Summer SCHOOL 2023 FROM 2 TO 7 JULY Prapoutel, French Alps

# Lecture of RD20 Summer school

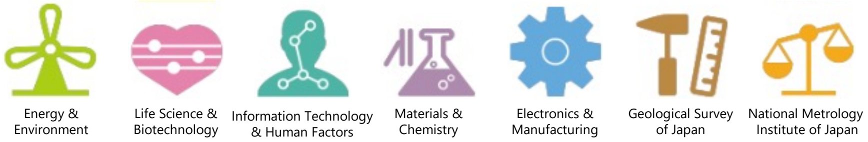
# Power System and Smart Grid: Enabling Sustainability

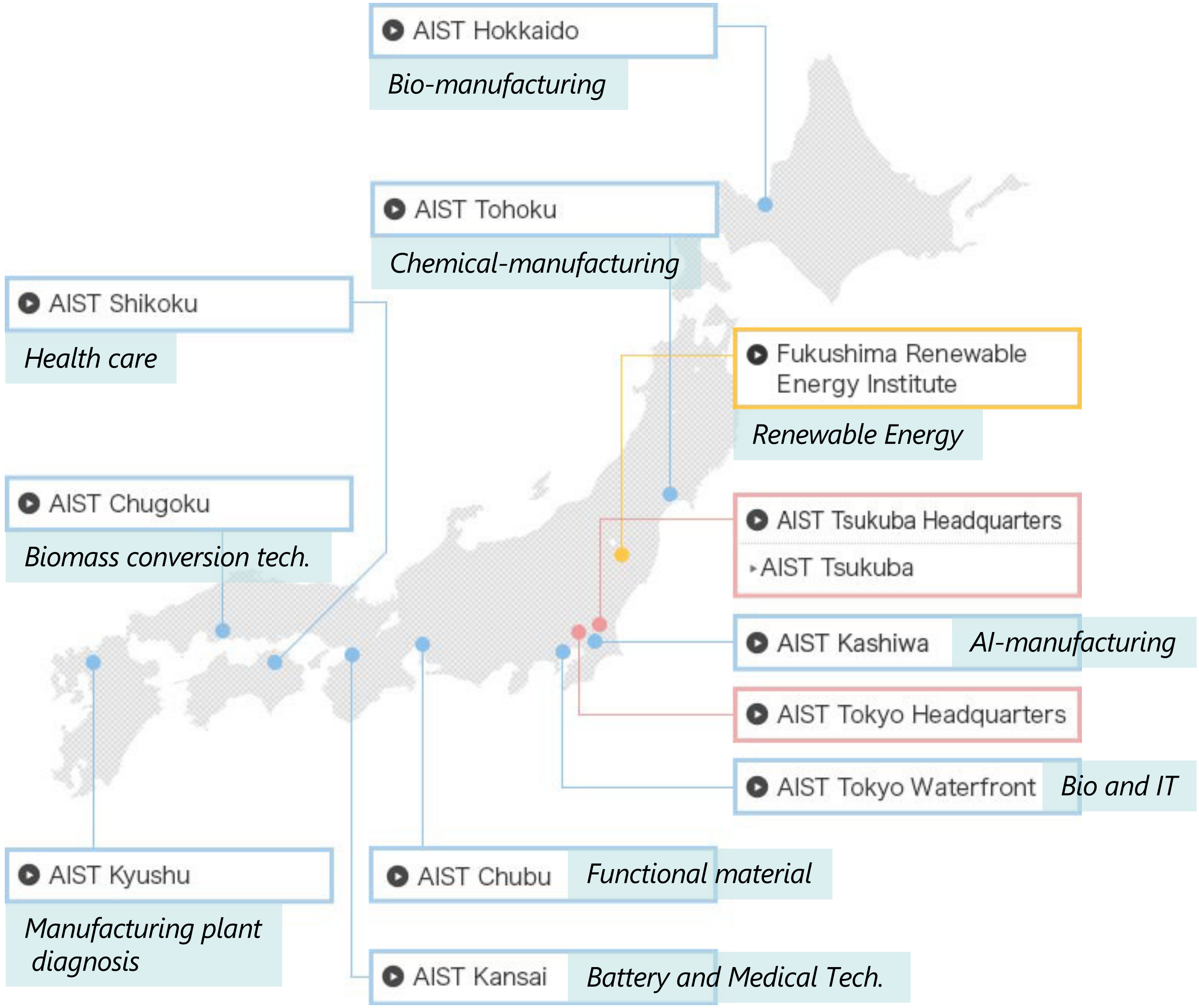
RD20 Summer School
@Prapoutel, France
July 7, 2023

Hiroshi KIKUSATO
AIST, Japan

# AIST (National Institute of **A**dvanced **I**ndustrial **S**cience and **T**echnology)

- Established in 2001 by reorganizing 16 institutes under METI
- Total income: 110 billion JPY
  - 90%: Government, 10%: Industry
- 2901 employees (as of July. 2022)
  - 2214 researchers
  - 687 administrative employees
  - + executives, visiting researchers, postdocs, technical staff
- 7 research departments

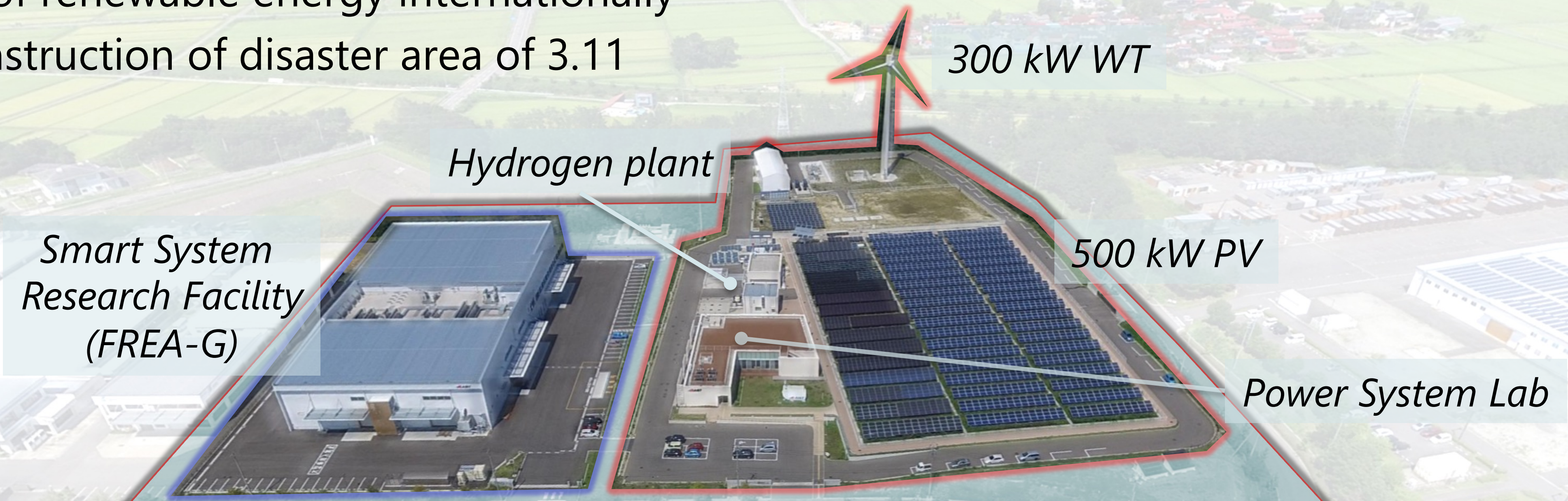



Source: AIST, JP) https://www.aist.go.jp/ , EN) https://www.aist.go.jp/index_en.html

# FREA (**F**ukushima **R**enewable **E**nergy Institute, **A**IST)

- Established in Koriyama, Fukushima in 2014 for promoting
  - R&D of renewable energy internationally
  - Reconstruction of disaster area of 3.11




- Has over 200 researchers in 9 research teams

***Energy Network*** | *Hydrogen* | *Photovoltaic* | *Wind Power* | *Geothermal* | *Shallow Geothermal*

Source: FREA https://www.aist.go.jp/fukushima/

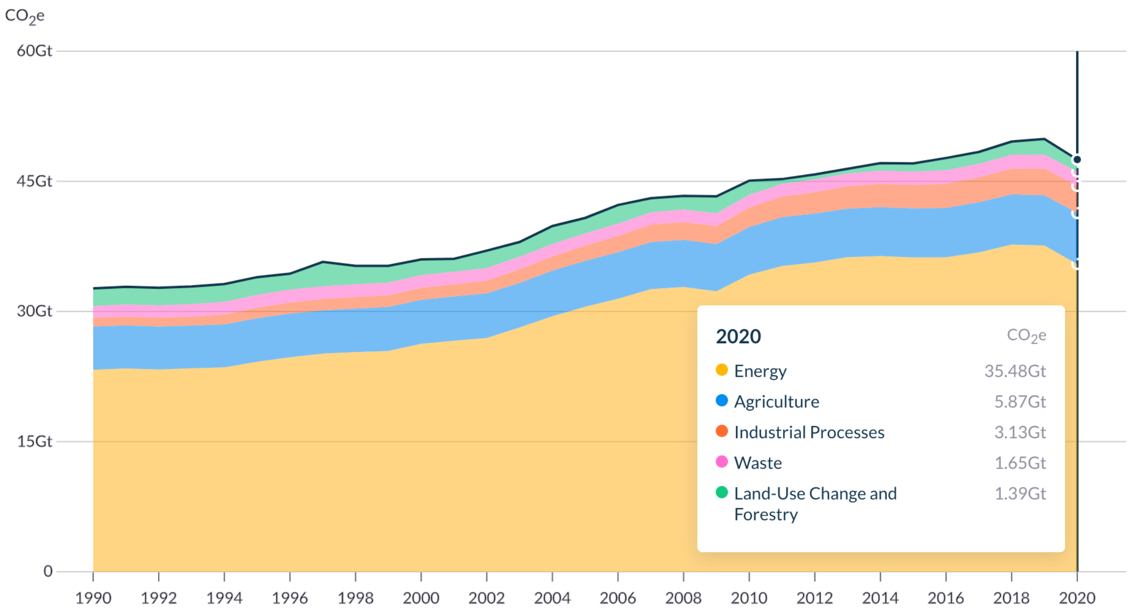
# Table of contents

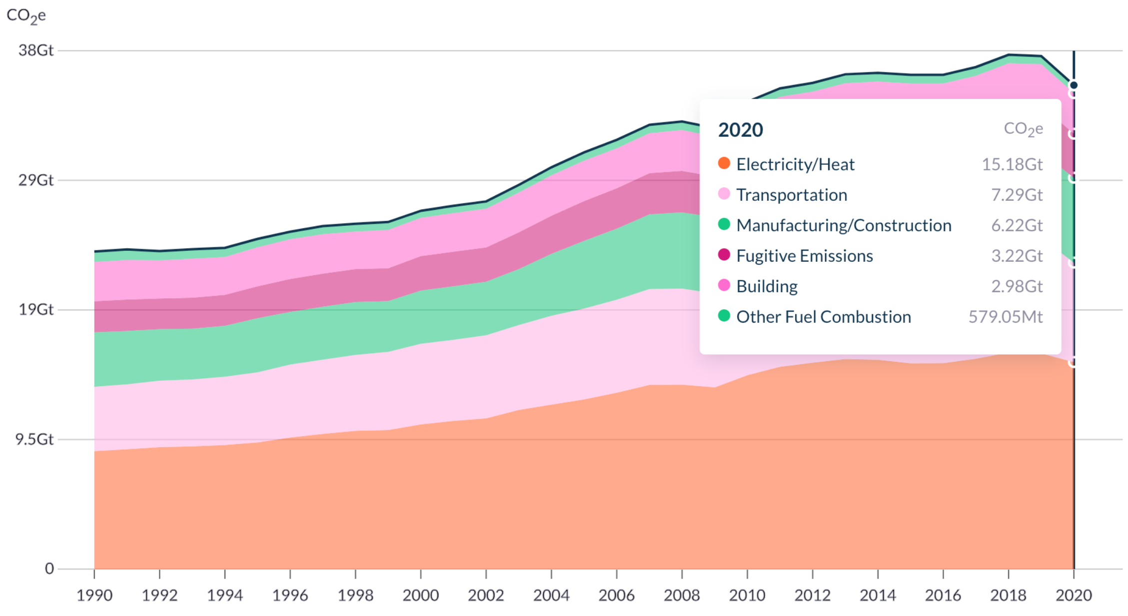
# Background

AIST FREA

# About 1/3 of GHG emissions come from the electricity/heat sector

- Energy sector accounts for 74.7% of total
- Electricity/heat sector accounts for 42.9% of Energy sector



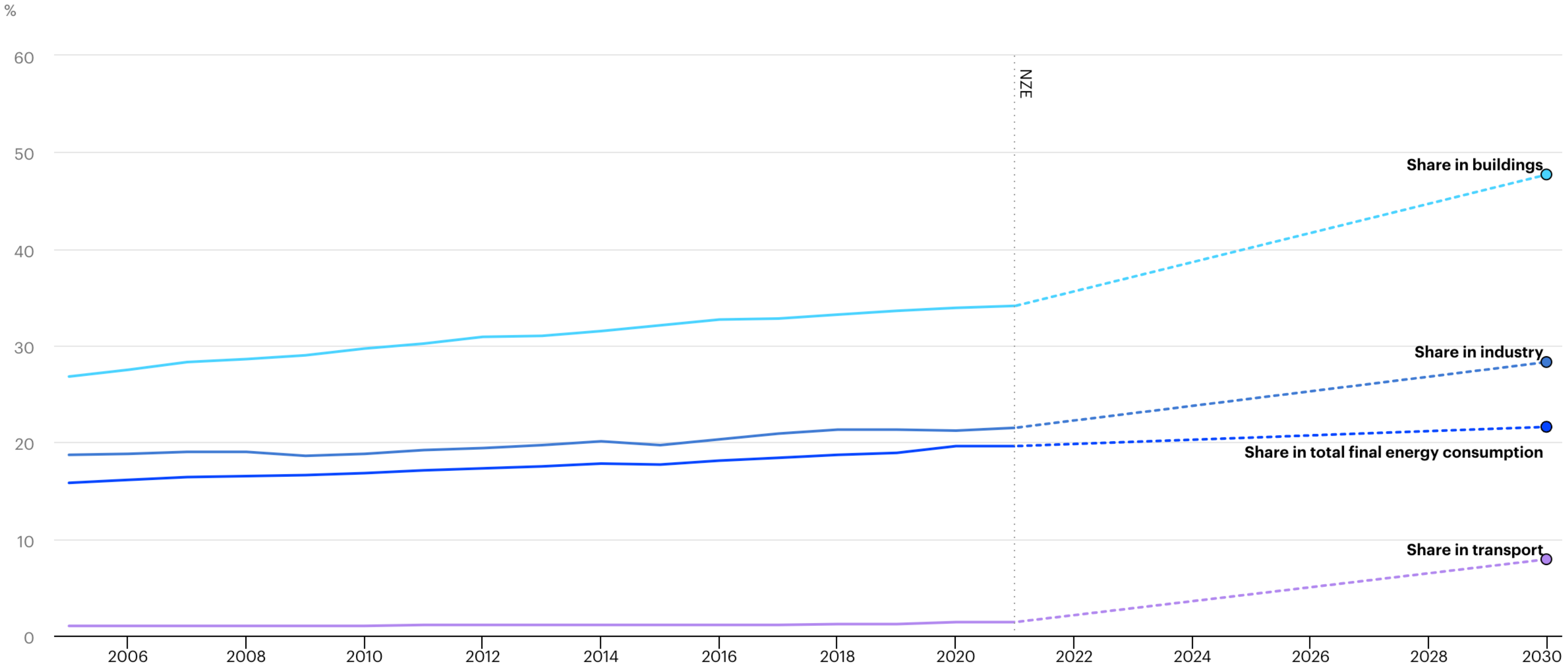




**Significant room for reduction**

Source: Climate Watch, Historical GHG Emissions
https://www.climatewatchdata.org/ghg-emissions?breakBy=sector&chartType=area&end_year=2020&sectors=total-excluding-lucf&start_year=1990
https://www.climatewatchdata.org/ghg-emissions?breakBy=sector&chartType=area&end_year=2020&sectors=building%2Celectricity-heat%2Cfugitive-emissions%2Cmanufacturing-construction%2Cother-fuel-combustion%2Ctransportation&start_year=1990

# Electrification is important strategy to reach net zero goals

- To get on track with the Net Zero Scenario, the share of electricity in energy demand will need to increase by around 3.5% per year

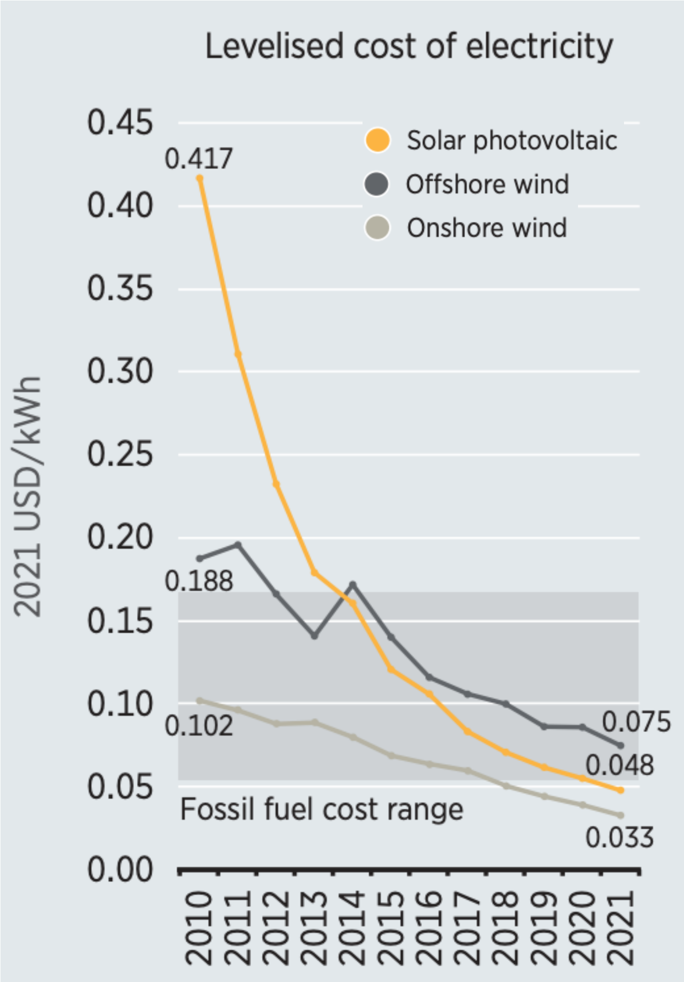


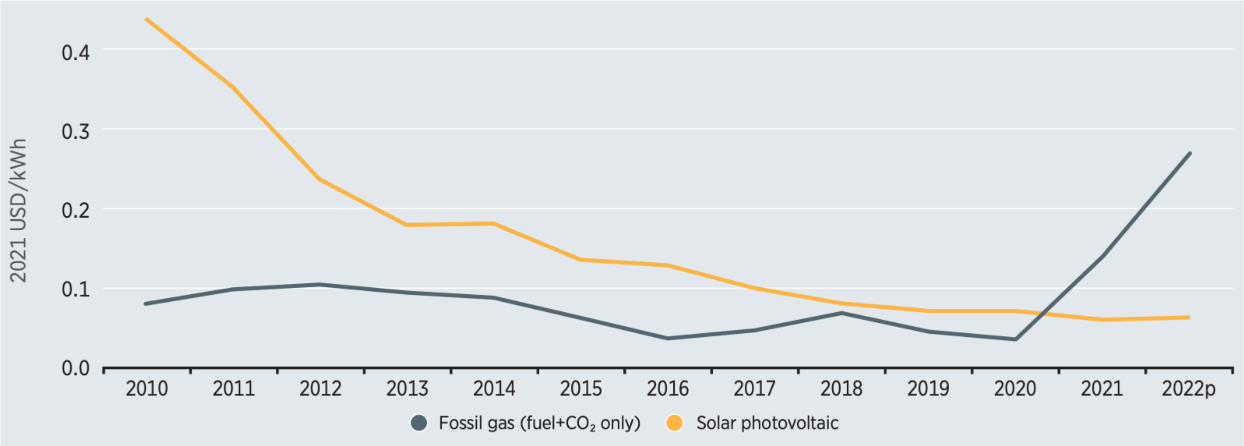

Share of electricity in total final energy consumption, 2005–2030

Source: IEA, https://www.iea.org/reports/electrification

# PV and wind became a promising measures toward net zero goals

- Between 2010 and 2021, the global weighted average LCOE of newly commissioned utility-scale solar PV projects declined by 88%, onshore wind by 68%, and offshore wind by 60%



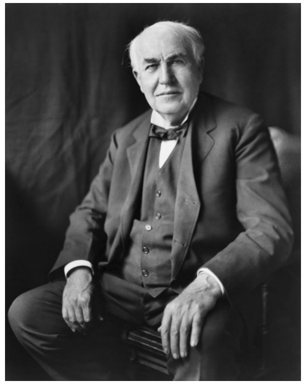




Source: IRENA, Renewable Power Generation Costs in 2021 https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

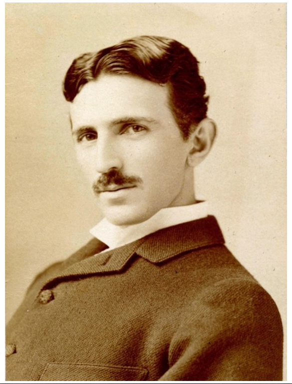
# What is Power System?

# Electric power system history

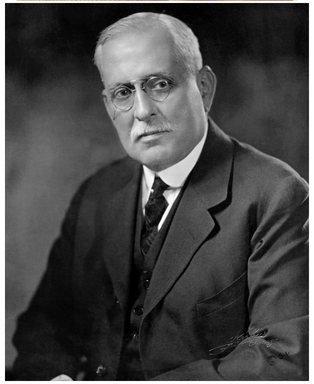
- *Thomas Edison*
  - Started the world’s first power utility business in 1882
  - To promote the incandescent light bulbs
  - Adopted direct current (DC) systems



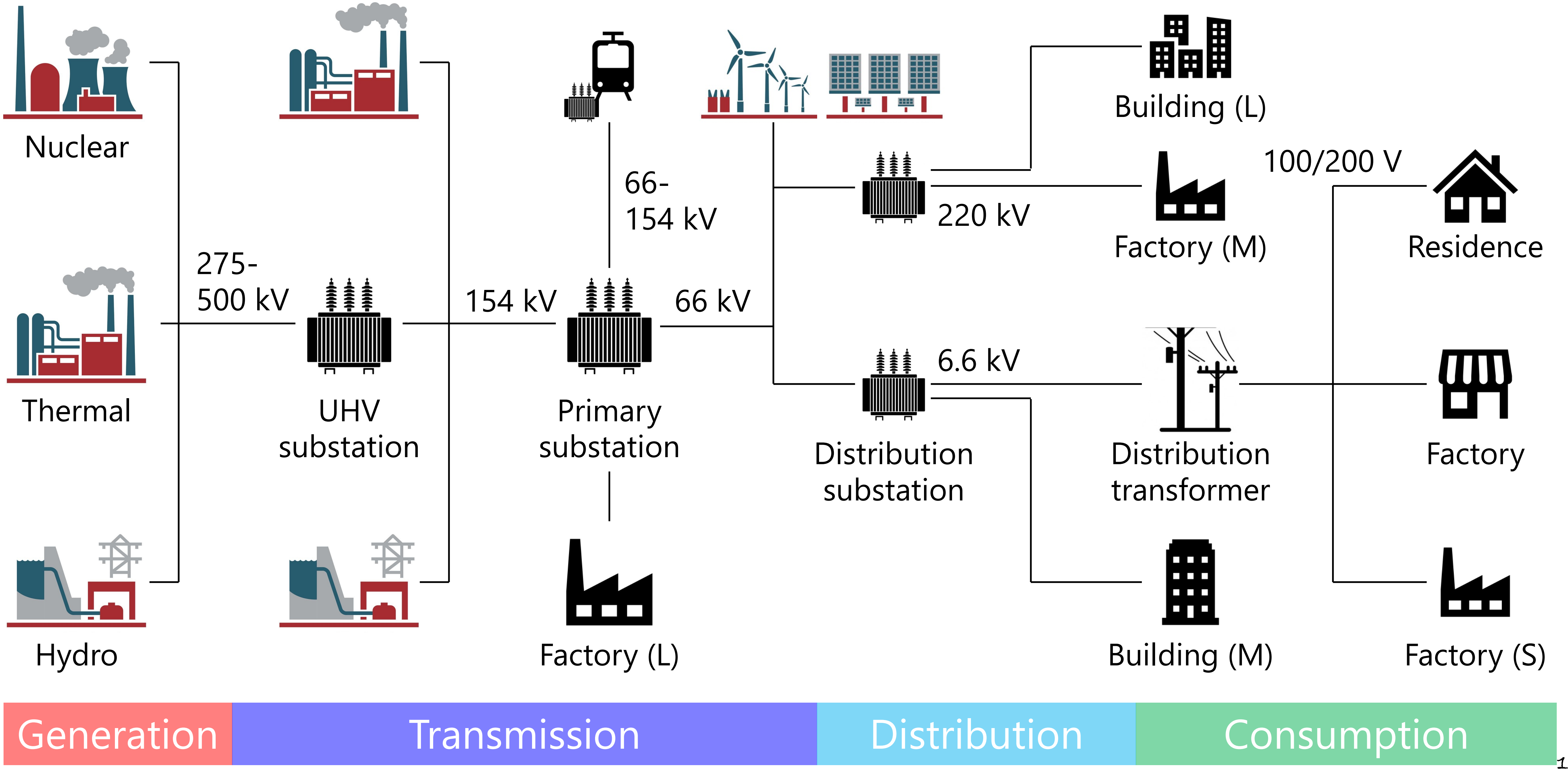
- *Nikola Tesla*
  - Adopted alternating current (AC) systems
  - Developed AC generator, motor, and 3-phase AC system
  - Achieved large-scale, high-capacity, and long-distance transmission



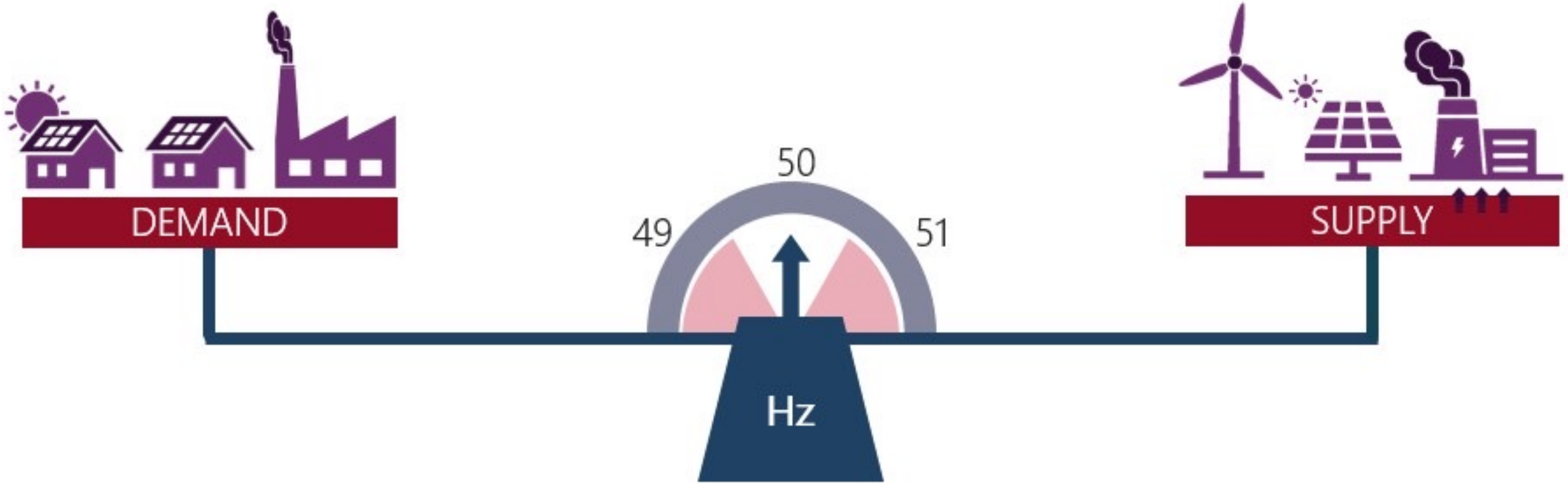
- *Samuel Inusull*
  - Built a modern electric power business model with economies of scale
    - Integrated various loads to increase asset utilization
    - Flat rate bill → demand metered bill
    - Natural monopoly, supply duty, rate-of-return regulation



# Large-scale platform for matching generation and consumption



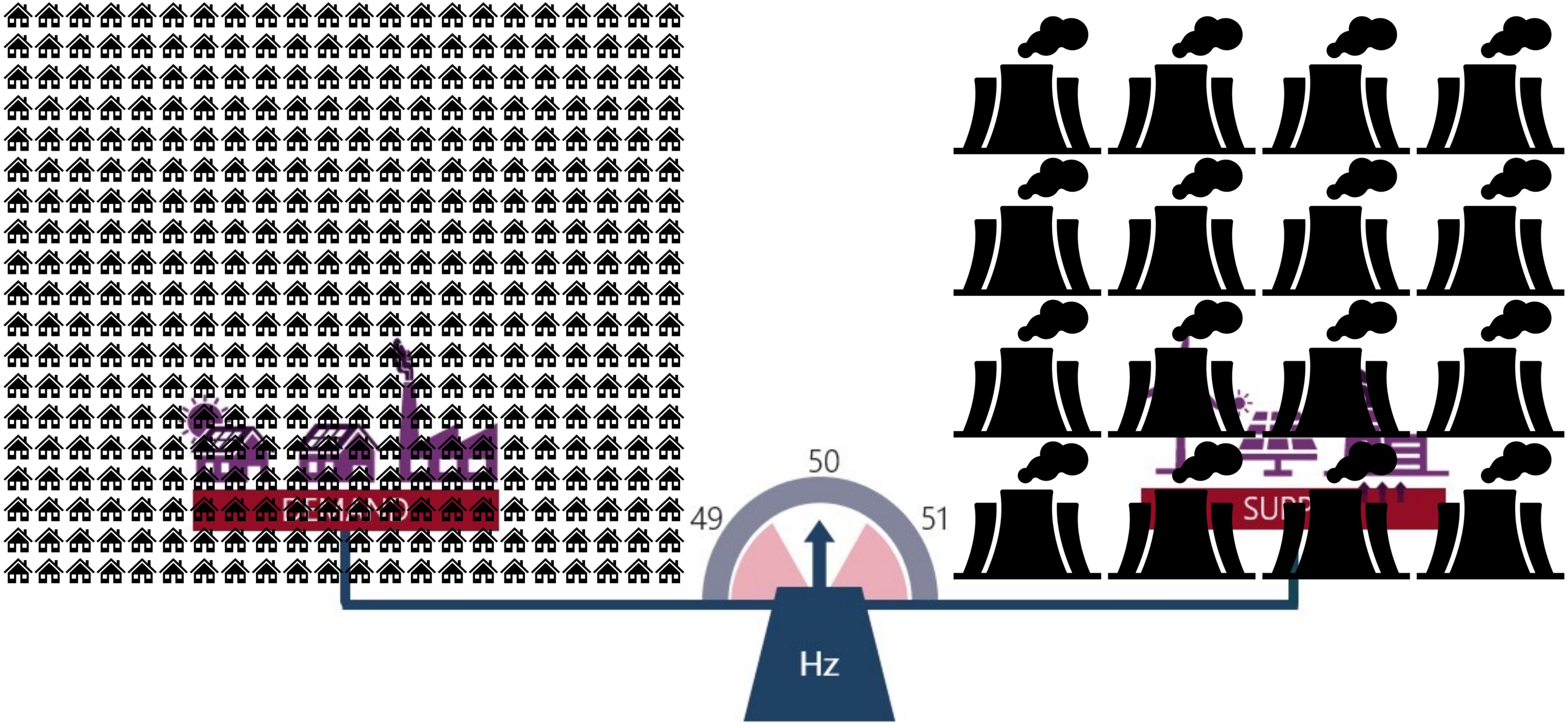
# A main role of power system is **always** to balance supply and demand




**Frequency**

Source: AEMO https://aemo.com.au/learn/energy-explained/energy-101/energy-explained-frequency

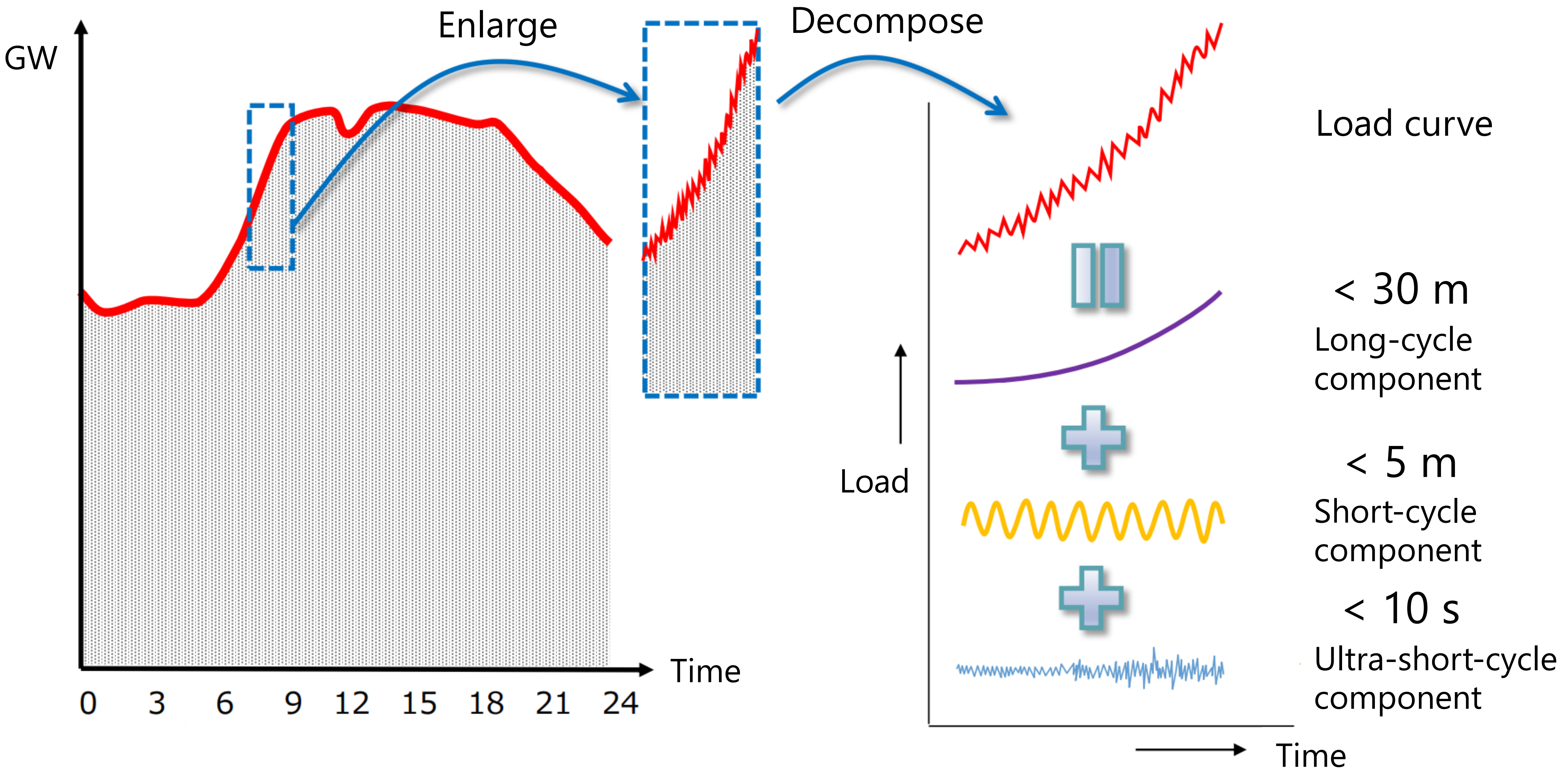
# Don't forget power system is composed of many components




**Frequency**

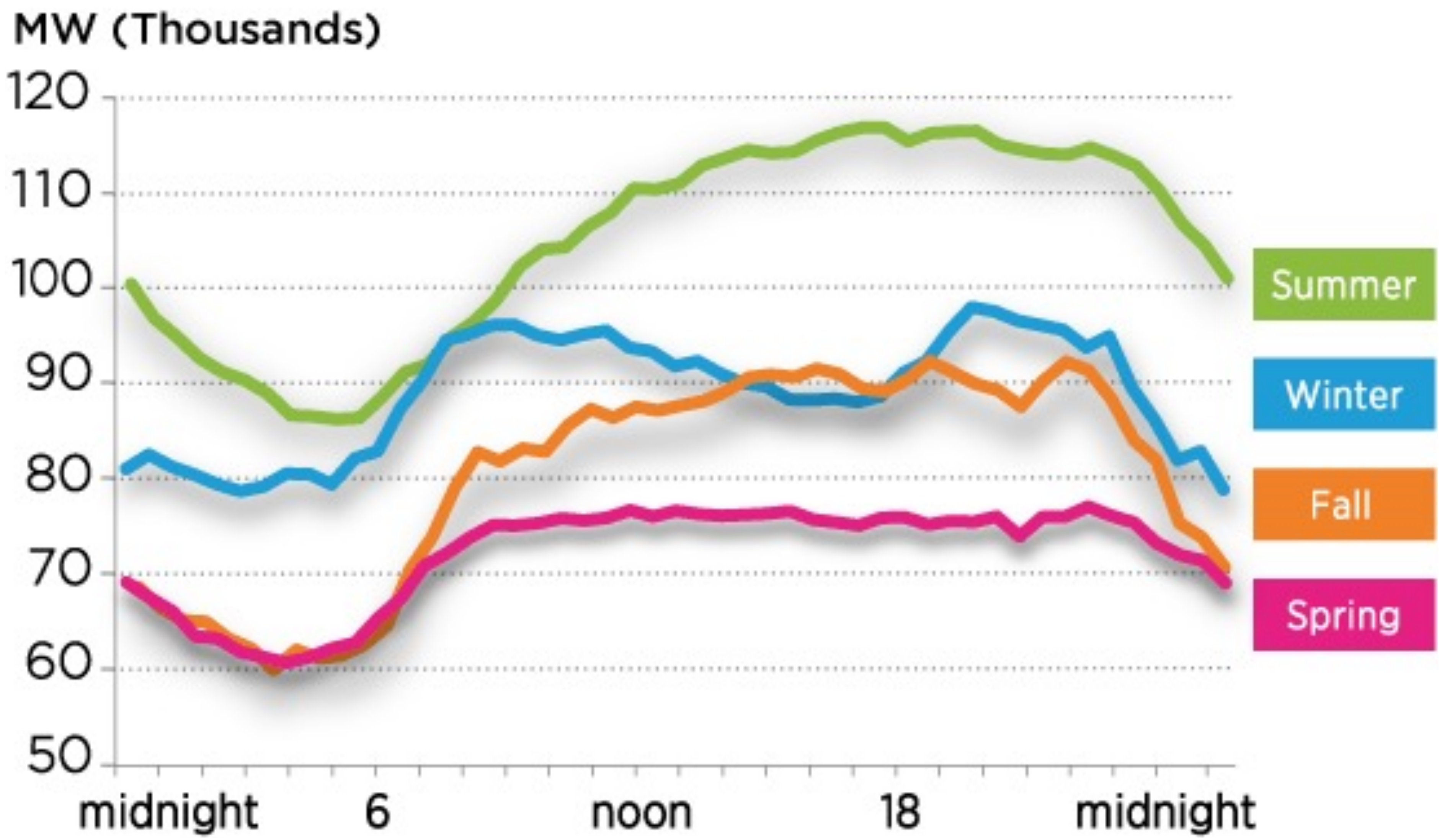
Source: AEMO https://aemo.com.au/learn/energy-explained/energy-101/energy-explained-frequency

# Daily change in electricity demand



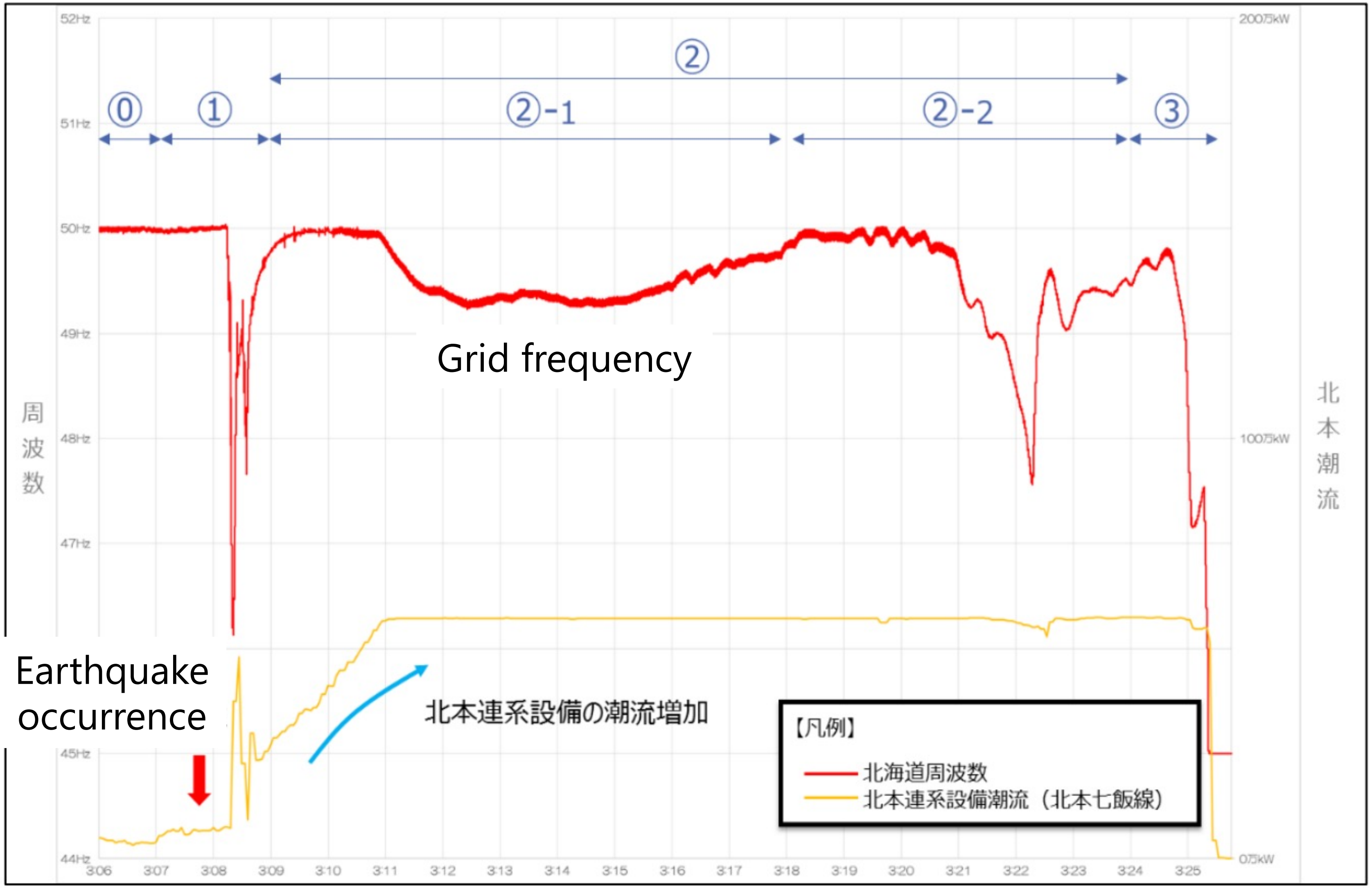

Source: OCCTO https://www.occto.or.jp/iinkai/chouseiryoku/jukyuchousei/2019/2019_jukyuchousei_14_haifu.html

# Seasonal change in electricity demand




Source: pjm https://learn.pjm.com/three-priorities/keeping-the-lights-on/how-energy-use-varies

# Always need to be prepared for contingencies





Source: Google maps

Earthquake-induced blackout in Hokkaido, Japan on September 6, 2018

Source: OCCTO https://www.occto.or.jp/iinkai/hokkaido_kensho/files/181219_hokkaido_saishu_honbun.pdf

# What Happens in Power Systems with High Variable Renewable Energy (VRE) Penetration?

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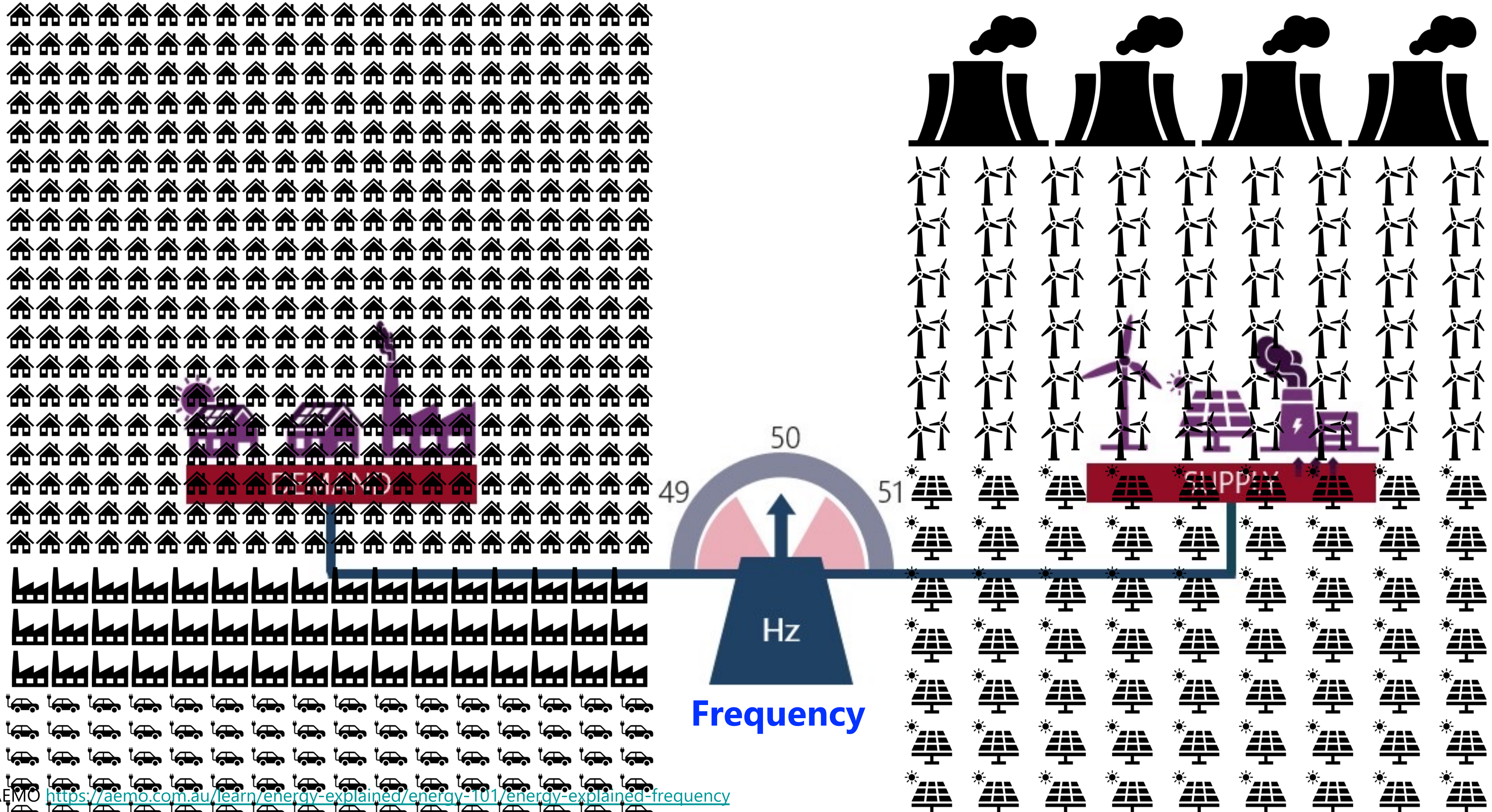
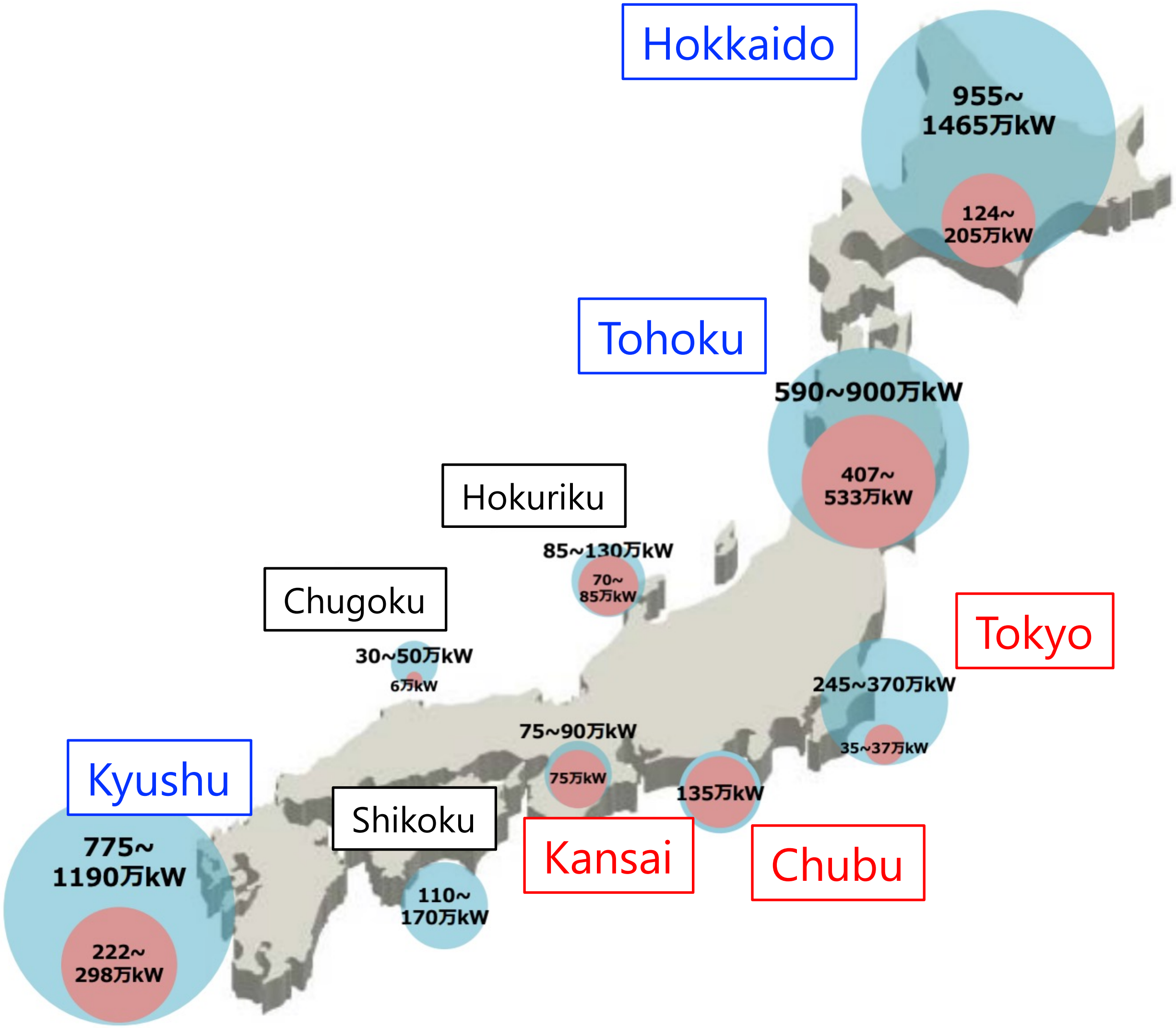
# It will be more complicated




Source: AEMO https://aemo.com.au/learn/energy-explained/energy-101/energy-explained-frequency

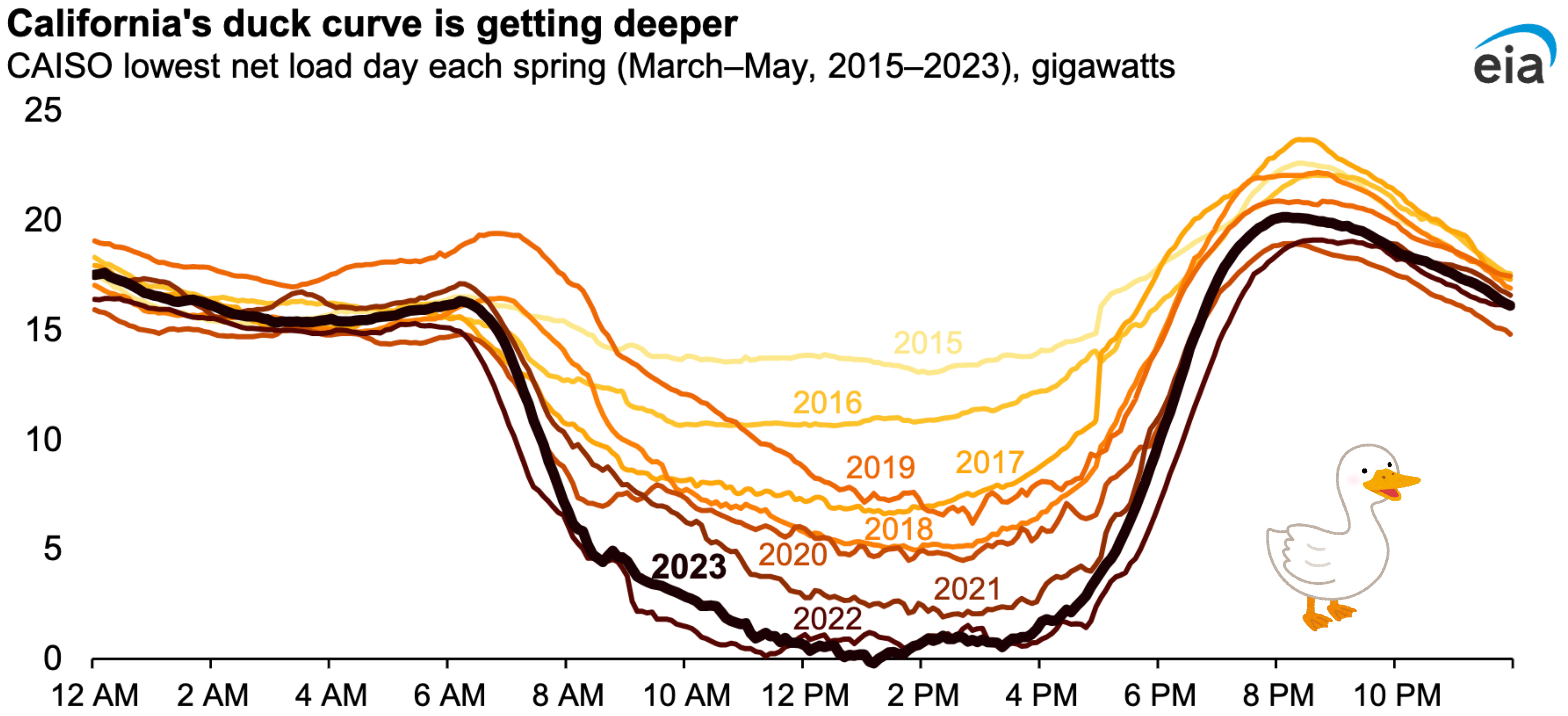
# Issue 1: Spatial mismatch




Offshore wind installation targets in Japan for 2030 and 2040

Source: METI https://www.meti.go.jp/shingikai/energy_environment/yojo_furyoku/pdf/002_02_01.pdf

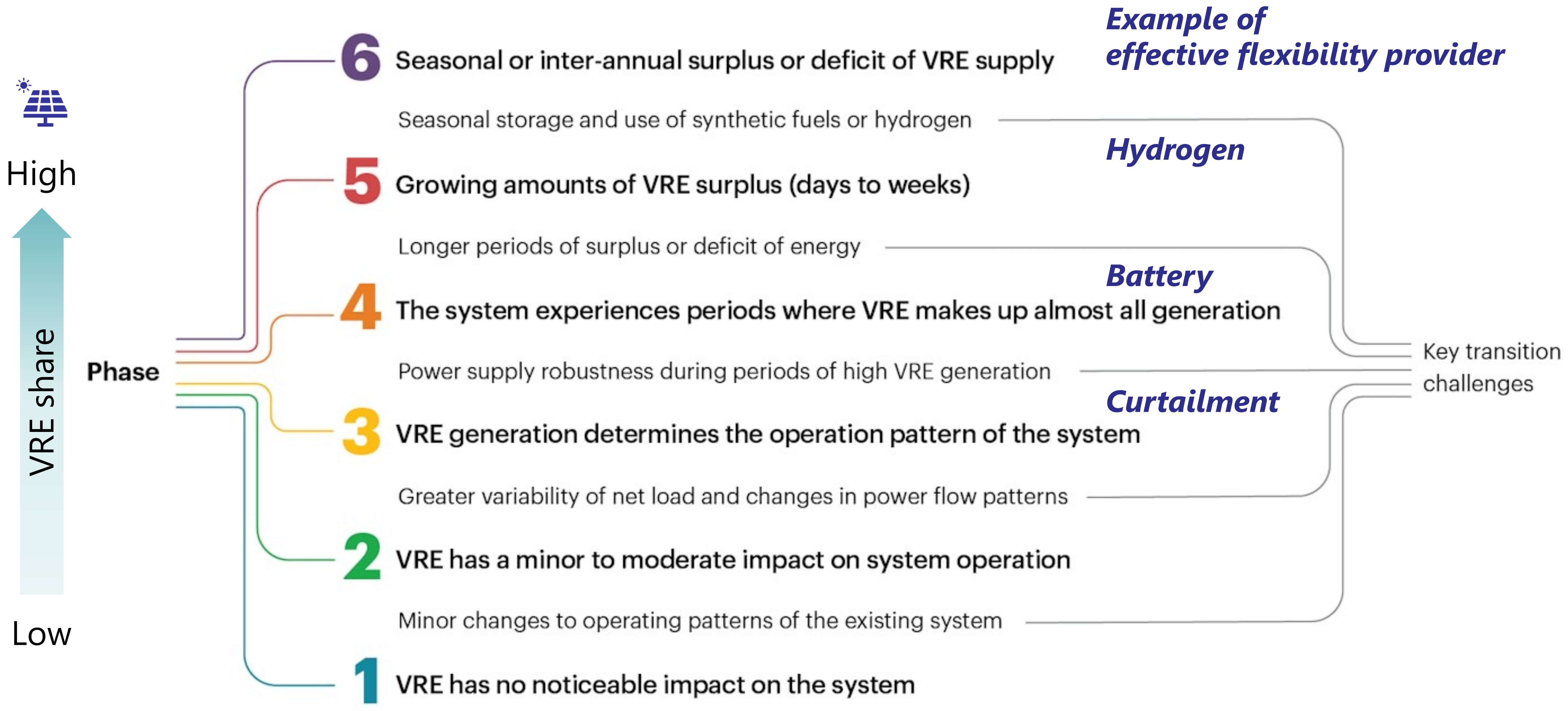
# Issue 2: Temporal mismatch




**Flexibility, which is capability to balance supply and demand, is required**

Source: U.S. Energy Information Administration https://www.eia.gov/todayinenergy/detail.php?id=56880

# VRE integration phases, relevant challenges, and effective flexibility



# System integration phase in selected countries/regions

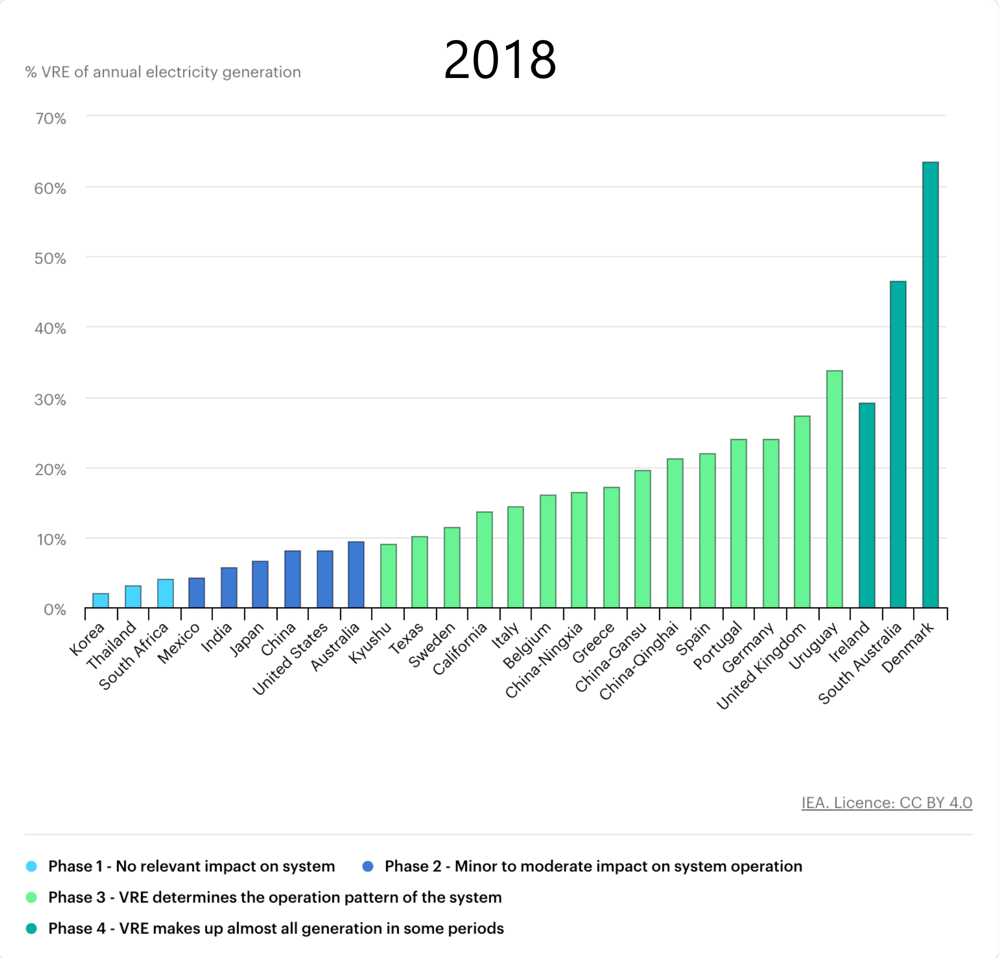
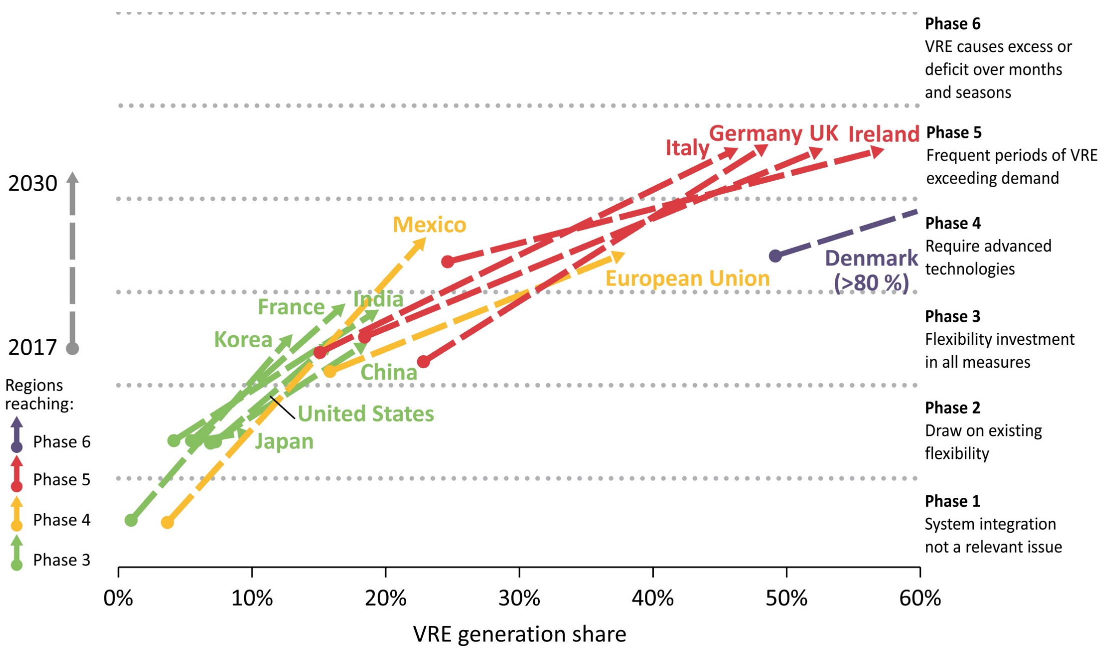



**Figure 1.15** ▷ **Evolving flexibility needs in the power sector in the New Policies Scenario**

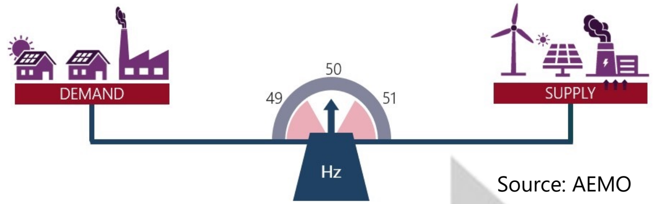



*The need for extra flexibility in power systems rises substantially as new wind and solar PV resources are added*

Source: IEA, Annual variable renewable energy share and corresponding system integration phase in selected countries/regions, 2018, IEA, Paris https://www.iea.org/data-and-statistics/charts/annual-variable-renewable-energy-share-and-corresponding-system-integration-phase-in-selected-countries-regions-2018, IEA. Licence: CC BY 4.0
IEA (2018), World Energy Outlook 2018, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2018, License: CC BY 4.0

# Technology Options for Flexibility

# Issues seen at different flexibility timescales



Source: AEMO

Subseconds → Seconds → Minutes → Hours → Days → Months → Years

| | | | | | | |
|---|---|---|---|---|---|---|
| **Issues addressed** | system stability | Short-term frequency control | Changes in the supply/demand; system regulation | Generation dispatch and operation scheduling | Scheduled maintenance; longer periods of surplus/deficit | Seasonal and interannual varable generation and demond |
| **Example issue** | Withstanding large disturbances such as losing a large power plant | Random fluctuations in power demand | Increasing demond following sunrise or rising net load at sunset | Decide how many thermal plants should remain connected to the system | Hydropower availability during wet and dry season | |
| **Relevant to integration phase** | Phase 4 | Phase 2 and 3 | | Phase 3 and 4 | Phase 4 and 5 | Phase 5 and 6 |

Source: IEA (2020), Introduction to System Integration of Renewables, IEA, Paris https://www.iea.org/reports/introduction-to-system-integration-of-renewables, License: CC BY 4.0

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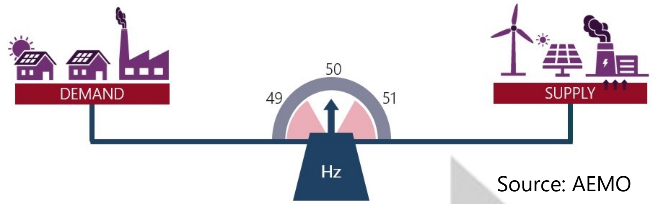
# Technology options for flexibility




Source: AEMO

| | Subseconds | Seconds | Minutes | Hours | Days | Months | Years |
|---|---|---|---|---|---|---|---|
| Issues addressed | system stability | | system regulation | scheduling | longer periods of | varable generation ...nd | |
| Example issue | Withstand... disturban... such as lo... a large po... | | | | | ...et and | |
| Relevant to integration phase | Phase 4 | Phase 2 and 3 | | Phase 3 and 4 | Phase 4 and 5 | Phase 5 and 6 | |

## Conventional power plants & fossil fuels

- Conventional power plants are currently the predominant source of system flexibility in modern power systems.
- It can provide flexibility over a wide range of timescales.
- In the future, more flexible operations will be more valuable, including sudden changes in power plant output, more rapid starts/stops, and lower power plant output with high efficiency.
- Fossil fuels are very powerful energy storages.

Source: IEA (2020), Introduction to System Integration of Renewables, IEA, Paris https://www.iea.org/reports/introduction-to-system-integration-of-renewables, License: CC BY 4.0

# Power plant control mechanisms at several time scales

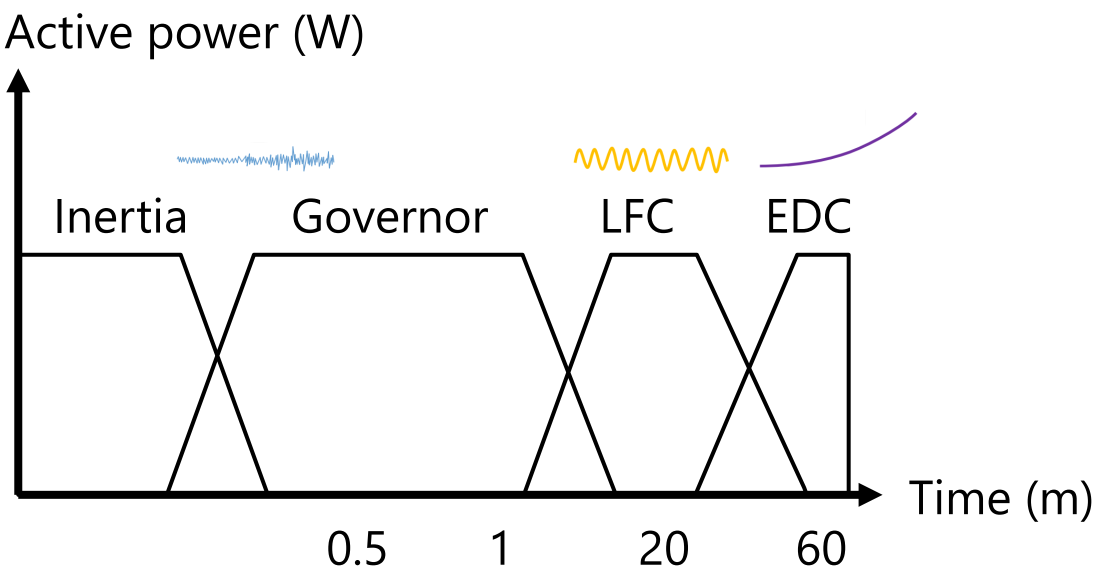
- Centralized control
  - Economic dispatch control (EDC)
  - Load frequency control (LFC)

- Autonomous control
  - Governor control
  - Inertial response

Swing equation

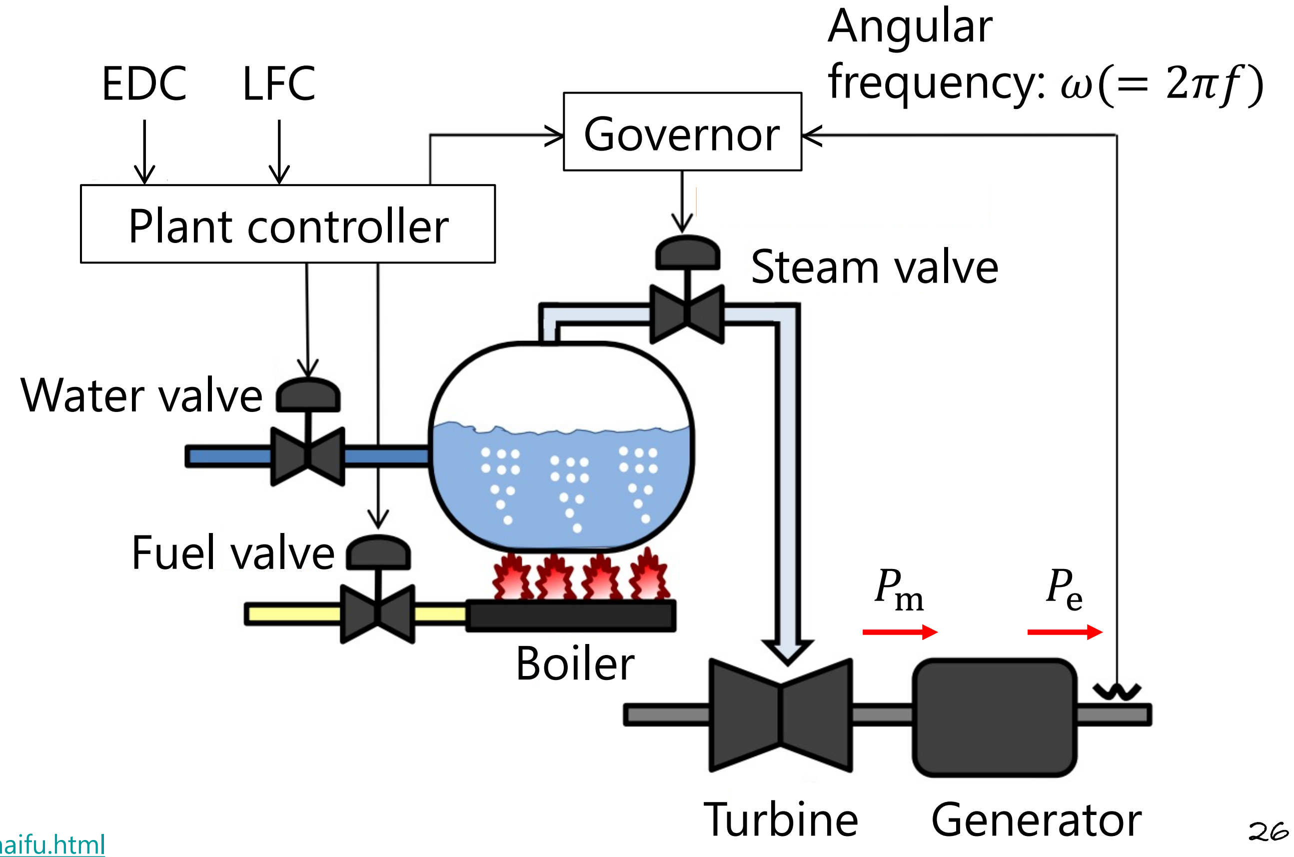
$$M\frac{d\omega}{dt} = P_\mathrm{m} - P_\mathrm{e}$$

$M$: Inertia constant
$P_\mathrm{m}$: Mechanical input
$P_\mathrm{e}$: Electrical output




Unit commitment (UC)...

Fuel procurement ...




Source: OCCTO https://www.occto.or.jp/iinkai/chouseiryoku/jukyuchousei/2020/2020_jukyuchousei_19_haifu.html

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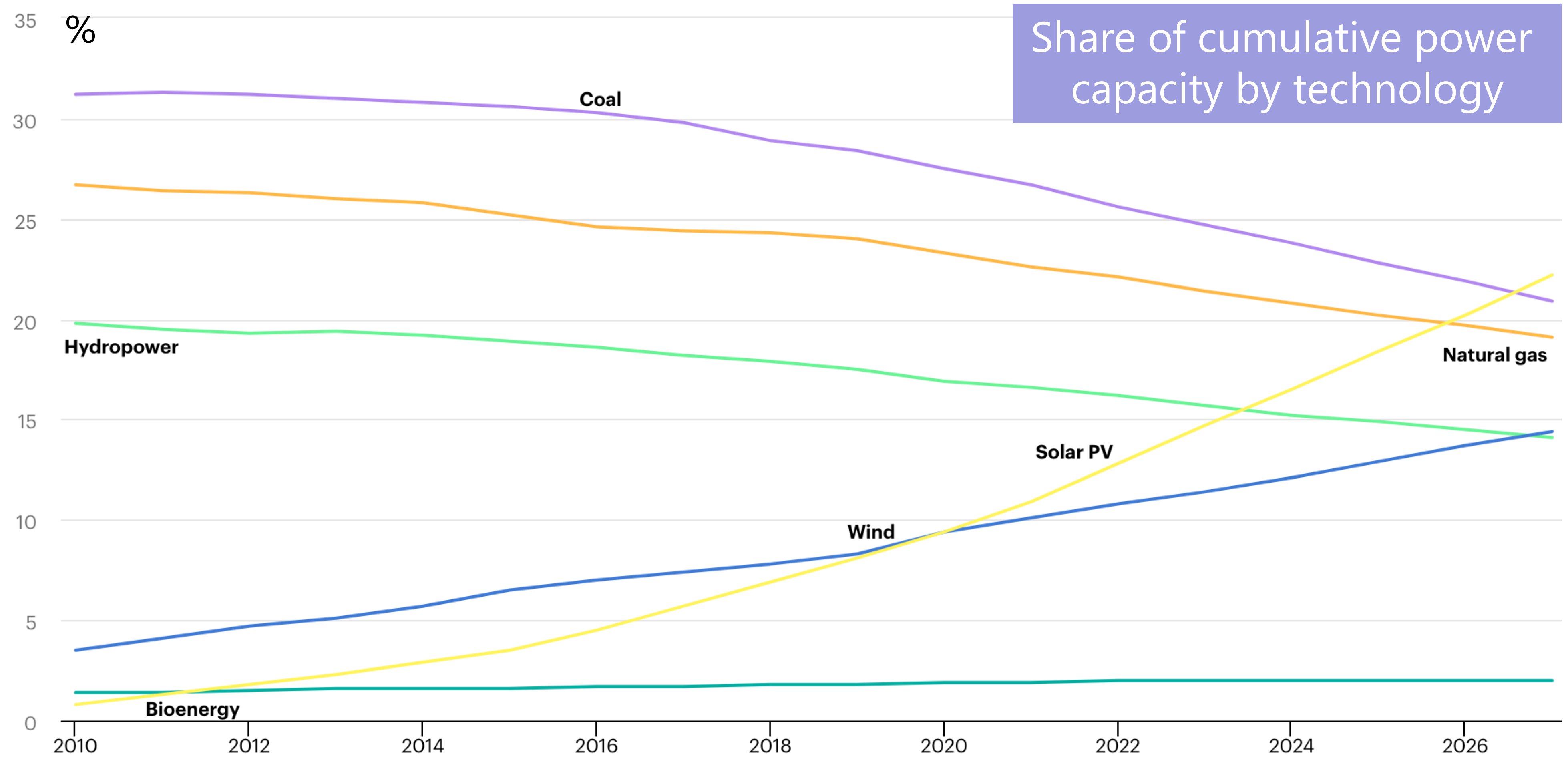
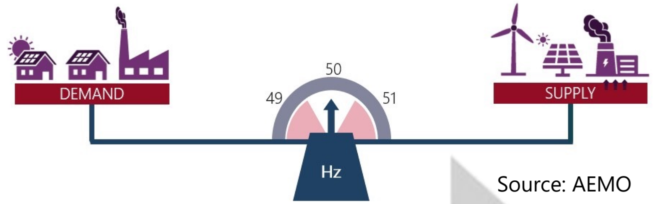
# Variable renewable energy (VRE) will increase and conventional power plants will decrease

- The flexibility provided by conventional power plants needs to be replaced somehow.

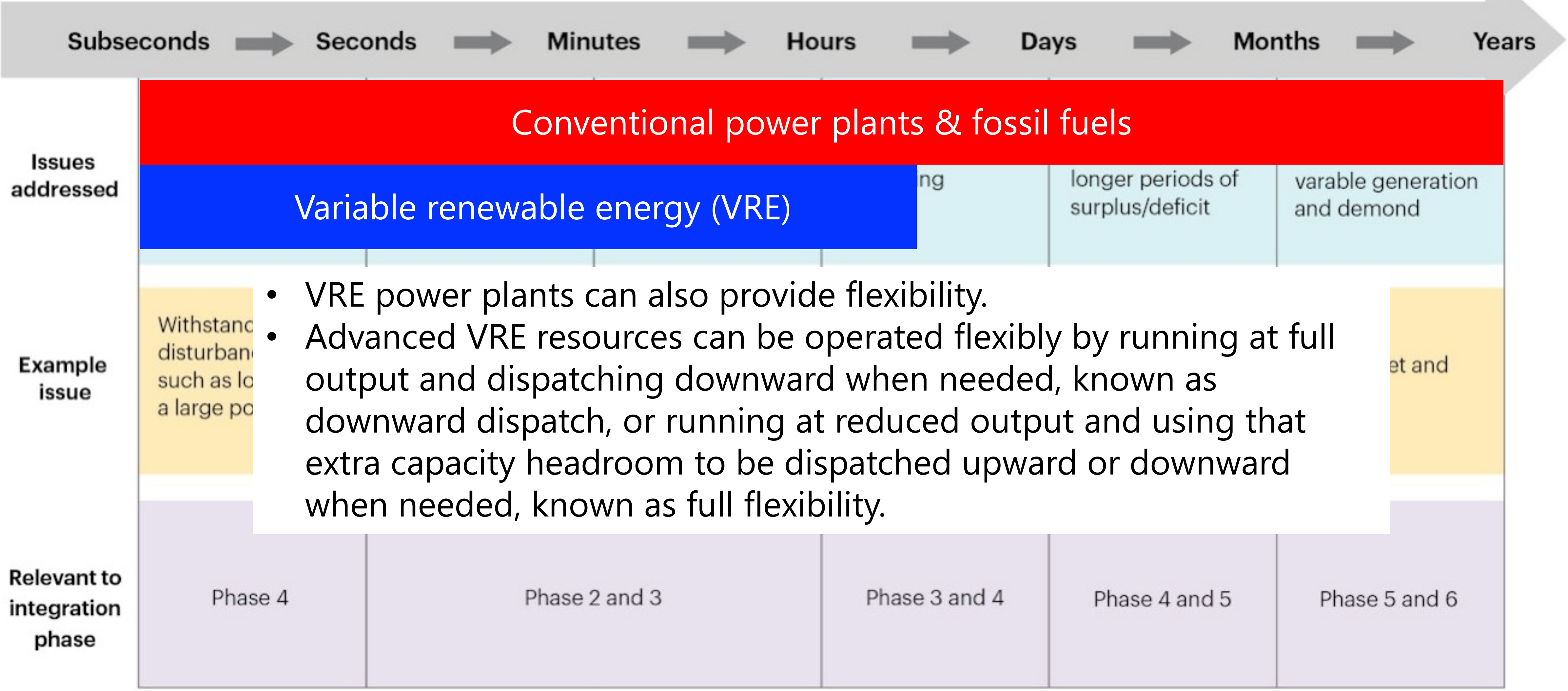



Source: IEA, Share of cumulative power capacity by technology, 2010-2027, IEA, Paris https://www.iea.org/data-and-statistics/charts/share-of-cumulative-power-capacity-by-technology-2010-2027, IEA. Licence: CC BY 4.0

# Technology options for flexibility



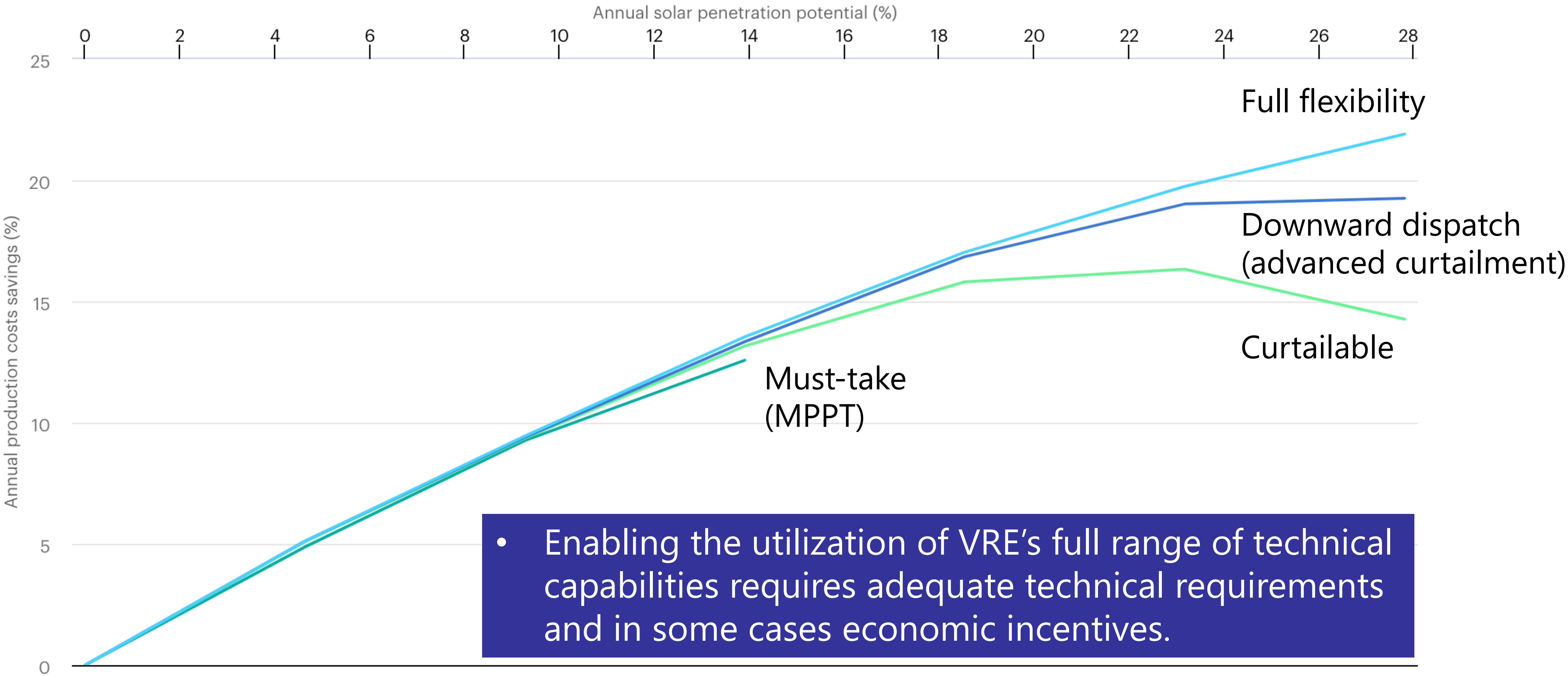

Source: AEMO




- VRE power plants can also provide flexibility.
- Advanced VRE resources can be operated flexibly by running at full output and dispatching downward when needed, known as downward dispatch, or running at reduced output and using that extra capacity headroom to be dispatched upward or downward when needed, known as full flexibility.

Source: IEA (2020), Introduction to System Integration of Renewables, IEA, Paris https://www.iea.org/reports/introduction-to-system-integration-of-renewables, License: CC BY 4.0

# As annual PV penetration increase, flexible operation of PV provides greater operational cost saving than must-run operation




- Enabling the utilization of VRE's full range of technical capabilities requires adequate technical requirements and in some cases economic incentives.

Source: IEA, Modelled annual operational cost savings for the TECO power system in Florida, as a percentage of total system operational costs without solar PV generation, IEA, Paris https://www.iea.org/data-and-statistics/charts/modelled-annual-operational-cost-savings-for-the-teco-power-system-in-florida-as-a-percentage-of-total-system-operational-costs-without-solar-pv-generation, IEA. Licence: CC BY 4.0

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# Appropriate curtailment is not the enemy

- Transmission system operators are not wasting power, they are optimizing the entire system.

## Renewables curtailment rose by 40% in Australia in 2022, says market operator

Daniel Westerman, the CEO of the Australian Energy Market Operator (AEMO), says that renewable curtailment in Australia has risen by approximately 40% from last year.

MAY 17, 2023 BELLA PEACOCK

COMMERCIAL & INDUSTRIAL PV | MARKETS | MARKETS & POLICY | RESIDENTIAL PV | UTILITY SCALE PV | AUSTRALIA

*Image: CAN Europe, Flickr*

## Japan's Okinawa prefecture curtails solar generation for first time

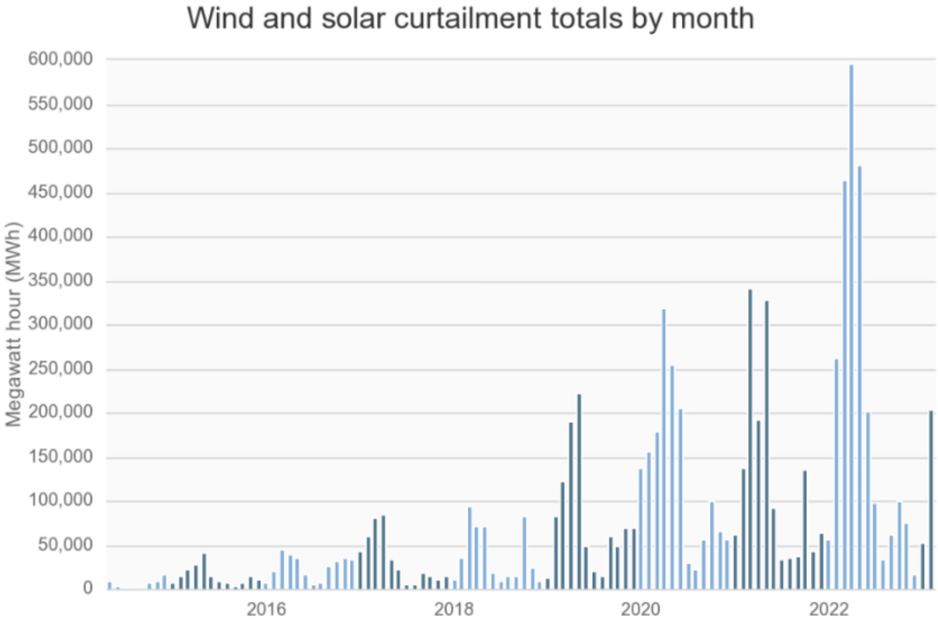
Japan's Okinawa Electric Power Co. has introduced PV curtailment measures in response to high solar radiation levels and low energy demand.

JANUARY 2, 2023 EMILIANO BELLINI

COMMERCIAL & INDUSTRIAL PV | HIGHLIGHTS | MARKETS | MARKETS & POLICY | RESIDENTIAL PV | UTILITY SCALE PV | JAPAN

*Image: AV Solar*

## California, US




Source:
pv magazine https://www.pv-magazine.com/2023/05/17/renewables-curtailment-rose-by-40-in-australia-in-2022-says-market-operator/
pv magazine https://www.pv-magazine.com/2023/01/02/japans-okinawa-prefecture-applies-solar-curtailment-for-first-time/
https://energyathaas.wordpress.com/2023/03/13/californias-duck-belly-blues/

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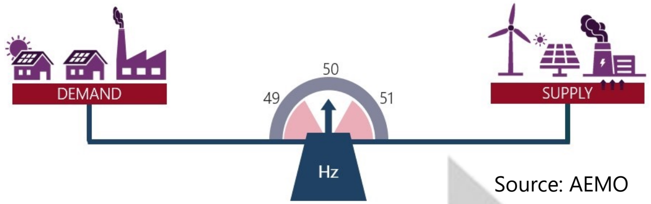
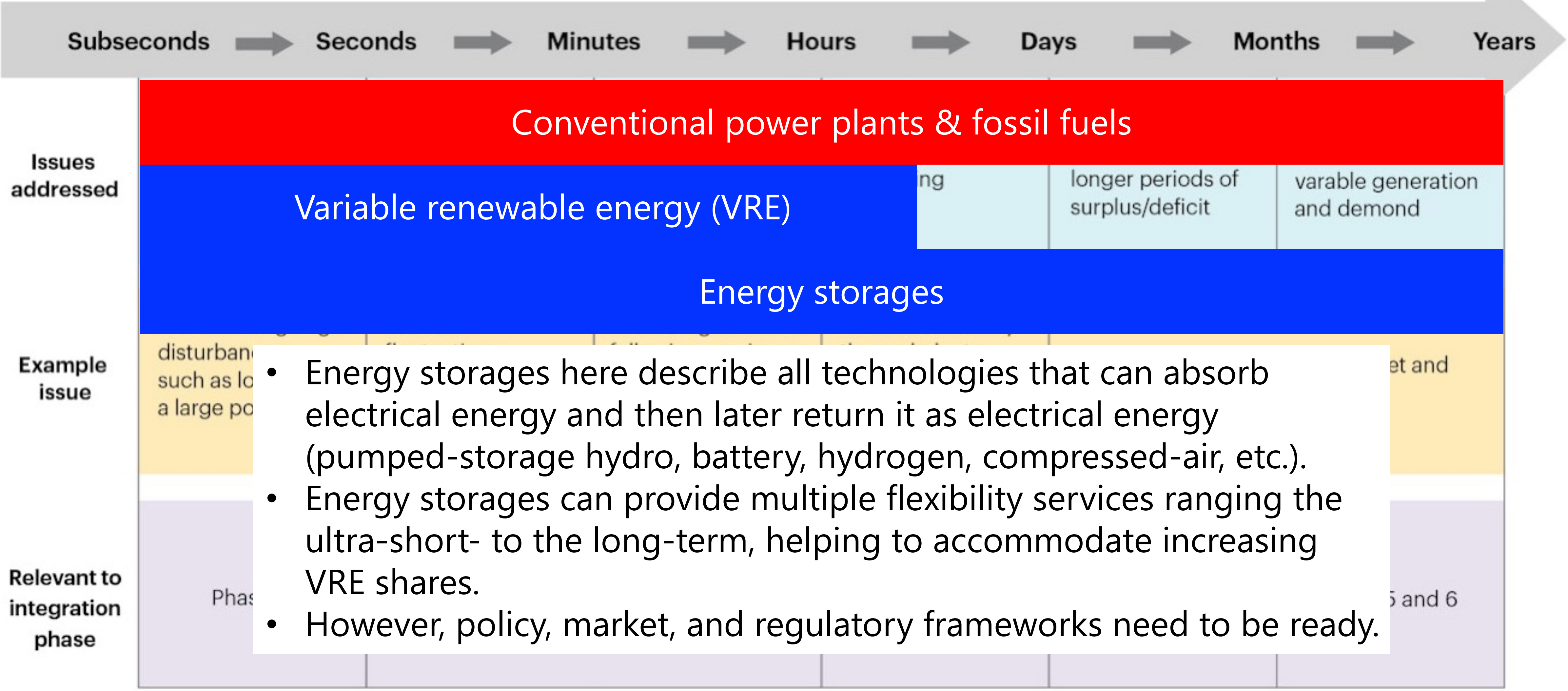
# Technology options for flexibility




Source: AEMO



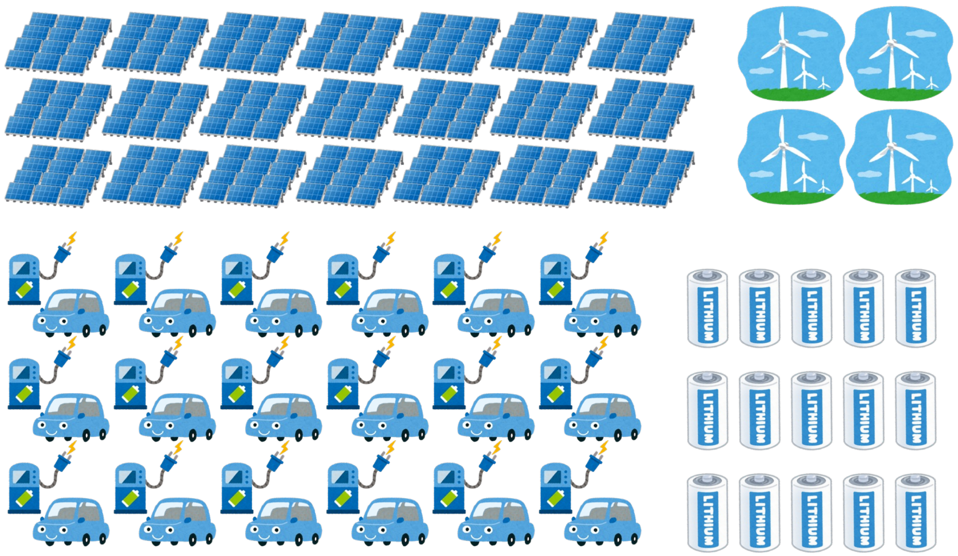

- Energy storages here describe all technologies that can absorb electrical energy and then later return it as electrical energy (pumped-storage hydro, battery, hydrogen, compressed-air, etc.).
- Energy storages can provide multiple flexibility services ranging the ultra-short- to the long-term, helping to accommodate increasing VRE shares.
- However, policy, market, and regulatory frameworks need to be ready.

Source: IEA (2020), Introduction to System Integration of Renewables, IEA, Paris https://www.iea.org/reports/introduction-to-system-integration-of-renewables, License: CC BY 4.0

# Distributed energy resources (DERs)

- Virtual power plant (VPP)
  - Aggregating distributed energy resources (DERs) and providing grid services like conventional large-scale power plants
  - VRE, battery, electric vehicle, heat pump, demand response

Approx. $10^8$– $10^9$ (W)



Approx. $10^0$– $10^7$ (W) **x *N***

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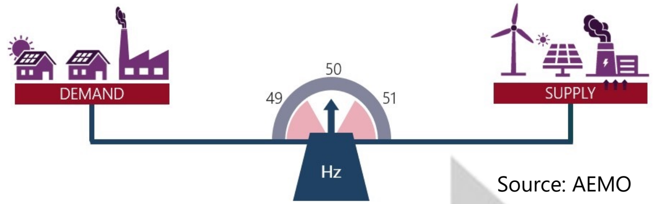
# Technology options for flexibility




Source: AEMO

Subseconds → Seconds → Minutes → Hours → Days → Months → Years

**Conventional power plants & fossil fuels**

**Variable renewable energy (VRE)**

**+ Advanced inverter technology**

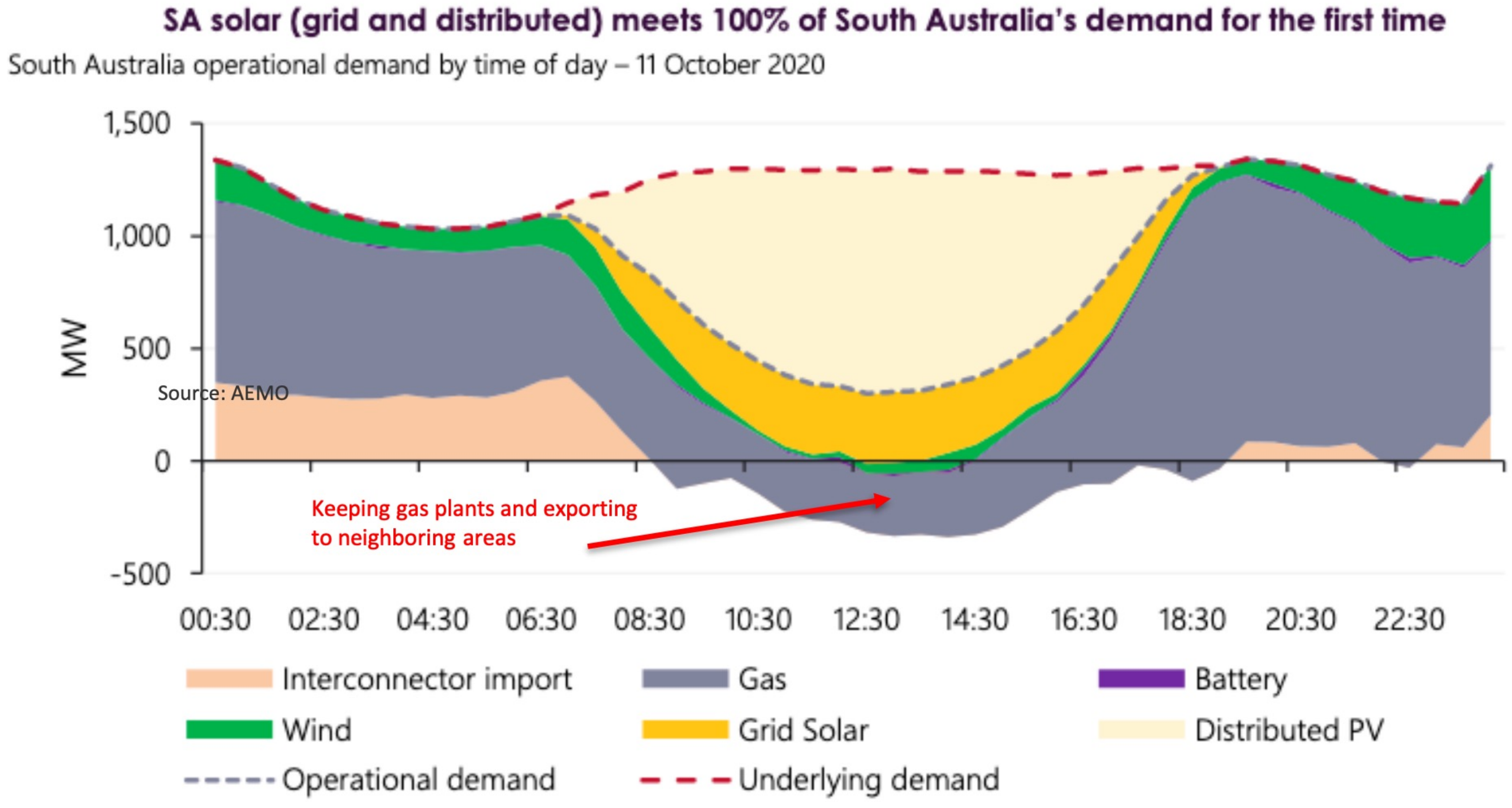
**Energy storages**

| | Subseconds | Seconds | Minutes | Hours | Days | Months | Years |
|---|---|---|---|---|---|---|---|
| **Issues addressed** | | | | ng | longer periods of surplus/deficit | varable generation and demond | |
| **Example issue** | disturbances such as losing a large power plant | fluctuations in power demand | following sunrise or rising net load at sunset | thermal plants should remain connected to the system | Hydropower availability during wet and dry season | | |
| **Relevant to integration phase** | Phase 4 | Phase 2 and 3 | | Phase 3 and 4 | Phase 4 and 5 | Phase 5 and 6 | |

Source: IEA (2020), Introduction to System Integration of Renewables, IEA, Paris https://www.iea.org/reports/introduction-to-system-integration-of-renewables, License: CC BY 4.0

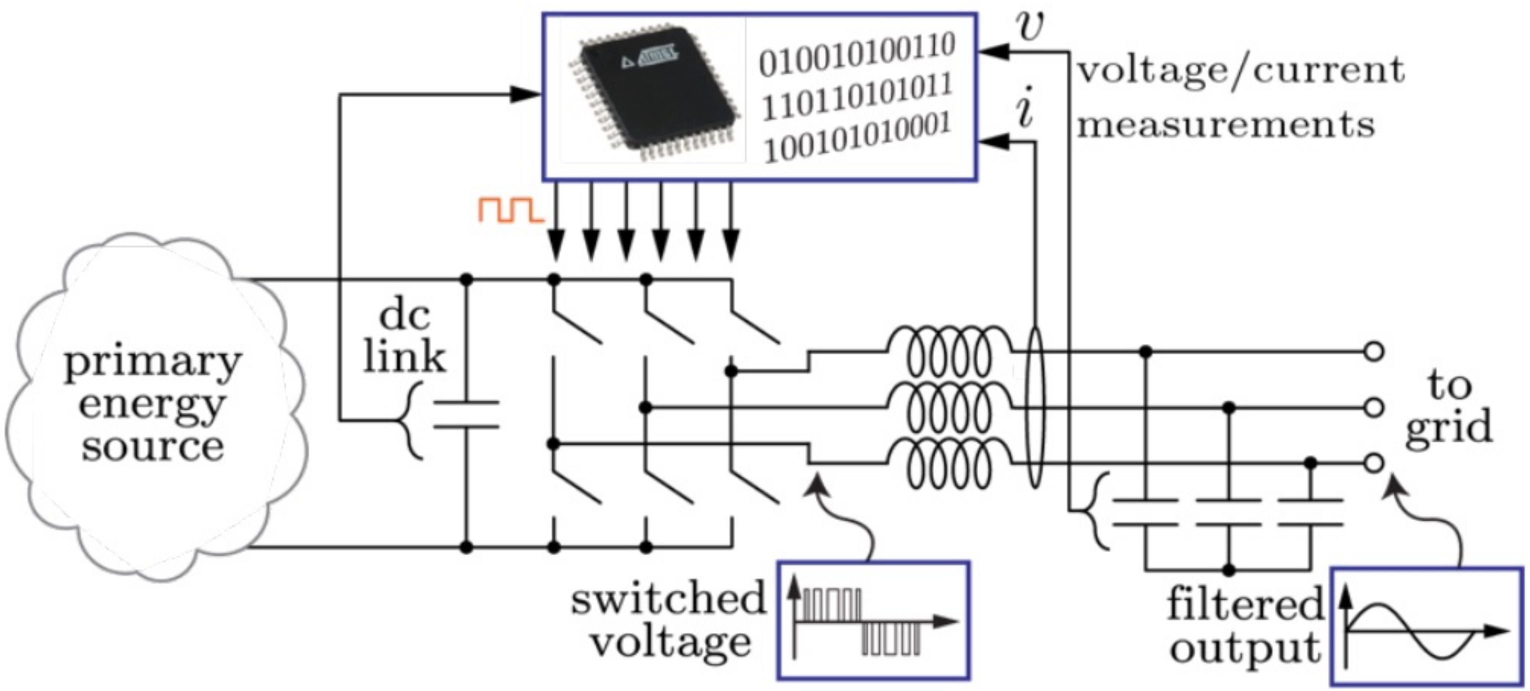
# Technical challenges at high shares of inverter-based resource (IBR)

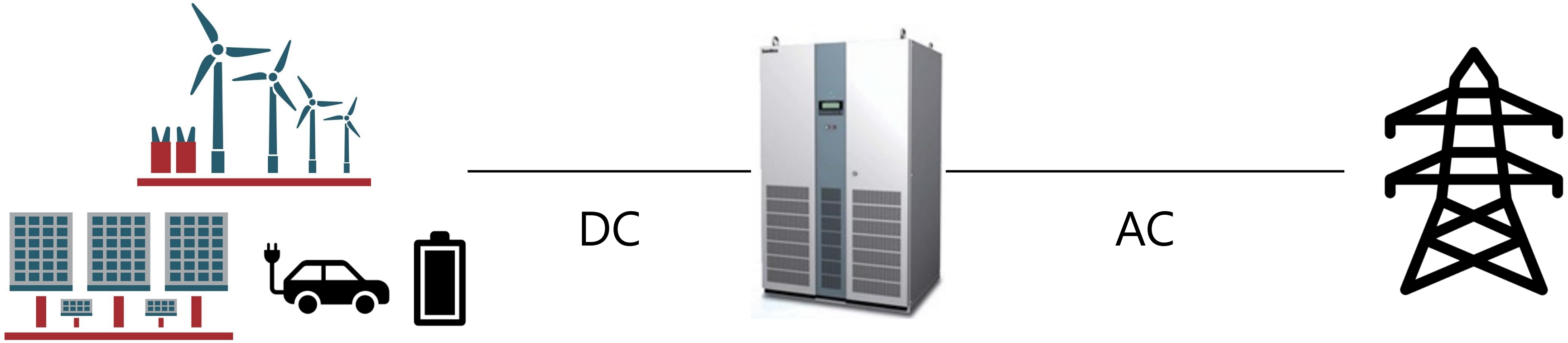
## South Australia – Already at 100% IBR (but…)


Source: B. Kroposki, "The Need for Grid-forming (GFM) Inverters in Future Power Systems"
https://research.csiro.au/ired2022/wp-content/uploads/sites/477/2022/11/The-Need-for-Grid-forming-GFM-Inverters-in-Future-Power-Systems.pdf

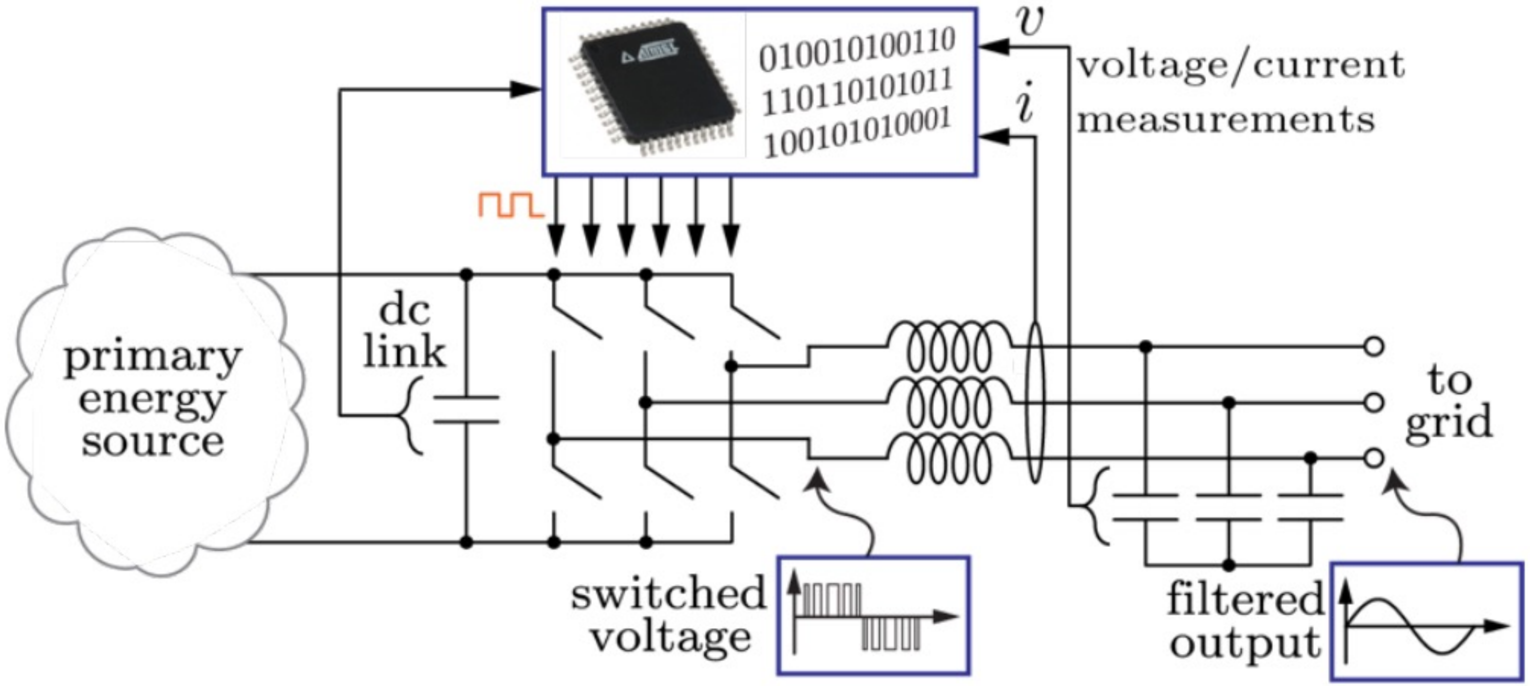
# General structure of DER inverter



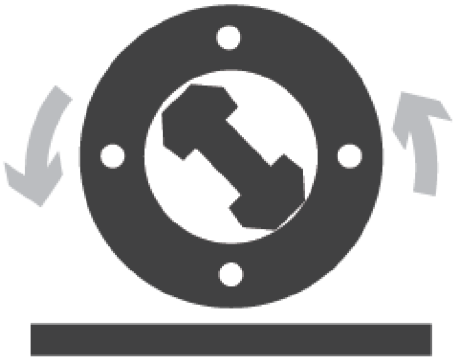



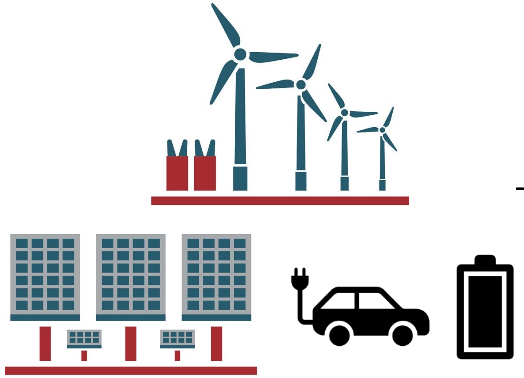

Source: UNIFI, "Research Roadmap on Grid-Forming Inverters" https://www.nrel.gov/docs/fy21osti/73476.pdf

# Grid-following (GFL) inverter requires a grid voltage reference to follow



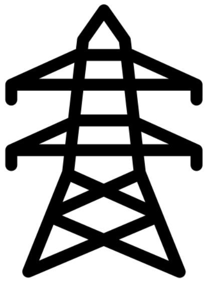

Need synchronous generators (SGs) on the grid





DC

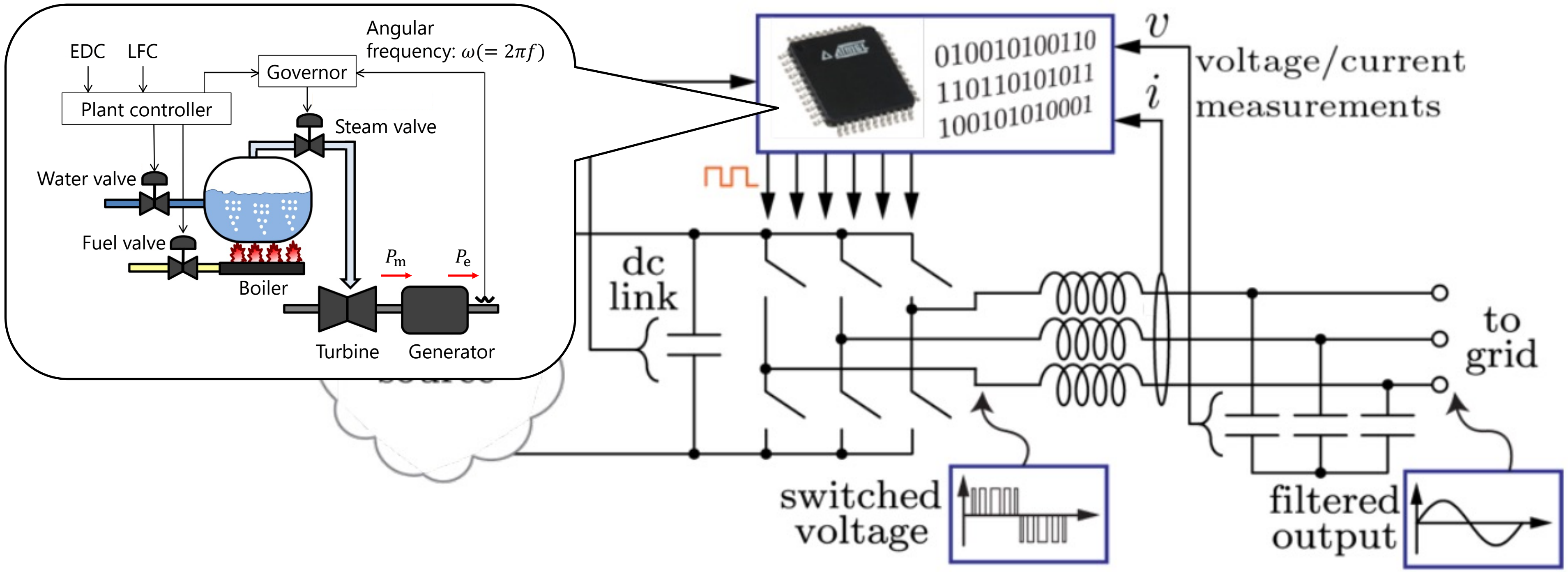
AC



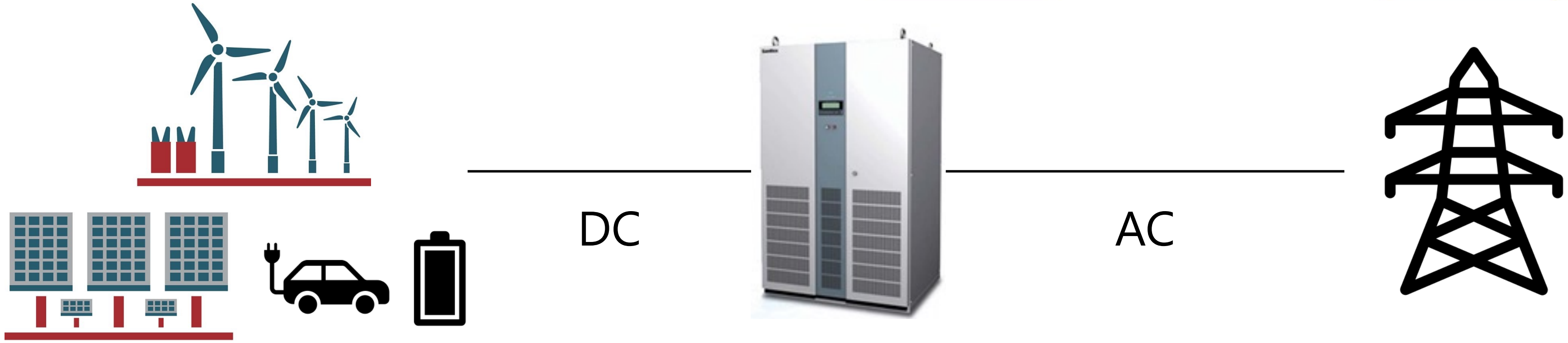
Source: UNIFI, "Research Roadmap on Grid-Forming Inverters" https://www.nrel.gov/docs/fy21osti/73476.pdf

AIST FREA

# Grid-forming (GFM) inverter act as voltage source




Need only
the smallest/zero
SG on the grid




Source: UNIFI, "Research Roadmap on Grid-Forming Inverters" https://www.nrel.gov/docs/fy21osti/73476.pdf

AIST FREA

# Tested five inverter prototypes with flexibility offering (virtual inertia)

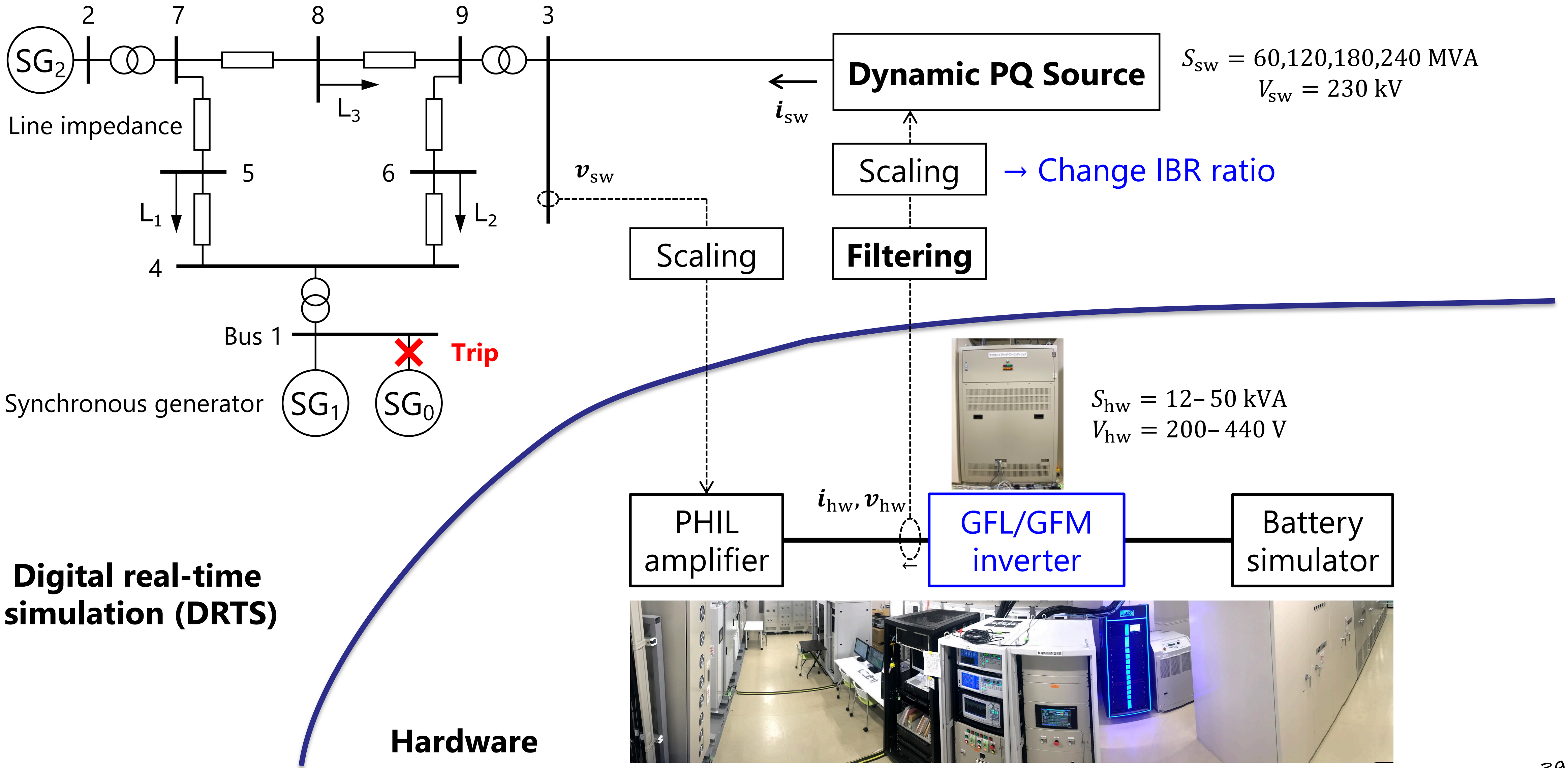
| | Grid-following inverter | | Grid-forming inverter | | |
|---|---|---|---|---|---|
| | GFL 1 | GFL 2 | GFM 0 | GFM 1 | GFM 2 |
| Control function | df/dt-P droop<br>f-P droop | df/dt-P droop<br>f-P droop | VSM<br>Q-V droop | P-f droop<br>Q-V droop | VSM<br>Q-V droop |
| Rated capacity (kVA) | 20 | 49.9 | 12 | 20 | 50 |
| Rated AC voltage (V) | 200 | 200 | 420 | 200 | 440 |




AIST FREA

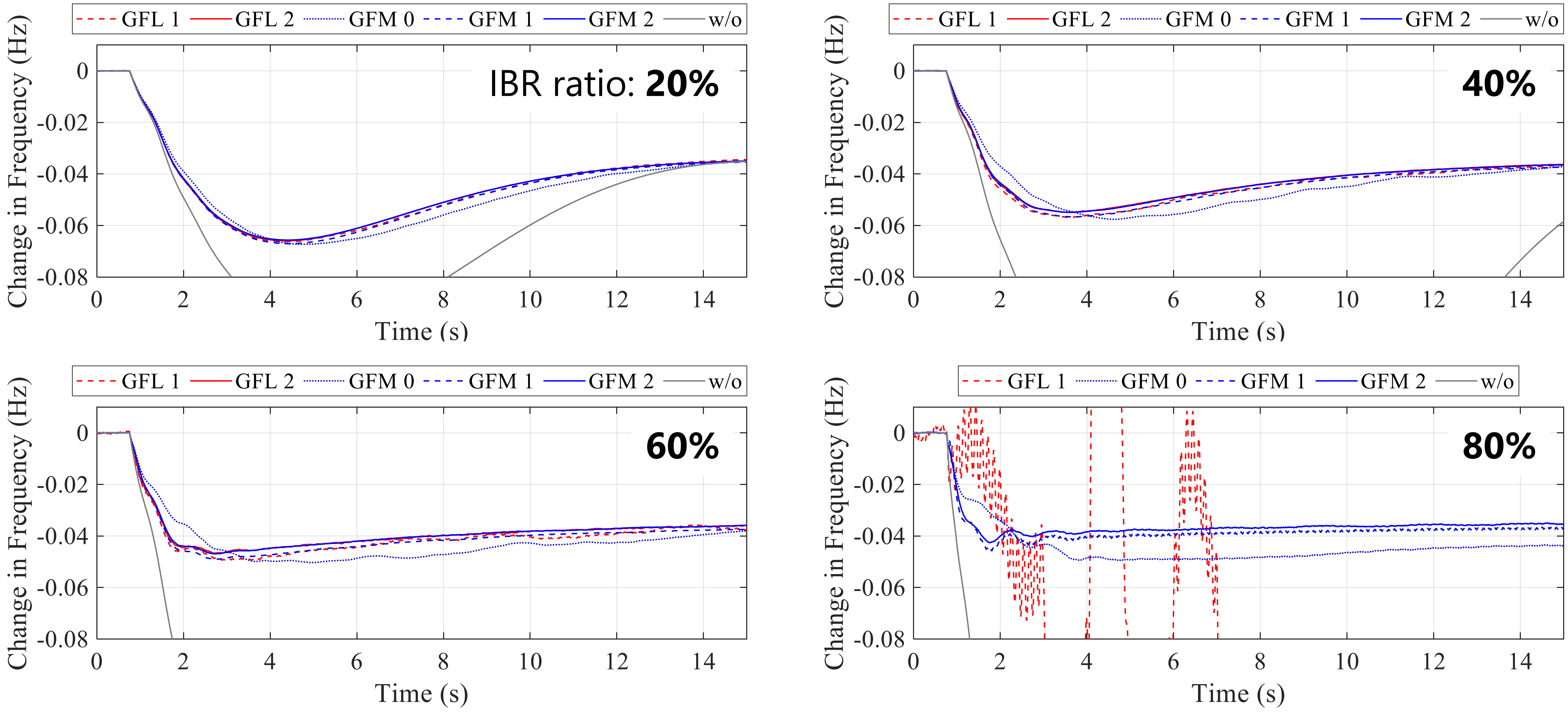
# Test setup for GFL/GFM inverters using modified IEEE 9-bus system model

## Modified IEEE 9-bus system model (300 MW)



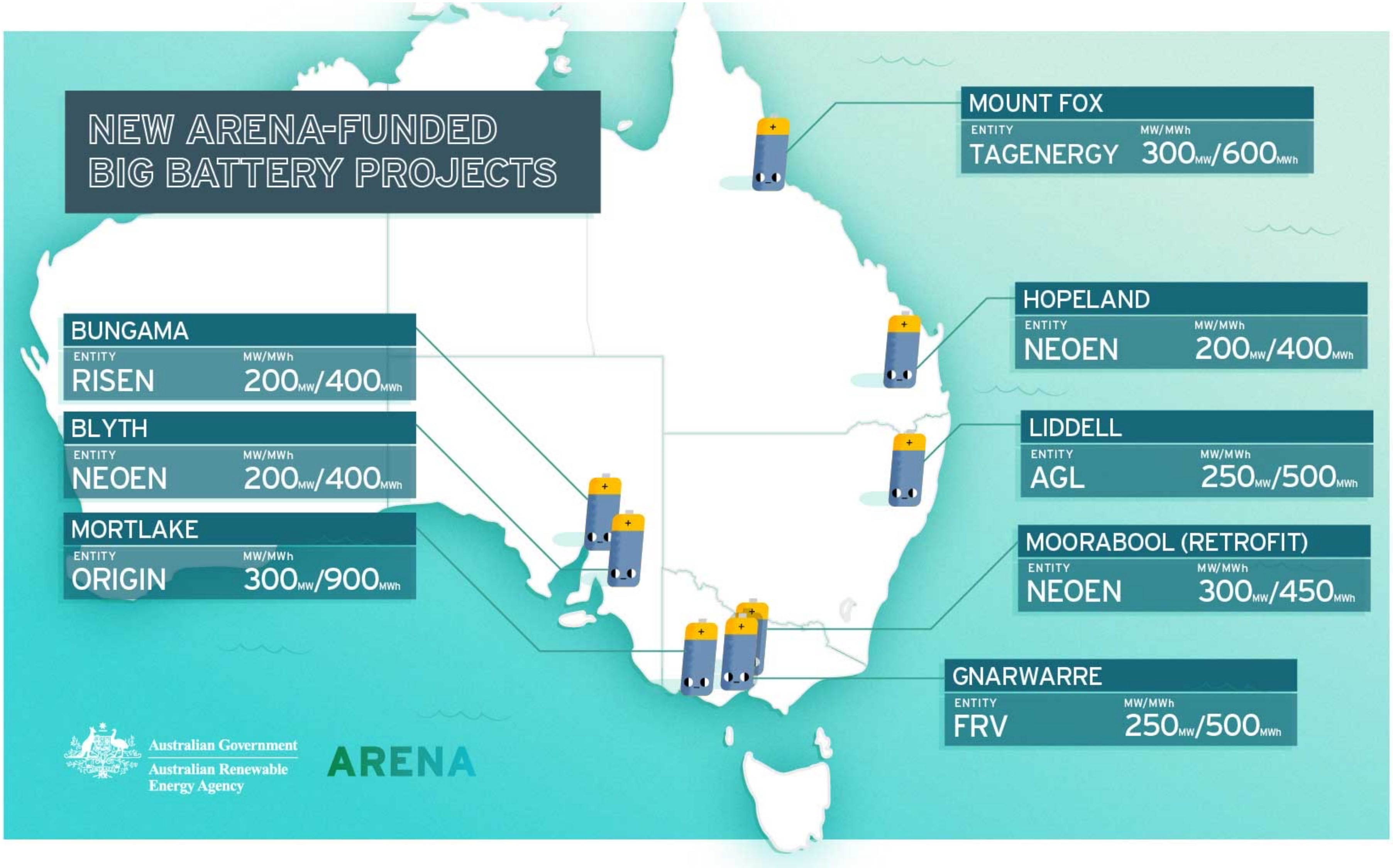

Source: H. Kikusato, et al., "Verification of Power Hardware-in-the-Loop Environment for Testing Grid-Forming Inverter," Energy Reports 2023, 9 (supplement 3), 303–311.

# As IBR ratio increased, frequency change increased for conv. IBR, decreased for GFL and GFM Inverters. GFM inverters were stable at 80%.




Source: H. Kikusato, et al., "Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing," Energy Reports 2023, 9 (supplement 1), 381–392.

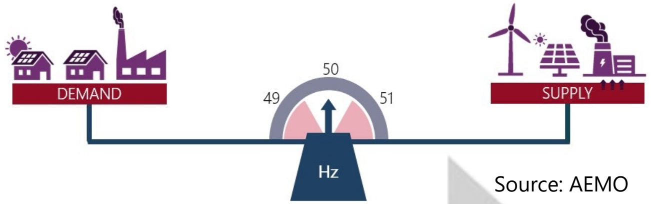
# 8 GFM batteries with total capacity of 2.0 GW/4.2 GWh




Source: ARENA, Large Scale Storage Funding Round https://arena.gov.au/news/arena-backs-eight-grid-scale-batteries-worth-2-7-billion/
ARENA https://arena.gov.au/blog/arena-backs-eight-big-batteries-to-bolster-grid/

AIST FREA

# Technology options for flexibility



Source: AEMO

Subseconds → Seconds → Minutes → Hours → Days → Months → Years

Issues addressed

Conventional power plants & fossil fuels

+ Advanced inverter technology

Variable renewable energy (VRE)

ng

longer periods of surplus/deficit

varable generation and demond

Energy storages

Example issue

Electricity network reinforcement

Relevant to integration phase

Phas

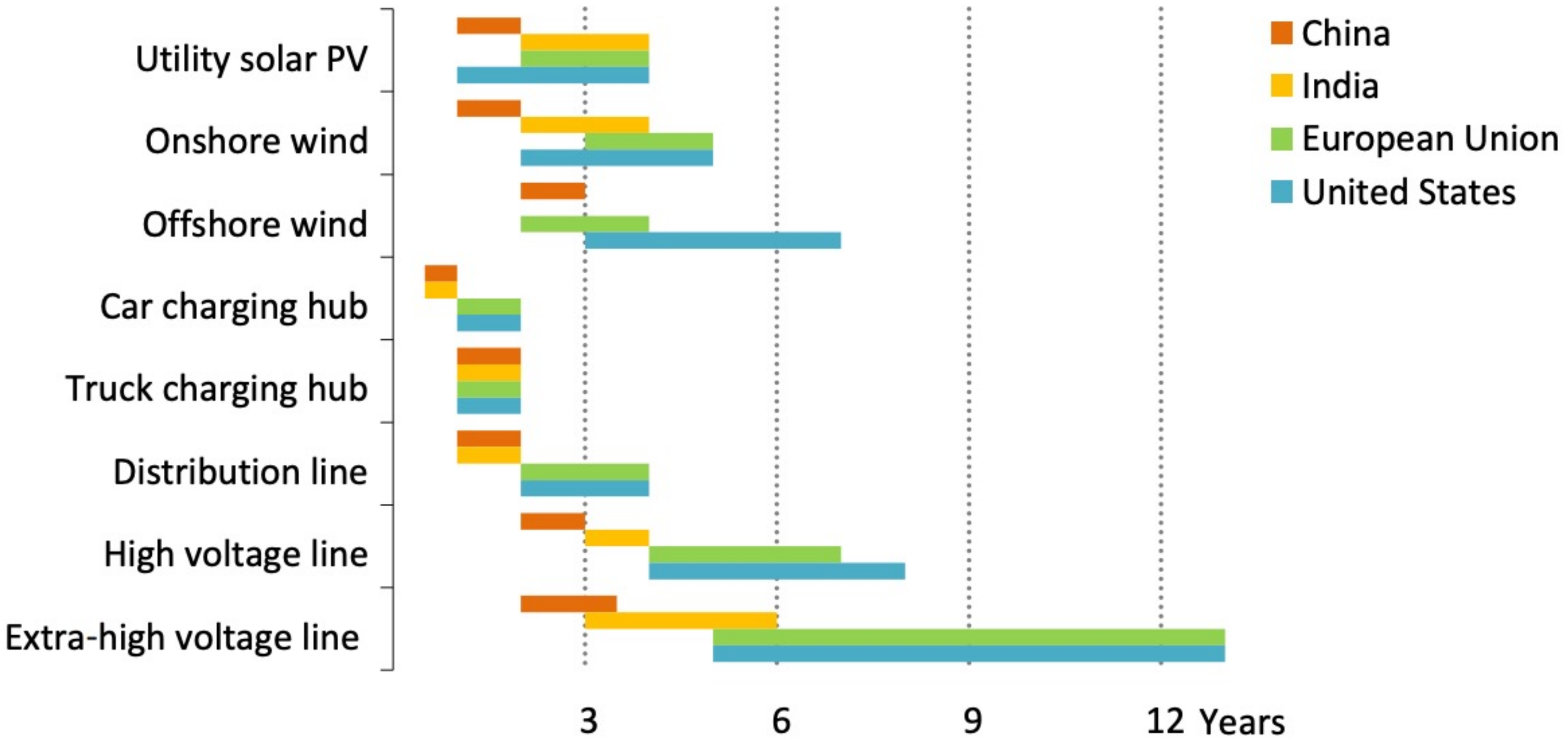
5 and 6

- Network reinforcement and intra-/inter-regional interconnections benefit to improve security of supply, system efficiency, and integration of VRE resources.
- Electricity networks enhance system flexibility by allowing a wider set of flexible hardware resources to be shared across different regions.
- Today, significant flexibility resources are still being underutilised due to transmission and interconnection bottlenecks.

Source: IEA (2020), Introduction to System Integration of Renewables, IEA, Paris https://www.iea.org/reports/introduction-to-system-integration-of-renewables, License: CC BY 4.0

# Electricity network reinforcement takes many years

- Electricity grid deployment is complex and involves many stakeholders
- Flexibility by VRE should be utilized first




Typical deployment time for electricity grid and DERs

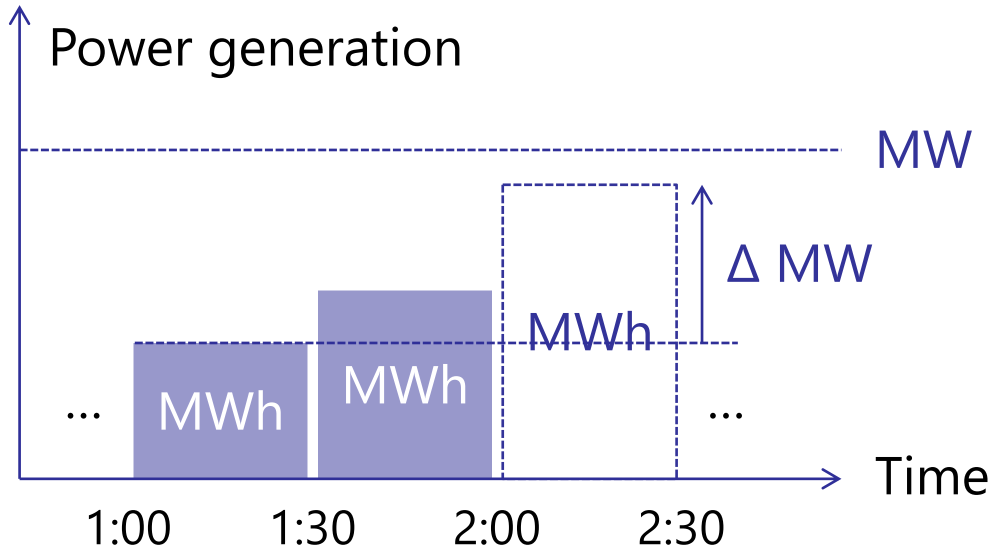
Source: IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)

# How to Ensure Flexibility

# Market

- Subsidy-based incentives (feed-in-tariff, feed-in-premium, etc.) contributed significantly to increasing the VRE penetration in the early stages, but cannot continue forever

- Electricity markets are being redesigned to better suit DERs by classifying value of flexibility
  - Long, medium, short-term markets, and ancillary services markets



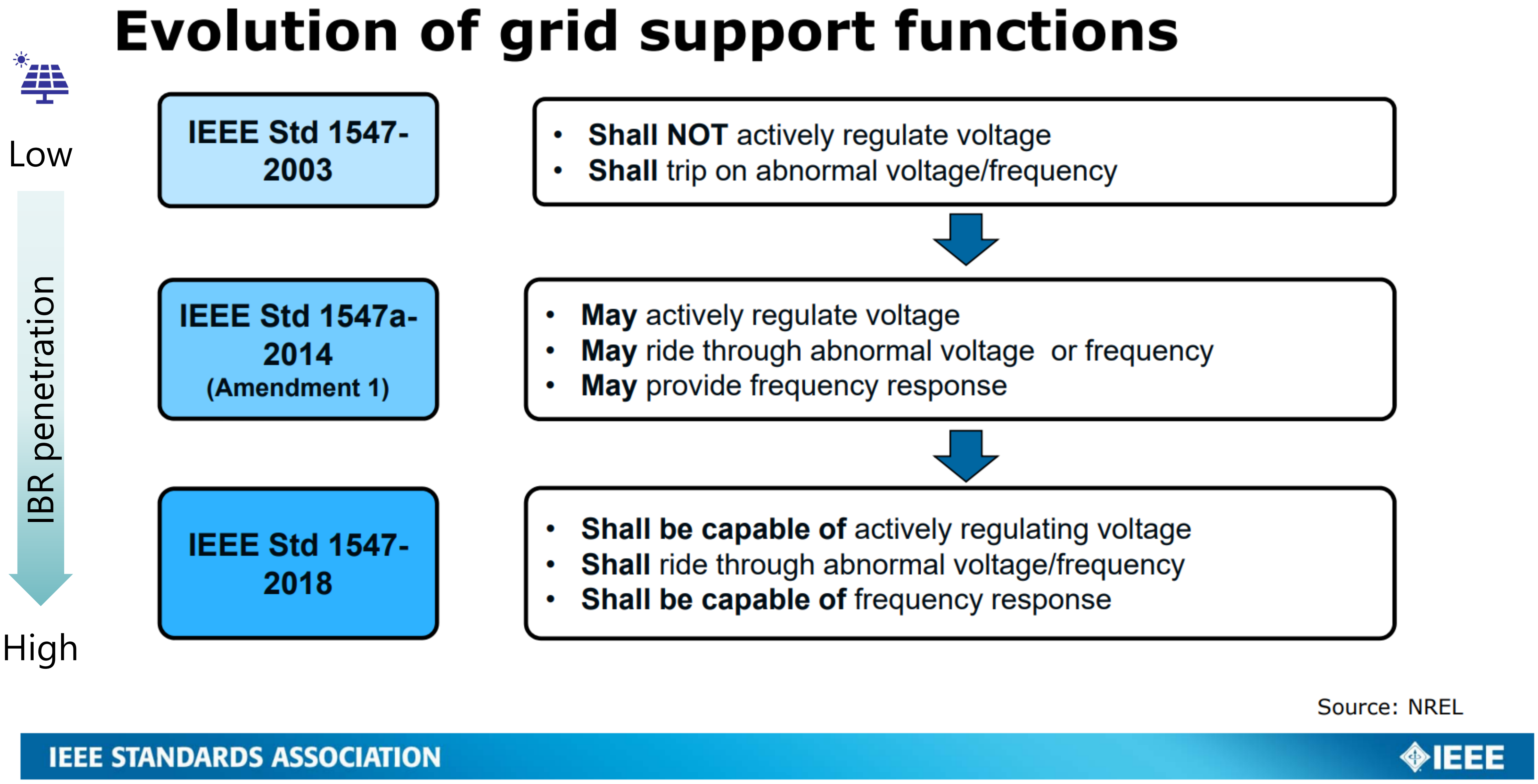

Source: IEA (2020), Introduction to System Integration of Renewables, IEA, Paris https://www.iea.org/reports/introduction-to-system-integration-of-renewables, License: CC BY 4.0

# Grid Code: Connection Requirements

- To ensure proper coordination of all components in the power system, a set of rules and specifications called the "grid code" should be developed and adhered to by all stakeholders in the power sector.
- Grid codes cover many aspects, including connection codes, operating codes, planning codes and market codes.
- Grid codes are particularly relevant for wind and solar PV plants because they are technically very different from traditional generators.
- As the share of VRE replacing conventional generation increases, the need for VRE to contribute to providing grid support services such as frequency regulation, active/reactive power control, voltage control, and operating reserves.
- As a result, more strict and precise technical requirements are required from VRE plants connected to the grid.
- Many system operators around the world have already enabled the provision of system services from new system resources through technical and operational requirements embedded in grid codes.

Source: IEA (2020), Introduction to System Integration of Renewables, IEA, Paris https://www.iea.org/reports/introduction-to-system-integration-of-renewables, License: CC BY 4.0

# Changes in technical requirements due to increase in IBRs

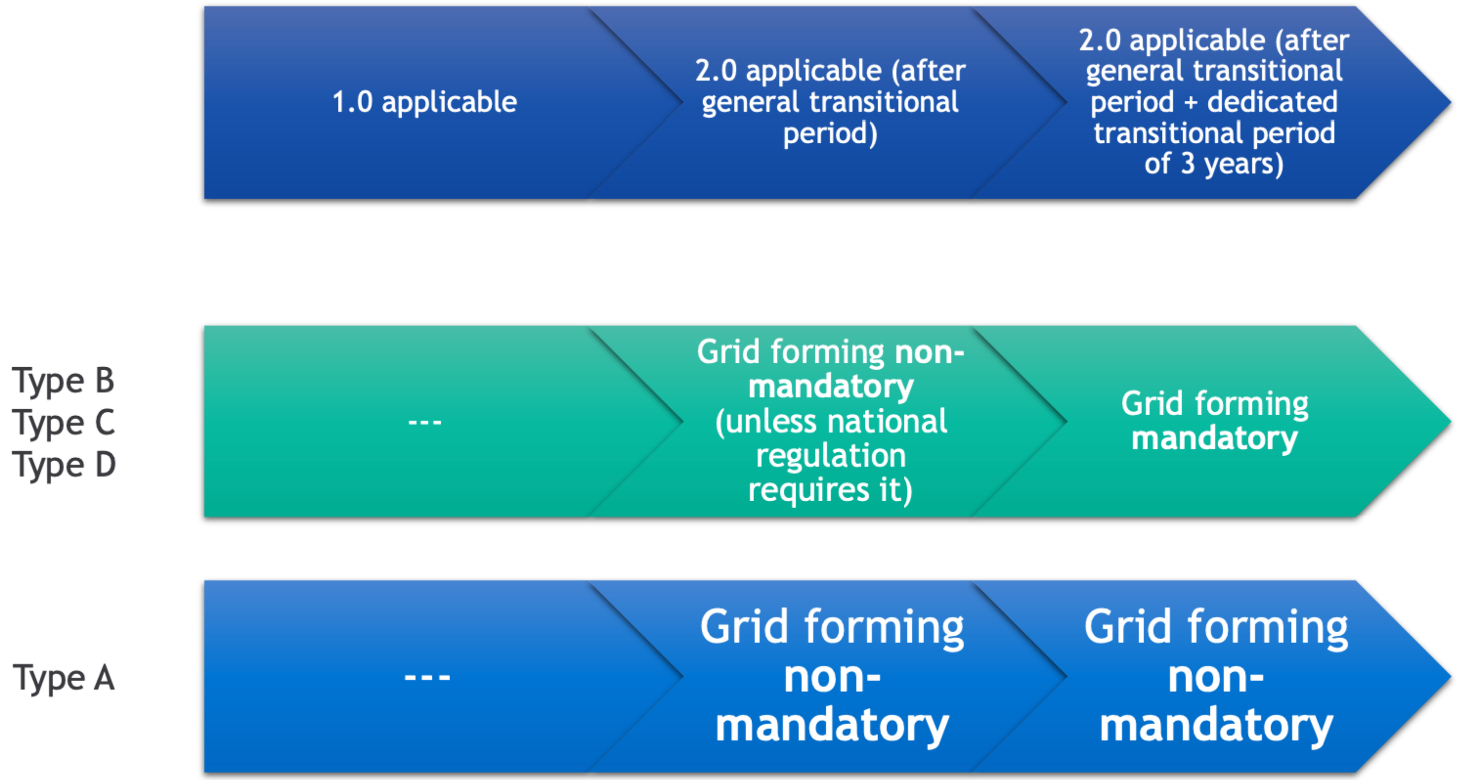



Source: C. Stice, et al., "IEEE Std 1547-2018," NERC SPIDER WG Meeting, 2019

# Implementation of GFM capability is just around the corner

- NC RfG 2.0 with GFM requirement will enter in force in 2024 and will be reflected in national grid codes within three years

## NC RfG 2.0 / Grid forming new Article




entsoe 6

Source: "ENTSO-E amendment proposal for NC RfG: on Grid Forming Capability," ENTSO Public Workshop, 2022

# It is important to involve all stakeholders in the power sector

| | |
|---|---|
| Government | Energy strategies, legal framework |
| Regulatory/ Standard body | Regulator framework (market rule, retail electricity pricing, etc.), standard |
| System operator | Grid code, power system operation |
| Manufacturer | Incorporate technical requirements into equipment and systems |
| Prosumer | End-users of electricity and DERs |

Source: TBS NEWS https://www.youtube.com/watch?v=0IKVb2flxxc


*"Not that I can see them clearly, the number 46 came to me dimly. A silhouette came to mind."*

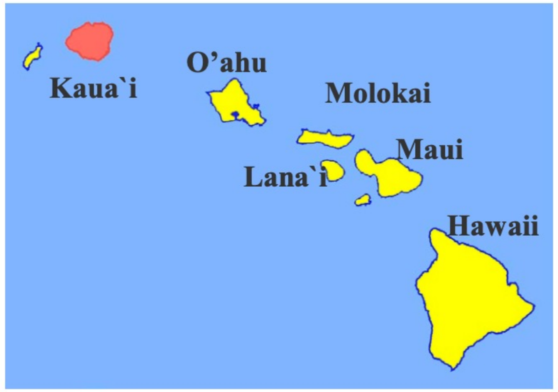
*Shinjiro Koizumi*
*Former Minister of the Environment*

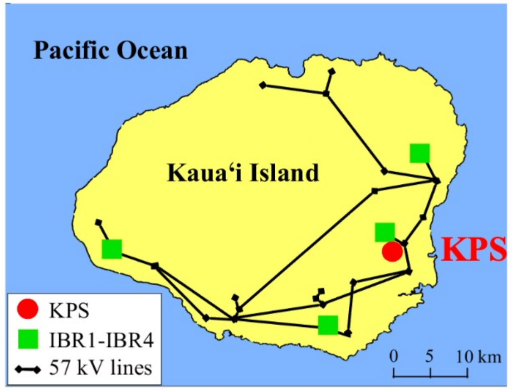
# Appendix

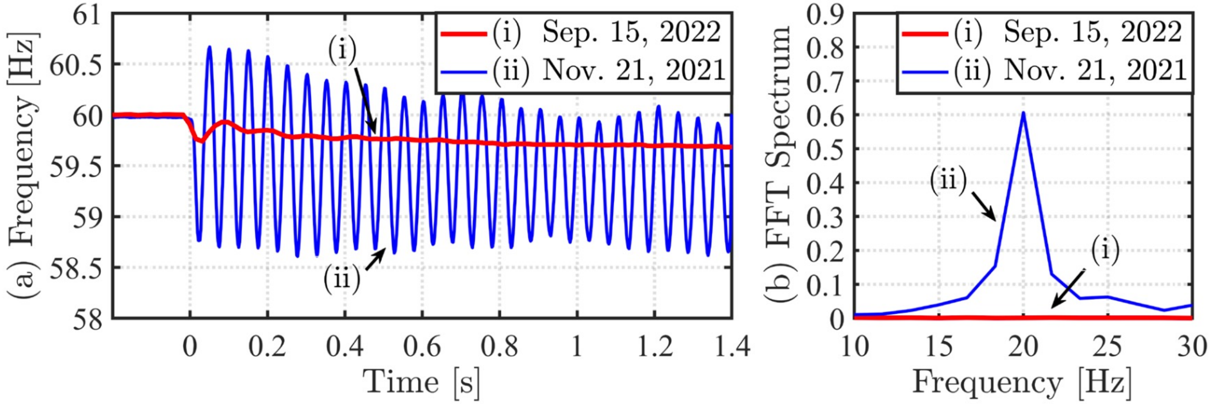
# Actual Events Led by High Share of IBR

# 19.5 Hz oscillation event on Kauai island in 2021

- November 21, 2021
  - The largest generator (26.6 MW output, 60.6% of power demand) on Kauai tripped
  - Fast power response from 4 BESSs avoided significant load shedding and possible blackout, but significant 19.5 Hz oscillations lasted for about one minute
- September 15, 2022
  - The generator with 8.6 MW has tripped again. But IBR1 has been upgraded to GFM controllers in the field
  - There was no ~19Hz oscillation following the generator trip
  - Converting IBR1 from GFL to GFM effectively mitigated the oscillations




Source: J. Tan et al., "Analysis of 19.5 Hz Oscillation on Kaua'i Island System"
https://www.esig.energy/download/session-5-analysis-of-19-5-hz-oscillation-on-kauaiisland-system-jin-tan/?wpdmdl=10026&refresh=6426fae6a53031680276198

# Disturbances in Odessa, Texas

- May 9, 2021
- Experienced a widespread reduction of over 1,100 MW of solar PV resources due to a normally cleared fault on the bulk power system

| Table I.1: Predisturbance Resource Mix | | |
|---|---|---|
| **BPS Operating Characteristic** | **MW** | **%** |
| Internal Net Demand | 47,434 | - |
| Solar PV Output | 4,533 | 9% |
| Wind Output | 15,952 | 34% |
| Synchronous Generation | 26,383 | 56% |

*ERCOT was importing 566 MW through dc ties

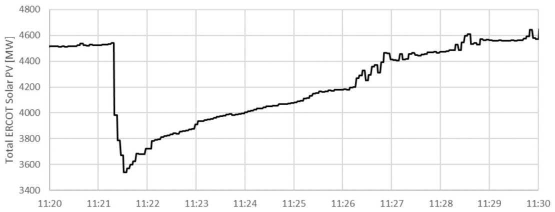



Figure I.5: ERCOT BPS-Connected Solar PV during Disturbance [Source: ERCOT]

| Table ES.1: Reductions of Output by Unit Type | |
|---|---|
| **Plant Type** | **Reduction [MW]** |
| Combined Cycle Plant | 192 |
| Solar PV Plants | 1,112 |
| Wind Plants | 36 |
| **Total** | **1,340** |

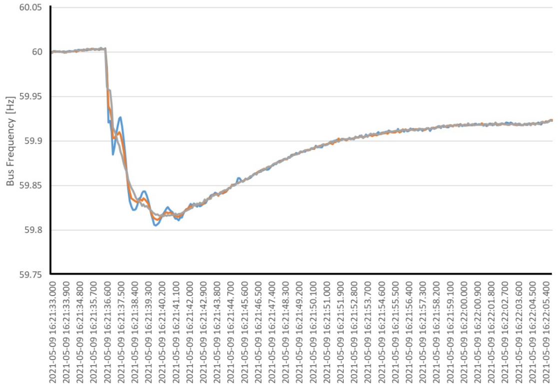



Figure I.6: System Frequency during Event [Source: UTK/ORNL]

- June 4, 2022
- 1,711 MW of IBRs from many different facilities unexpectedly reduced power output due to the protection and controls at each site due to normally-cleared fault

| Table I.1: Predisturbance Resource Mix | | |
|---|---|---|
| **BPS Operating Characteristic** | **MW** | **Percentage** |
| Internal Net Demand | 55,436 | - |
| Solar PV Output | 8,740 | 15.8% |
| Wind Output | 5,742 | 10.4% |
| Synchronous Generation | 40,744 | 73.5% |

*ERCOT was importing 210 MW

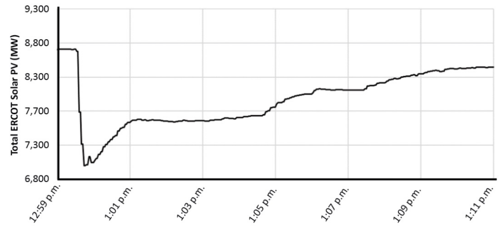



Figure I.4: ERCOT BPS-Connected Solar PV Generation during Disturbance [Source: ERCOT]

| Table ES.1: Reductions of Output by Unit Type | |
|---|---|
| **Plant Type** | **Reduction [MW]** |
| Synchronous Generation Plants | 844 |
| Solar PV Plants | 1,711 |
| **Total** | **2,555** |

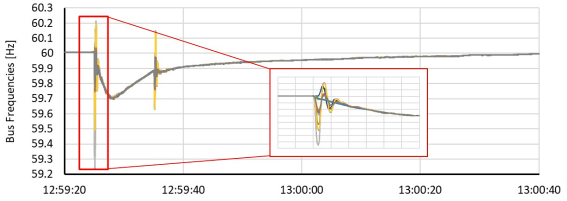
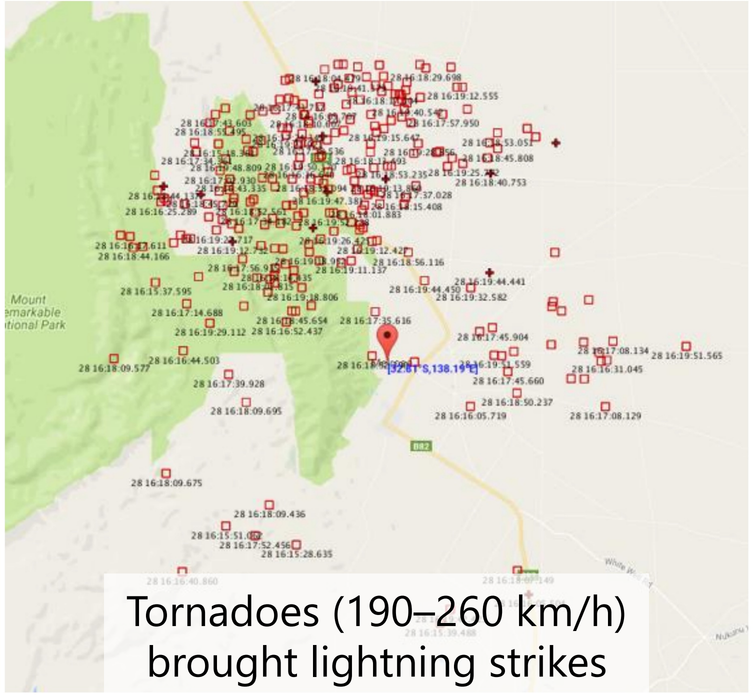



Figure I.5: ERCOT System Frequency

Source: NERC https://www.nerc.com/pa/rrm/ea/Pages/May-June-2021-Odessa-Disturbance.aspx ; https://www.nerc.com/comm/RSTC_Reliability_Guidelines/NERC_2022_Odessa_Disturbance_Report%20(1).pdf

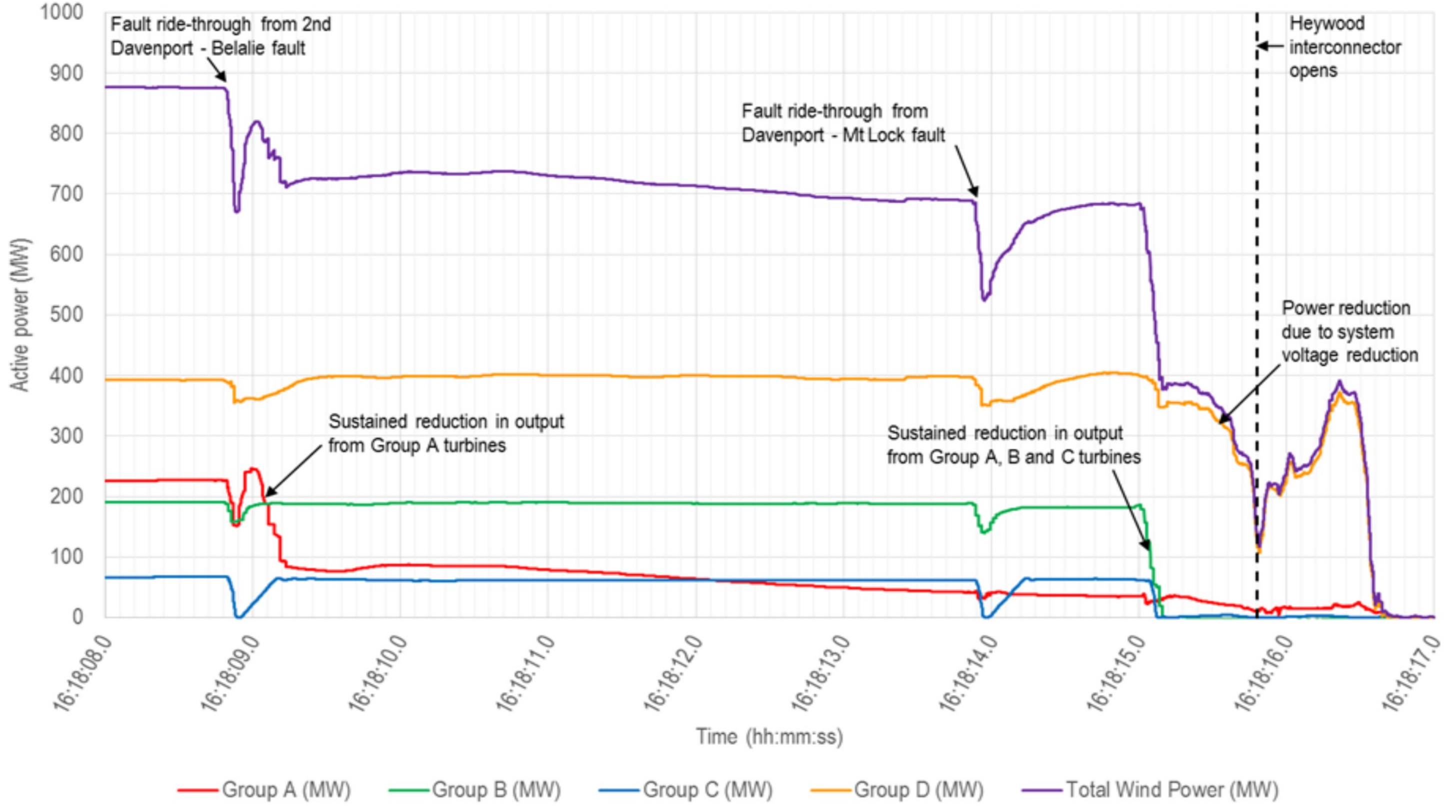
# Blackout in South Australia (SA) on September 28, 2016

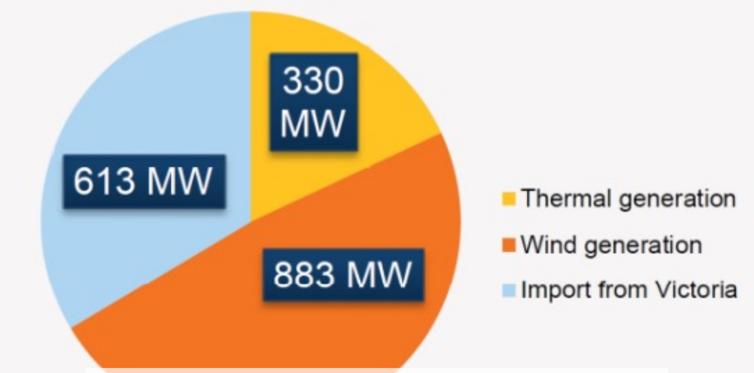
Figure 7 Lightning stike map for Melrose area in the five minutes prior to the Black System



Tornadoes (190–260 km/h) brought lightning strikes

**Figure 11 Wind farm power reduction based on wind turbine grouping**




SA generation mix pre-event

- Damage to 3 TLs and **a series of** voltage dips over a 2-min. period
- 8 wind farms withstood a pre-set number of voltage dips
- When this protection was activated, a significantly sustained power reduction of 456 MW occurred in less than 7 sec.
- Significant increase in imported power flowing
- 850,000 SA customers lost electricity supply

Source: AEMO https://www.aemc.gov.au/markets-reviews-advice/review-of-the-system-black-event-in-south-australi

# [Reference] Power System Voltage and Frequency

**Figure 4 275 kV voltage decline across SA prior to separation**

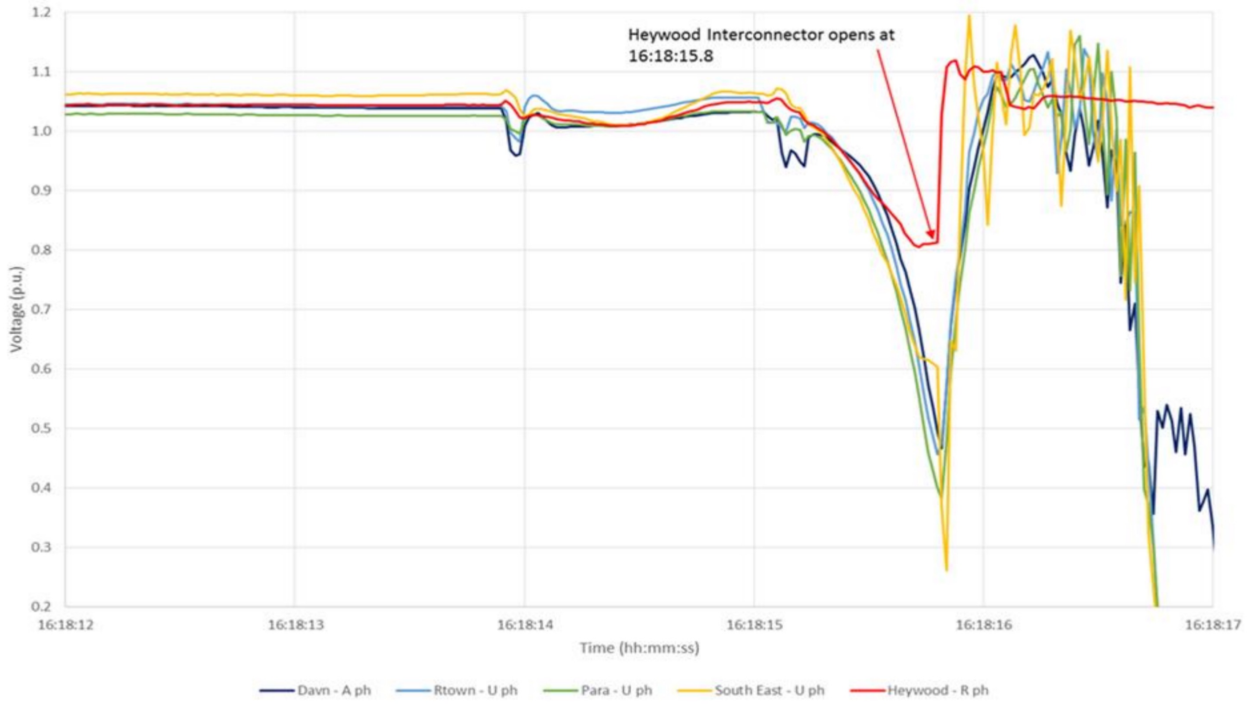
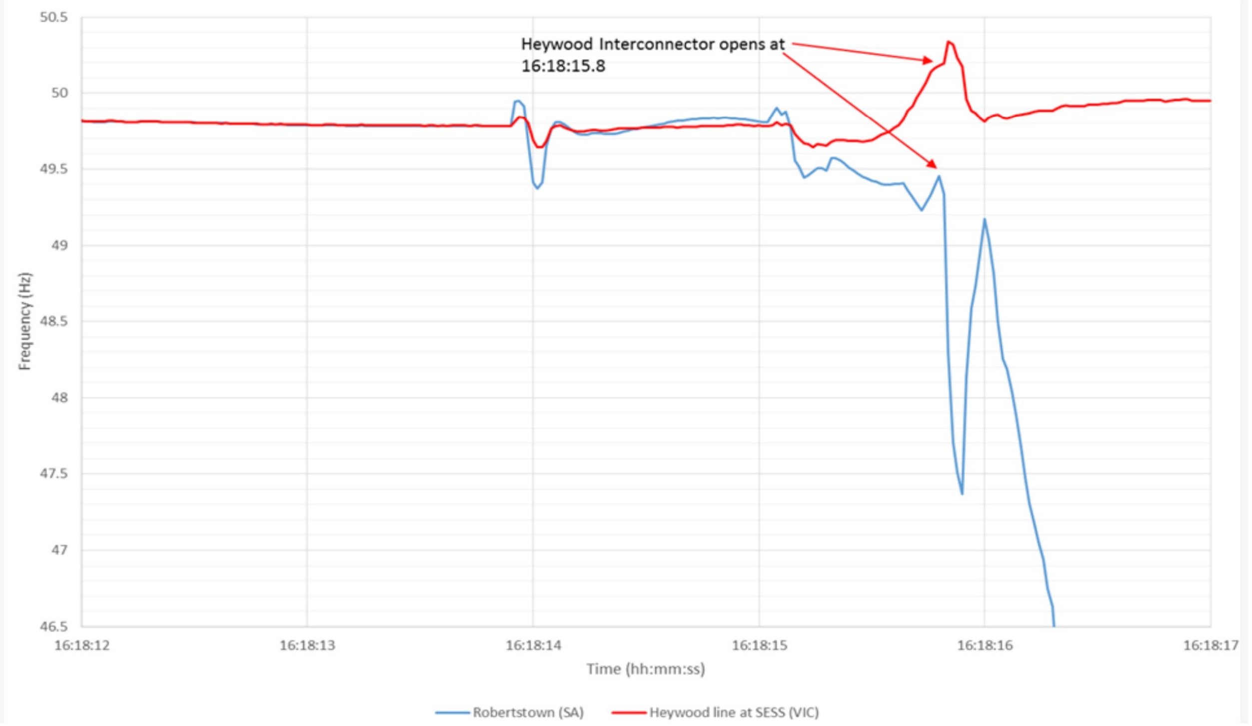
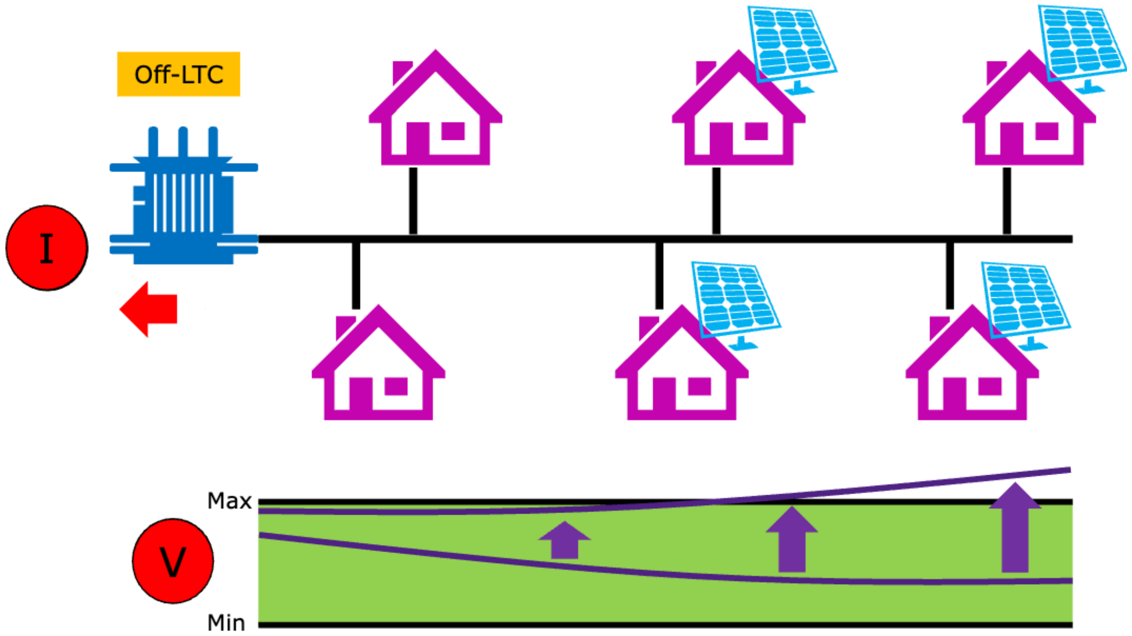



**Figure 5 SA frequency compared to Victoria during event**

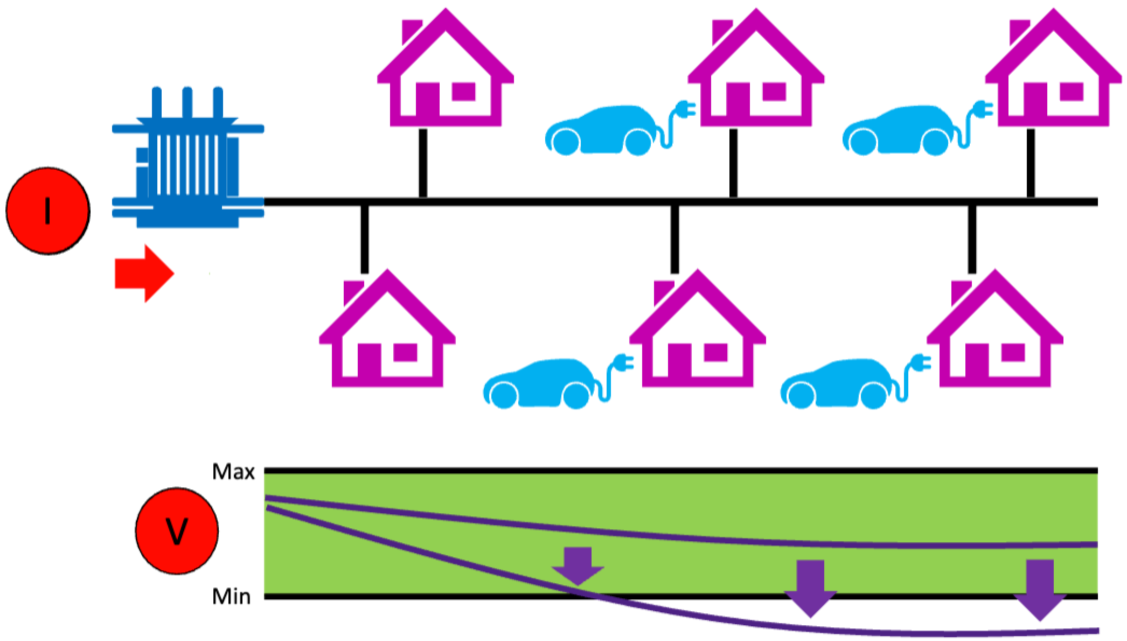



Source: AEMO https://www.aemc.gov.au/markets-reviews-advice/review-of-the-system-black-event-in-south-australi

# Voltage (& Overloading) Issues in Distribution Systems




Voltage rise due to PV generation



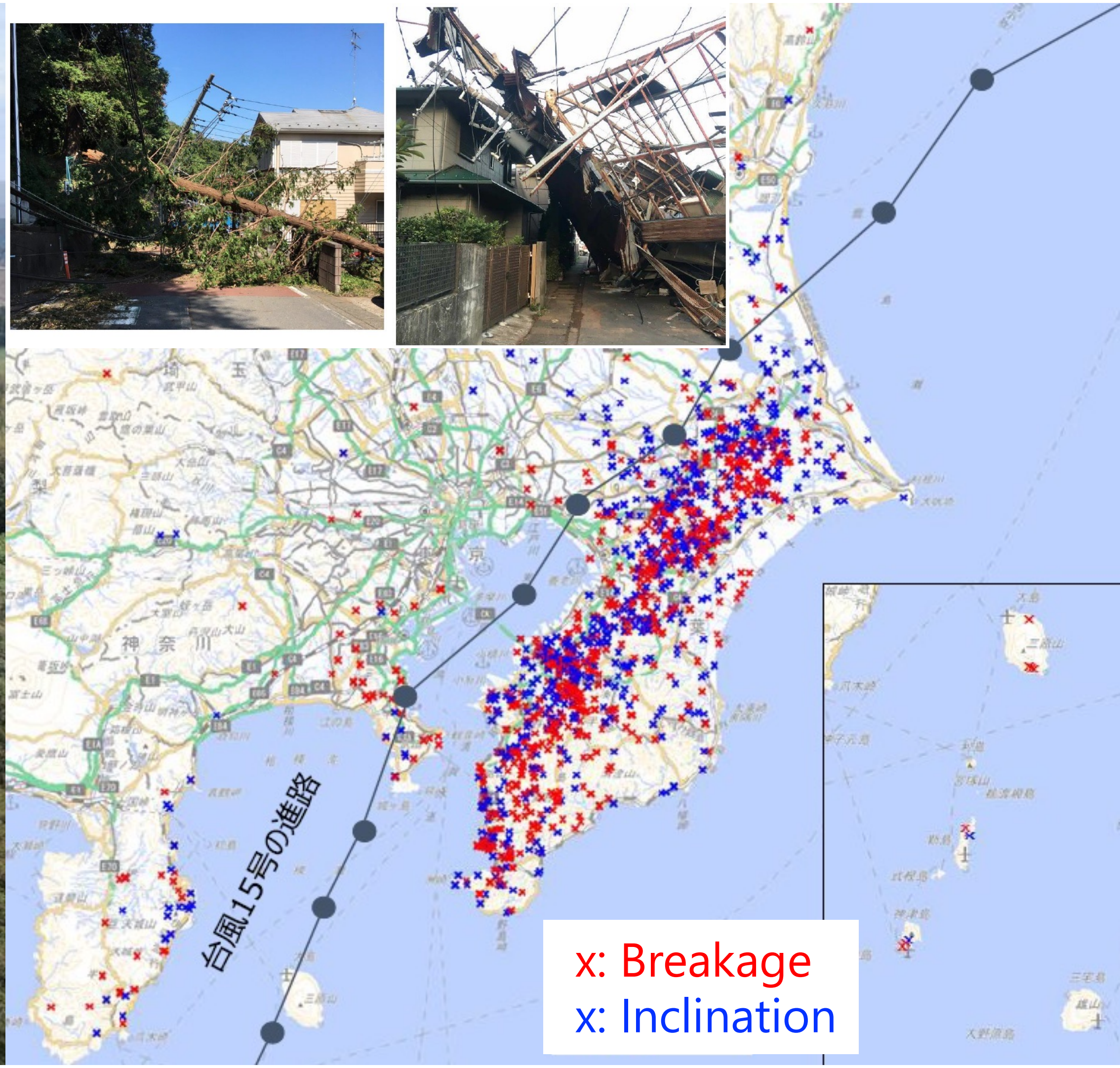

Voltage drop due to EV charging

Source:
Luis(Nando) Ochoa, “The Future of DER Hosting Capacity and Orchestration –Making the most of Smart Meter Data–”, DOI: 10.13140/RG.2.2.32952.52486
Jing Zhu, “Understanding the Effects of EV Management and TOU Tariffs in Future Distribution Networks”, DOI: 10.13140/RG.2.2.14519.39842

# Resilience and Microgrid

# Damage due to Typhoon No. 15

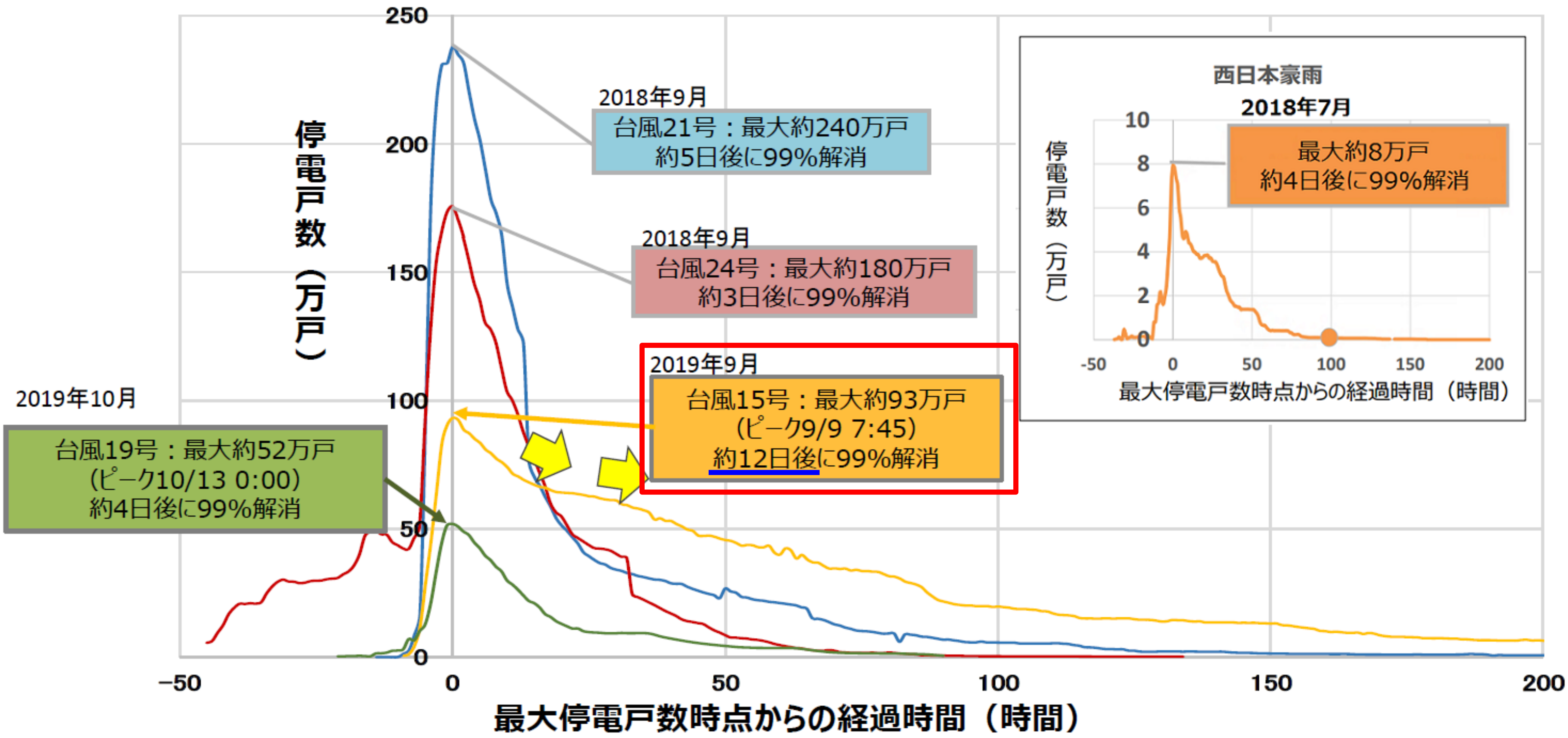
Steel tower collapsed in Chiba, Japan




Damage to utility poles

Source: METI, https://www.enecho.meti.go.jp/about/special/johoteikyo/typhoon.html

# 930,000 customers lost power and it took 12 days to restore it




Source: METI, https://www.enecho.meti.go.jp/about/special/johoteikyo/typhoon.html

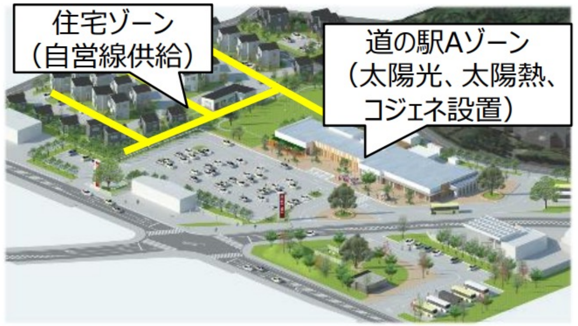
# Mutsuzawa Microgrid contributed to early restoration

## （参考）むつざわスマートウェルネスタウン（特定供給）

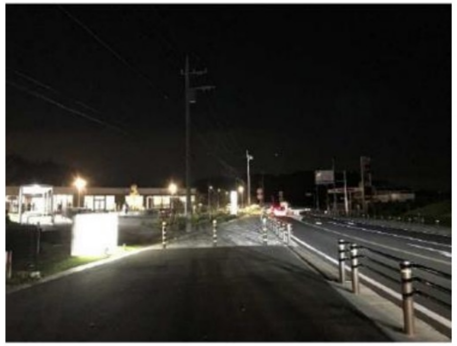
- **再エネ**と**調整力**（コジェネ）を組み合わせたエネルギーの面的利用システムを構築することで、**災害時の早期復旧**に大きく貢献。
- 千葉県睦沢町では、防災拠点である道の駅を近隣住民に開放し、トイレや温水シャワーを提供、800人以上の住民が利用。

むつざわスマートウェルネスタウン　経過概要

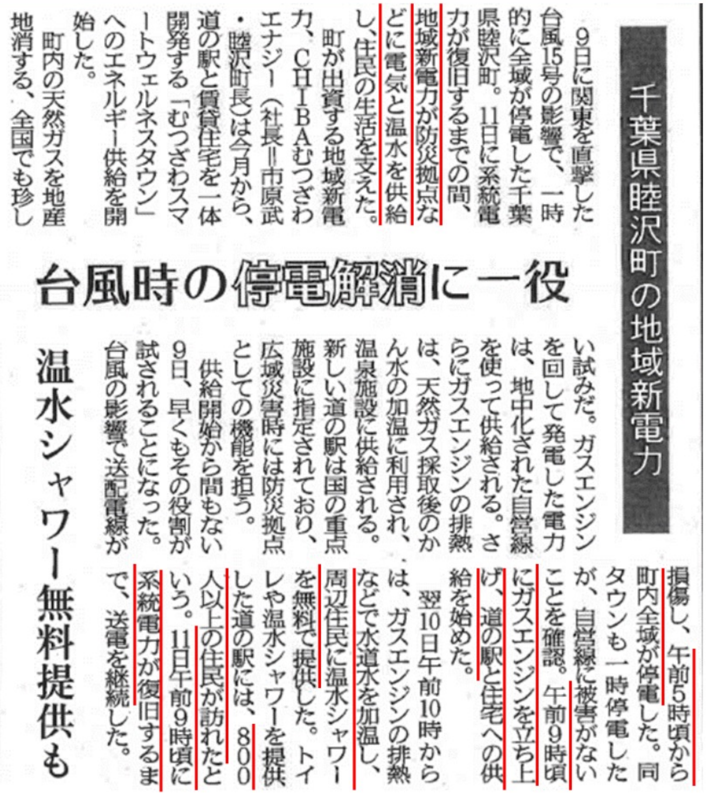
| | | |
|---|---|---|
| 9月9日（月） | 5時 | 町内全域停電 |
| 9日（月） | 9時 | コジェネを立ち上げ住宅と道の駅に供給開始 |
| 10日（火） | 10時 | コジェネの排熱を活用し温水シャワーを提供 |
| 11日（水） | 9時 | 系統復電 |




**<むつざわスマートウェルネスタウン（SWT）>**
事業者：㈱CHIBAむつざわエナジー
システム概要：天然ガスコジェネと再エネ（太陽光と太陽熱）を組み合わせ、自営線（地中化）で道の駅（防災拠点）と住宅へ供給。コジェネの排熱は道の駅併設の温浴施設で活用。
供給開始：2019年9月1日
※経産省、及び環境省の予算事業を活用



↑周辺が停電する中、照明がついている
むつざわSWT
【引用：㈱CHIBAむつざわエナジーHP】



千葉県睦沢町の地域新電力

台風時の停電解消に一役

温水シャワー無料提供も

9日に関東を直撃した台風15号の影響で、一時的に全域が停電した千葉県睦沢町。11日に系統電力が復旧するまでの間、地域新電力が防災拠点などに電気と温水を供給し、住民の生活を支えた。

町が出資する地域新電力、CHIBAむつざわエナジー（社長＝市原武・睦沢町長）は今月から、道の駅と賃貸住宅を一体開発する「むつざわスマートウェルネスタウン」へのエネルギー供給を開始した。

町内の天然ガスを地産地消する、全国でも珍しい試みだ。ガスエンジンを回して発電した電力は、地中化された自営線を使って供給される。さらにガスエンジンの排熱は、天然ガス採取後のかん水の加温に利用され、温泉施設に供給される。新しい道の駅は国の重点施設に指定されており、広域災害時には防災拠点としての機能を担う。

供給開始から間もない9日、早くもその役割が試されることになった。台風の影響で送配電線が損傷し、午前5時頃から町内全域が停電した。同タウンも一時停電したが、自営線に被害がないことを確認。午前9時頃にガスエンジンを立ち上げ、道の駅と住宅への供給を始めた。

翌10日午前10時からは、ガスエンジンの排熱などで水道水を加温し、周辺住民に温水シャワーを無料で提供した。トイレや温水シャワーを提供した道の駅には、800人以上の住民が訪れたという。11日午前9時頃に系統電力が復旧するまで、送電を継続した。

↑ 2019年9月17日付　電気新聞

Source: METI https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/system_kouchiku/007/007_06.pdf

# Big Data and AI in Power System

# Smart Meter

- Automation and remote control
  - Meter-reading
  - Breaker replacement at contract
  - Connection/disconnection to grid
  - Dynamic pricing

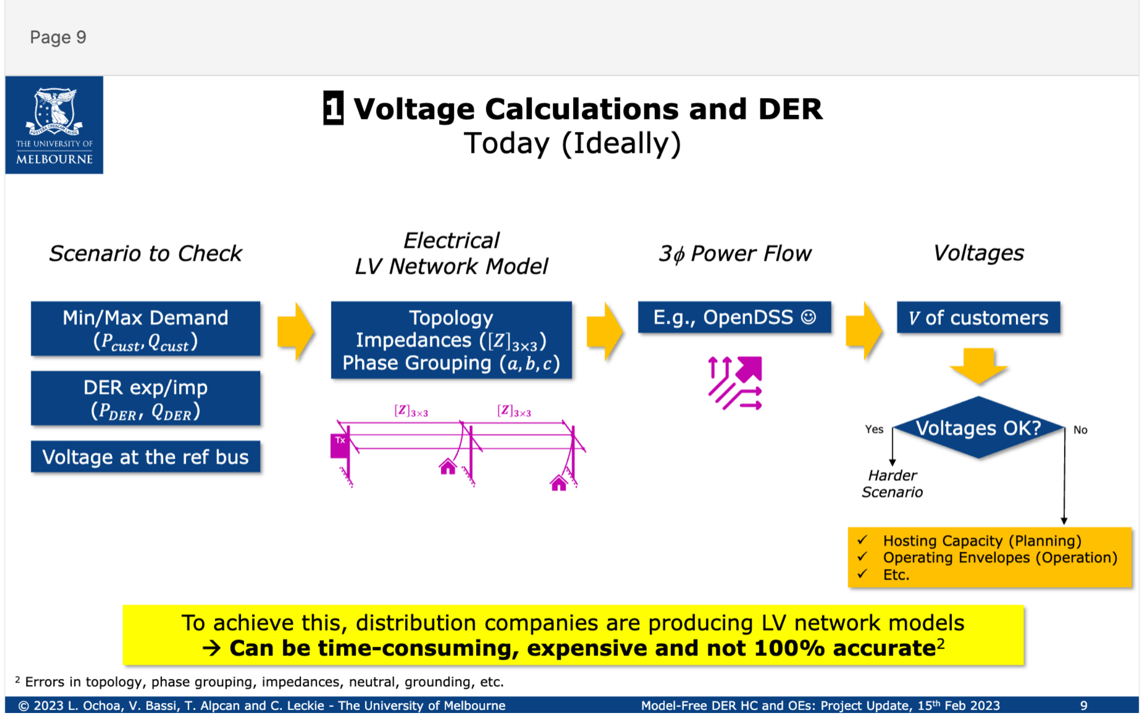
- **Data acquisition**
  - Electricity consumption every 30 min.

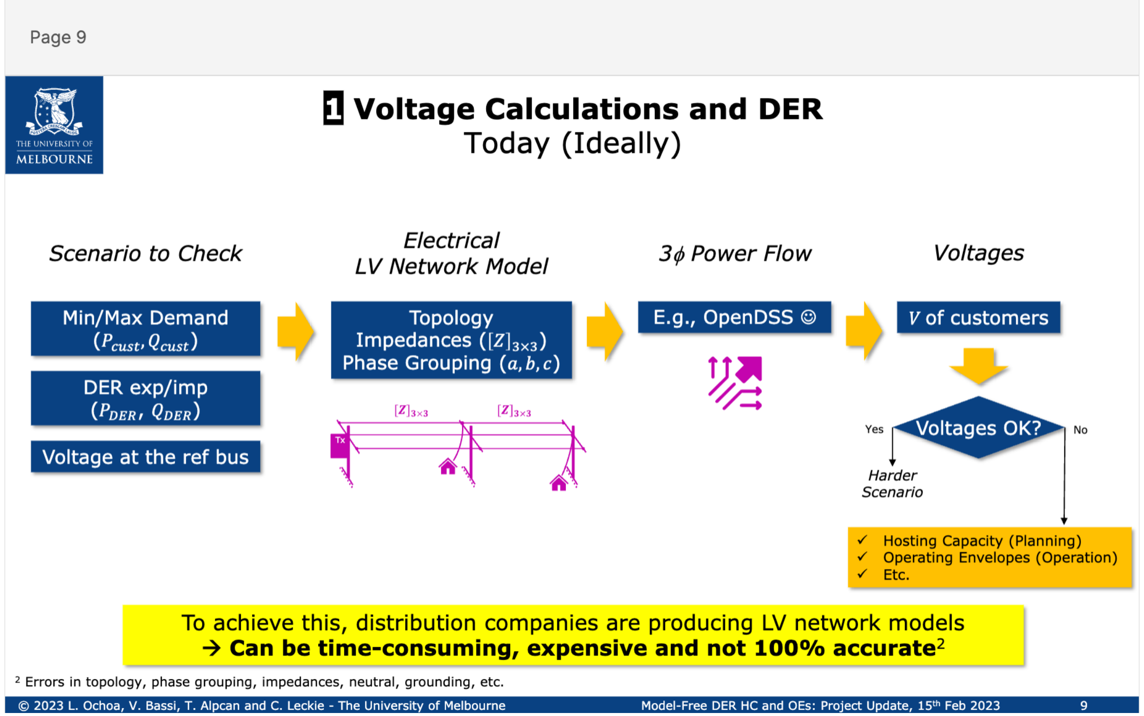
- Examples of data utilization
  - Home delivery service
  - Optimization of home appliance control
  - Population flow estimation for real estate business
  - Monitoring services for the elderly



Source: TEPCO PG https://www.tepco.co.jp/pg/technology/smartmeterpj.html

# Model-Free Approach of Power System Analysis



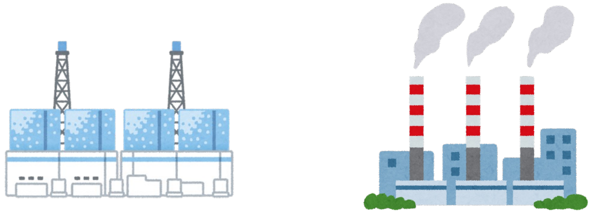

Source:
Luis(Nando) Ochoa, “Model-Free DER Hosting Capacity and Operating Envelopes: Project Update”, DOI: 10.13140/RG.2.2.22483.66087

# Democratization of Power System

# Democratization of Power System Has Begun

- The Internet has democratized various businesses


- Now anyone can become an electric utility company



# Tesla Became the Most Valuable Automaker

Bloomberg Subscribe

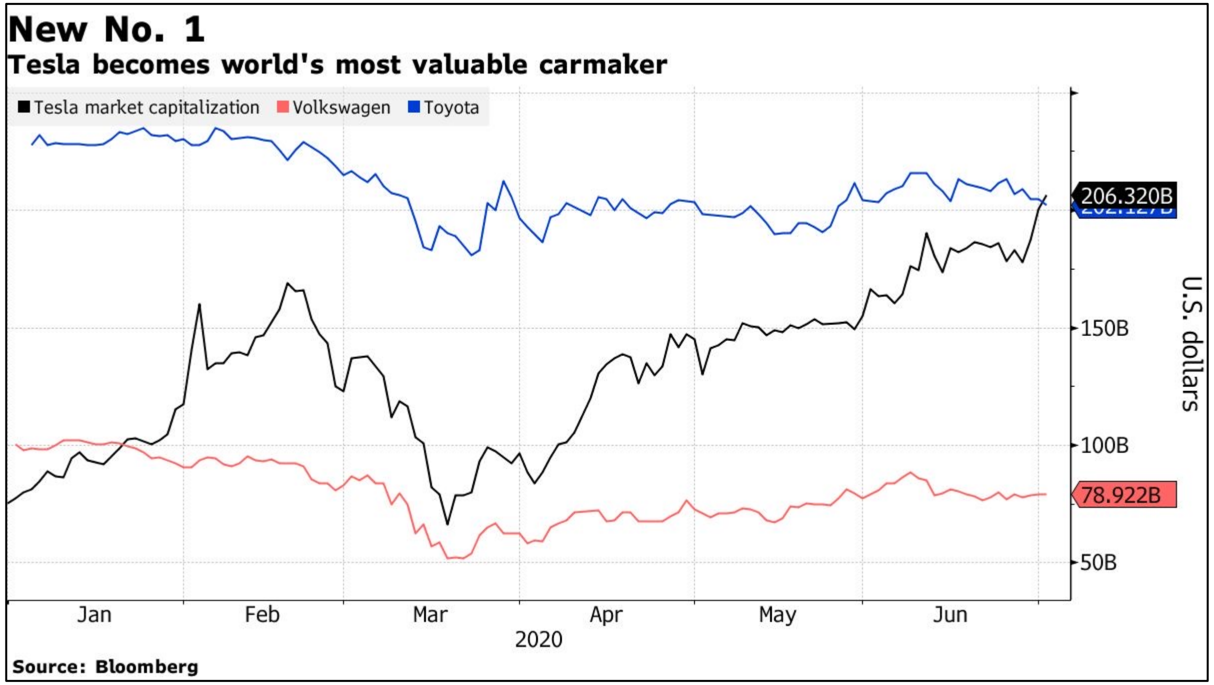
*Photographer: Luke MacGregor/Bloomberg*

Hyperdrive

**Tesla Overtakes Toyota as the World's Most Valuable Automaker**

By Reed Stevenson

2020年7月1日 22:53 GMT+9

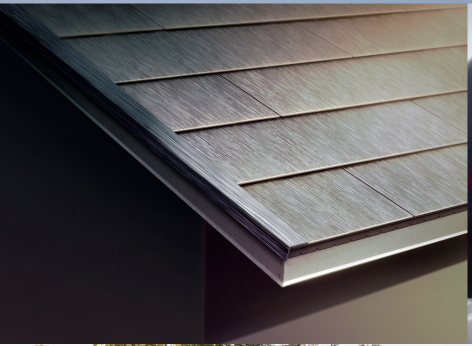



Source: Bloomberg, July 1, 2020, https://www.bloomberg.com/news/articles/2020-07-01/tesla-overtakes-toyota-as-the-world-s-most-valuable-automaker

# But That is Not All

Source: Tesla https://www.tesla.com/en_eu/tesla-gallery

# But That is Not All





Source: Tesla https://www.tesla.com/en_eu/tesla-gallery