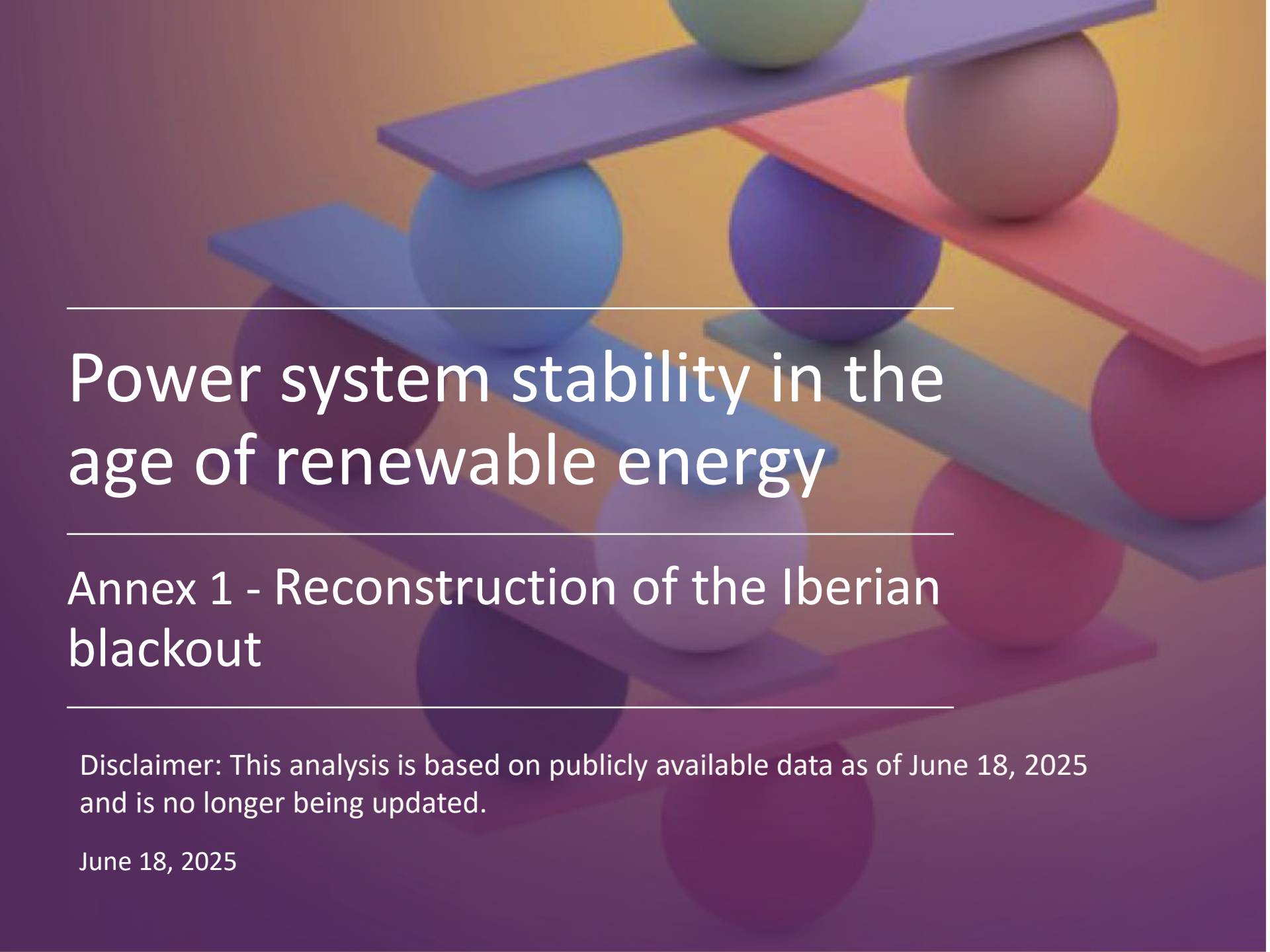


Power system stability in the age of renewable energy

Annex 1 - Reconstruction of the Iberian blackout

Disclaimer: This analysis is based on publicly available data as of June 18, 2025 and is no longer being updated.

June 18, 2025

Agora Energiewende

The Iberian blackout at a glance

What happened?

- On Monday, April 28, 2025, the Iberian Peninsula (i.e. Peninsular Spain and Continental Portugal) suffered a **blackout**
- Within 20 seconds, 3 losses of generation with a total capacity of **2.2 GW** occurred in the Southwest of Spain
- This was followed quickly by a **cascade of disconnections**, the **decoupling** of the Iberian system from the rest of Europe, and finally the blackout

Why did it happen?

- **Investigations** by the Spanish government, TSO and ENTSO-E* are ongoing. Much remains unclear, however, the Spanish government concluded** that the blackout was caused by a multifactorial system failure:
  - **Voltage fluctuations** were observed in the days leading up to the event and were more intense on the morning of the 28th
  - **Multiple oscillations** required modifications to the system configuration, increasing the difficulty in stabilising the voltage
  - There was i**nsufficient voltage control** due to too few synchronous units scheduled and several conventional generators failing to respond correctly to operator requests
  - Some **conventional power plants disconnected** before the regulated voltage thresholds were exceeded

What was the role of solar and wind?

- Right before the blackout solar and wind accounted for **~70%** of Spain's electricity generation
- This led to early speculation on solar and wind's role, notably linked to their lack of **inertia**. But initial findings of the Spanish government **do not attribute explicit responsibility to wind and solar power**
- While high share of variable renewable energy (VRE) may affect system stability, **reliable power systems with very high shares of VRE** are already a reality, as demonstrated in e.g. Ireland, Denmark, South Australia and Texas

- * ENTSO-E is the European Network of Transmission System Operators for Electricity. For the latest information about the ENTSO-E investigation into the blackout, visit ENTO-E's webpage on the blackout
- ** https://www.miteco.gob.es/es/prensa/ultimas-noticias/2025/junio/se-presenta-el-informe-del-comite-de-analisis-de-la-crisis-elect.html

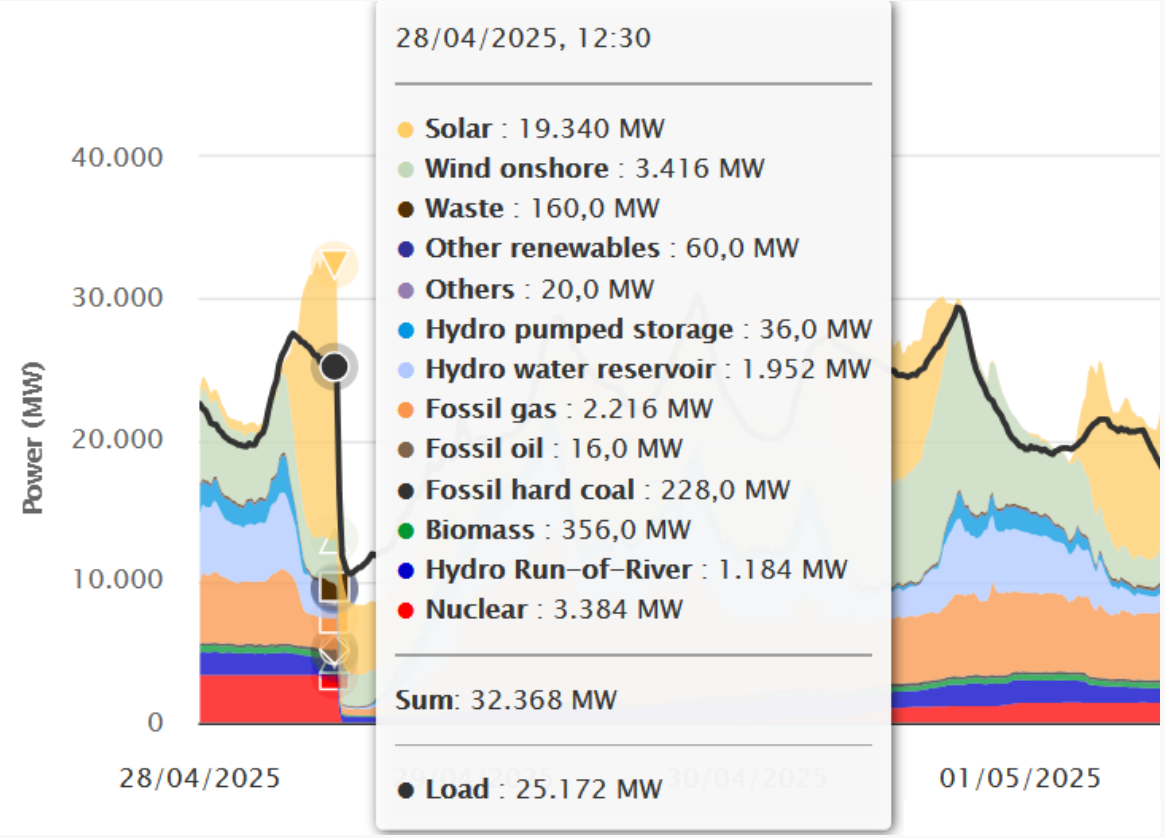
On April 28 at 12:33:24 the Iberian peninsula experienced a blackout

Part of the European Synchronous Power System impacted by the Spanish Blackout

- → The Iberian peninsula suffered a complete blackout
- → A small part of France, close to the border, was affected for a limited time
- → The rest of the Continental European synchronous area remained in operation
- → Power was restored the next day at 00:22 in Portugal and around 04:00 In Spain

Right before the blackout, ~70% of electricity generation in Peninsular Spain was coming from solar and wind

Public net electricity generation in Spain in the week of the 28th of April 2025



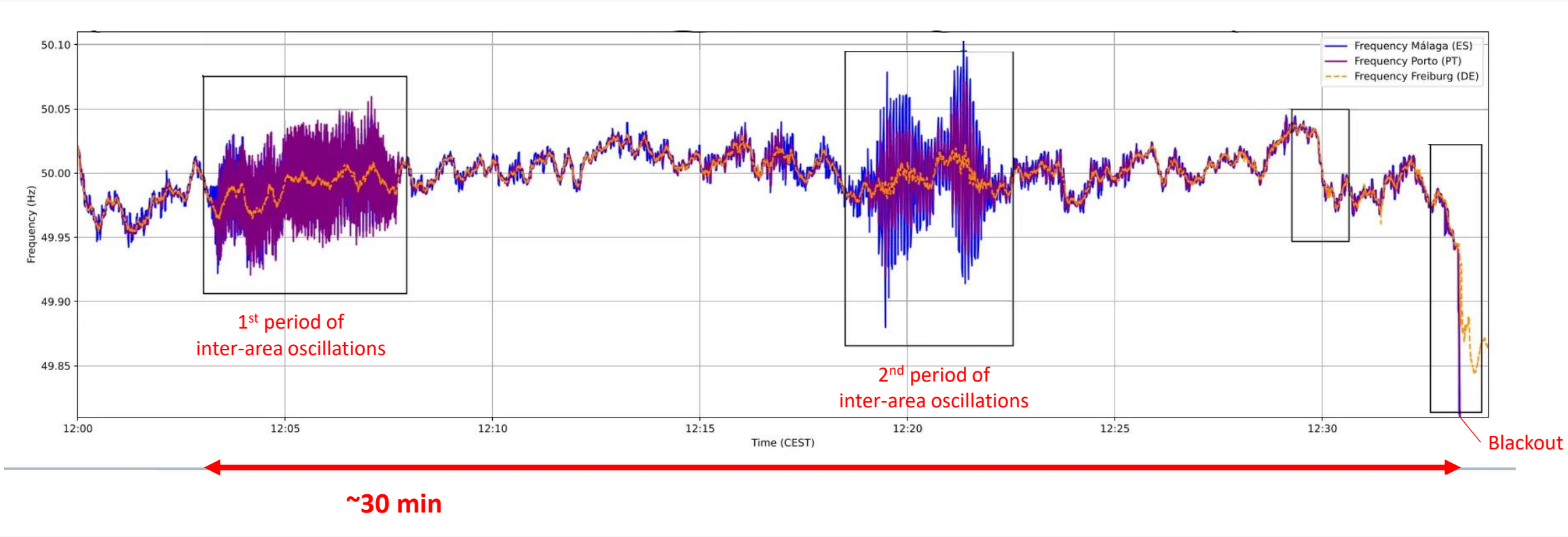
- At 12:30, ENTSO-E data for Peninsular Spain shows:
  - 32.4 GW of total generation
  - 25.2 GW of load
- At this time, **solar and wind** made up **~70% (22.8 GW)** of generation
- Almost all remaining generation, just under **30% (~9 GW)**, came from **synchronous generators**
- Spain was **exporting 3.8 GW**
  - 1 GW to France
  - 2 GW to Portugal
  - 0.8 GW to Morocco
- The connected hydro stations were **pumping** at a cumulative capacity of **3 GW**

Source: Energy-Charts (last update: 14/05/2025, 07:16 CEST)
* This refers to technologies that provide inertia through their spinning generator shafts. In this case, it included nuclear, coal, gas, oil, biomass and all hydro

Agora Energiewende

Starting around 30 minutes before the blackout, two periods with inter-area oscillations were recorded

Oscillations before the blackout in Europe

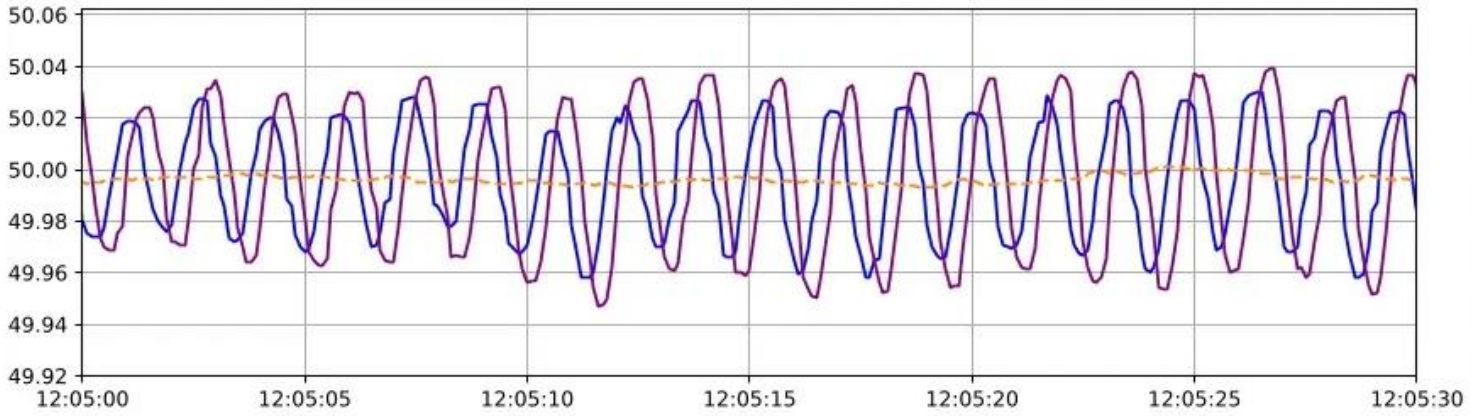


Source: Leonhard Probst from Fraunhofer ISE with data from Gridradar ^(Malaga and Porto) and Energy-Charts (Freiburg)
Note that “coupled” and “uncoupled” here refers to the interconnection between Spain and France being connected and disconnected, respectively

Agora Energiewende

Available data suggests that in the 1st oscillation period, starting at 12:03 and lasting ~4 minutes, there was a new kind of inter-area oscillations

Frequency in Spain (Malaga), Portugal (Porto) and Germany (Freiburg) from 12:05pm

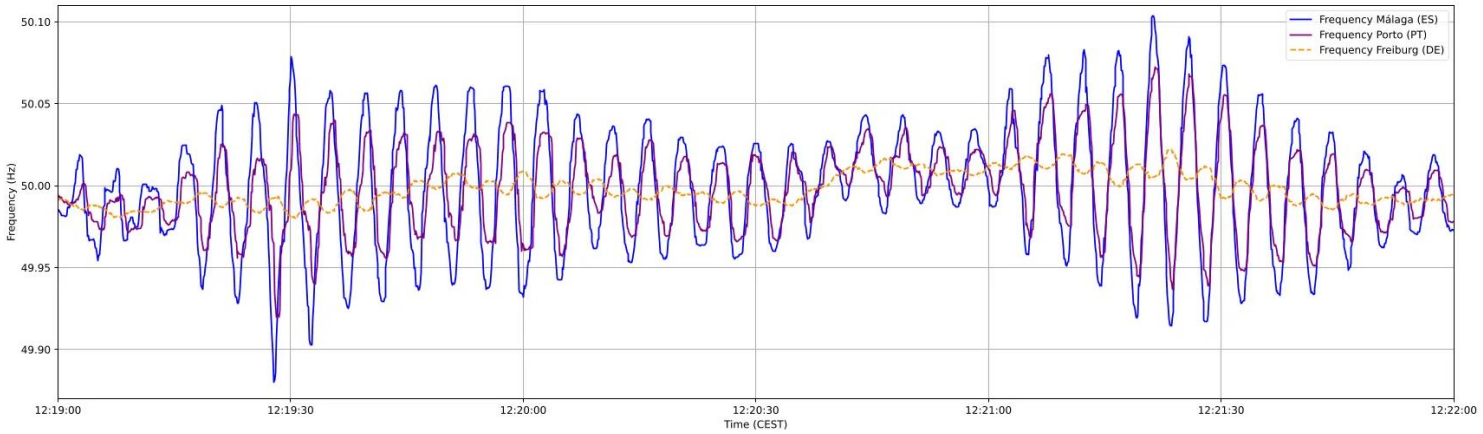


- The first period (12:03-12:07) showed the biggest swings in Porto, and a noticeable phase angle between Porto and Malaga (i.e., the frequency waves are shifted relative to each other)
- Early analysis by Leonhard Probst finds that these oscillations had a dominant mode* of 0.631 Hz
- According to this analysis, such inter-area oscillations are **atypical**
- ENTSO-E states that preliminary analysis indicates that this was a local oscillations, mostly affecting the Spanish and Portuguese power systems

Source: Leonhard Probst with data from Gridradar and Energy-Charts
* The dominant mode is the most significant pattern of power swinging back and forth between the regions

The same data suggests that in the 2nd oscillation period, starting at 12:19 and lasting ~2 minutes, the inter-area oscillations were of a known kind

Frequency in Spain (Malaga), Portugal (Porto) and Germany (Freiburg) from 12:19pm



- The second period (12:19-12:21) showed the biggest swings in Malaga, with no noticeable phase angle between Malaga and Porto
- These oscillations had a dominant mode* of 0.215 Hz
- ENTSO-E reports that this inter-area oscillations corresponds to “the well-known East-West Continental mode,” and that it was effectively dealt with
- The same kind of oscillation was seen again on May 1 (i.e., after service had been restored) with no reported loss of generation

Source: Leonhard Probst with data from Gridradar and Energy-Charts, ENTSO-E
* The dominant mode is the most significant pattern of power swinging back and forth between the regions

It is still unclear what effect, if any, these inter-area oscillations had

Oscillations were gone before the blackout according to ENTSO-E

- → The French and Spanish TSOs took action to mitigate them
- → ENTSO-E reports that: “Following the second oscillation, the voltage was within the range of 390–420 kV, before increasing again, but still within the operational voltage range in the transmission network”
- → ENTSO-E and the Spanish government continue to investigate if there is a link between these oscillations and the events that followed

A sign of instability in the system?

- → At the edge of European system & **weakly interconnected**, Spain is more exposed to oscillations
- → The **high share of solar & wind** could have reduced the system’s ability to dampen oscillations
- → In a similar event in 2016 there was only ~10% of solar and wind, so causality is not yet clear

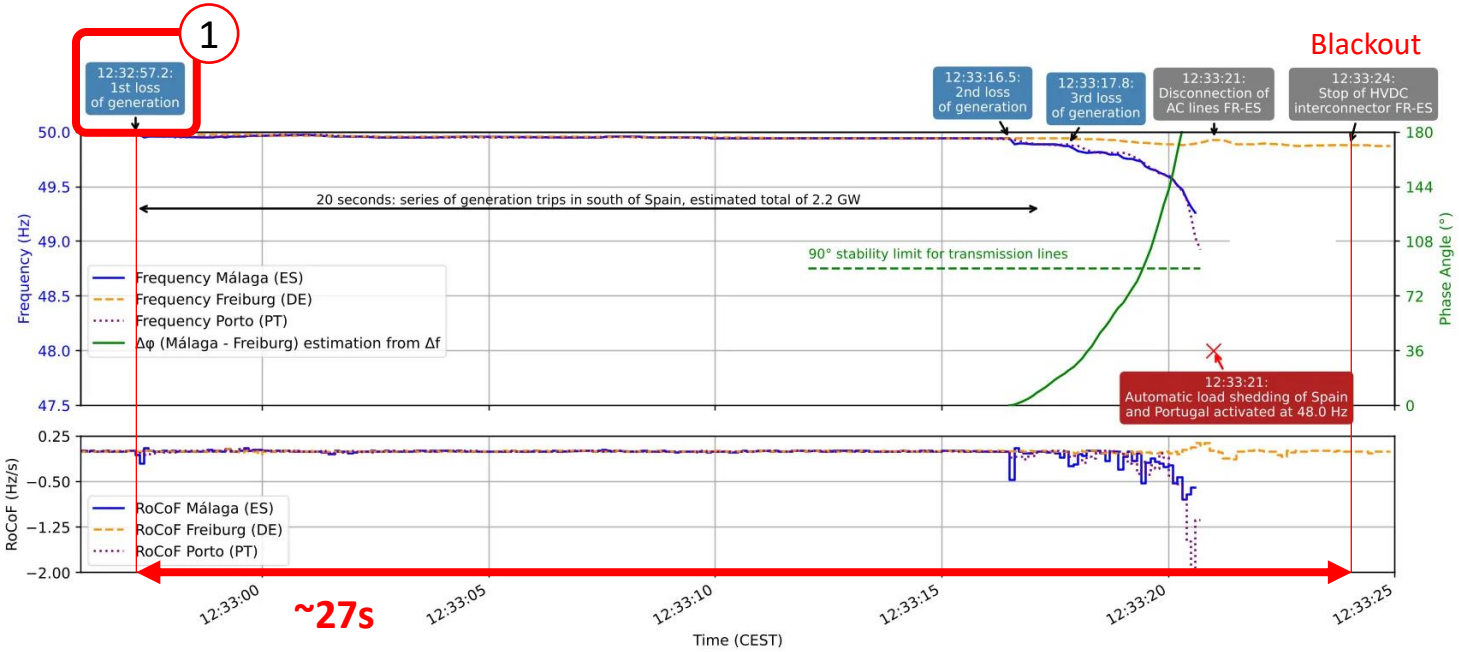
Other factors could be at play

- → The recent **connection of the Baltic states and Ukraine** could affect inter-area oscillations
- → There were also **voltage oscillations** (see further)
- → If the oscillations played a role, it is likely that they were just one of several factors contributing to the adverse system conditions

 Source: interpretation draws on ENTSO-E’s report of May 9, ENTSO-E’s webpage on the blackout, and analysis by Leonhard Probst, among others

At 12:32:57, 27 seconds before the blackout, a 1st loss of generation occurred at a substation in Granada

Frequency (top) and Rate of Change of Frequency (RoCoF; bottom) from 12:32:57 in Spain (Malaga), Portugal (Porto) and Germany (Freiburg)



1

Fraunhofer ISE

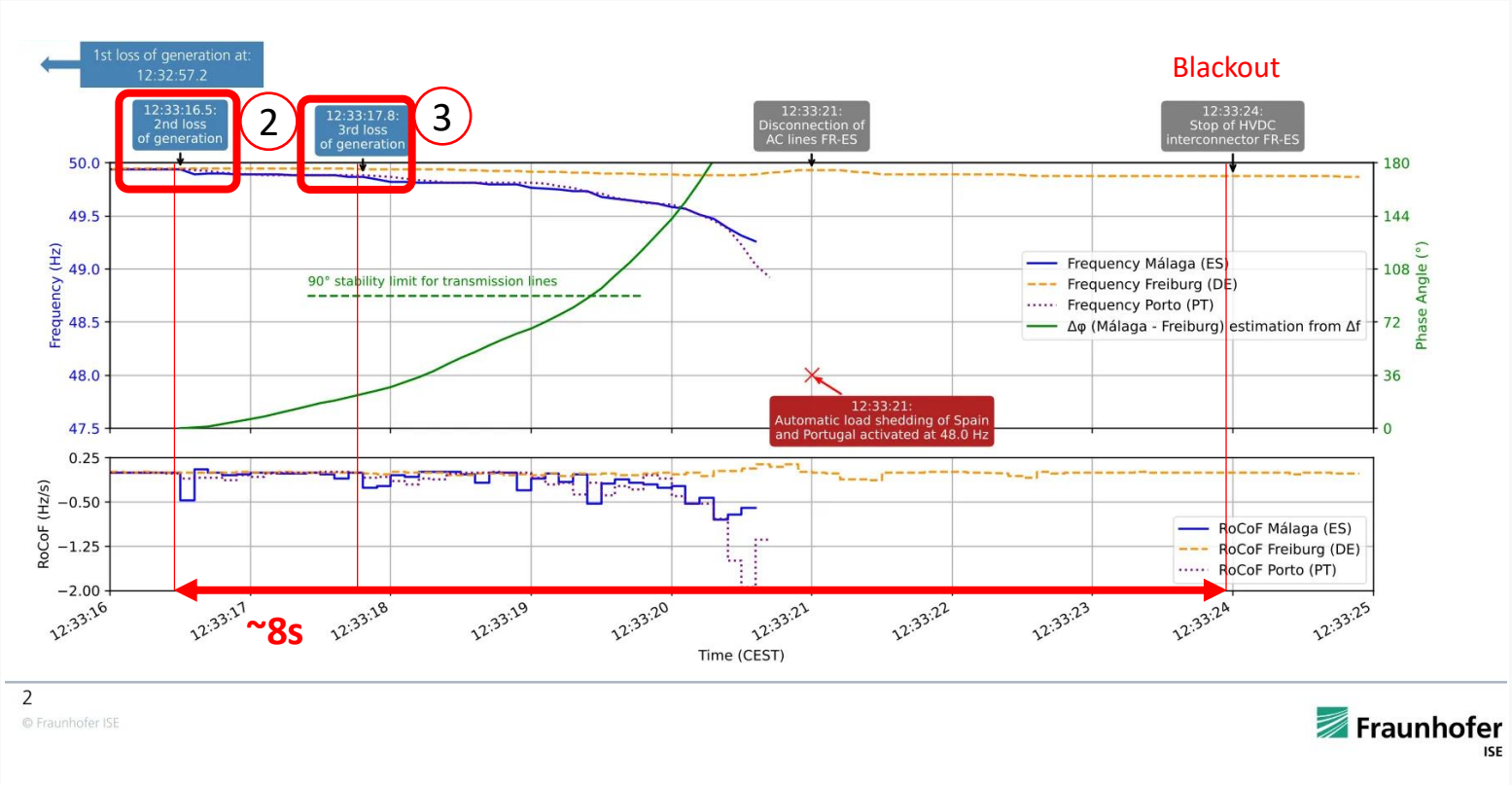
- In the span of 20 seconds, Spain suffered the **loss of 2.2 GW** of generation capacity in 3 events
- The **1st loss** happened at 12:32:57 at a substation in **Granada**
- The frequency data suggests that the system was able to manage the impact of this loss, but it is still unclear if/how this 1st loss affected the subsequent losses

 | Source: Leonhard Probst, El Pais and Reuters

Agora Energiewende

At 12:33:16, 8 seconds before the blackout, a 2nd loss of generation occurred in Badajoz, followed moments later by a 3rd loss in Sevilla

Frequency (top) and Rate of Change of Frequency (RoCoF; bottom) from 12:33:16 in Spain (Malaga), Portugal (Porto) and Germany (Freiburg)



2

Fraunhofer ISE

- → The **2nd loss** occurred in **Badajoz** (on ES-PT border) at 12:33:16.5
- → The system seems not to have fully recovered yet by the time the **3rd loss** hit 1.3s later, at 12:33:17.8, in **Sevilla**
- → It is still unclear what caused these 3 initial losses
  - The Spanish TSO, Red Electrica, stated that all losses *"occurred **due to causes outside the grid**, possibly at generation plants themselves or in smaller grids not managed by [Red Electrica]"*
  - The Spanish TSO & government already independently stated that it was **not a cyberattack**

Agora Energiewende