# Power system stability in the age of renewable energy

## Recommendations in the context of the Iberian blackout

June 18, 2025, updated July 1, 2025

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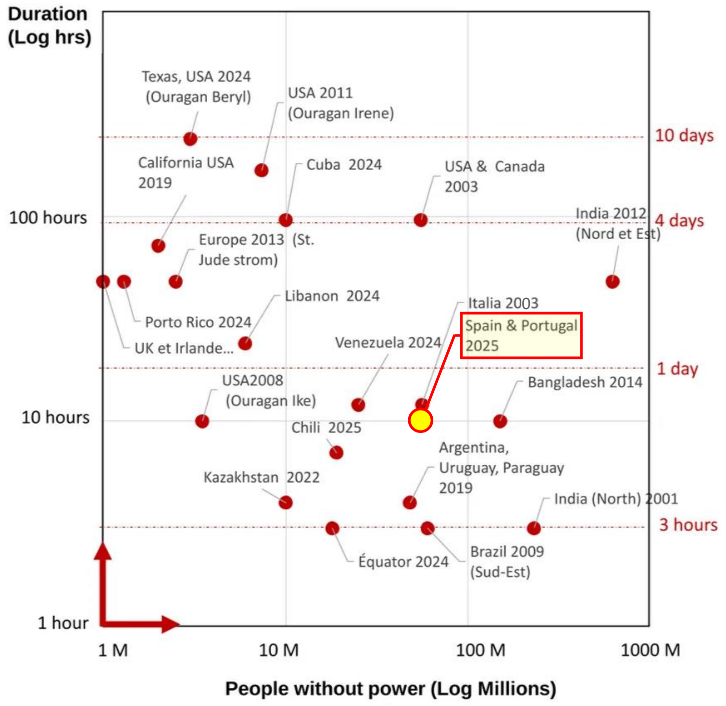
# Key findings

1. **The Iberian blackout put a spotlight on reliable electricity supply as Europe transitions to climate-neutral power systems.** Experts and system operators have long recognised that the increasing reliance on inverter-based resources such as wind, solar and battery storage fundamentally transforms how the grid operates. Renewable energy could have helped stabilise the system in Spain but was held back by technical regulations. This underlines the need to accelerate efforts to align system stability frameworks with renewables-based power systems.
2. **Reliable renewables-dominated power systems are both possible and already in use.** Countries like Ireland, Denmark and the state of South Australia regularly operate with >70% instantaneous variable renewables, thanks to advanced services like fast frequency response, synthetic inertia and voltage support. These real-world examples show that, with the right tools and strategies, power system stability can be guaranteed as systems transform to high renewables and electrification shares.
3. **Grid modernisation and development must accelerate to keep pace with the clean energy transition.** Stronger connection between the Iberian Peninsula and the rest of European grid would have helped reduce the severity of the Iberian blackout – provided robust coordination between operators. Infrastructure planning and investments must advance in parallel with regulatory reforms that enable more flexible and proactive system management.
4. **System stability requirements must be transparently quantified and services optimally sourced.** Good practice examples include the UK’s inertia needs assessments and the fast-reserve auctions used in Texas and Australia. In the EU, the ongoing network code revision is an opportunity to support the integration of stability technologies like grid-forming solutions - while striking the right balance between universal requirements and remuneration for the sourcing of services.

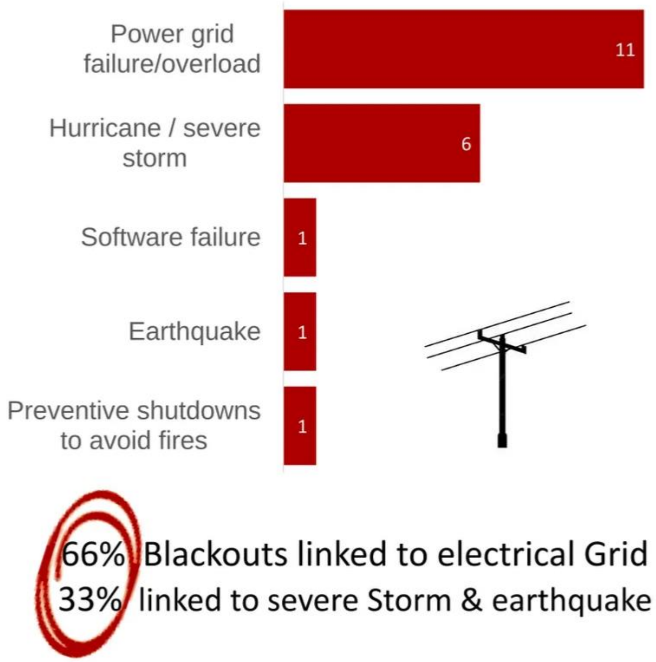
# Big blackouts are rare, but they do happen. When they do, the issue is often related to grid infrastructure and practices.

## The world's 20 biggest blackouts in 2000-2025




*Sources :* World Bank's Data portal; *Nexans internal data*

## Causes of the major blackouts




*Period 2000 - 2025 for a blackout affecting more than 1M people*

# The 28 April Iberian blackout unfolded as a cascading system failure. A series of technical issues triggered widespread instability and collapse.

## 1. Oscillations brought the Spanish power system in a less robust state

→ Just after noon, the Spanish grid experienced **several low-frequency power oscillations** (at ~0.6 Hz and ~0.2 Hz), causing average voltage to fall across parts of the system.

→ The 0.6 Hz oscillation seems to have originated in a **solar PV plant in Badajoz**, likely due to an operational anomaly (this is still being investigated).

→ The Spanish grid operator, Red Eléctrica, intervened to stop the oscillations and raised voltage. These actions **reduced the power system's ability to absorb further disturbances** later on.

## 2. Voltage control problems triggered a cascade of generation trips

→ As the system became more stressed, some distributed plants reduced their output as scheduled, while others disconnected unexpectedly. Both contributed to **rising voltage levels**.

→ Several conventional power plants **failed to provide the voltage control** they were expected to deliver.

→ As voltage continued to climb, a major **substation and many smaller generators shut down**, some unexpectedly.* Each disconnection pushed voltage even higher, setting off a chain reaction.

## 3. The frequency dropped, triggering a blackout

→ The combined loss of generation caused the **system frequency to fall** below safe limits.

→ **Underfrequency load-shedding was activated automatically**. As it is a frequency-control measure, it failed to address the issue, and in fact even further increased voltage.

→ The interconnection to France **reversed from export to maximum import** to support the system but failed to prevent a loss of synchronism.

→ As the connection to France and Morocco disconnected, the system collapsed, resulting in a **blackout**.

Source: Red Electrica (18 June 2025), Blackout in Spanish Peninsular Electrical System the 28th of April 2025.
For a detailed and regularly updated timeline of the blackout, see ENTSO-E's official webpage on the Iberian Peninsula Blackout.
* Disconnections happened while the voltage at the point of interconnection was still in the voltage range in which substations/generators are obliged to remain connected

# Renewables could have helped stabilise the system but were constrained by existing technical regulations

## Some conventional generators failed to deliver sufficient dynamic voltage control

→ Under Spanish rules (Operational Procedure 7.4), large plants, like **nuclear, coal, gas and hydro** must support the grid **by adjusting voltage** (e.g. providing reactive power) **independently from how much active power** they are producing.

→ On April 28th, only **10 such conventional plants** were scheduled to provide this service, the lowest number all year according to the Spanish government.

→ Several of these plants, although contracted and paid to help control voltage, **failed to respond adequately** during the disturbance.

## The restriction on wind and solar from providing dynamic voltage support worsened the situation

→ In Spain, so-called "Renewables, Cogeneration and Waste (RCW)" plants, which include solar and wind, are currently only allowed to **provide limited "static" voltage** support, based on a **fixed power factor** (Royal Decree 413/2014).

→ Consequently, when RCW plants reduced their active power output as scheduled on April 28, they also reduced their reactive power absorption, causing voltage to rise.

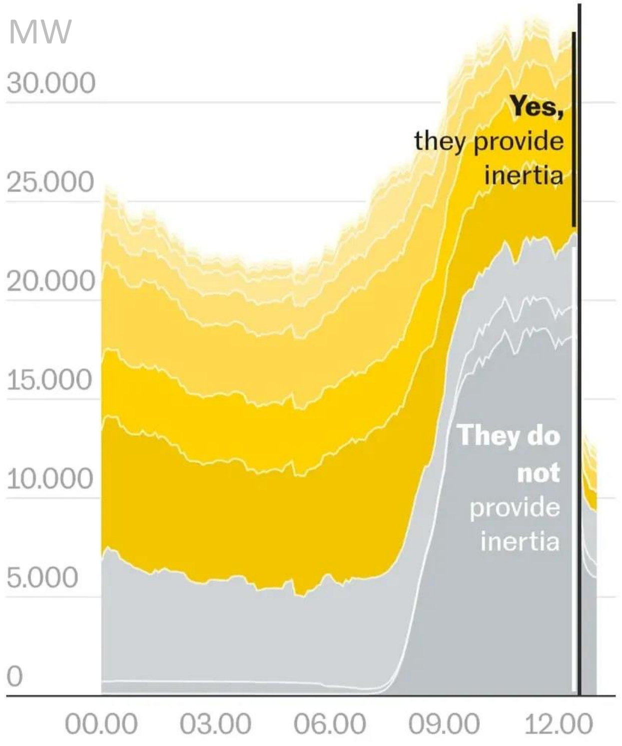
→ Additionally, about 20% of RCW plants **failed to maintain a fixed power factor**,* absorbing less reactive power than expected, thereby causing voltage to rise further.

→ **Wind and solar plants are technically able to provide more advanced ("dynamic") voltage support, but current Spanish regulations do not allow this.** A reform has been pending since 2021 and is now to be implemented 2026.**

Source: Red Electrica (18 June 2025), Blackout in Spanish Peninsular Electrical System the 28th of April 2025
* Red Electrica does not mention what share of the RCW failures came from solar and wind plants vs. other kinds of RCW plants.
** https://www.cnmc.es/prensa/po-control-tension-20250617

# Low inertia was not the problem. Voltage collapse came first.

Share of generation with/without inertia in Spain on April 28: right before the blackout ~30% of generation provided inertia




- → Spain's grid operator, Red Eléctrica, had **assessed the risks of low-inertia operation*** in its 2021-2026 transmission development plan.
- → **On April 28, ~30% of generation provided inertia**, a level consistent with past stable conditions and aligned with the transmission development plan analysis.
- → In fact, the Spanish **power system had recently operated reliably with even higher shares of renewables and less inertia-providing generation.**
- → In their June 18 report, Red Eléctrica concluded “the inertia of the system in this incident is irrelevant, since the system was already condemned by the massive loss of generation” following the cascade of voltage-related disconnections of power plants.

 Source figure: El Pais * The TSO concluded that at any time at least 5 nuclear generators, 3,750 MW run-of-river hydro and 860 MW of solar thermal had to be online (note that these plants do not have to be working at full capacity to provide their inertia). If any of this was unavailable, it would bring online up to 5 additional thermal combined cycle (i.e., gas) generators.

# As power systems evolve, so must approaches to power system reliability, with a particular focus on power system stability

## Power systems are entering the era of power electronics

→ The old security and stability paradigm - built around a few large (fossil-fuel) power plants - is no longer fit for purpose.

→ New practices are needed for a system that will be built on a lot of **inverter-based resources (IBRs)**, e.g. solar, wind, batteries.

→ **Growing electrification** only makes this paradigm shift more urgent, as the consequences of brown- and blackouts will grow.

## System reliability must consider a broad range of new trends

→ A digitising and more connected power system demands attention for **cybersecurity** concerns.

→ A changing climate will make **extreme weather** more frequent, requiring a more resilient grid.

→ A **decentralising** power system offers opportunities for enhanced reliability, e.g. through greater potential for islanding.

→ Locally produced renewables strengthen **energy independence**, shielding countries from global geopolitical tensions.

## Solutions exist to guarantee stability in IBR-dominated systems

→ To successfully integrate and leverage inverter-based resources, **grid modernisation and development must accelerate** (see slides 8 and 9).

→ A **new approach to stability** is paramount (see slides 10 to 14):

- Power system stability **needs** will have to be more clearly defined (e.g. inertia, voltage regulation)
- Required **services** will have to be sourced in a way that ensures reliability, is cost-effective and encourages innovation.

# As seen in South Australia, blackouts can be critical wake-up calls, driving upgrades in grid infrastructure and practices in line with ambitious RE goals

One of several grid pylons knocked over by the storm on Sep 28, 2016

→ **In 2016 South Australia experienced a blackout affecting 850,000 customers**

- Two tornadoes damaged three 275 kV lines, causing several voltage dips
- The dips triggered protections of 9 wind farms, reducing their output
- This reduction caused a significant increase of imports over the interconnector
- The interconnector overloaded and tripped, islanding South Australia

→ **Since its full investigation, the operator has updated their grid and practices, e.g. by:**

- **Reviewing conservative VRE protection settings**
- **Adding a new interconnector** with New South Wales
- **Investing in inertia** and adding several >100 MW **batteries**

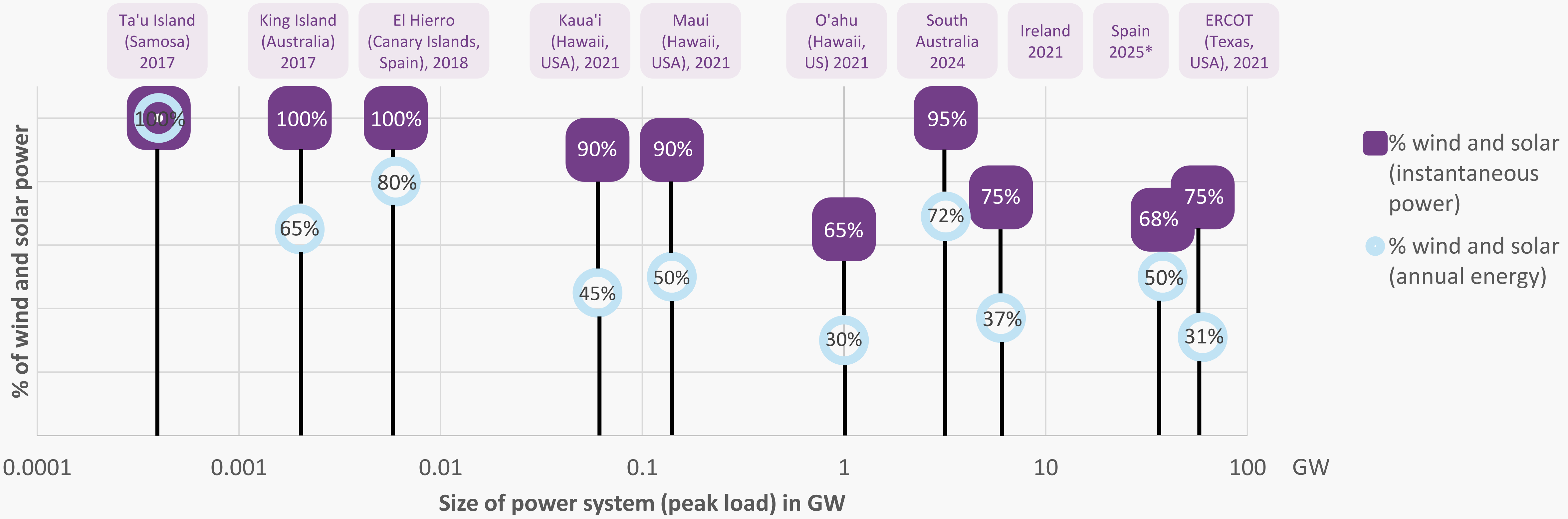
→ **Today, South Australia (SA) is a leader in the clean energy transition**

- In 2024, solar and wind made up 72% of SA net electricity generation
- In Oct 2021, SA met 100% of operational demand with VRE for the first time
- It now regularly meets 100% of its demand from renewables
- It has a target to hit 100% renewable electricity generation by 2027


Source photograph: Debbie Prosser/AFP/Getty Images
Source information: Australian Energy Regulator, Australia Energy Market Commission, Renew Economy, Government of South Australia – Energy & Mining

# Several power systems around the world are operating reliably today with very high instantaneous VRE shares, also in islanded/isolated systems

Max instantaneous and annual shares of wind and solar power (in %) in generation




Source: adapted from NREL (2024), Red Eléctrica (2025), AEMO (2024), SEAI (2025)
* excluding 28.04.2025



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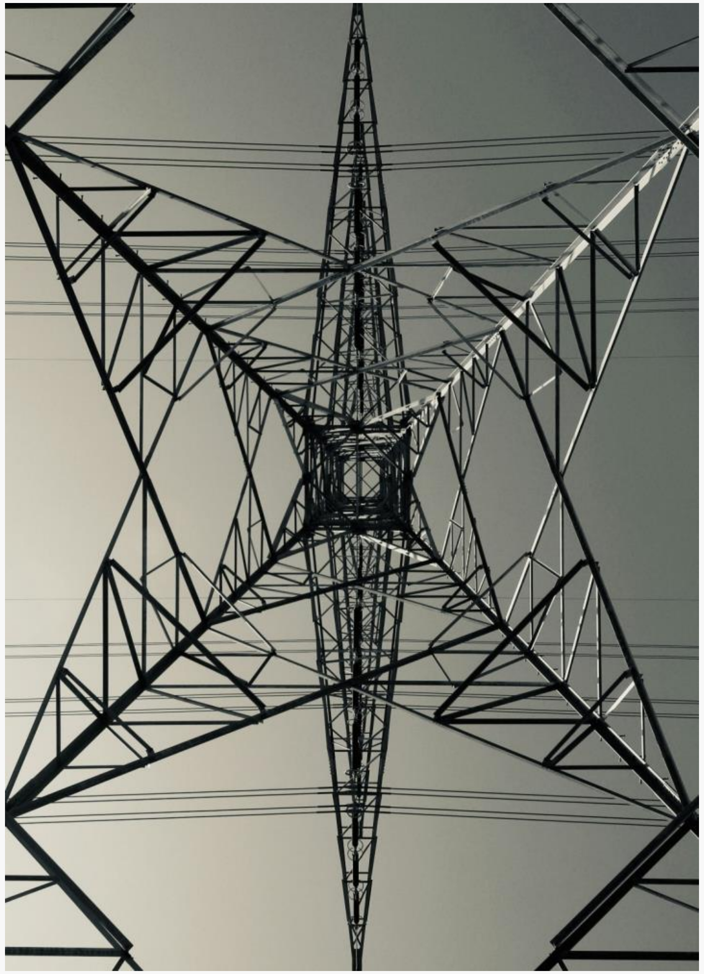
# 1. Grid modernisation: Efforts must speed up to keep up with an evolving electricity supply and increasing demand



Grids modernisation should speed up to match the pace of renewable energy deployment and new electricity demand (e.g. EVs, heat pumps). This includes:

→ Equipping the grid with **advanced remote monitoring and control** equipment, including down into the distribution grid as needed

→ **Optimising the use of existing lines**, e.g. by using grid-enhancing technologies, before reinforcing existing lines and before building new lines

→ **Updating planning and operating practices**, including deeper integration between the transmission and distribution levels

→ **Strengthening mandates and incentives** for grid operators and regulators to plan proactively future grids needs

→ **Investing in workforce and digital tools** to ensure safe, reliable grid operations



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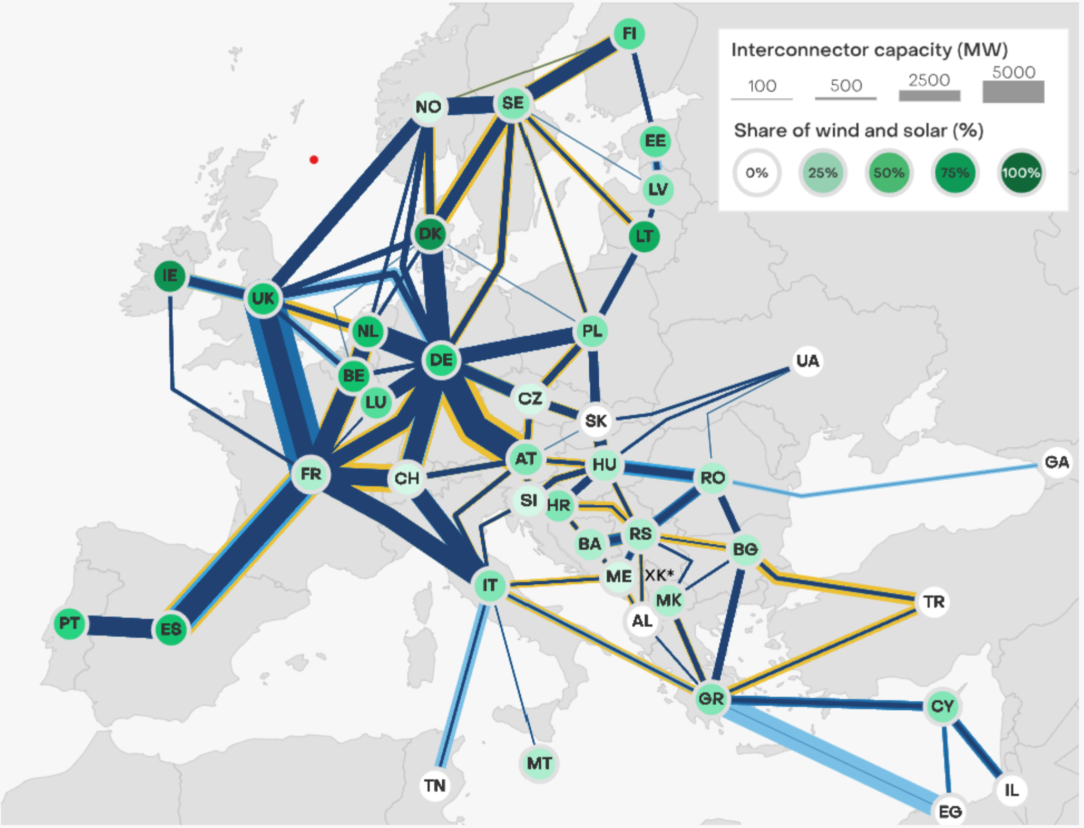
# 1. Grid development: Stronger grids, including well-designed and well-managed interconnections, generally reduce the risk of blackouts

2030 EU interconnections in ENTSO-E NECP+ scenario




- → **More interconnection** enhances system flexibility, resilience and efficiency, e.g. by helping to integrate renewables by smoothing variability across regions.
- → **Spain's limited interconnection** (4.4%, well below the EU's 15% recommendation) could have contributed to the severity of the 2025 blackout; stronger links would have enabled more robust support.
- → **The interconnector between France and Spain played an important role in system restoration,** highlighting the value of these connections for backup power and black-start capability.
- → Increased interconnection adds **operational complexity**, requiring better coordination between operators and diligent management of any added cybersecurity risks, but benefits outweigh challenges.

 | Source: Ember, ENTSO-E Model Data

# 2. Stability needs: By transparently defining and quantifying power system stability needs, operators can remain on top of changing requirements

Most important stability phenomena* (left), the power system functions they relate to (middle) and the geographical scale on which they have to be managed (right)

| | | |
| --- | --- | --- |
| Frequency stability | - Active power balance<br>- Inertia and frequency control | Global, system-wide |
| Rotor angle stability | - Synchronising power and damping<br>- Large power transfers | Local, regional, system-wide (depending on grid structure) |
| Voltage stability | - Reactive power balance<br>- Large power transfers | Local, regional (depending on grid structure) |
| Resonance stability | - Controller response<br>- Multi-frequency network characteristics | Local |

→ Operators and regulators should be required to **conduct and report regular, transparent assessments** of stability needs.

→ **Overestimating** needs can cause extra costs and delays for renewable integration and electrification, while **underestimating** them could threaten grid stability.

→ Clearly quantifying needs allows **targeted procurement** and **identifying stability gaps.**

→ Assessments should also look at **long-term capabilities** (e.g. system strength in 100% RE future).

 * According to IEEE/CIGRE Joint Task Force on Stability Terms and Definitions (Definition and Classification of Power System Stability), *IEEE Transactions on Power Systems*, Vol. 19, No 2, May 2004)

# 3. Stability services (1): It is crucial to strike the right balance between (universal) requirements and remuneration for the sourcing of services

Required ⟷ Remunerated

### Requirements

- → Requirements are set for new renewables, batteries and/or (hydrogen-ready) gas power plants to provide system services, either included in tender specifications or in grid codes
- → Costs are recovered through higher prices for the investments, leading potentially to higher wholesale electricity prices

### System operators

- → System operators invest in solutions (E-Statcoms, MSCDNs, synchronous compensators) that can provide system services or agree bilateral contracts to provide system services
- → Costs are recovered through the grid component of tariffs

### Service markets

- → Markets are organised to procure system services from existing or new assets. The markets could be shorter term if existing capacities are available or longer term if they need to trigger investments
- → Costs are recovered through the market, financed by tariffs

# 3. Stability services (2): Different technologies can provide stability services that can be leveraged through an effective sourcing approach

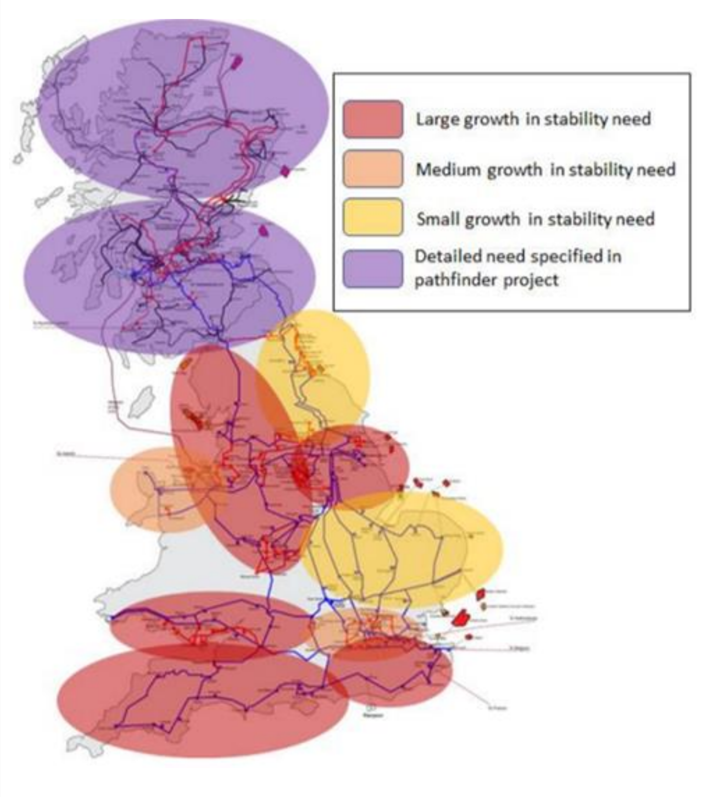
Ability of selected technologies to provide system services (active power, reactive power, and restoration services)

| | Synchronous | | Inverter-Based Resources | | | | |
|---|---|---|---|---|---|---|---|
| | Generator | Condenser | VRE[3] | Batteries | Demand[4] | STATCOM | HVDC-VSC |
| Synchronizing inertia | ■ | ■ | GFM[A] | GFM[A] | | GFM+ES[D] | Async[E] |
| Artificial inertia / FFR[1] | | | ■ | ■ | ■ | | |
| Primary reserves[2] | ■ | | ■ | ■ | ■ | | |
| Secondary reserves[2] | ■ | | Down[B] | ■ | ■ | | |
| Tertiary reserves[2] | ■ | | Down[B] | ■ | ■ | | |
| Short-Circuit Current | ■ | ■ | ■ | ■ | | GFM+ES[D] | ■ |
| Dynamic Voltage Support | ■ | ■ | ■ | ■ | | ■ | ■ |
| Static Voltage Support | ■ | ■ | ■ | ■ | | ■ | ■ |
| Black-Start Capability | ■ | | GFM[A,C] | GFM[A] | | | Async[E] |

1. Fast Frequency Reserves – 2. Mapped onto Europe's FCR, aFRR and mFRR – 3. VRE = Variable Renewable Energy (e.g., solar and wind) – 4. For controllable loads (e.g., HVAC, EVs, electrolysers)
A. If equipped with grid-forming (GFM) inverters (solar: commercial availability limited, wind: impacts turbine & blade design, increasing costs) – B. Downward reserves can be provided through curtailment; upward reserves require structural curtailment (possible, but often too costly) – C. Less practical due to variability – D. If equipped with GFM inverters and energy storage (ES) – E. If connecting asynchronous grids

# Examples of good practices (1): UK approach to guarantee grid stability while integrating high renewables shares

Stability needs across the Great Britain electricity grid




Under the System Operability Framework & Stability Pathfinder initiatives of the National Energy System Operator (NESO):

→ Models and publishes **location-specific system stability requirements**, including inertia, short-circuit strength and voltage support

→ Procures **long-term contracts for essential services** such as inertia, reactive power, voltage control and fast frequency response

→ Provides **transparent signals to investors and technology providers**, enabling non-traditional resources (e.g., batteries, synchronous condensers) to contribute to stability

The programme has three phases and focus areas:

1. Phase 1 focuses on synchronous condensers and novel stabilising services
2. Phase 2 addresses the system services required due to the higher concentration of renewables in Scotland
3. Phase 3 aims to enhance inertia and short-circuit capacity in England & Wales



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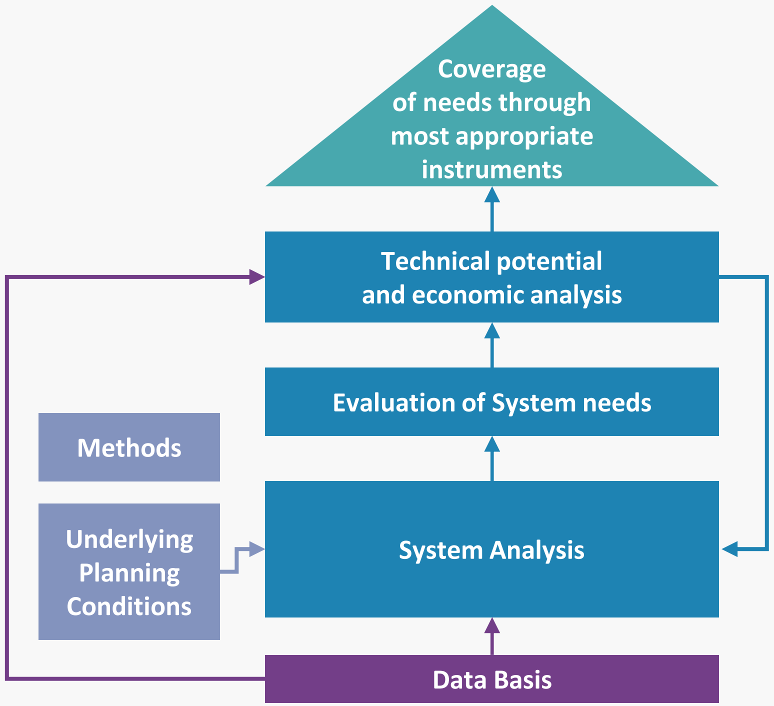
# Examples of good practices (2): Germany has mandated regular assessments of all dimensions of system stability in its energy legislation

Illustration of system stability as in the German Energy Industry Act




→ Section 12i of the German Energy Industry Act (EnWG) establishes a legally binding mechanism for regular, comprehensive assessment and strategic planning of power system stability, with a forward-looking horizon, including 100% renewable scenarios

→ The TSOs are required to **submit a System Stability Report every two years** to the regulatory authority (BNetzA). The report must:

- **Present the current status** of all system stability domains
- **Identify needs and gaps** for secure grid operation
  - This includes the consideration of a 100% renewable generation
- **Quantify service needs** for the next 10 years
- Evaluate and compare **concrete action options** (cost, impact, implementation time, etc.) and define at least one **transformation path with actionable steps**

→ The identified needs are intended to feed into concrete, system-wide implementation strategies outlined in **Germany's System Stability Roadmap**



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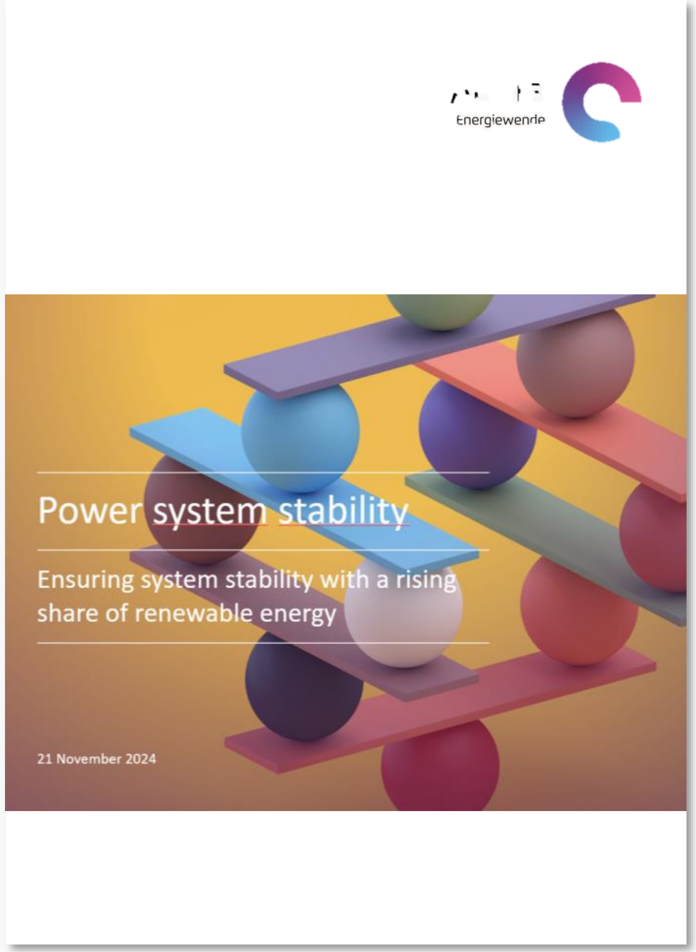
# Agora’s 2024 publication on power system stability provides detailed insights into the various technological and regulatory aspects




1. **A successful transition to climate-neutral power generation requires a new approach to system stability.** System operation methods have traditionally been built around the physical properties of conventional power plants. Wind and solar power, and batteries are inverter-based technologies, connected by power electronics without intrinsic mechanical inertia. Aligning system stability management with renewables-based power systems should feature high on the agenda of policymakers and regulators.
2. **To make informed decisions for a renewables-powered grid, it is important to clearly quantify system stability needs using transparent methods.** As renewable energy share increases, grid operators and regulators should carefully evaluate whether there are enough stability resources. Overestimating these needs can cause extra costs and delays in integrating more renewable energy, while underestimating them could threaten grid
3. **An optimal approach to system stability should focus on using the most cost-effective resources at the relevant location.** For example, while batteries, hydrogen and gas turbines can provide system services with few adjustments, it can be more technically complex for wind and solar, potentially leading to higher costs and delays. Such considerations should determine whether system operators install new technology or run system service auctions, or public authorities set technical provisions in tenders or enforce requirements through national and European network codes.
4. **A comprehensive dialogue among system operators, manufacturers of generation and storage and relevant authorities is critical to identify the best solutions.** A shared understanding of terminology is essential to accurately identify and quantify system stability needs. The ongoing European network code revision is an important opportunity for such alignment. Converging towards harmonised EU-wide standards would further help make supply chains for clean technologies more efficient and thus support the transition to climate-neutral power systems.

# Imprint

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