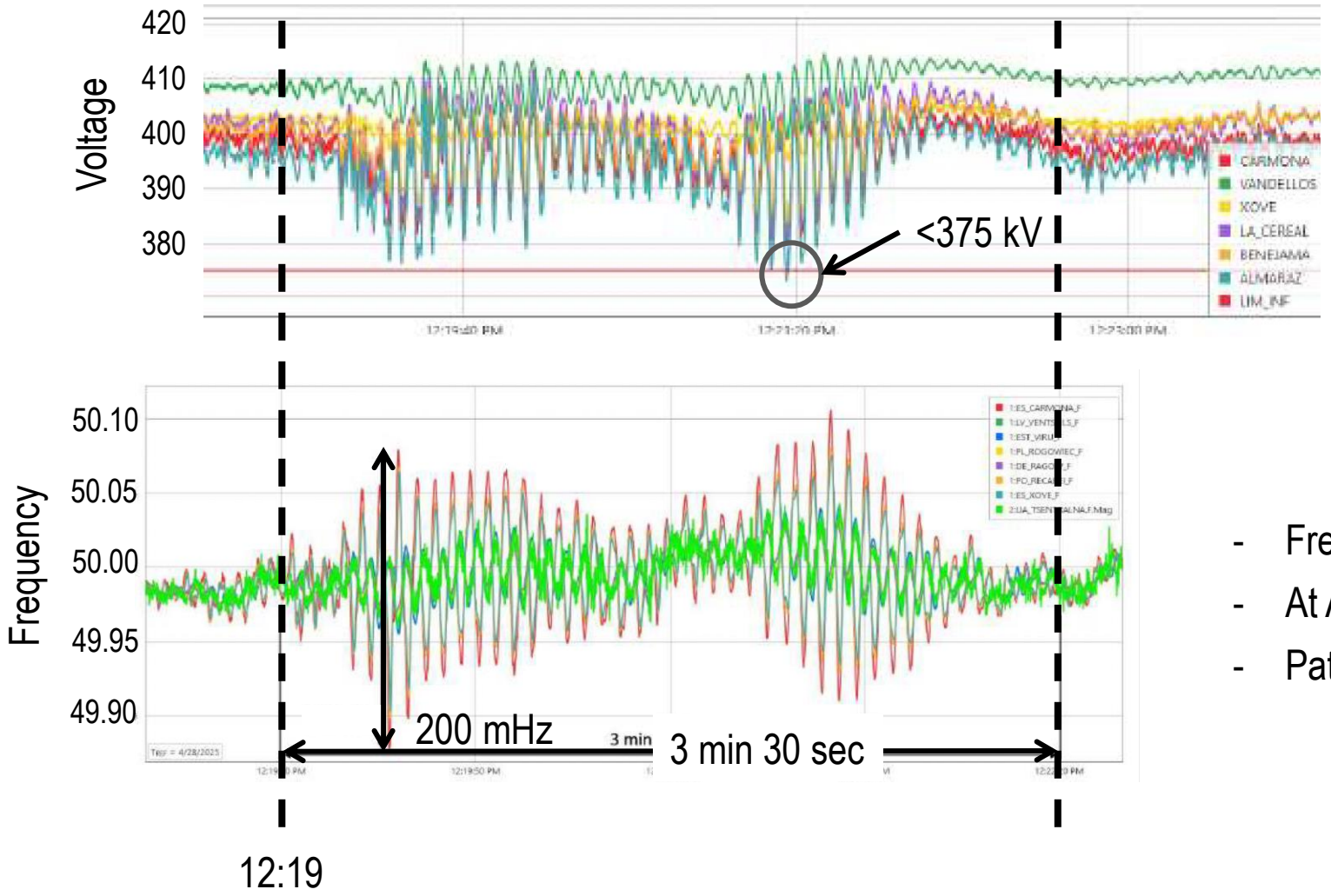
↓

Lower load on grid
Additional gridlines

↓

Voltage increases

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



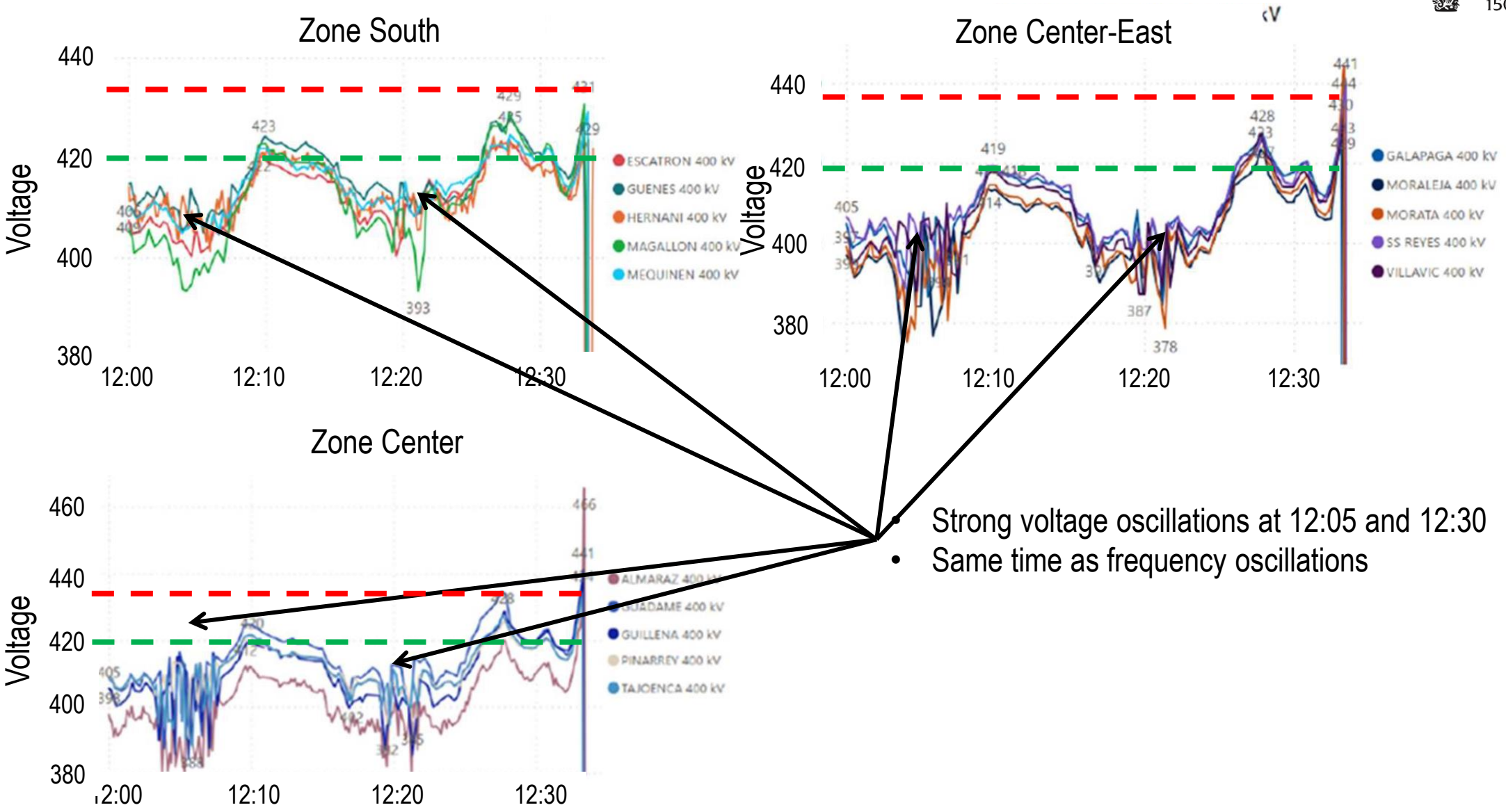
- Frequency and voltage oscillation at 0.2 Hz
- At Almaraz (marked), ΔV is 24 kV (peak-to-peak)
- Pattern is known across Europe

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

ACTIONS

- 12:19 Energy exported to France decreased to 1000 MW (12:07 – 14:00)
  - Period is extended to 14:00
- 12:15 REE asks REN to reduce energy exported 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 a Thermal Power Station in the South which can start immediately
  - Fastest power plant able to come online in 1h 30 min (hot start)
  - This group shut down at 9:00
  - It is agreed to come online at 14:00
  - This power station never synchronized (blackout at 12:33)
- 12:XX A plant operator reports (TSO) it 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)



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

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

ACTIONS

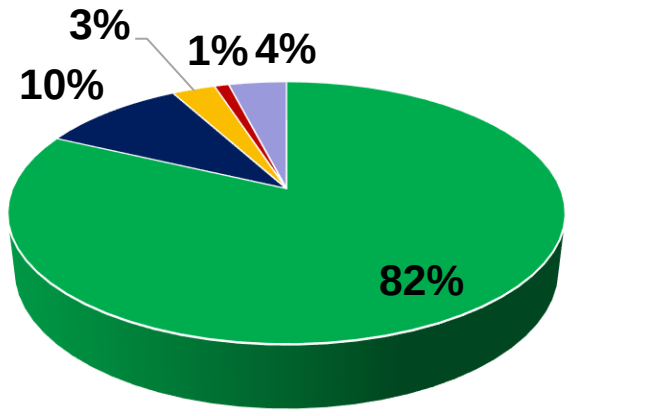
- 12:04 – 12:05 REE takes four shunt reactors offline at critical nodes with low voltage
  - 3 400 kV + 1 220 kV shunt reactors (reactance)
- 12:17 – 12:24 REE performs the same action (since voltage dropped again at 12:16)
  - 3 400 kV + 1 220 kV shunt reactors (reactance) – in addition to the previous ones
- 12:26 – 12:28 Generalized trend towards higher voltages → shunt reactors come online again
  - 4 400 kV + 1 220 kV shunt reactors (reactance)
- **No voltage excursions beyond the upper and lower limits observed from 12:00 to 12:30**

Source: Red Eléctrica Española

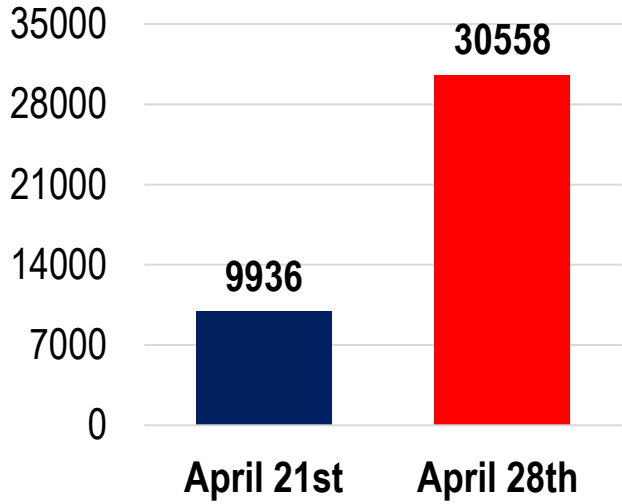
Phase 1 – Morning of April 28th (12:30 h)

- Voltage:
  - At 12:30, voltage oscillations have been damped
  - Voltage between 400 and 420 kV
- Frequency
  - ~50 Hz
  - Low damping
- Energy exported reduced to 1000 MW (France & Portugal)
- Connection to France in DC mode
- Generation - Demand
  - Demand is 25184 MW
  - Pumped hydro 2978 MW

Before moving on: what was the situation at this stage?



Source: D. Sánchez, based on data from REE



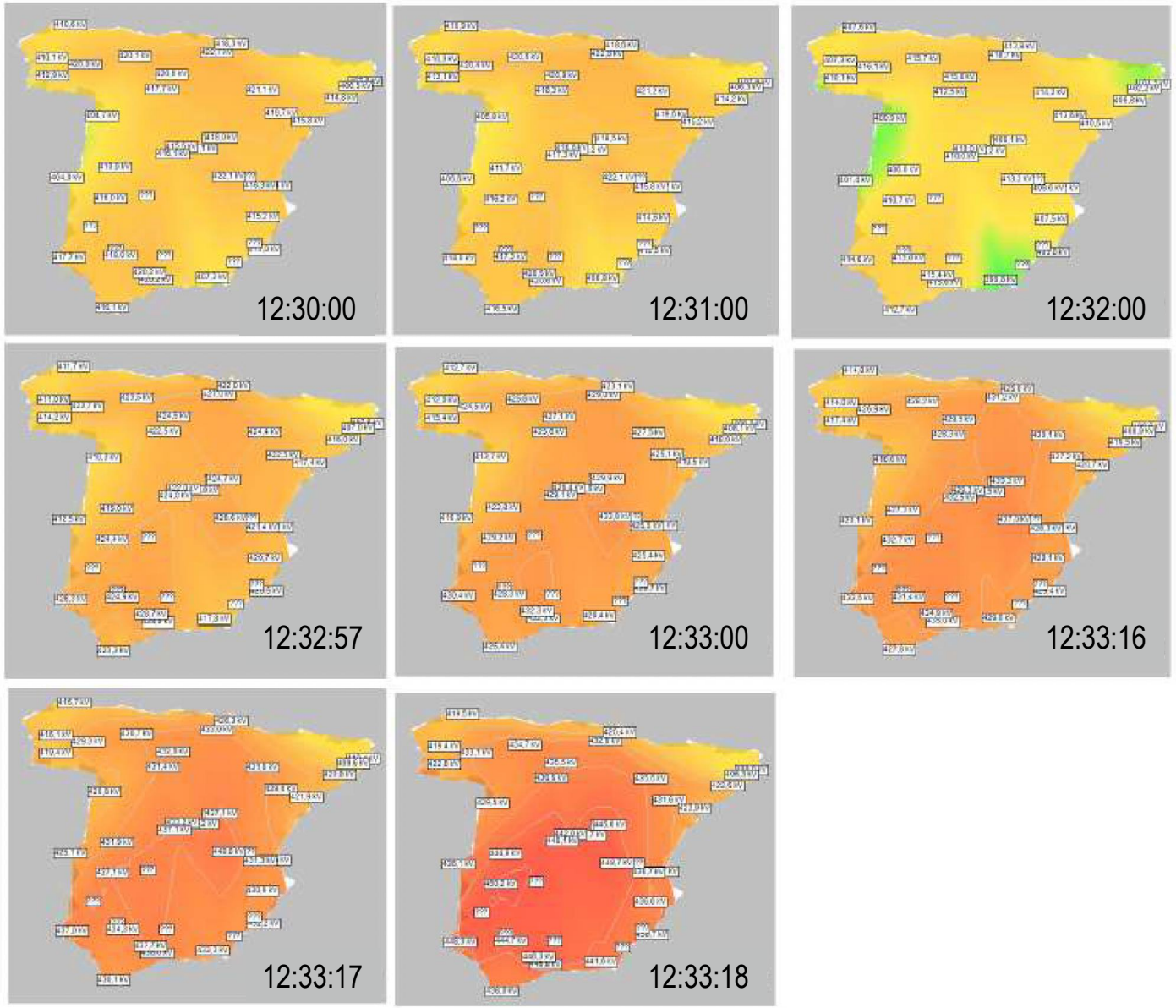
Overvoltage warnings registered at control centers (before 12:00)

Source: 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

Everyone has a plan until they get punched in the face (Mike Tyson)

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

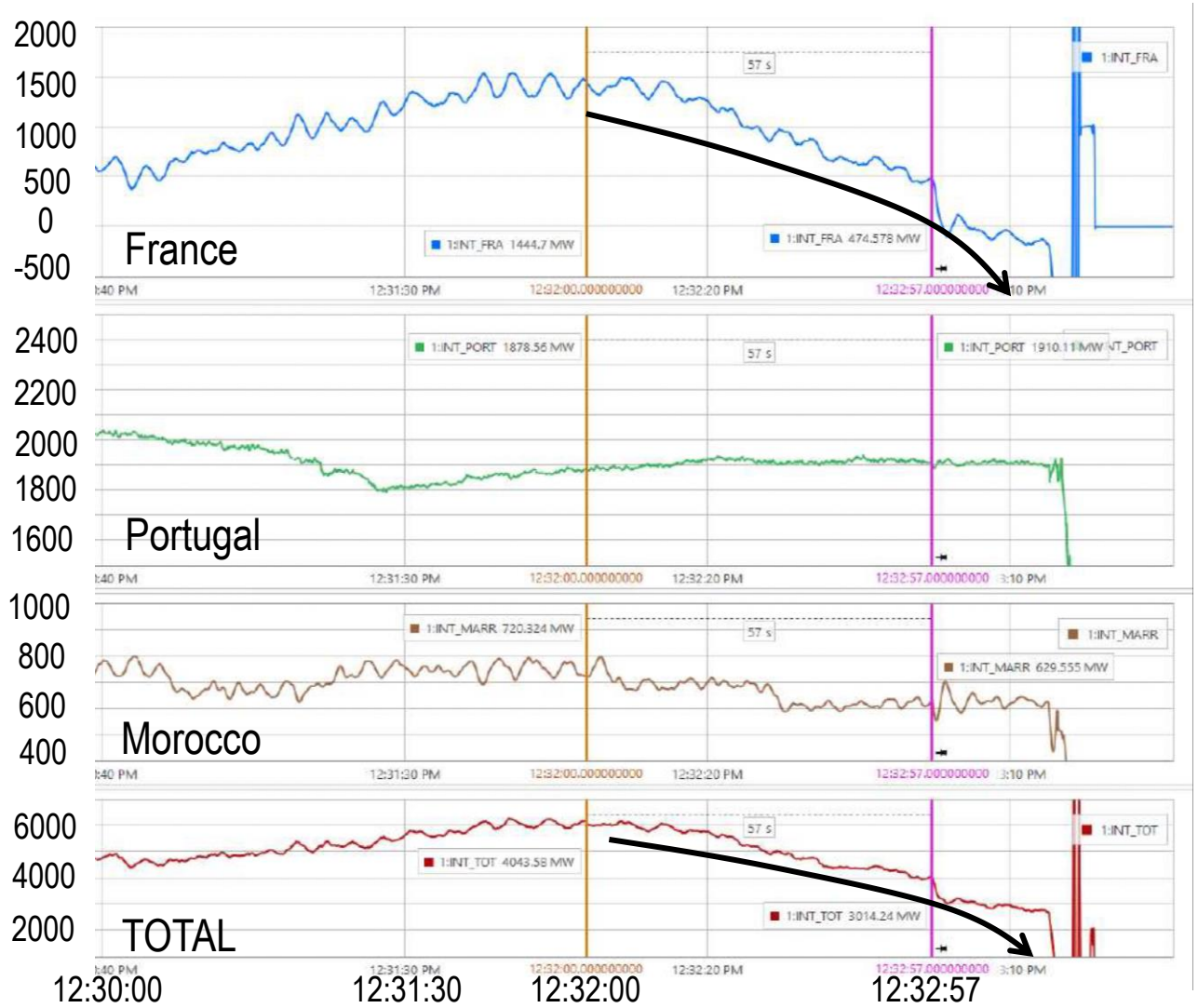


12:32

- Linear and QUICK voltage increase at this time

- Values registered at substations:
  - Olmedilla: 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)



12:32

- Linear and QUICK voltage increase
- Energy exported to France starts to decrease (to enhance damping of voltage oscillations)

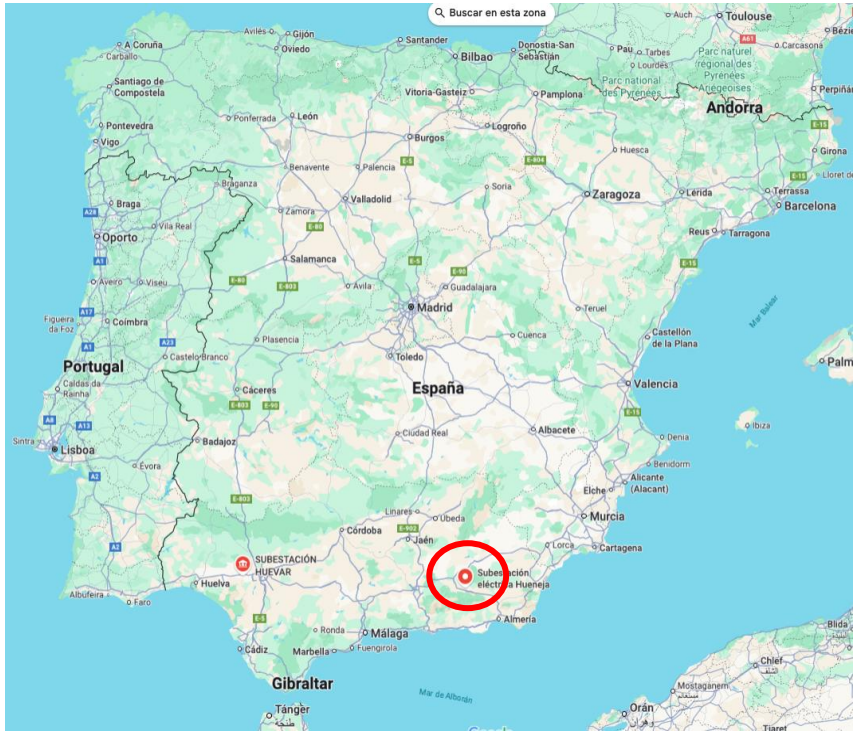
Phase 2 – Morning of April 28th (12:32:00 – 12:33:18 h)

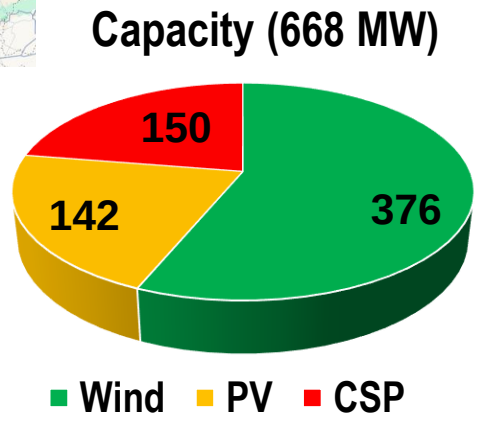
Time	MW	Time	MW
12:32:05	2.6	12:32:29	2.3
12:32:09	21.6	12:32:45	0.6
12:32:09	5.9	12:32:49	13.3
12:32:09	4.8	12:32:49	1.1
12:32:09	2.9	12:32:53	11.9
12:32:25	19.2	12:32:53	20.0
12:32:25	3.4	12:32:53	4.8
12:32:29	22.4	12:32:53	10.0
12:32:29	55.6	12:32:53	6.0
In 24 seconds, this small-scale power was lost 525 MW (2%) | 317 MW DG<1MW (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)





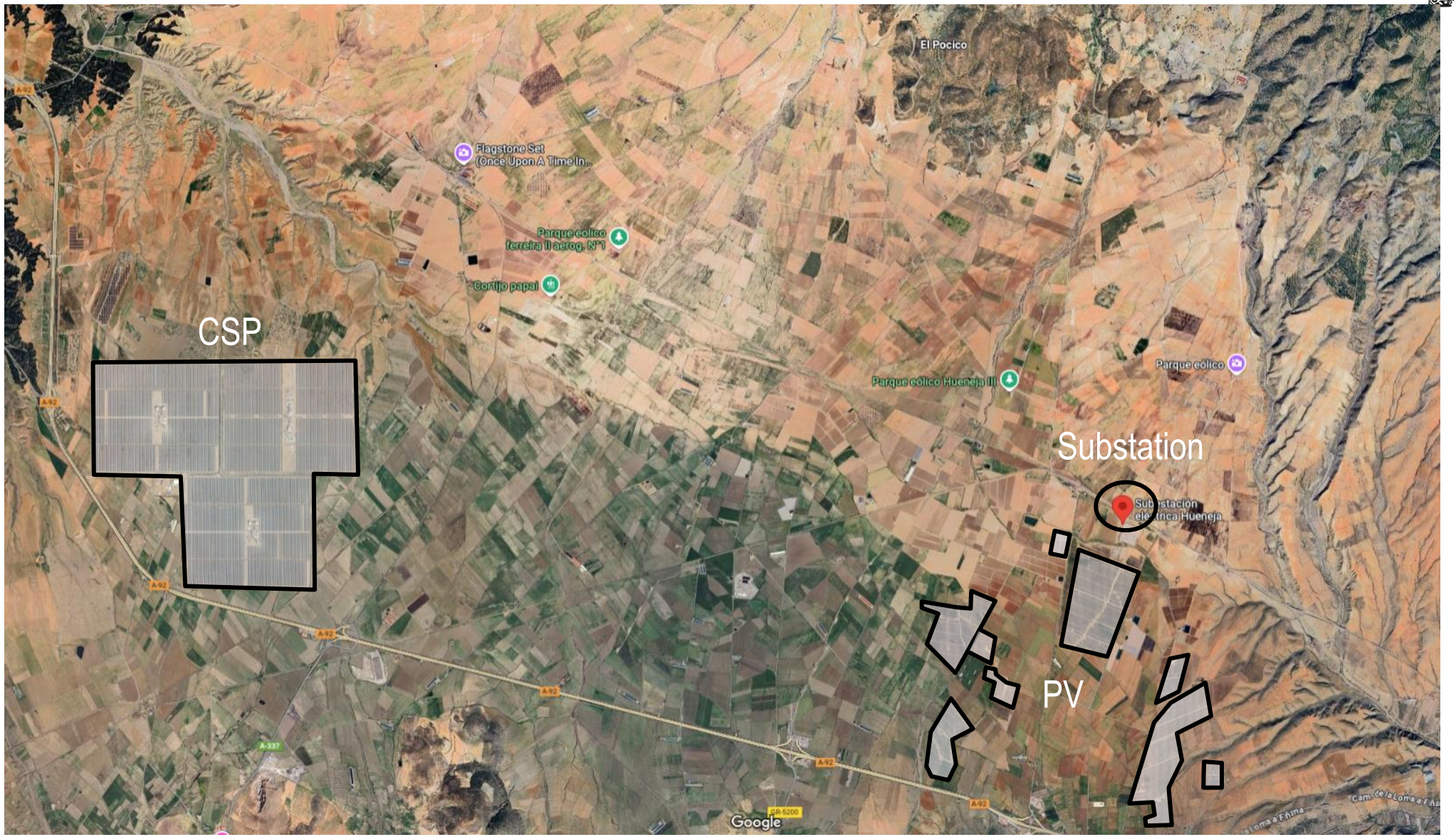
Source: D. Sánchez, based on data from REE

12:32:57.140

- Loss of generation capacity starts
  - Substation in SE trips
    - 355 MWe active power
    - 165 MVAr reactive power absorbed
  - Trip triggered by **overvoltage** at SUT (400/220) at a power plant connected to this substation
- Energy exported to France further reduced by 450 MW
- Frequency drops and recovers in 3 s
- Voltage increases beyond 430 kV at critical nodes but does not exceed 435 kV

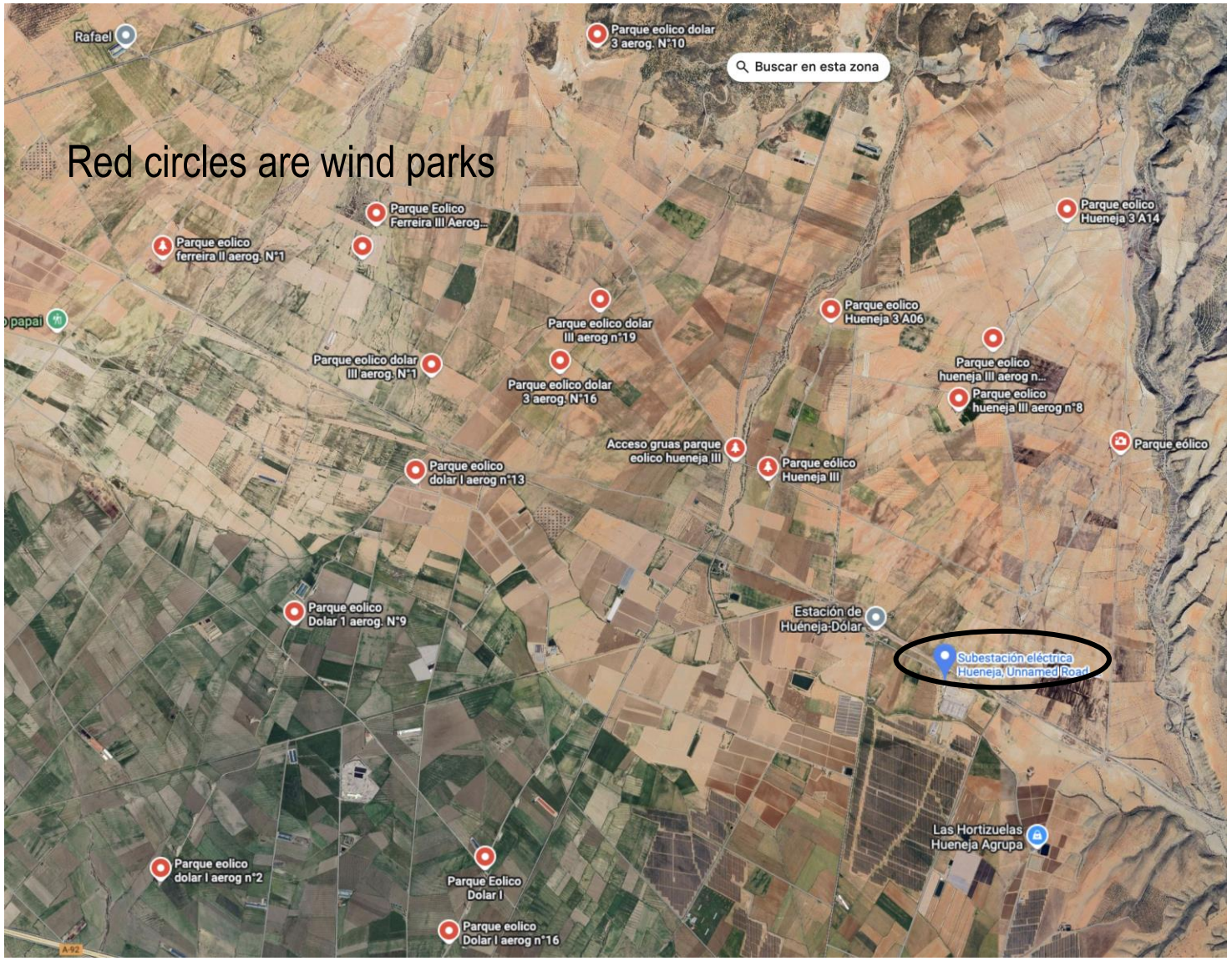
NOTE: On May 5th, The Government approved to increase the capacity of this substation by 200 MW

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



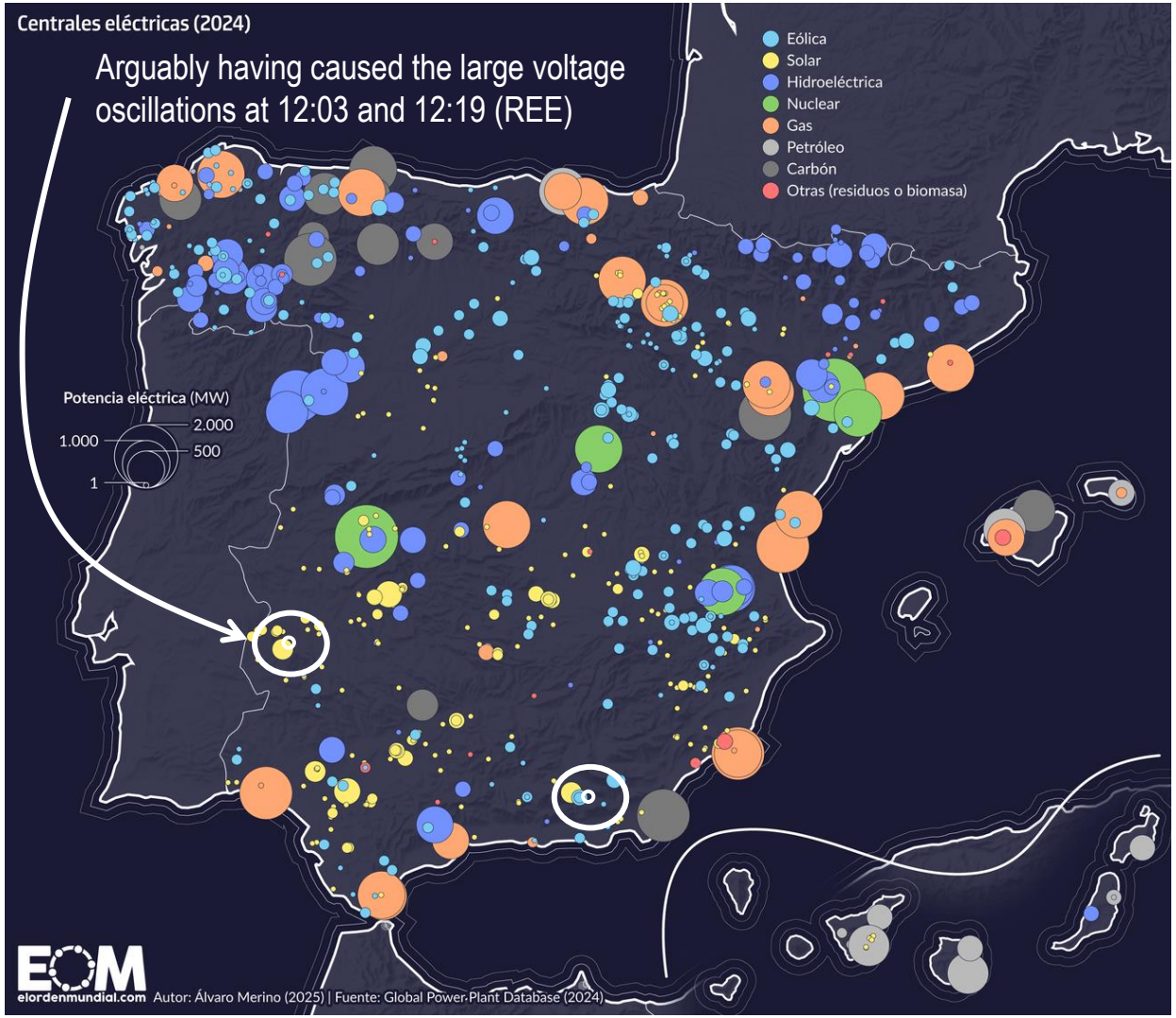
Source: D. Sánchez

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



Source: D. Sánchez

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



12:33:16.460

- Two substations trip in the SW of Spain
  - 12:33:16.460 & 12:33:17.520
- Substations connected to PV plants
- Total loss of power is 730 MW (582 + 118)
- Due to loss of power, frequency drops 55 mHz
- Frequency oscillation damped, but 50 Hz not recovered
- Energy IMPORTED from France → 895 MW
- Voltage increases again (same as previous power loss at 12:32:57)
- Cascaded trips of small RREE plants between 12:33:16.820 and 12:33:17.547

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

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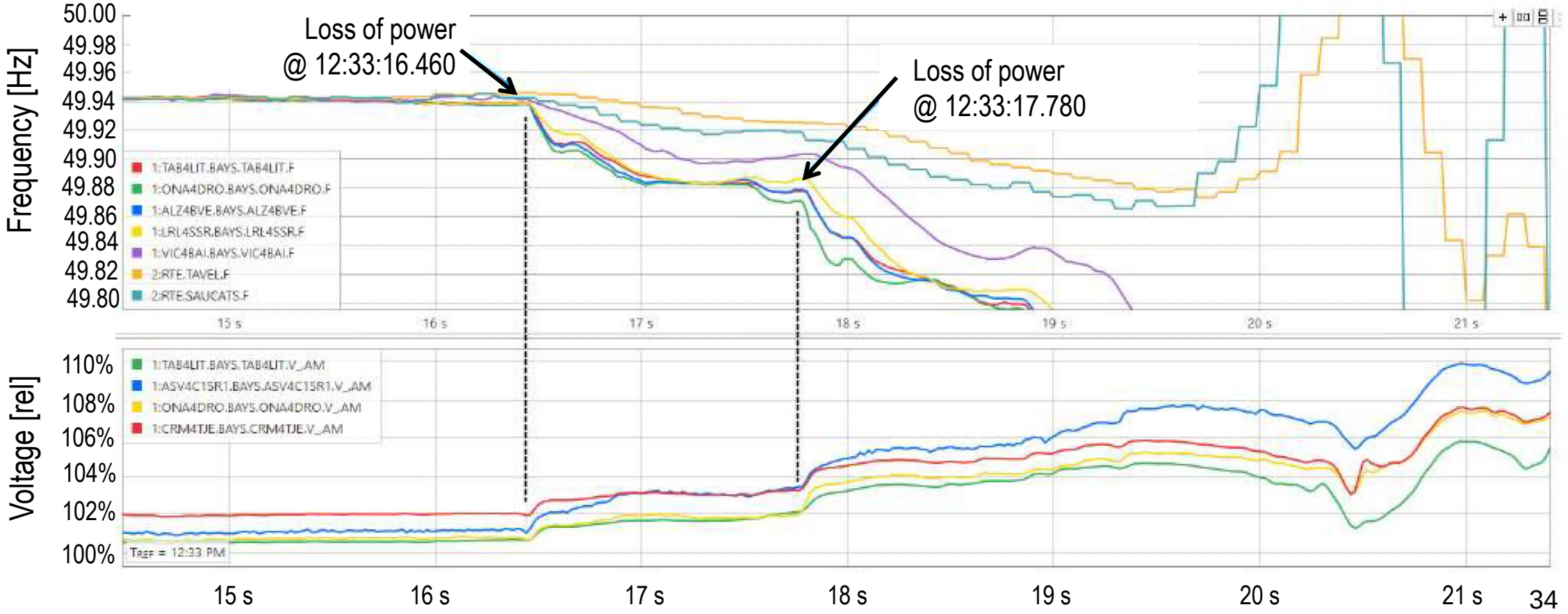
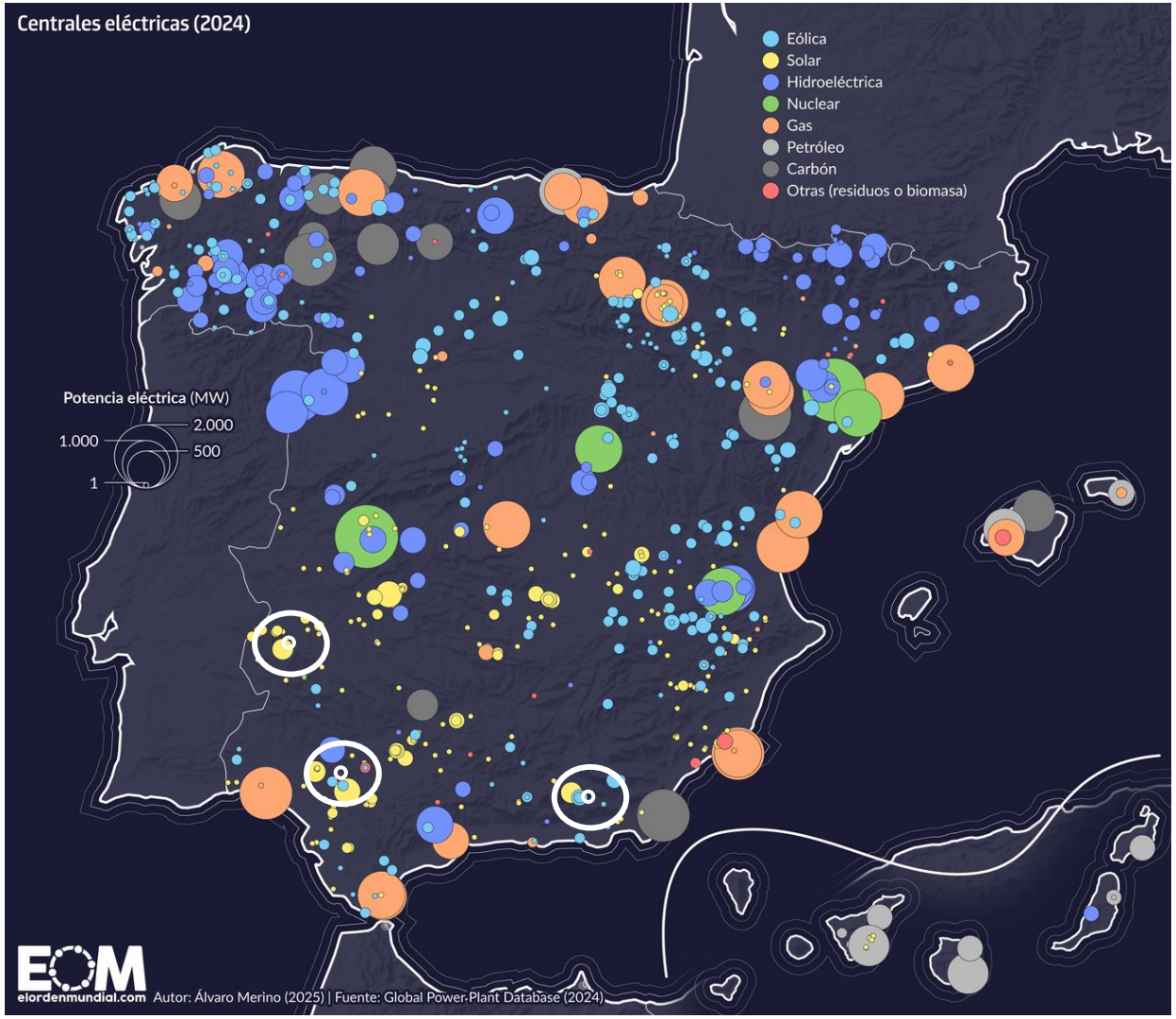
12:33:16.460



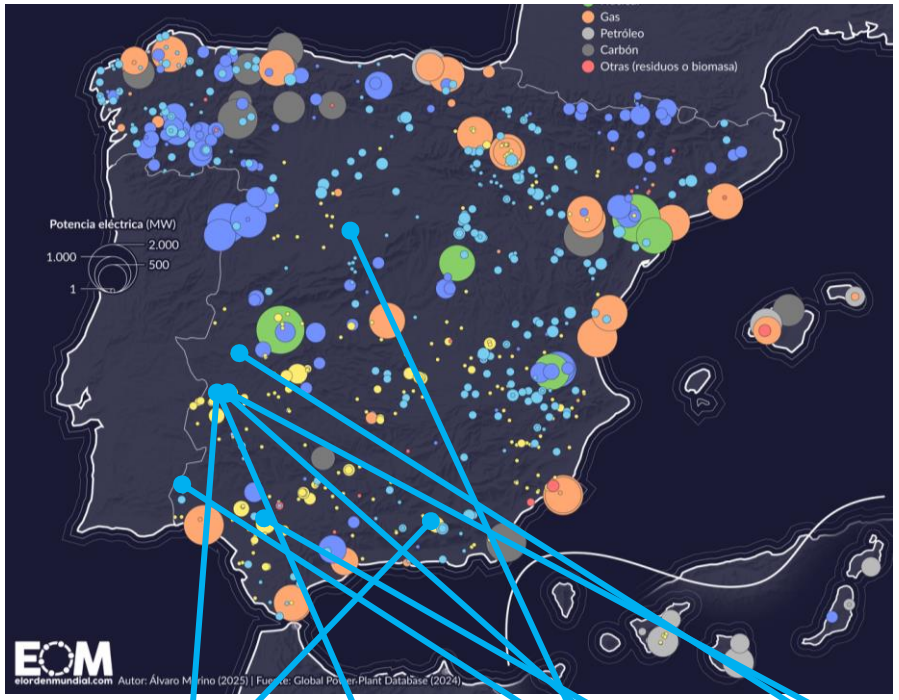
Phase 2 – Morning of April 28th (12:32:00 – 12:33:18 h)

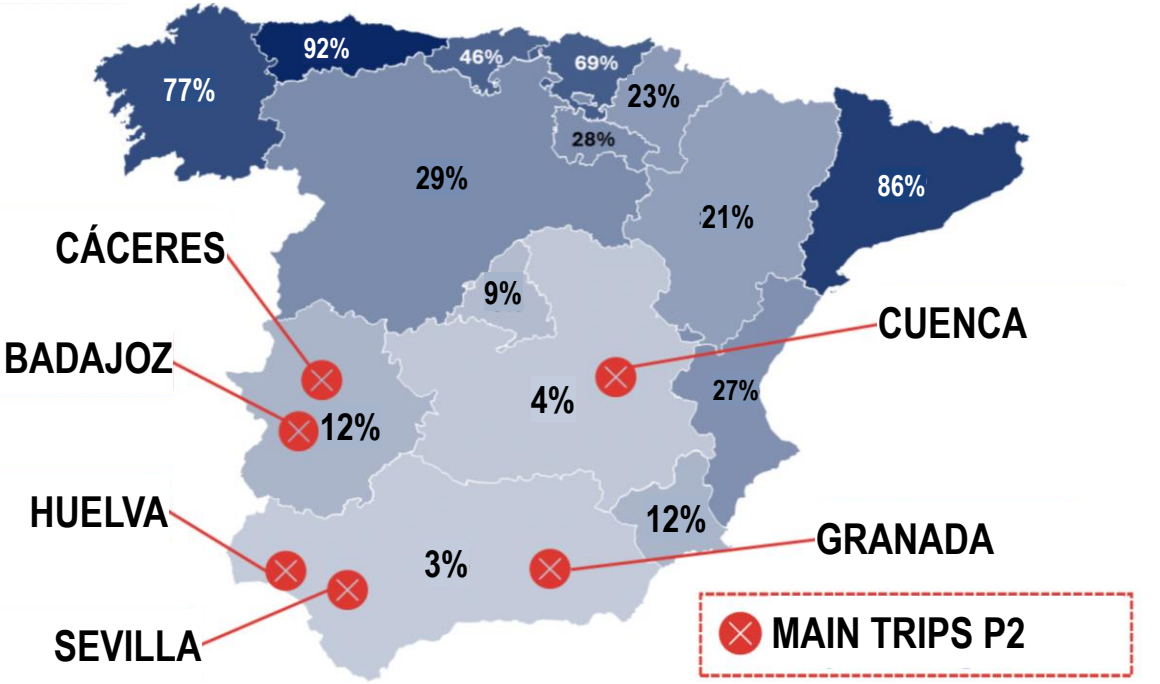


12:33:17.780

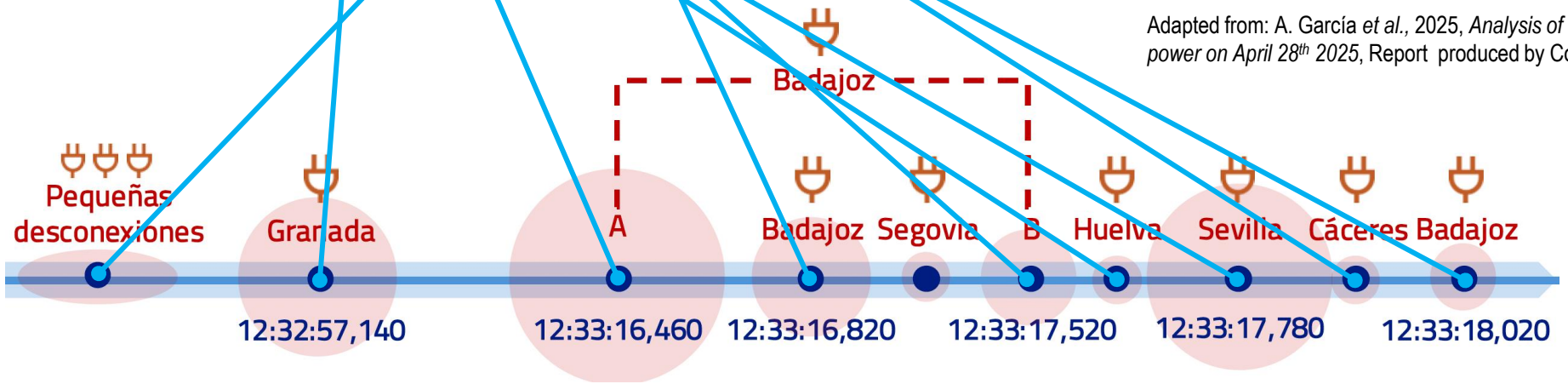
- 12:37:17.780 Large power loss (550 MW) at a substation in the S of Spain → RR.EE. node
- Cascaded trips follow
  - 12:33:17.975 PV in W (220 kV line reported to be running at 240.98 kV)
  - 12:33:18.020 PV in W (220 kV line reported to be running at 239.38 kV)
- Due to loss of power, frequency drops 75 mHz
- This frequency oscillation CANNOT be damped
- Energy IMPORTED from France → 1510 MW
- Voltage keeps increasing at several 400 kV nodes

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





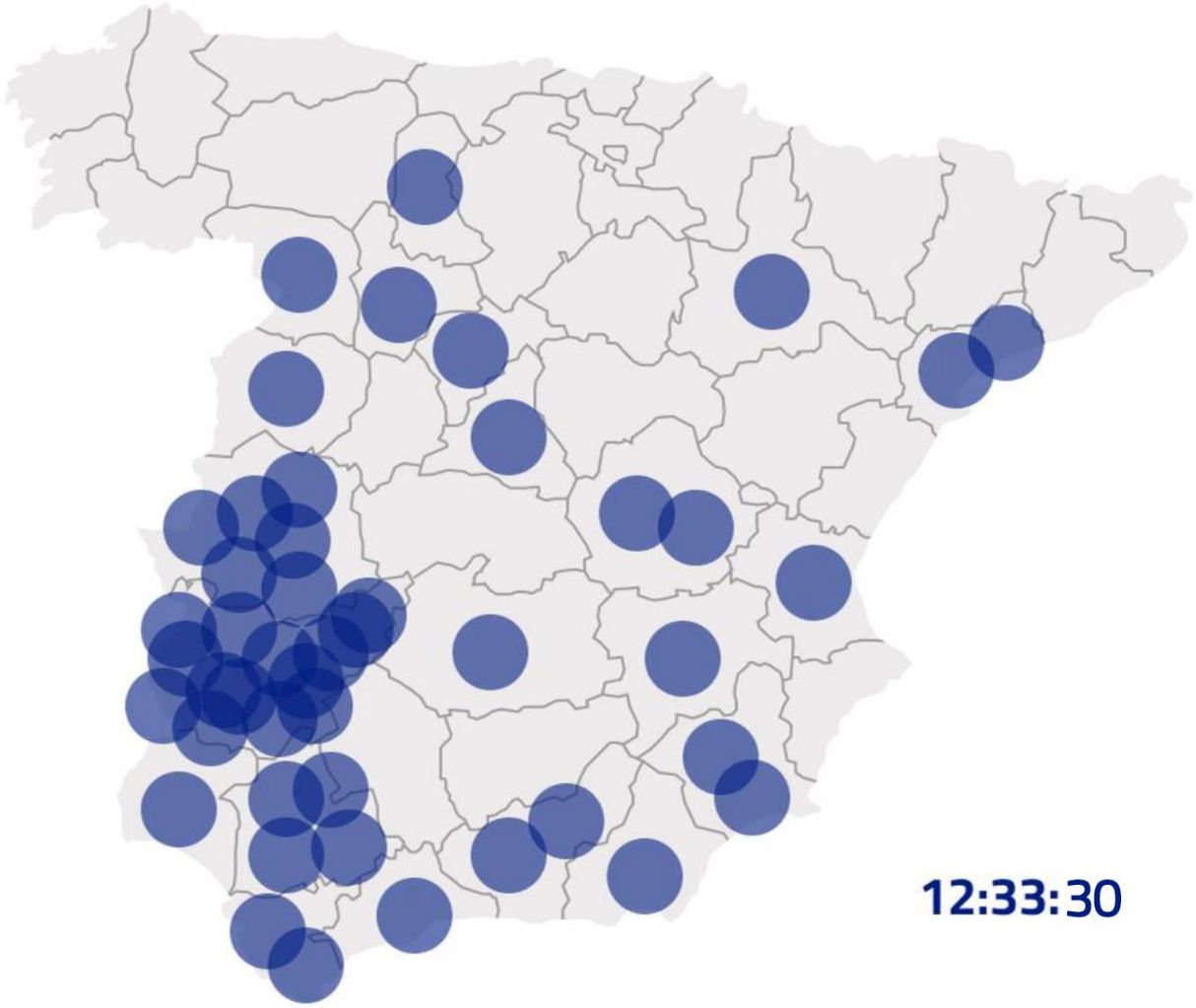
Adapted from: A. García *et al.*, 2025, *Analysis of the events leading to the loss of power on April 28th 2025*, Report produced by Compass-Lexecon and INESCTEC



PHASE 3

I can't believe this is happening to me. The weirdest thing is it was just a dream, and now it's actually real (Carrie Underwood)

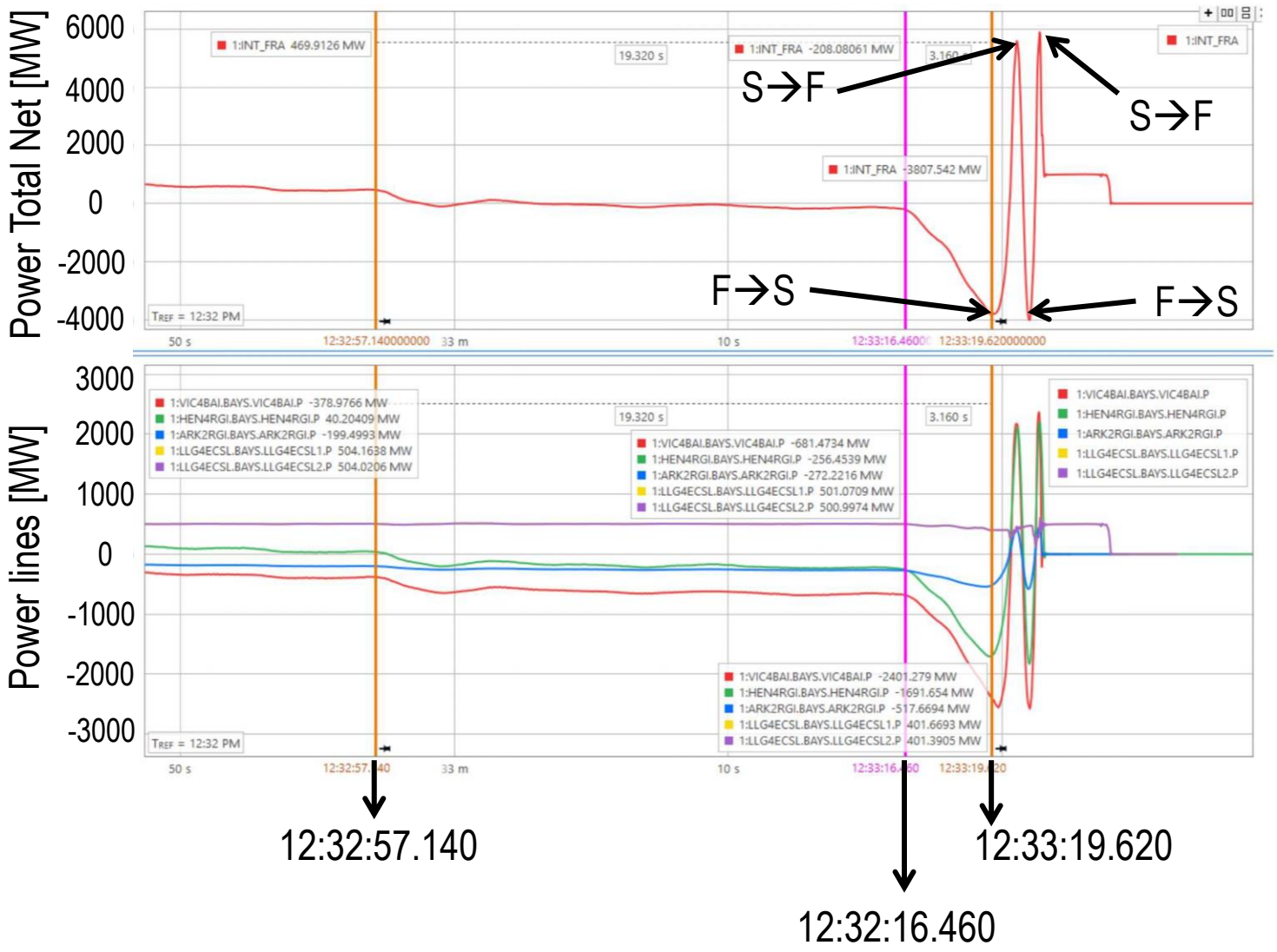
Phase 3 – Morning of April 28th (12:33:18 – 12:33:30 h)



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)

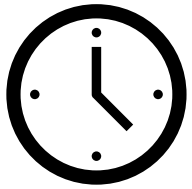


12:33:23.960

- **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) substations managing AC interconnections with France start to trip
- 12:33:23.960 HVDC connection ceases operation

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

- 12:33:20.180 Frequency drops to 49.48 Hz (below 1st 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 (2nd pumping load shedding threshold) → 588 MW go offline automatically**
- **12:33:20.600 Frequency falls below 49.00 Hz (1st 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 (2nd LST)
- 12:33:21.000 Frequency falls below 48.6 Hz (3rd LST)
- 12:33:21.380 Frequency falls below 48.40 Hz (4th LST)
- 12:33:21.820 Frequency falls below 48.20 Hz (5th LST)



12:33:29.741

- 12:33:22.040 Frequency falls below 48.00 Hz (6th 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**

WRAP-UP

SHE CANNOT SINK, SAYS OFFICIAL OF WHITE STAR LINE

"Absolutely No Fear Is Entertained for the Safety of the Passengers."

Owners Say Great Vessel Is Unsinkable

New York, April 15.—The White Star officials, after a conference lasting more than an hour, today, issued an official statement in which they stated that the great liner was unsinkable and that there was no reason to believe that she either had or could founder. They declared that the interruption of wireless communication was not significant of danger. The statement was signed by Vice-President P. A. S. Franklin and was as follows:

"While we are not in direct communication with the Titanic, we are perfectly satisfied that the ship is unsinkable. That no more wireless messages are coming from the ship is not a sign of danger and may be due to atmospheric conditions or something like that.

"We cannot state too strongly our belief that the ship is unsinkable and the passengers perfectly safe. We figure that the ship is 1,080 miles from New York and 600 miles from Halifax. The Virginian is now on her way to the distressed vessel."

WM. TAFT IS AFRAID OF THE PEOPLE AND WE DON'T BLAME HIM A BIT

The Seattle Star

ONLY INDEPENDENT NEWSPAPER IN SEATTLE

HOME EDITION

TITANIC HITS ICEBERG; PEOPLE SAFE

DR HAZZARD ON 21ST DAY OF FAST PULLS A FAST OAR IN BOAT RACE

CHOP DOWN DOORS FOR CONVENTION

RELIEF IN SIGHT FROM LOCAL FLOOD

LA FOLLETTE CAN'T COME TO THIS STATE

BIG LINER SUSTAINS A TERRIFIC SHOCK; TOWED TO HALIFAX

Breaks Athletic Records After Fasting 7 Days

Great Reception For "Battle Bob" in Eugene

Will Override Mayor's Veto

WOMEN HELPING

HODGE'S FIGHT

Enticed From Home

More Flood Funds

Prize Winner Loses

After Murderer of Millionaire

SHE OUTGAMED 'EM

Like the Small Boy Rolling the Snowball

Star Want Ads will roll up the dollars for those who use them.

"All the News That's Fit to Print."

The New York Times.

THE WEATHER.

TITANIC SINKS FOUR HOURS AFTER HITTING ICEBERG; 866 RESCUED BY CARPATHIA, PROBABLY 1250 PERISH; ISMAY SAFE, MRS. ASTOR MAYBE, NOTED NAMES MISSING

Col. Astor and Bride, Isidor Straus and Wife, and Maj. Butt Aboard.

"RULE OF SEA" FOLLOWED

Women and Children Put Over in Lifeboats and Are Supposed to be Safe on Carpathia.

PICKED UP AFTER 8 HOURS

Vincent Astor Calls at White Star Office for News of His Father and Leaves Weeping.

FRANKLIN HOPEFUL ALL DAY

Manager of the Line Insisted Titanic Was Unsinkable Even After She Had Gone Down.

HEAD OF THE LINE ABOARD

Biggest Liner Plunges to the Bottom at 2:20 A. M.

RESCUERS THERE TOO LATE

Except to Pick Up the Few Hundreds Who Took to the Lifeboats.

WOMEN AND CHILDREN FIRST

Cunarder Carpathia Rushing to New York with the Survivors.

SEA SEARCH FOR OTHERS

The California Stands By on Chance of Picking Up Other Boats or Rafts.

OLYMPIC SENDS THE NEWS

Only Ship to Flash Wireless Messages to Shore After the Disaster.

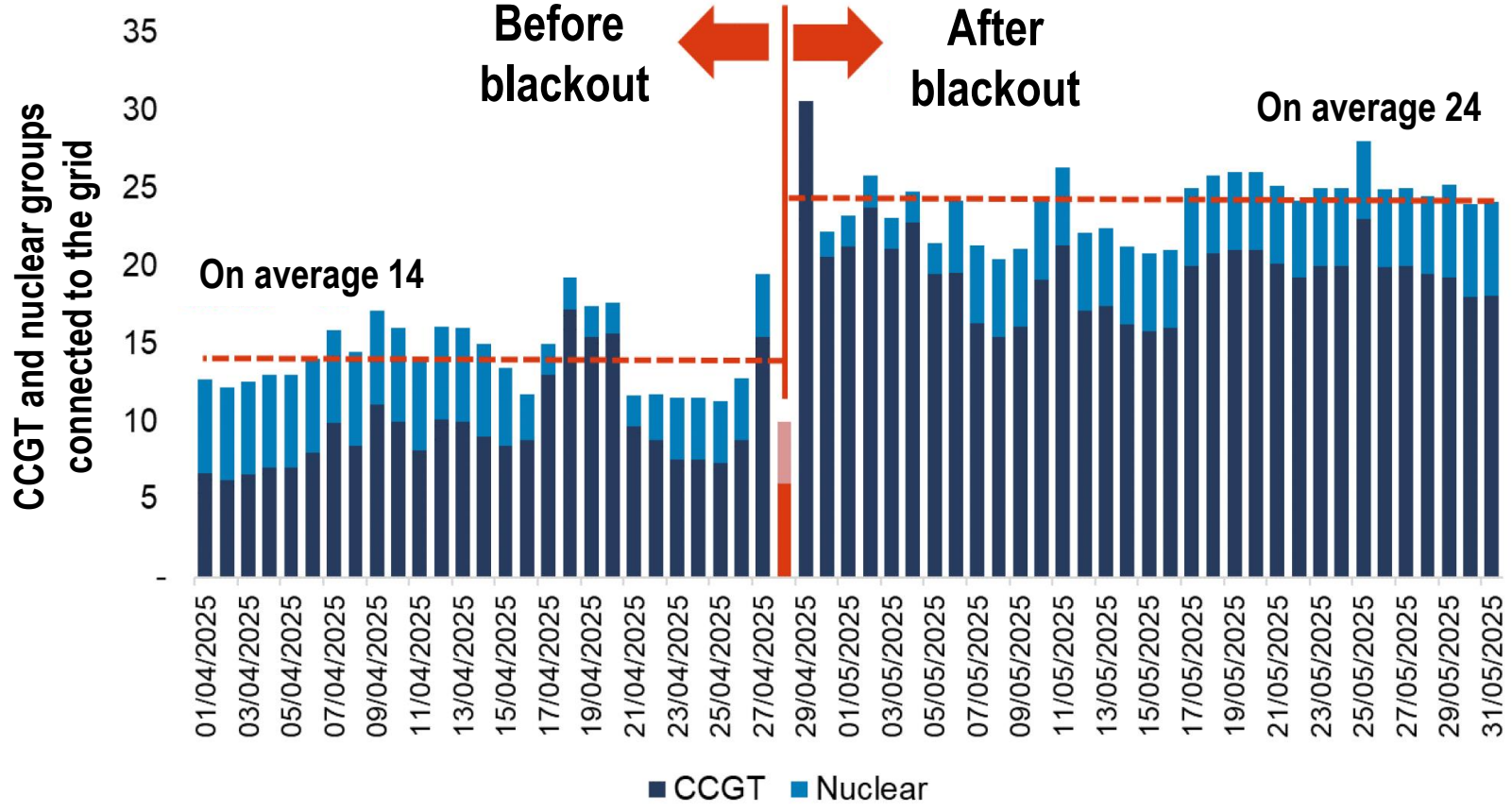
The Lost Titanic Being Towed Out of Belfast Harbor.

PARTIAL LIST OF THE SAVED.

LATER REPORT SAVES 866.

CAPT. E. J. SMITH, Commander of the Titanic.

Wrap-up and conclusions



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Who turned off the light?
Storyboard of the total blackout in Spain

7th Thermal, Mechanical and Chemical Energy Storage Workshop
July 30th & 31st 2025 – San Antonio, TX

David Sánchez
University of Seville

Disclaimer: Except where noted, this presentation is based on the non-confidential version of the report on the causes leading to the blackout on April 28th 2025, issued by the Government of Spain: *Versión no confidencial del informe del comité para el análisis de las circunstancias que concurrieron en la crisis de electricidad del 28 de abril de 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)

- Intro power grid in Spain: 2 slides
- 01:30
- Intro to situation: 7 slides
  - Spot market and planning 1 slide
  - Voltage-frequency control 3 slides
  - Measures & organization 1 slide
- 05:00
- Phase 0 4 slides
- Phase 1 8 slides
  - General & 12:03 3 slides
  - 12:19 and wrap-up 5 slides
- Phase 2 11 slides
  - 12:32 (Huénajar) 6 slides
  - Núñez de Balboa 3 slides
  - Sevilla 1 slide
  - Summary 1 slide
- 17:00
- Phase 3 3 slides
- 20:00
- Wrap-up 2 slides