



KUBECON + CLOUDNATIVECON EUROPE 2026

Virtual Power Plants

Cloud-Native Infrastructure for the Energy Grid



Enpal

Building Europe's Largest Virtual Power Plant

Agenda

- | | | |
|----|--|---------|
| 01 | The Grid
How the world's largest machine works — and how it fails | ~10 min |
| 02 | The Renewable Revolution
Why cheap clean energy creates expensive new problems | ~7 min |
| 03 | The Virtual Power Plant
Software that turns millions of devices into grid infrastructure | ~10 min |
| 04 | Resilience
What the future grid looks like — and why you already know how to build it | ~3 min |

PART I

The Grid

The world's largest machine — and why it keeps failing

RESET

▶ STORM URI



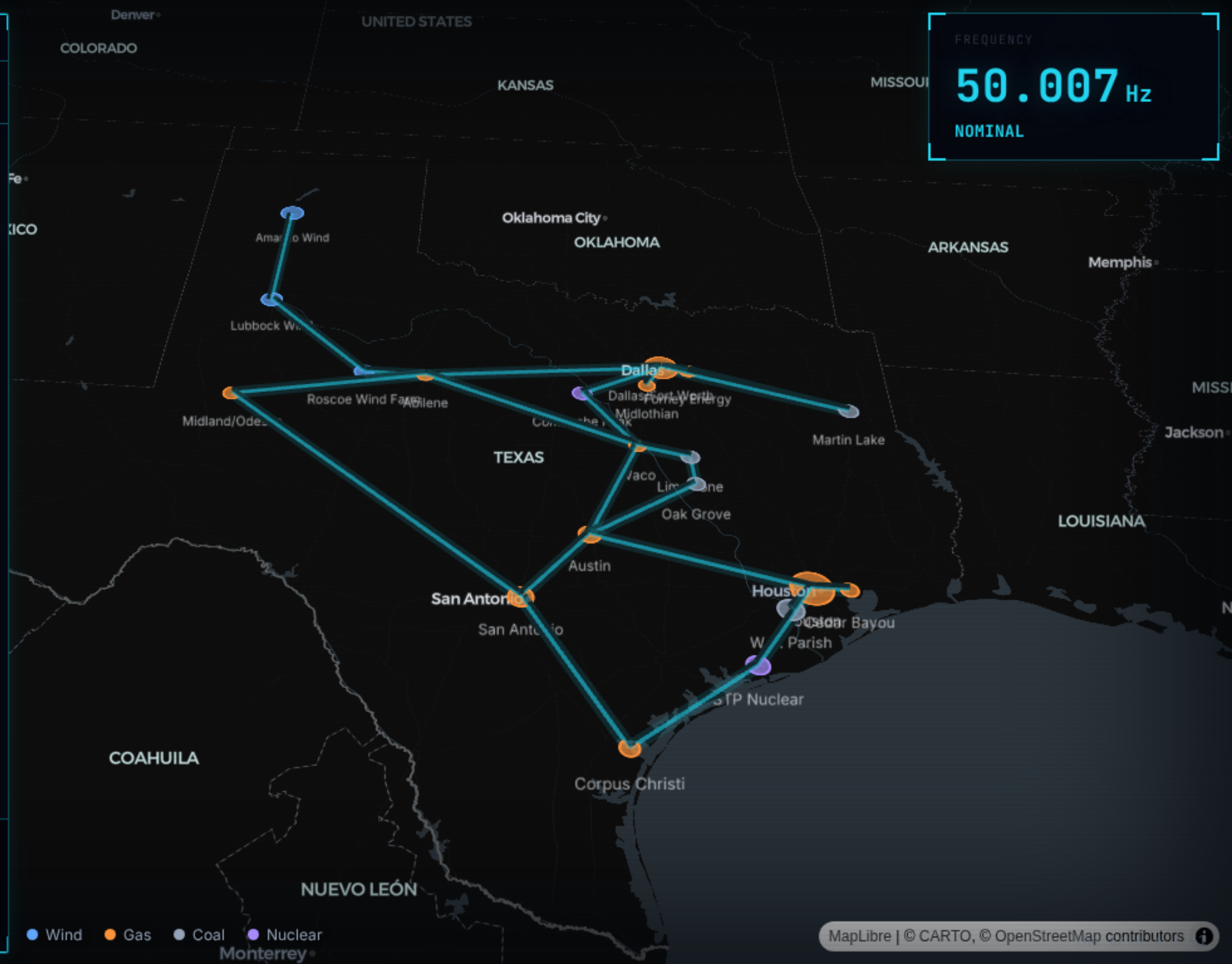
SYSTEM LOG

> ERCOT GRID MONITOR v2.1 INIT...

FREQUENCY

50.007 Hz

NOMINAL



● Wind ● Gas ● Coal ● Nuclear

Monterrey



"The Texas grid was **4 minutes and 37 seconds** from total collapse."

A cold restart would have taken weeks. Maybe months.

4:37

FROM TOTAL COLLAPSE

246

PEOPLE DEAD

\$195B

IN DAMAGE

4.5M

HOMES DARK

Wholesale electricity spiked to **\$9,000/MWh** — a **180x** increase.

Families received **\$7,000 bills** in a single week. Their provider — Griddy — went bankrupt.

How did the most energy-rich state in America come this close to total infrastructure failure?

Running the Largest Machine

50 Hz

synchronized frequency

305,000 km

transmission lines

400,000,000

connected consumers

1,100 GW

installed capacity

3,000 TWh

annual production

Running the Largest Machine

60,000
WORKERS

World's Largest Factory



50 Hz

synchronized frequency

305,000 km

transmission lines

400,000,000

connected consumers

1,100 GW

installed capacity

3,000 TWh

annual production

Running the Largest Machine

728,627
WORKERS



50 Hz

synchronized frequency

305,000 km

transmission lines

400,000,000

connected consumers

1,100 GW

installed capacity

3,000 TWh

annual production

Running the Largest Machine

2,300,000
WORKERS

European Power Grid

0

ZERO DOWNTIME

This machine has never been shut down.

50 Hz

synchronized frequency

305,000 km

transmission lines

400,000,000

connected consumers

1,100 GW

installed capacity

3,000 TWh

annual production

STEP 1 / 5

Generation

A power plant near Munich, Bavaria

10-25 kV

Fuel → heat → steam → turbine → 50
Hz alternating current

50.005 Hz

MUNICH
Power Plant

• Wind • Gas • Nuclear • Hydro • Solar • Coal

STEP 2 / 5

Step-Up & Transmission

Voltage multiplied 20× for long-distance transport

220-400 kV

Transformers step up voltage to minimize losses across hundreds of km

• Wind • Gas • Nuclear • Hydro • Solar • Coal



STEP 3 / 5

Regional Grid

5 major hubs connected across
Southern Germany & Alps

110-400 kV

Multiple generation sources — gas,
solar, hydro, nuclear — feed the
regional network

49.996 Hz

• Wind • Gas • Nuclear • Hydro • Solar • Coal

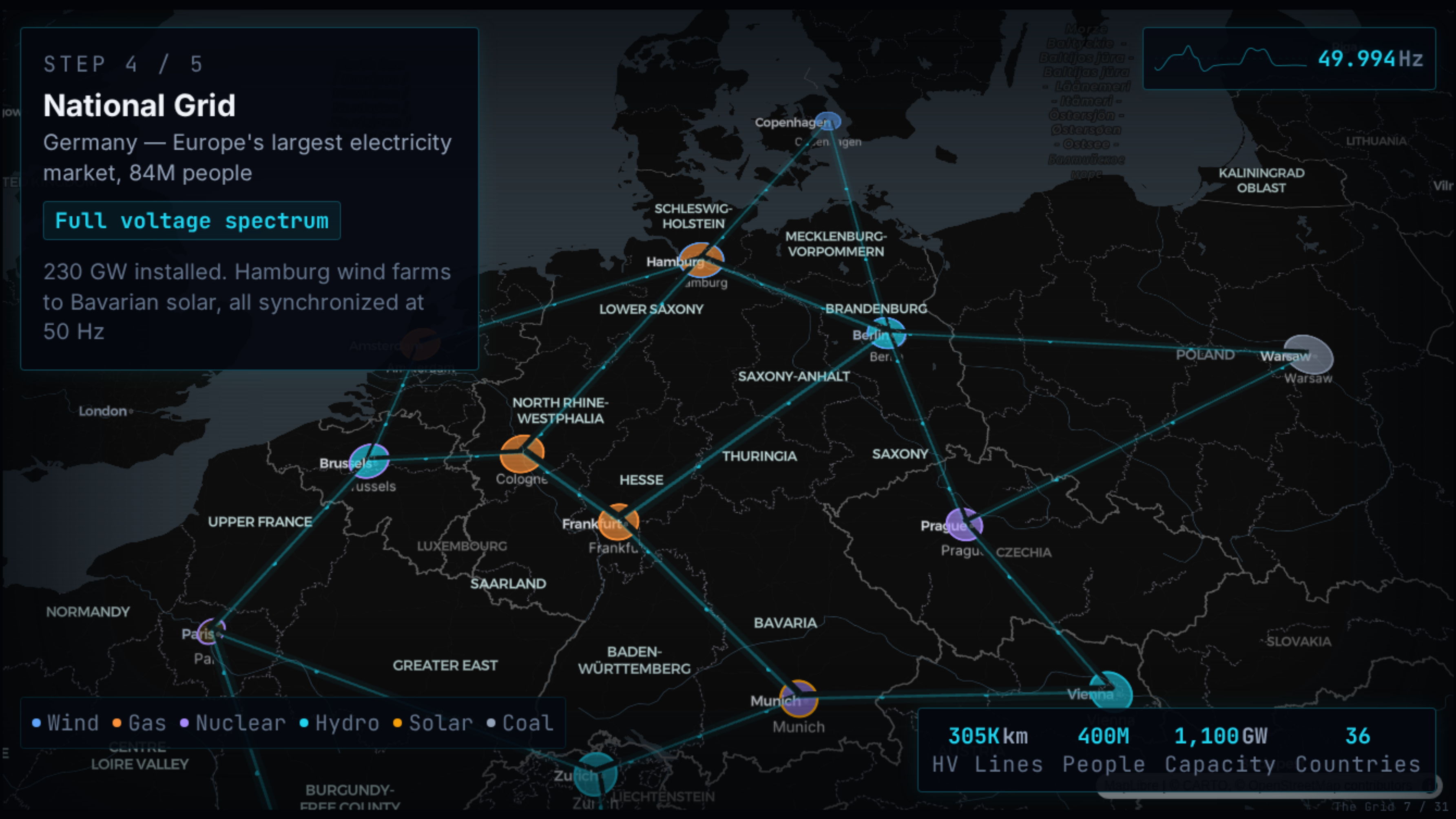
STEP 4 / 5

National Grid

Germany — Europe's largest electricity market, 84M people

Full voltage spectrum

230 GW installed. Hamburg wind farms to Bavarian solar, all synchronized at 50 Hz



- Wind
- Gas
- Nuclear
- Hydro
- Solar
- Coal

305K km	400M	1,100 GW	36
HV Lines	People	Capacity	Countries

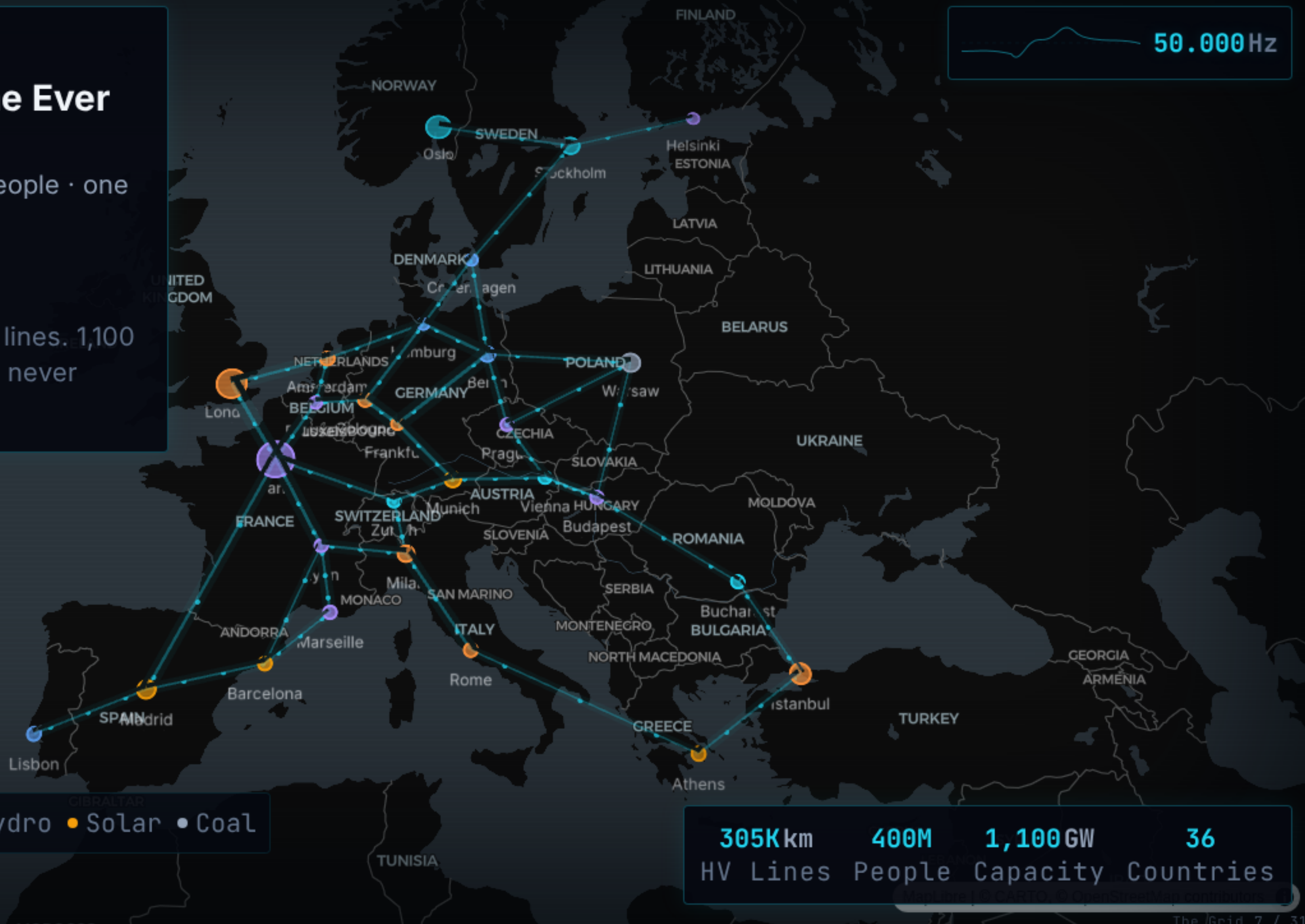
STEP 5 / 5

The Largest Machine Ever Built

36 countries · 400 million people · one frequency

50.000 Hz

305,000 km of high-voltage lines. 1,100 GW installed capacity. It has never been turned off.



• Wind • Gas • Nuclear • Hydro • Solar • Coal

305K km 400M 1,100 GW 36
HV Lines People Capacity Countries

Map data © CARTO © OpenStreetMap contributors

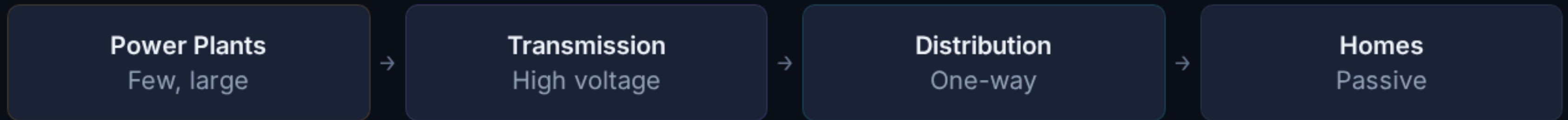
The Grid: A Balancing Act

This enormous machine maintains a constant 50 Hz frequency — supply and demand balanced every second. Click an event to simulate what happens when something goes wrong.



The entire European grid operates within a **±0.2 Hz** band. Cross those thresholds and automated protection systems start disconnecting load or generators.

Designed for a Different World



"Built in the 1950s. One-directional. No flexibility."

The Old Playbook

Before batteries and software, this is how the grid stayed stable. Expensive, dirty, and blunt.

Peaker Plants

261 GW of gas turbines in the US alone — sitting idle 95% of the year. They fire up for peak demand at 2–5x the cost of baseload.

\$110–228/MWh

Spinning Reserves

Generators running at partial load 24/7 "just in case." 15% capacity margin required. Burning fuel to produce nothing.

15% over-provisioned

Load Shedding

The last resort: deliberate rolling blackouts. Texas 2021 shed 20 GW — the largest in US history. The crisis cost ERCOT customers \$52.6B in excess charges.

\$52.6B in 5 days

Curtailement

Too much sun or wind? Turn it off. Germany wasted 19 TWh of clean energy in 2023. California curtailed 3.4 TWh in 2024.

EUR 3.3B/yr (DE)

"261 GW of capacity that runs 5% of the year. Rolling blackouts as policy. Clean energy thrown away. This is the toolkit we inherited."

Why Texas Failed

The gas-electric death spiral — a cascading feedback loop.

- 1 Extreme cold hits Texas
- 2 Generators freeze and trip offline
- 3 ERCOT orders emergency load shedding
- 4 Load shedding cuts power to gas compressors & pipelines
- 5 Gas supply drops — more generators lose fuel and trip
- 🔄 More load shedding needed — cycle accelerates

52 GW

offline (of 107 GW total)

Isolated

no grid interconnection

42 hrs

average outage duration

Not an Isolated Incident

2003 Northeast US/Canada
55M people, \$6B in damage

2003 Italy Blackout
56M people

2006 European Grid Split
15M affected

2016 South Australia (tornadoes)
Entire state, 1.7M people

2017 South Australia (heatwave)
90K homes, 45°C day

2021 Texas ERCOT
4.5M homes, 240+ deaths

2021 Europe Grid Split
1.25 Hz from collapse

2025 Spain/Portugal
60M people

2025 Berlin Arson (x3)
45K+ homes

2026 Berlin Teltow Canal
4-day outage

Every one of these failures shares one root cause:

No flexibility.

Now imagine adding the most variable energy source in history.

Demand Response in Action

Still in Infancy

Instead of building more power plants — reshape the demand. Trip a generator and watch what happens.



Note: Current deployment is extremely limited. Focus on the challenges — most grids have no demand-side flexibility at scale today.

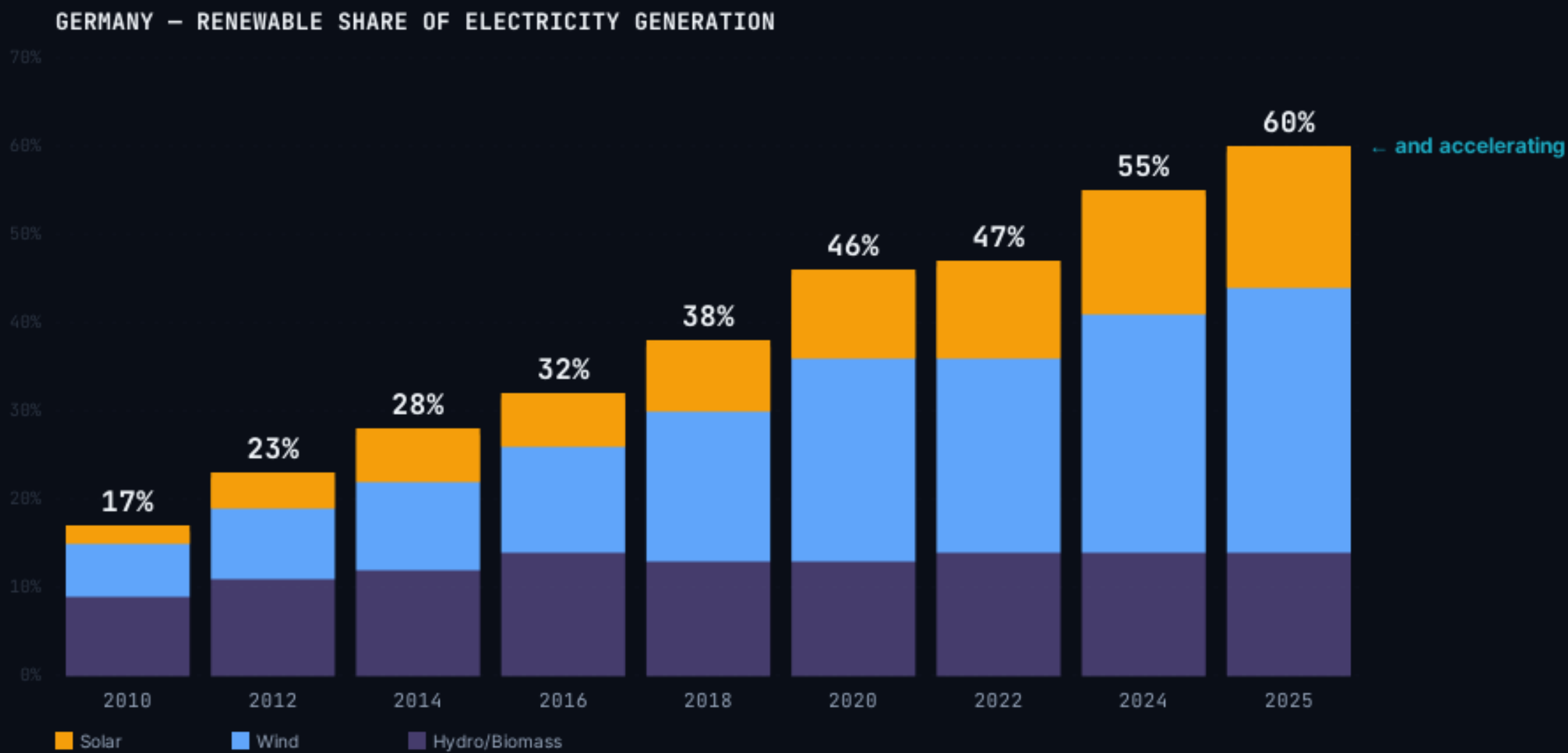
PART II

The Renewable Revolution

Inevitable, amazing — and a whole new kind of problem

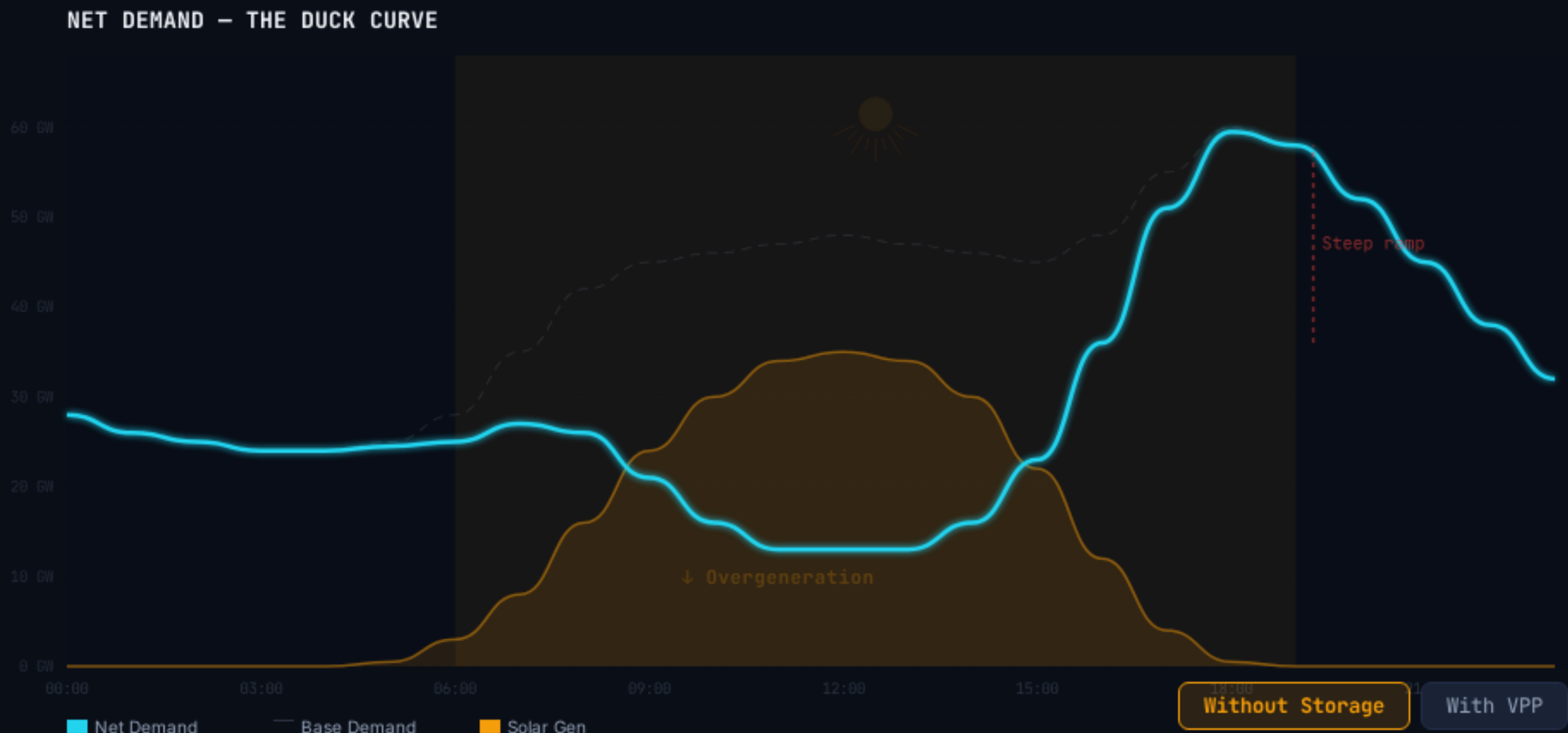
The Renewable Explosion

Germany's electricity from renewables — this is not slowing down.



The Duck Curve Problem

Solar floods the grid midday. Demand ramps steeply at sunset. The grid can't cope.



Clean Energy Has Outgrown the Grid

Germany paid generators **EUR 554 million** to *not* produce electricity in 2024.

9.3 TWh

Renewable energy curtailed (2024)

+97%

Solar curtailment increase YoY

2.7M

Homes that energy could have powered

Not just a transmission problem

49% of grid congestion measures are at the **local distribution level** — rooftop solar overwhelming neighborhood transformers. New long-distance cables don't fix this.

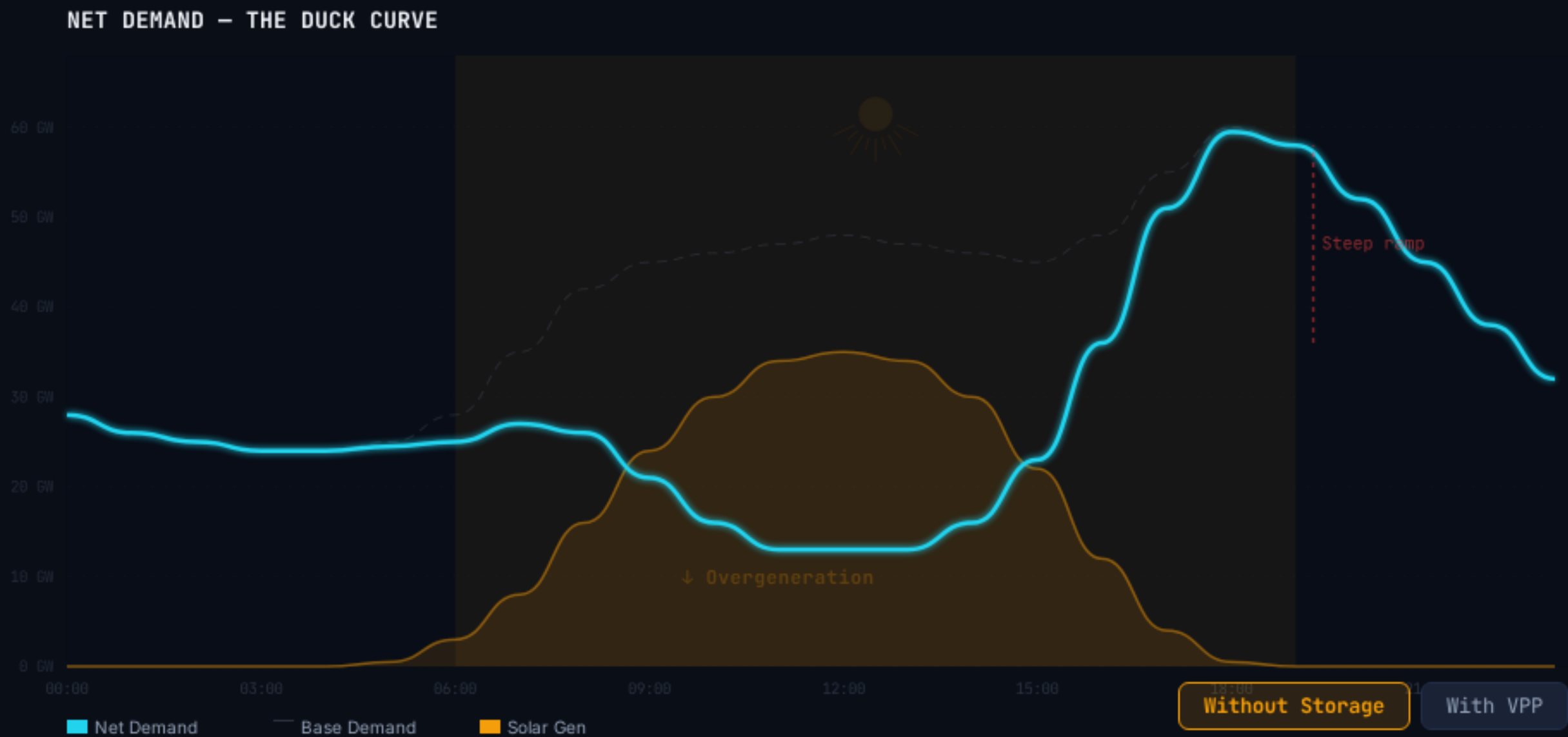
The missing buyer

When a wind farm is curtailed, there is no local demand to absorb the excess. A VPP could charge batteries, pre-heat buildings, and shift EV charging — **becoming the buyer of last resort.**

Germany — Bundesnetzagentur 2024 data. North-south transmission bottlenecks (SuedLink delayed to 2028) account for the other 51%.

What If You Could Shift the Load?

Batteries absorb midday solar. Discharge in the evening. Click "With VPP" below.



The Impact of Flexibility

Flexible demand doesn't just stabilize the grid — it makes electricity dramatically cheaper.

RMI – Power Shift (Texas / ERCOT, modeled)

Full demand flexibility cuts net generation costs by **20%**
Saves **\$140/household/year** with just 2 flexible devices
Avoids **75%** of new gas peaker units

Brattle Group – National US (projected)

60 GW of VPPs save **\$15–35B** over 10 years
Household bills **down up to 20%** (Australia ISP 2024)
Home batteries avoid **\$4.1B** in grid investment

20%

Generation cost reduction at full flexibility

\$10–15B/yr

US grid savings from 2 flexible devices per home

8%

Peak demand reduction from smart thermostats + water heaters

"The cheapest megawatt is the one you never have to generate."

Consumers Become Infrastructure

Homes with solar and batteries can **charge**, **export**, and **shift consumption**.

Your roof becomes a power plant.

Your garage becomes a grid asset.

Your house becomes a node in the largest distributed system ever built.

But coordinating millions of these devices? That's a distributed systems problem.

PART III

The Virtual Power Plant

Software that turns distributed energy into grid infrastructure

The Architecture Parallel

Few large generators, centralized dispatch

VS

Millions of edge nodes, distributed

Manual capacity planning

VS

Horizontal autoscaling

Isolated resilience (relays, islanding)

VS

Integrated resilience (coordinated)

Centralized observability (SCADA)

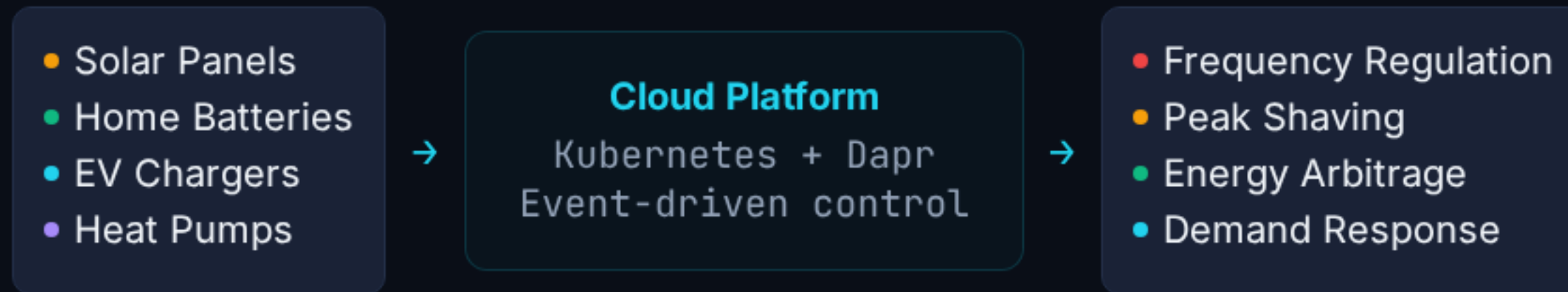
VS

Full-stack observability (per-device)

Frequency = SL0 • Cascade = failure propagation • Batteries = autoscaling

What Is a Virtual Power Plant?

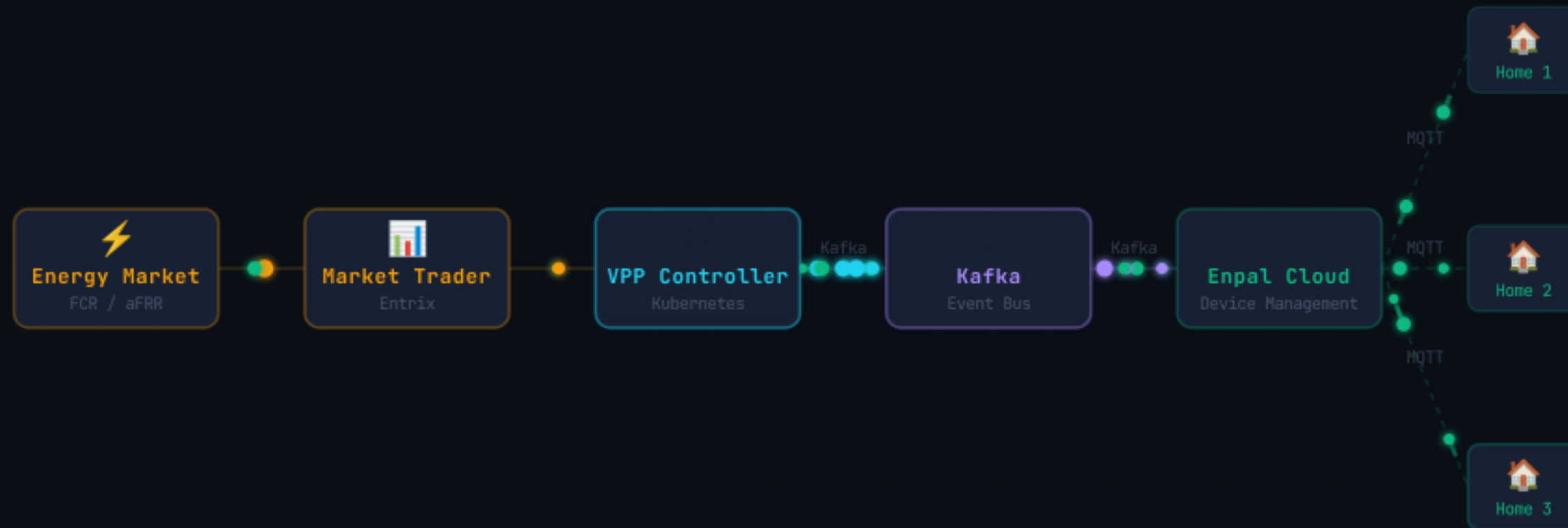
Software that **aggregates** distributed energy resources and **operates** them as a coordinated power plant.

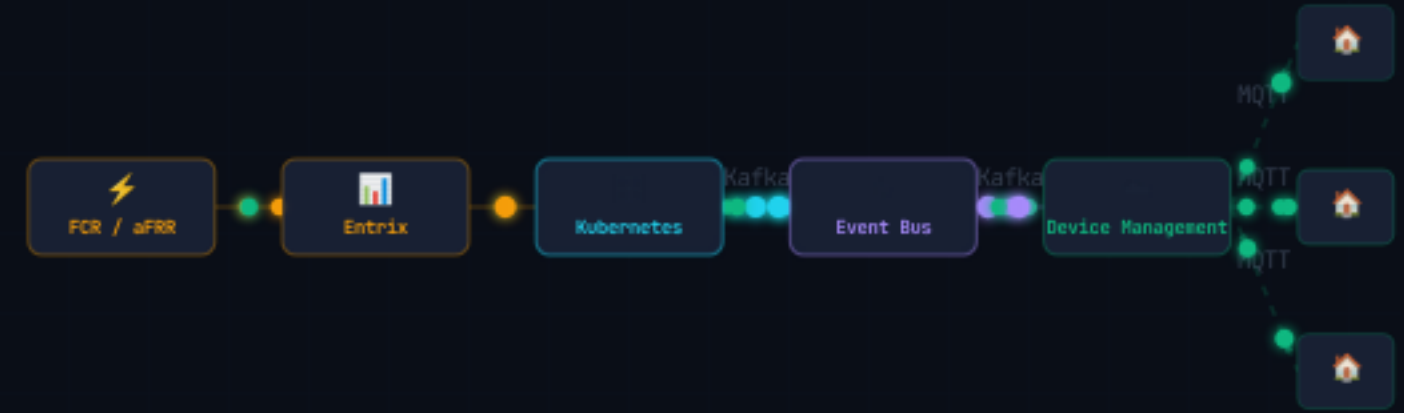


How It Works

COMMANDS →

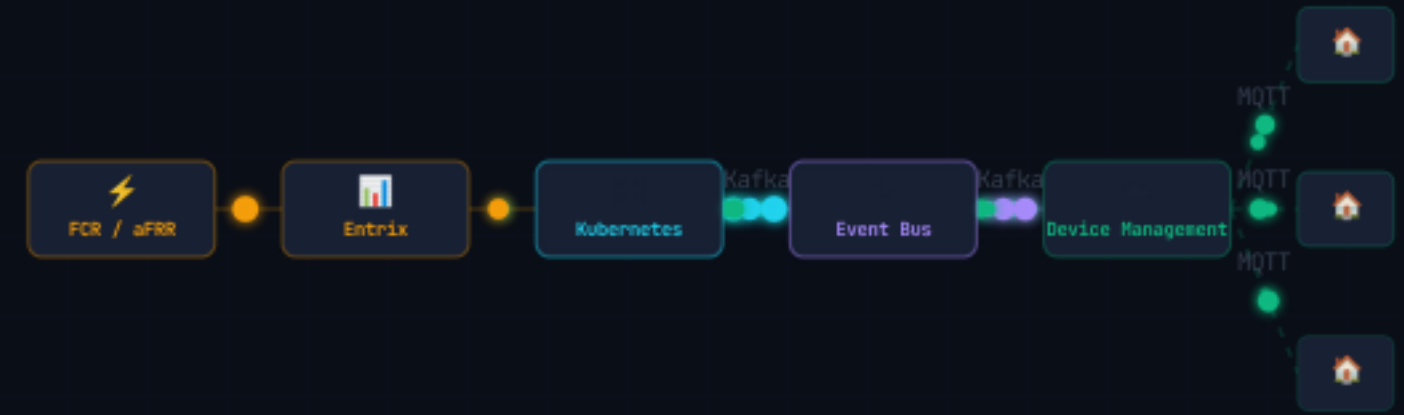
← TELEMETRY





The Architecture Parallel

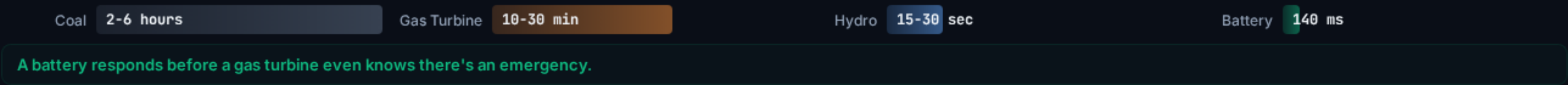
Few large generators, centralized dispatch	vs	Millions of edge nodes, distributed
Manual capacity planning	vs	Horizontal autoscaling
Isolated resilience (relays, islanding)	vs	Integrated resilience (coordinated)
Centralized observability (SCADA)	vs	Full-stack observability (per-device)



The Architecture Parallel

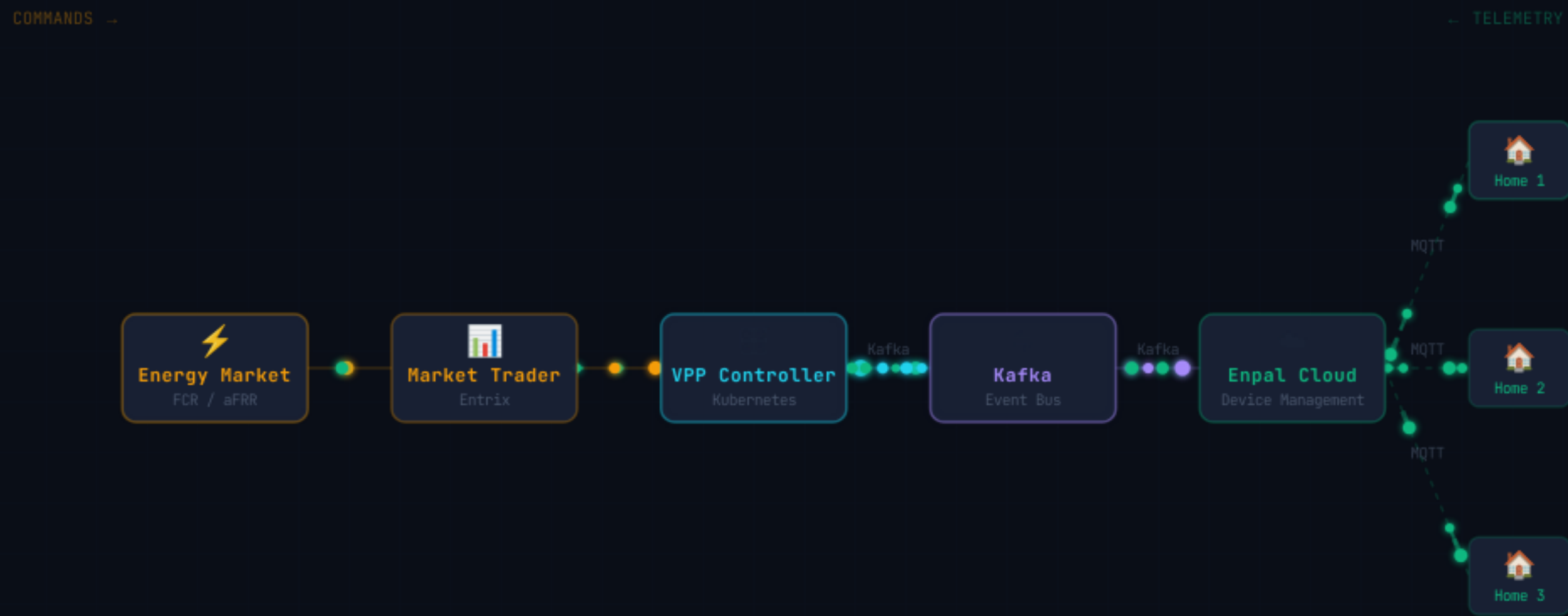
Few large generators, centralized dispatch	vs	Millions of edge nodes, distributed
Manual capacity planning	vs	Horizontal autoscaling
Isolated resilience (relays, islanding)	vs	Integrated resilience (coordinated)
Centralized observability (SCADA)	vs	Full-stack observability (per-device)

The Fastest Power Plant

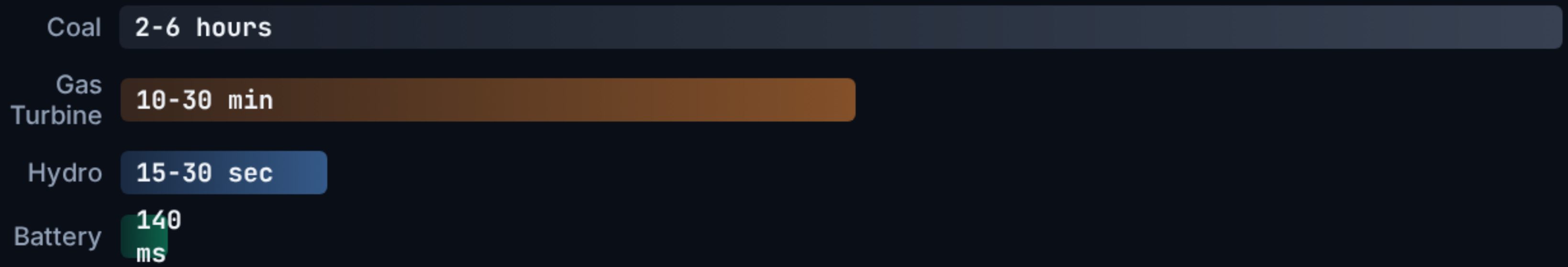


How It Works

From market signal to battery response — the command flow through our VPP architecture.



The Fastest Power Plant



A battery responds before a gas turbine even knows there's an emergency.

PROOF

SA Virtual Power Plant, 2019

748 MW coal plant trips. 1,100 homes respond autonomously.

1,100

Homes Responded

2%

of Planned Fleet

0

Humans Involved

Eleven hundred homes. Acting as one. **Without anyone pushing a button.**

BACK TO TEXAS

Remember those 4 minutes and 37 seconds?

With 10 GW of distributed batteries responding in 140 milliseconds, there is no cascade.

The frequency never drops. The gas plants never need to save you.

Because 1 million homes already did.

Thank You

Enpal — Building Europe's Largest Virtual Power Plant

The Dunkelflaute

Dark doldrums — when wind and solar collapse simultaneously. High pressure brings still air and overcast skies.

GERMANY — NOV 2024

Wind installed: **72.75 GW**

Wind output during event: **2.8 GW (3.8%)**

Solar contribution: **4.3%** vs ~25% summer

Renewables total: **30%** (vs normal 50%+)

DURATION

14 consecutive days below 10% of installed renewable capacity

PRICE IMPACT

Prices spiked to **EUR 175/MWh** — 4x the average

FREQUENCY

Occurs **2–10 times per year**, lasting 50–150 hours/month in winter

"You cannot go 100% renewable without storage and flexibility."