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Global Conference

Brussels, 14-16 October 2025

Session 2.3 Inertia and Grid Congestion: How Should you Ready your Project?

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Session 2.3 Inertia and Grid Congestion: How Should you Ready your Project?

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Artelys | OPTIMIZATION SOLUTIONS

Power system balancing

In **nominal state**, the power system is stable at $f_0 = 50\ Hz$

Imbalances between injection and offtake impact frequency

- Frequency drops after a decrease of injection and increases after a decrease of offtakes
- Imbalances result from ordinary variations of the load and of the intermittent generation or from contingencies (e.g. failure of assets)

The Rate of Change of Frequency (**RoCoF**) represents the speed at which the frequency changes (in Hz/s). It depends on the contingency ΔP (in MW) and system equivalent kinetic energy E_{kin}.
After a contingency, part of this equivalent kinetic energy is released to provide a power adjustment.

$$RoCoF = \frac{\Delta P * f_0}{2 * E_{kin}}$$

Power reserves are activated to stop frequency deviation and restore it to 50 Hz. The power adjustment is not instantaneous:

- Assets providing the fastest reserve in Continental Europe (Frequency Containment Reserve, FCR) typically start within a fewseconds and are fully activated in 30 seconds
- Some fast frequency reserves can start in about 1 s, but such reserves do not currently exist in Continental Europe

In exceptional situations, **defence plans** (e.g. load shedding) can be activated faster than balancing reserves, in around 500 ms.

Power system balancing relies on numerous mechanisms, in particular power reserves and defence plans.

The key role of inertia

Reserves and defence plans activations are based on frequency or RoCoF measurement, which require a few hundred milliseconds.

- **Frequency measurements** of reasonable quality need a window of **at least 100 ms**.
- Being the derivative of frequency, accurate enough **RoCoF estimation requires even more time**, usually over **200 ms**.
- Overall, taking into account the **time needed to process measurements and act**, it cannot be expected that **automata based on frequency or RoCoF measurement act in less than 500 ms**.

To avoid potential system collapse (blackouts), frequency and RoCoF requirements must be respected.

- **Before the fastest reserve** can stabilise frequency, RoCoF and frequency must respect requirements otherwise assets may **trip for their own protection**.
- **RoCoF** must **stay below 1 Hz/s at the system level** for CE SA *(at the centre of inertia in a 500 ms window)*.
- **Frequency** must **stay within the 47.5 – 51.5 Hz band**, which means that the balancing reaction must be fast enough *(how fast depending on RoCoF)*.

Inertia limits the value of RoCoF and slows frequency variation, giving time for reserves to be activated.

- **Immediately after a contingency**, the (system) **RoCoF** is proportional to the contingency size and **inversely proportional** to the system **equivalent kinetic energy**.
- Guaranteeing a sufficient level of **equivalent kinetic energy** in the system is the **only way to keep the RoCoF within an admissible range.**
- The **more inertia** present in the system, the **slowest the frequency decrease** (i.e. RoCoF is more limited).

Reserves and defence plans activations are based on measurements that require a few hundred milliseconds.
The key role of inertia is to limit the RoCoF, particularly right after a contingency before any remedial action can take place.

Inertia is needed to safeguard the system

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The key defining properties of inertia are that:
- it reacts immediately
- it does not necessitate any control systems.

- Inertia is the **property of the system** that enables an **immediate power adjustment proportional to the RoCoF.**
- Inertia is a **built-in feature of assets** capable of providing this power adjustment, **independently of any control system**.
- It is usually **defined** as an amount of "**equivalent kinetic energy**" (GWs) or as an **inertia constant** (s)

$$E_{kin} = \frac{\Delta P * f_0}{2 * |RoCoF|} \qquad H = \frac{E_{kin}}{P_{load}}$$

High RoCoF is the main frequency-related risk for CE SA system. RoCoF higher than 1 Hz/s are only expected during system split events.

- ENTSO-E indicates that **defence plans** should be enough to ensure survivability of the system (i.e. avoiding blackouts) **as long as the instantaneous RoCoF remains limited.**
- **The key driver of inertia needs** is therefore the **system operation limit** of **1 Hz/s RoCoF**.
- Such high RoCoF are not expected with normal interconnected operation, but only during **system split events** (separation into asynchronous islands **suddenly interrupting power flows**).

As inertia levels are expected to decrease with the energy transition, it is necessary to define inertia requirements.

- Inertia historically relied on the **kinetic energy of synchronous machines** which are **increasingly replaced** by **Inverter-Based Resources** (PV, wind, batteries…), which **do not provide inertia** with traditional **grid-following inverters**.
- ENTSO-E calculates that the median inertia constant could decrease from **5 s** in 2019 to below **3 s** in 2030.
- Key next steps are establishing **common parameters for inertia product definition** as well as **inertia requirement**.

Inertia is the only option to safeguard the system in case of system split events, as otherwise too high instantaneous RoCoF may lead to blackouts. It is therefore crucial to ensure that there are sufficient levels of inertia throughout the system (how much depending on risks to be covered).

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THANK YOU!

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Synthetic Inertia for Storage Systems: EU Regulatory Framework & German Market-Based Procurement

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entsoe

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Agenda

1. Technical & Regulatory Background
2. Grid Forming & Synthetic Inertia in EU Regulation
3. Market-based Procurement of Inertia in Germany

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Technical & Regulatory Background

Grid Forming vs Grid Following converters

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Create system voltage

- **Voltage source behaviour** in order to provide instant (within some ms) current reaction under system disturbances (e.g. voltage amplitude and phase angle jumps)
- Grid following converters behave as current source, and they do not react instantaneously (they need some cycles), which decreases the robustness of the system

Contribute to fault current

- Inject fast current during faults (**within some ms**)
- Grid following converters take some cycles
- Protection systems require sufficient amplitude of fault current in the first ms after the fault

Inertia contribution

- **Fast inertia contribution** is required to limit the Rate of Change of Frequency (RoCoF) in case of power imbalances
- Grid following converters lead to higher RoCoF values as their reaction is slower, which can impact the stability of the grid

System survival during system splits

- Capable of operating in **island mode**
- This is not possible for grid following converters as they need a reference voltage and frequency to operate

Source: ENTSO-E report from the Technical Group on High Penetration of Power Electronic Interfaced Power Sources (link)

Connection Network Codes

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Three European Union (EU) **Connection Network Codes** (CNCs) define the technical capabilities of system users to provide a system-supportive performance under all system operation conditions

Network Code on Demand Connection (NC DC)

Network Code on Requirements for grid connection of Generators (NC RfG)

Network Code on requirements for the grid connection of HVDC (NC HVDC)

- The storage systems requirements are addressed in the **NC RfG**, which entered into force in 2019 and is currently under an amendment process. However, the current NC RfG **excludes all storage systems except for pump storage**
- In December 2023, following stakeholders' proposals assessment, ACER (Agency for the Cooperation of Energy Regulators) submitted to the European Commission (EC) its recommendation for **NC RfG 2.0**
- The amendment proposal includes **requirements for all type of storage systems**. In particular, it requests **Grid Forming (GFM) & synthetic inertia capability for non-synchronous** Electricity Storage Modules (**ESM**)
- The process of finalising the adoption of the amended regulation is now the responsibility of the EC, and no specific deadline has been set

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Grid Forming & Synthetic Inertia in EU Regulation

Grid Forming & synthetic inertia requirements in draft NC RfG 2.0

Size

Non-mandatory | Non-mandatory if voltage level below 110 kV unless Pmax 10 ≥ MW | Mandatory

Type A

- **Voltage source behind an internal impedance** bahaviour under both normal and disturbed condtions within the current and energy limits of the ESM
- Upon inception of a disturbance, the Relevant System Operator (RSO) shall specify the dynamic performance

Type B

- **Type A** requirements
- Contribution to **limit transient frequency deviation under high & low frequency** conditions

Type C

- **Type A-B** requirements
- Possibility to require an **additional energy storage** beyond the inherent energy storage

Type D

- **Type A-D** requirements

Member States to decide whether mandatory requirement or market-based service

Out of scope: existing ESMs unless they conduct a significant modernization. Existing means connected to the network on the date of entry into force of the NC RfG 2.0 or owner has concluded a final and binding contract for the purchase of the main plant by three years after the entry into force

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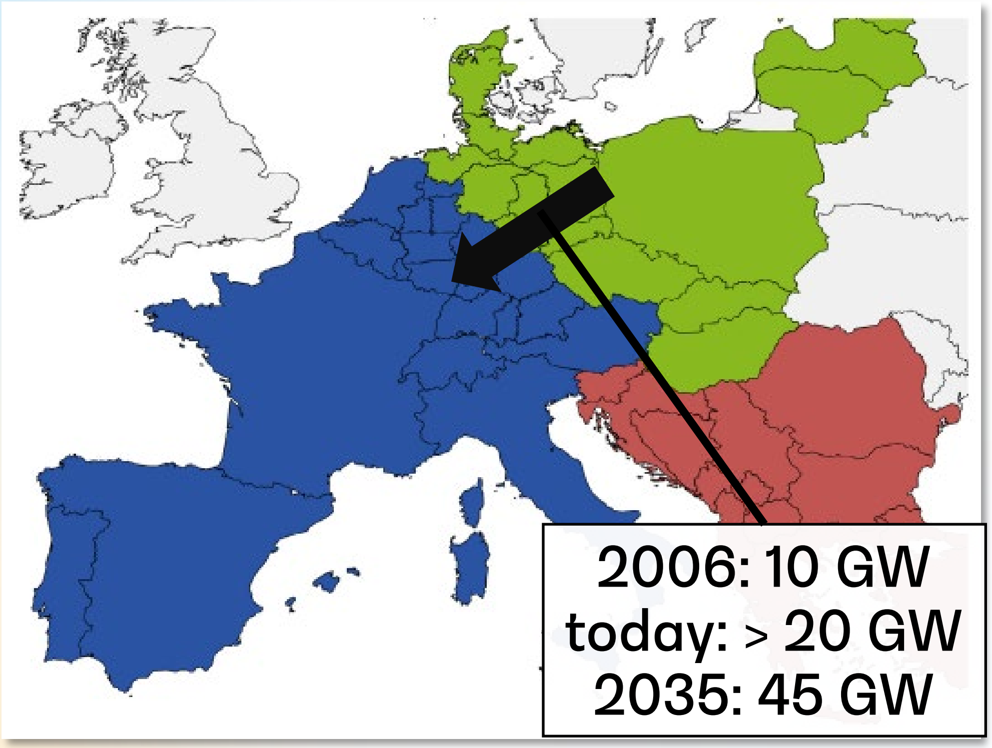
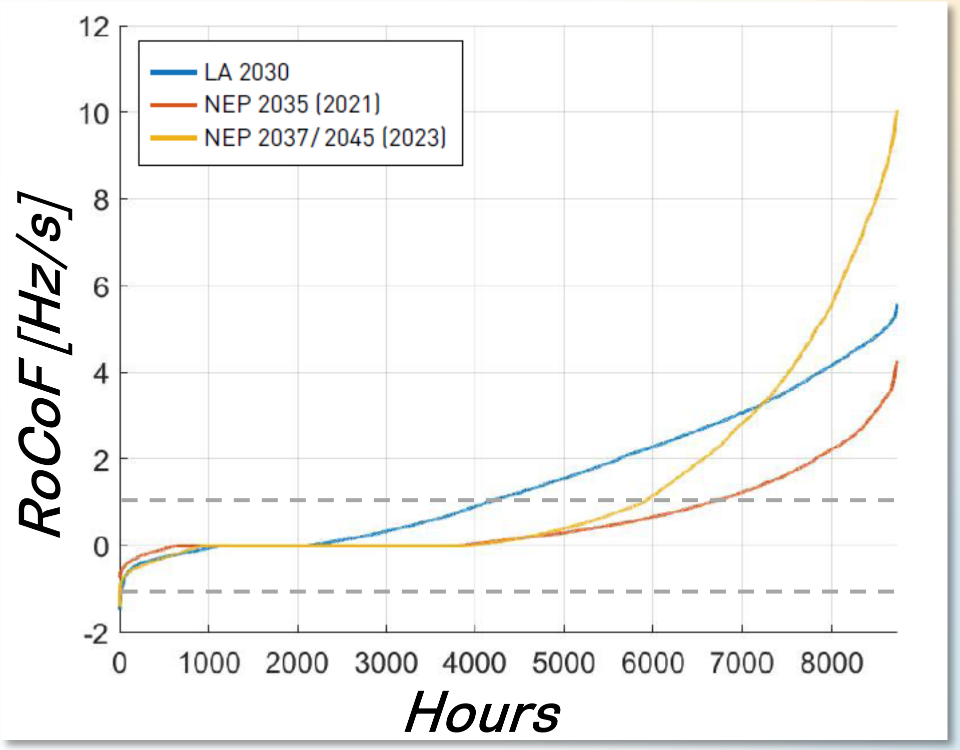
Market-based Procurement of Inertia in Germany

Why do we need additional Inertia?





Future system needs for inertia will increase due to:

1. Increasing power transfer due to greater distances between load and generation
2. Phase-out of conventional power plants that currently provide inertia

How can TSOs cover the Inertia Demand?

Three pillars to cover demand of inertia

TSO-Assets	Market-based Procurement	Grid Connection Requirements
Further development of the state of the art for TSO assets and covering residual demand.	Accelerating the technical and system readiness of assets (e.g., energy storage).	In the long term, all assets should contribute to covering system inertia demands.

All three aspects must be pursued to ensure a sufficient level of inertia and system resilience in the long term.

How can TSOs cover the Inertia Demand?

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Three pillars to cover demand of inertia

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Market-Based Procurement of Inertia in Germany

- The **EU Directive** on common rules for the internal market in electricity **requires TSOs to procure non-frequency ancillary services** (including “inertia for local grid stability”) in a market-based approach.
- In April 2025, the Federal Network Agency (German NRA) reached a **decision on the procurement design** for inertia.
- This decision marked the start of a **nine-month implementation period** for the German TSOs, after which procurement will **begin in January 2026.**

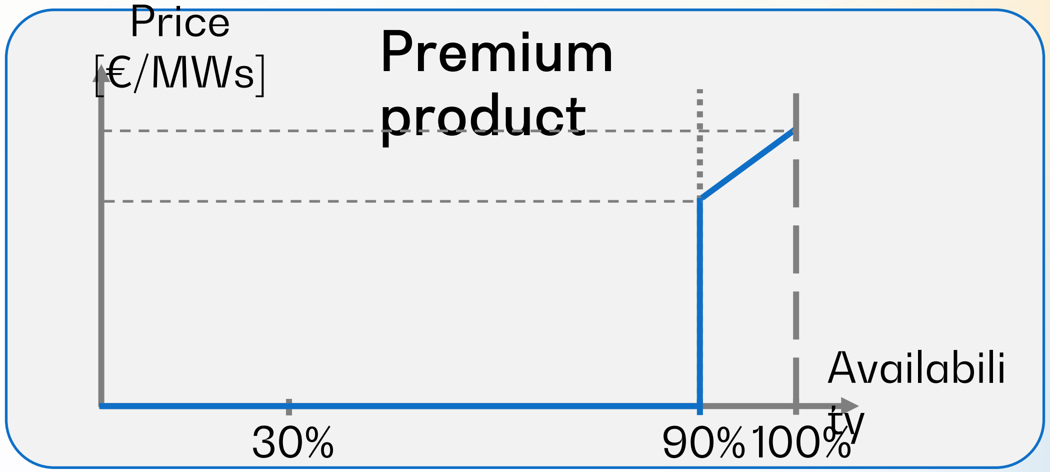
Market Design

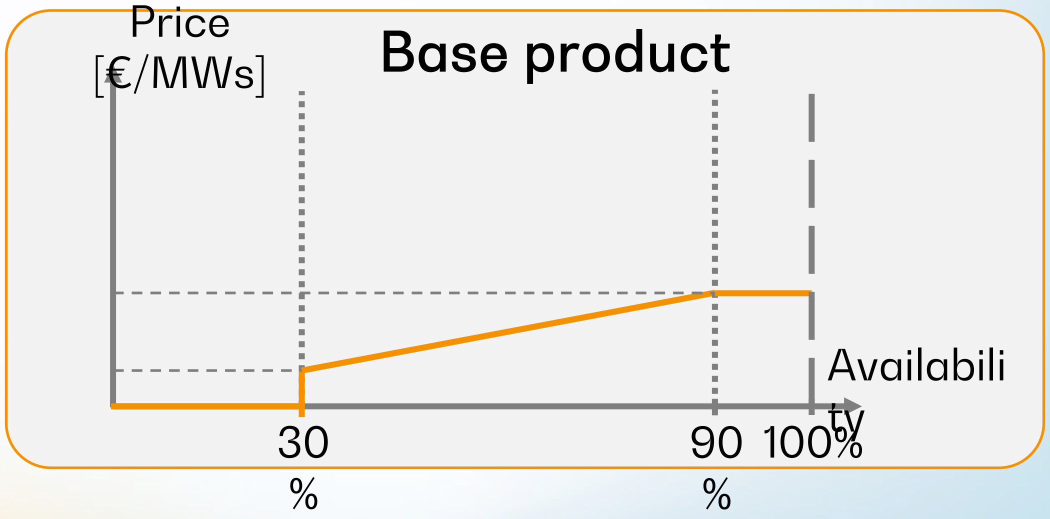
Fixed-price remuneration system will be applied.	Market participants can choose a contract duration of 2-10 years.	A certificate according to VDE FNN requirements to proof technical readiness is necessary.

Market-Based Procurement of Inertia in Germany

- In total **four different inertia products** will be procured.
  - Two different product qualities, distinguished by the **required minimum annual availability** (Base: 30%; Premium: 90%).
  - **Positive and negative** inertia will be procured separately.

- The **annual compensation per asset** will be based on:
  - The initially **offered product** (e.g. positive premium)
  - **Fixed price components** in the corresponding procurement region
  - The **availability** achieved within a settlement





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Energy Policy Manager
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Our mission is to accelerate the world's transition to sustai

Grid-Forming:
The path to a stable and sustainable grid

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Cécile Musialski

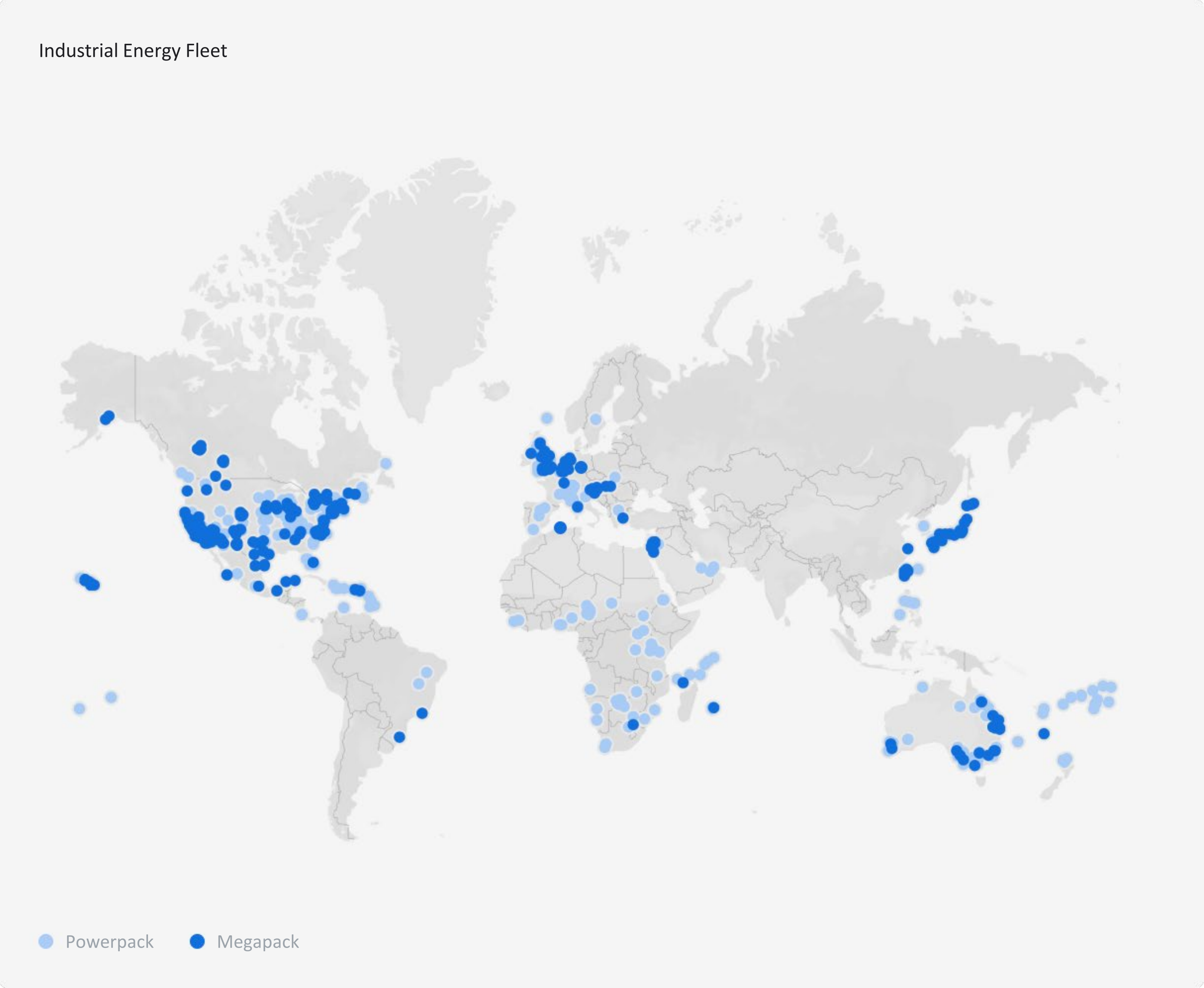
Gigafactory Berlin Brandenburg

>5B

invested

>11K

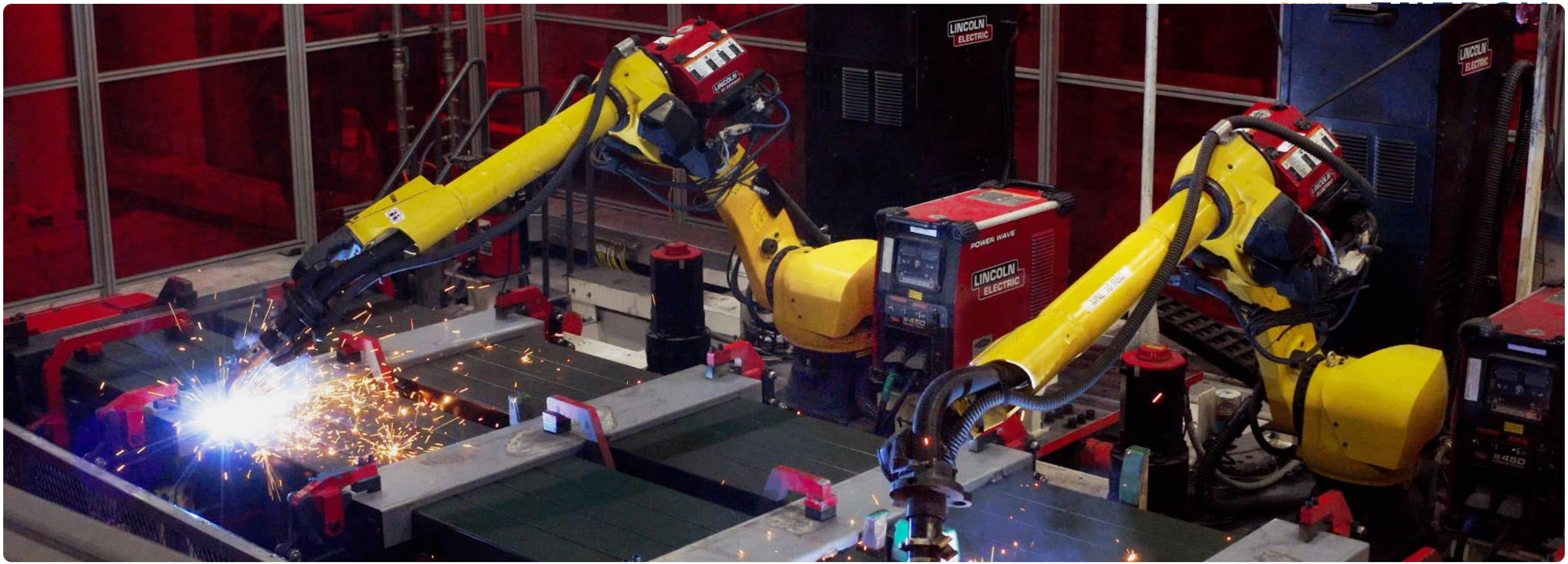
employees dedicated to the manufacturing of Model Y



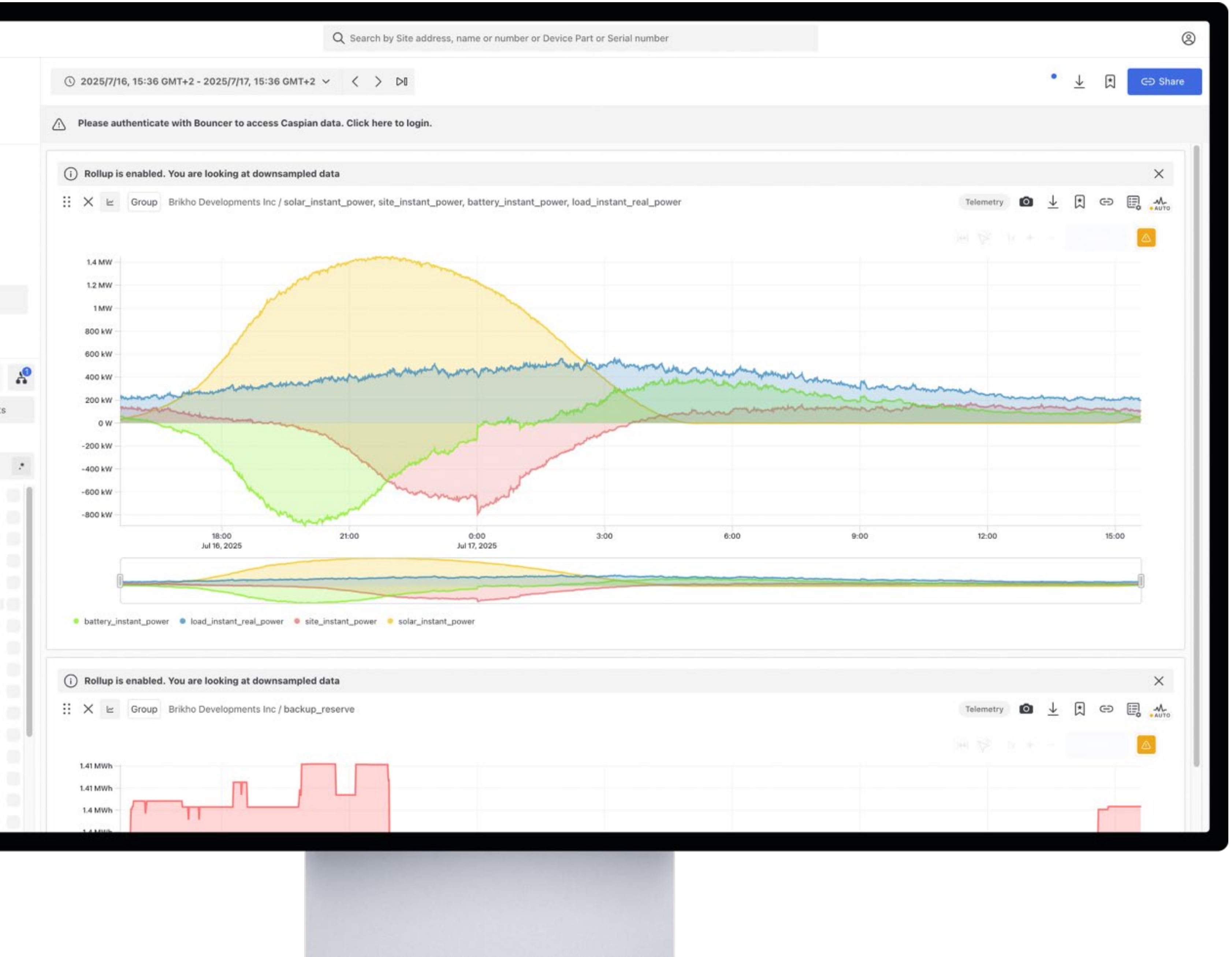
We have >60 GWh of energy storage in the world right now, now, in >65 countries.

Batteries are modular by design.

Any number of individual units can be combined to form a single large plant.



We manufacture our batteries like our cars—
In large volumes, standardized formats, through highly automated processes. This eliminates customization, ensuring fast deployment, at scale.



As with our cars,
our batteries are tunable using software, firmware, algorithms, and AI,
making them an agile energy resource that is ready to meet the grid’s evolving needs.

Batteries are a versatile energy resource, ready to meet the grid's evolving needs along with the increased electrification of society.

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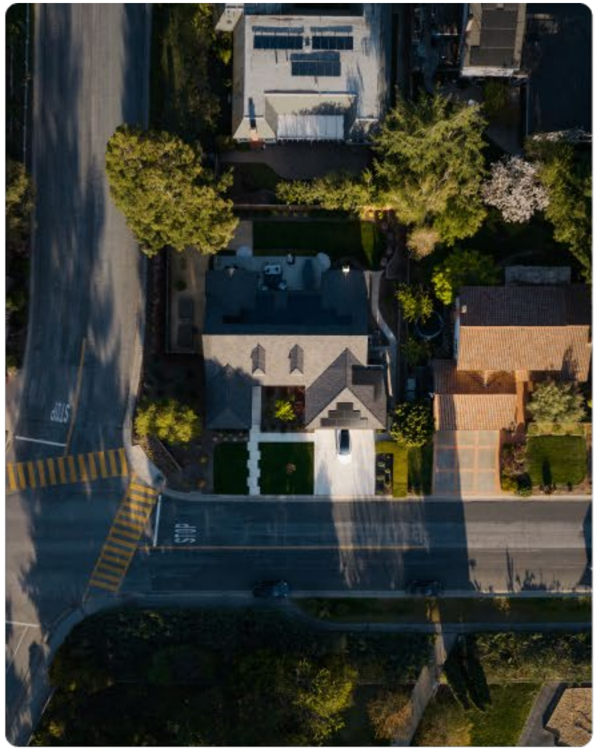
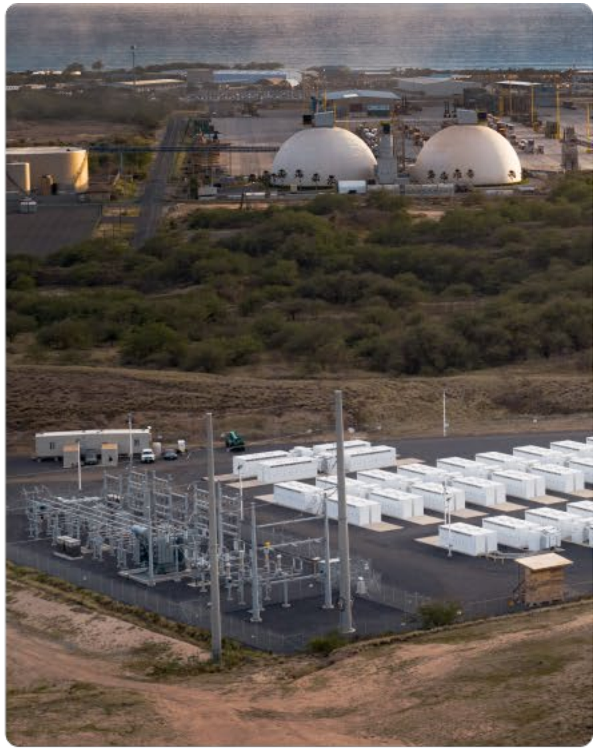
Helping to form the grid

Helping to recover from blackout



Powering homes & businesses

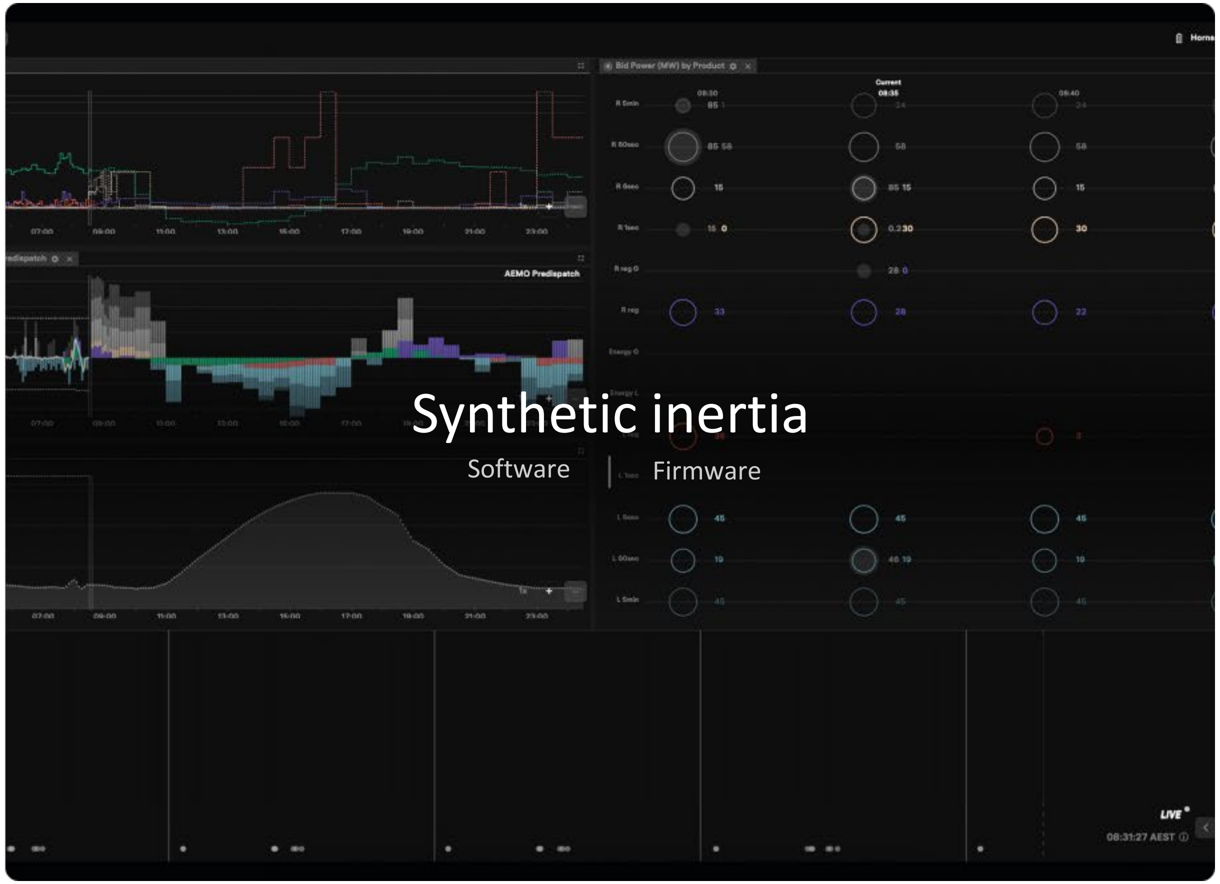


Providing grid services

Traditional generators historically provide inertia through the kinetic energy stored in their rotating mass.

As these traditional generators are phasing out, TSOs are looking for the same stability features elsewhere.

While mechanical, traditional inertia is well understood, TSOs are still defining the process for validating synthetic inertia, sometimes with tentative requirements.



Mechanical inertia is not the only option available to TSOs for securing inertia. Many TSOs are adopting grid-forming batteries, including in Europe.

AEMO – Australian Energy Market Operator

"The inertial response provided by the Hornsdale Power Reserve grid-forming battery is comparable to a typical inertial response provided by a synchronous machine. During a frequency event, the grid-forming battery provided its response to the rate of change of frequency like a synchronous machine."

Source: "Australian Landscape of Grid-Grid-Forming Batteries," ESIG, August 29, August 29, 2023

IEEE

"At about 12:30 p.m. on 14 November 2023, grid-forming inverters rapidly injected power in in less than a second to arrest the the frequency decline… It is safe to to say, and it has been confirmed confirmed through EMT simulation, simulation, that without the two GFM plants, the entire [Kauai, Hawaii] grid would have experienced experienced a blackout."

Source: "Grid-Forming Electric Inverters Inverters Unleash Renewable Energy", Energy", IEEE Spectrum, April 14, 2024

ercot – Your Power. Our Promise.

"New inverter-based energy storage storage resources will be required to required to provide advanced grid grid support… inverter-based energy energy storage resources are commercially available today to provide advanced grid support…ERCOT's preliminary assessments have identified the improvement of system stability performance and the benefits to the generic transmission transmission constraints."

Source: "Advanced Grid Support Inverter-Inverter-based Energy Storage System Assessment and Adoption Adoption Discussion," ERCOT, July 12, 12, 2024

EIRGRID

"Grid-forming inverters are a critical critical enabler for operating a low-low-inertia system securely… The The ability of batteries to provide provide synthetic inertia ensures we ensures we can maintain frequency frequency stability even as synchronous generation decreases." decreases."

Source: "Delivering a Secure Sustainable Sustainable Electricity System (DS3 Programme)," EirGrid Group, 2022 Annual Report

NESO

"Through our trials, grid-forming batteries have shown they can deliver inertia at a fraction of the time it takes synchronous machines, paving the way for a more resilient and renewable-led energy system."

Source: "System Stability: The Role of Grid-Forming Technology," National Grid ESO webinar transcript, June 2022

Hawaiian Electric

"It's the first time a battery has been used by a major utility to balance the grid: providing fast frequency response, synthetic inertia, and black start. This project is a postcard from the future — batteries will soon be providing these services, at scale, on the mainland."

Source: "Hawaii home to 'world's most advanced grid-scale battery'", Energy Source & Distribution, January 17, 2024

Tesla has a proven track-record of preventing blackouts with its grid-forming batteries

by arresting sudden frequency drop in a <5 millisecond response.

On February 9, 2024, 11 a.m., the tripping of a 208 MW generator on the Oahu grid, Hawaii, would have resulted in grid failure if unaddressed.

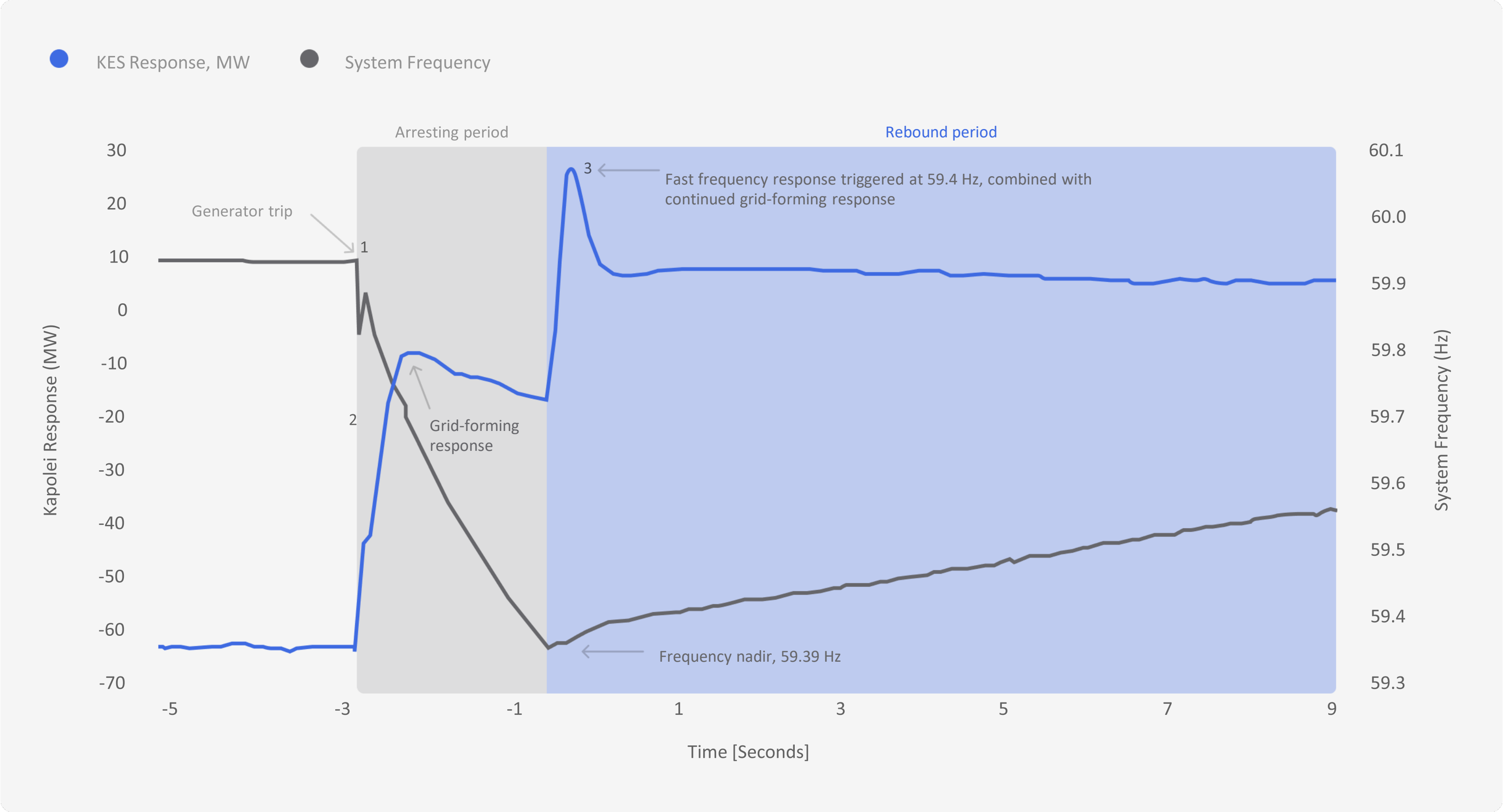
Hawaiian Electric dispatched the Kapolei Energy Storage as a backup, which triggered a grid-forming response.

Inertia from Tesla's grid-forming battery instantly and autonomously injected 50 MW of power to arrest the decline in frequency following the generator trip (battery's grid-forming response < 5 ms).

Once the frequency reached 59.4 Hz, the battery's Fast Frequency Response was activated and injected additional power within 250 msec, allowing the frequency to rebound.

This case study serves as a model for other regions with high penetration of variable renewable generation, demonstrating how advanced energy storage technology can improve grid reliability, and accelerate the transition to a sustainable energy future.

Source: Plus Power



01

208 MW generator trips

02

Battery's grid-forming response <5 milliseconds

03

Battery's Fast Frequency Response <250 <250 milliseconds

As TSOs are less familiar with synthetic inertia than with mechanical, traditional inertia,
grid-forming battery OEMs can team-up to accelerate grid-forming batteries validation.

Policymakers can help overcome TSOs' hesitations about synthetic inertia by providing providing political support and a supporting framework for deploying net-zero grid-forming batteries. forming batteries.

Traditional generators

- Multi-purpose purpose
- More value for money
- Not net-zero (hydro & nuclear excepted)
- Custom built on site site

Synchronous condensers

- Single purpose (inertia) (inertia)
- Less value for money money
- Net-zero
- Slow deployment

Grid-forming batteries

- Multi-purpose, agile
- More value for money
- Net-zero
- Modular, fast deployment

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Grid-Forming: The path to a stable and sustainable future
future