Laboratory Testing on Grid-Following and Grid-Forming Inverters with Virtual Inertia Functions

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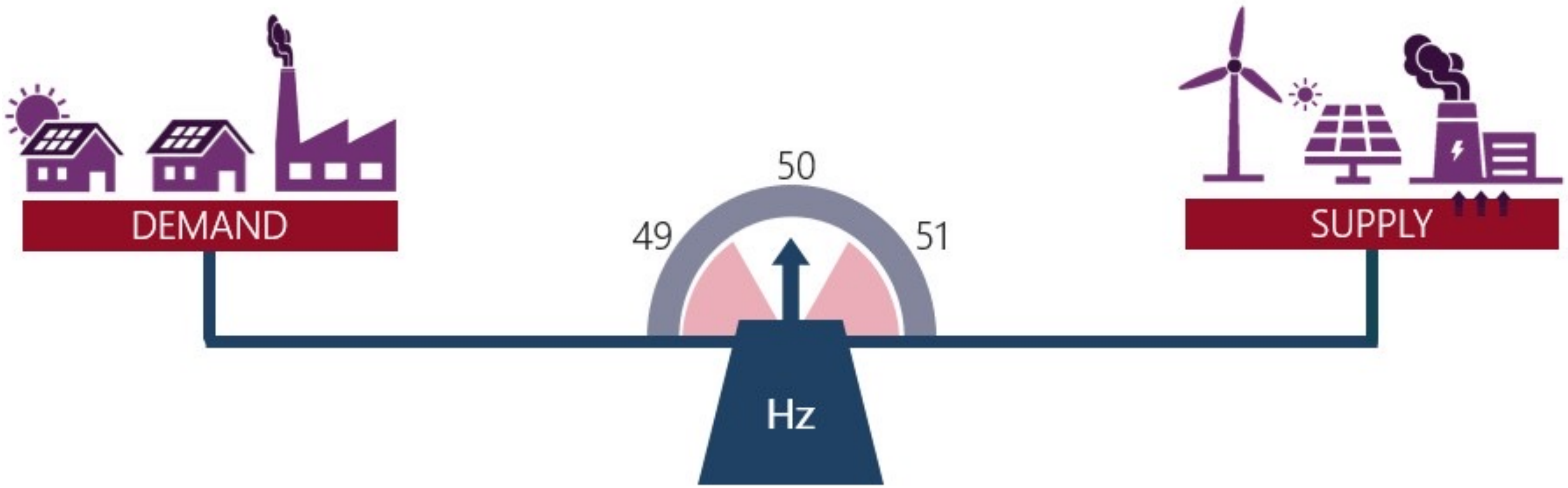
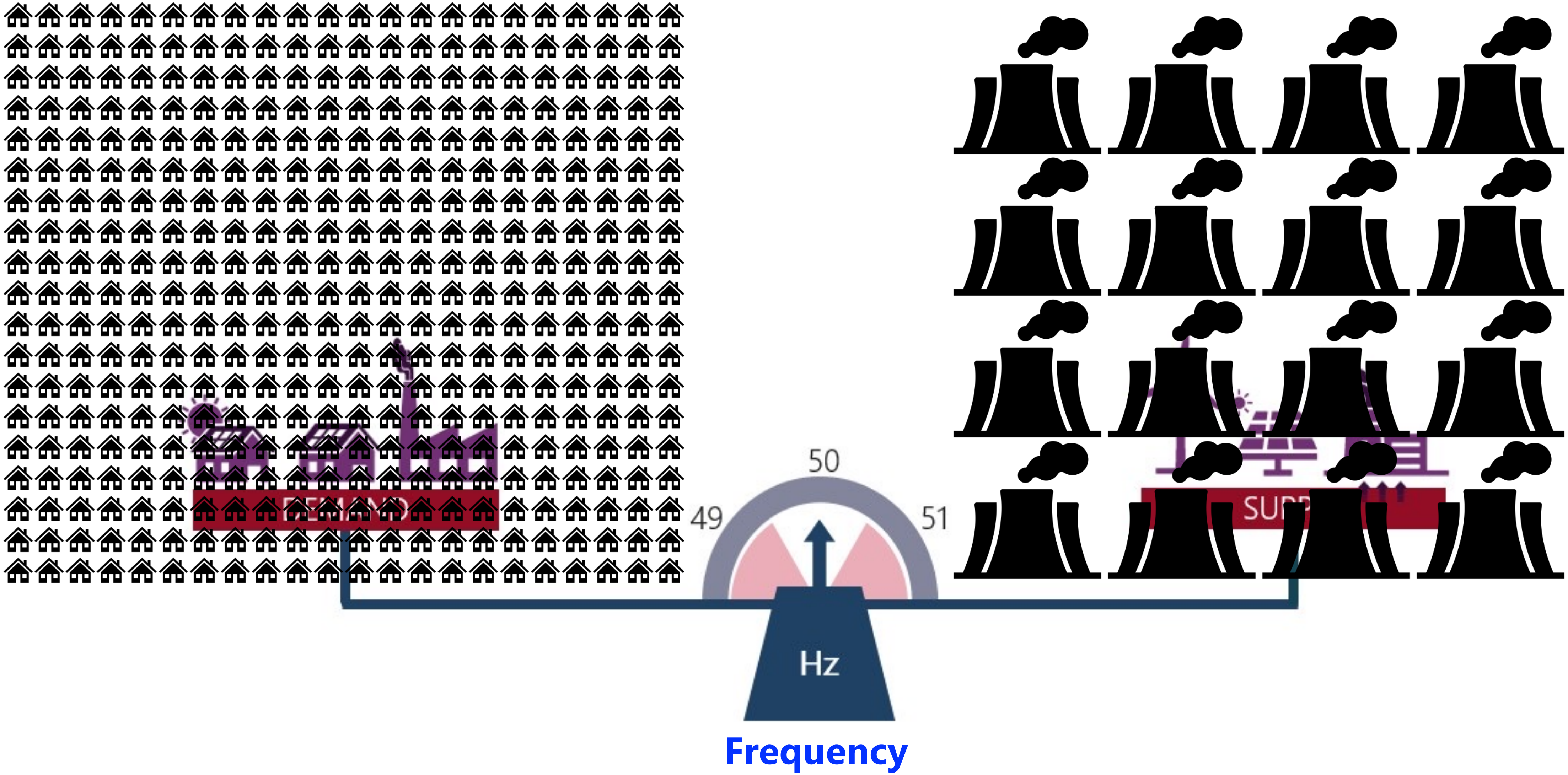
A main role of power system is **always** to balance supply and demand



Frequency

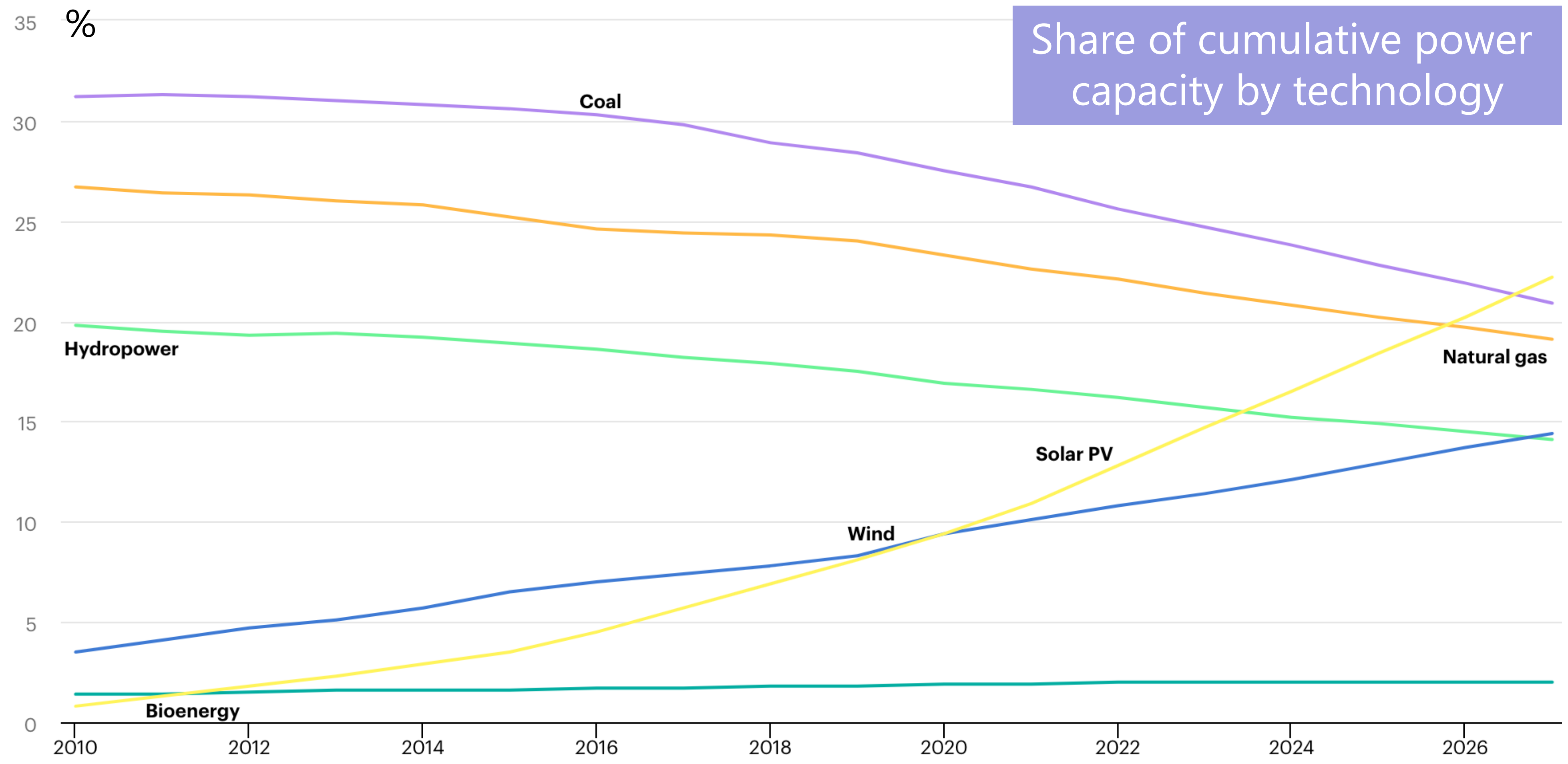
Source: AEMO https://aemo.com.au/learn/energy-explained/energy-101/energy-explained-frequency

Don’t forget power system is composed of many components



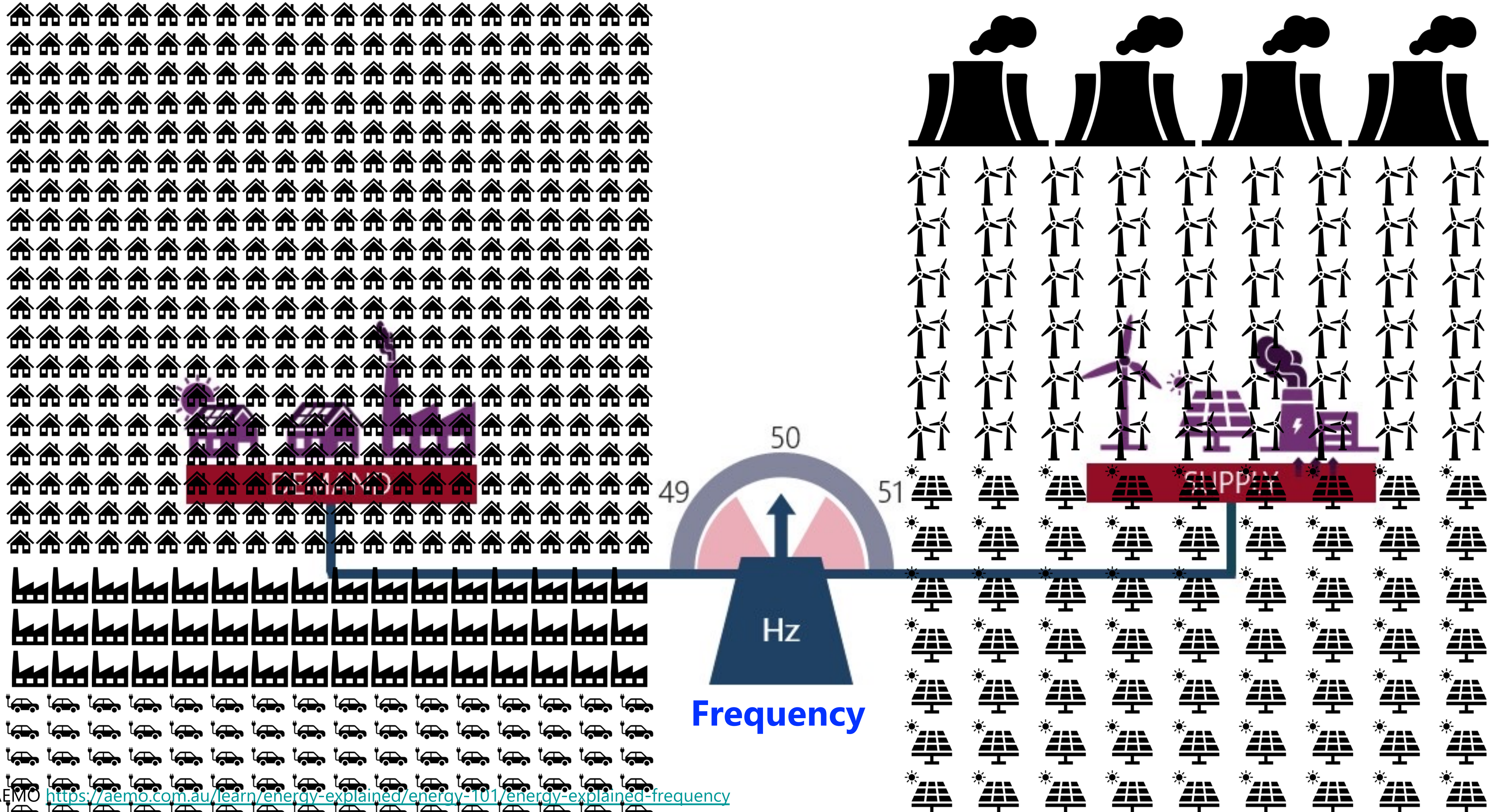
Source: AEMO https://aemo.com.au/learn/energy-explained/energy-101/energy-explained-frequency

Inverter-based resources (IBRs) will increase, and synchronous generators (SGs) will decrease.



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

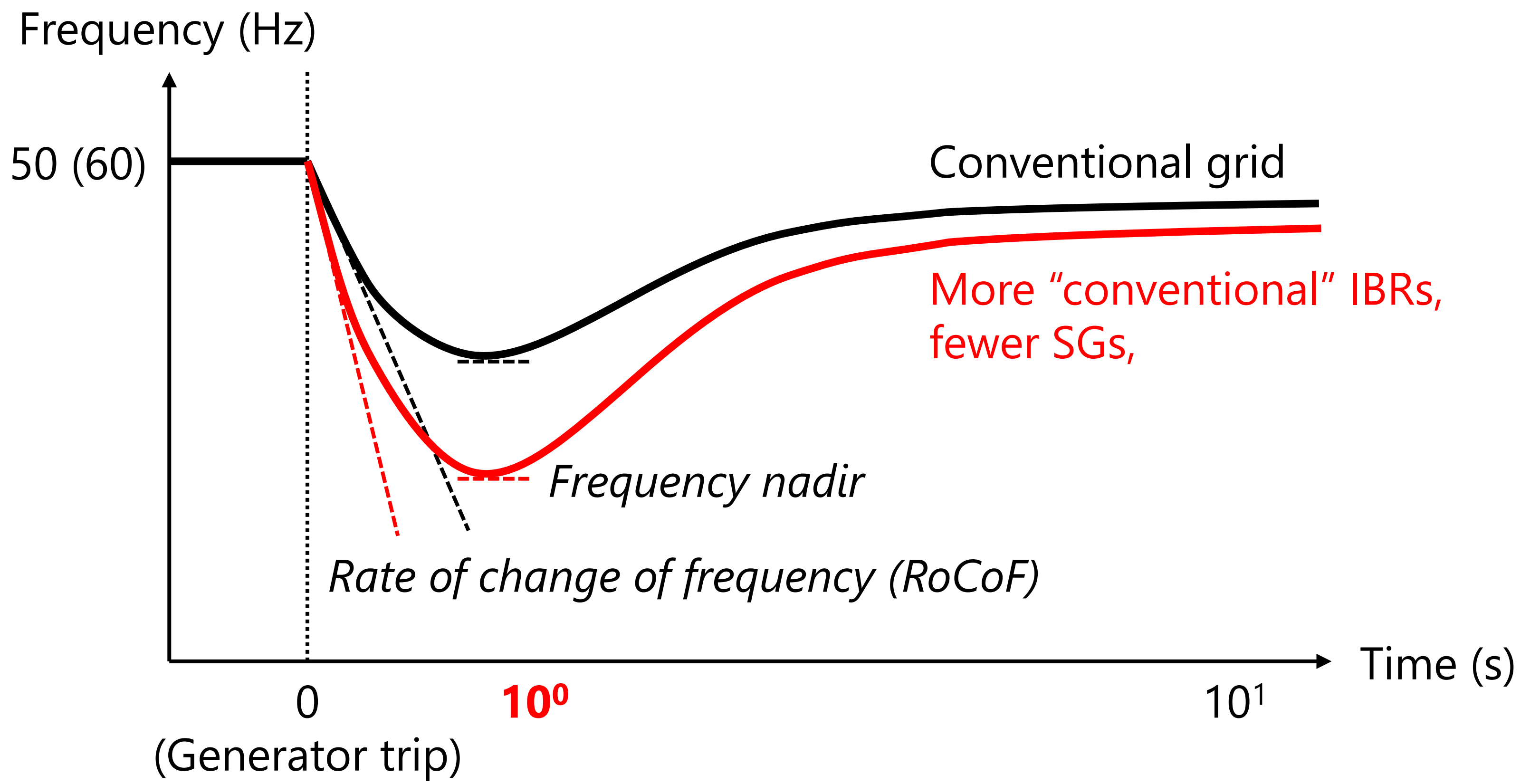
It will be more complicated



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

IBRs are expected to replace some of services provided by SGs

- Reducing the number of synchronous generators (SGs) declines grid frequency stability
- Frequency control including **inertial response** is required for inverter based-resources (IBRs)



Changes in technical requirements due to increase in IBRs

Evolution of grid support functions

Low

IBR penetration

High

IEEE Std 1547-2003	• **Shall NOT** actively regulate voltage • **Shall** trip on abnormal voltage/frequency
IEEE Std 1547a-2014 (Amendment 1)	• **May** actively regulate voltage • **May** ride through abnormal voltage or frequency • **May** provide frequency response
IEEE Std 1547-2018	• **Shall be capable of** actively regulating voltage • **Shall** ride through abnormal voltage/frequency • **Shall be capable of** frequency response

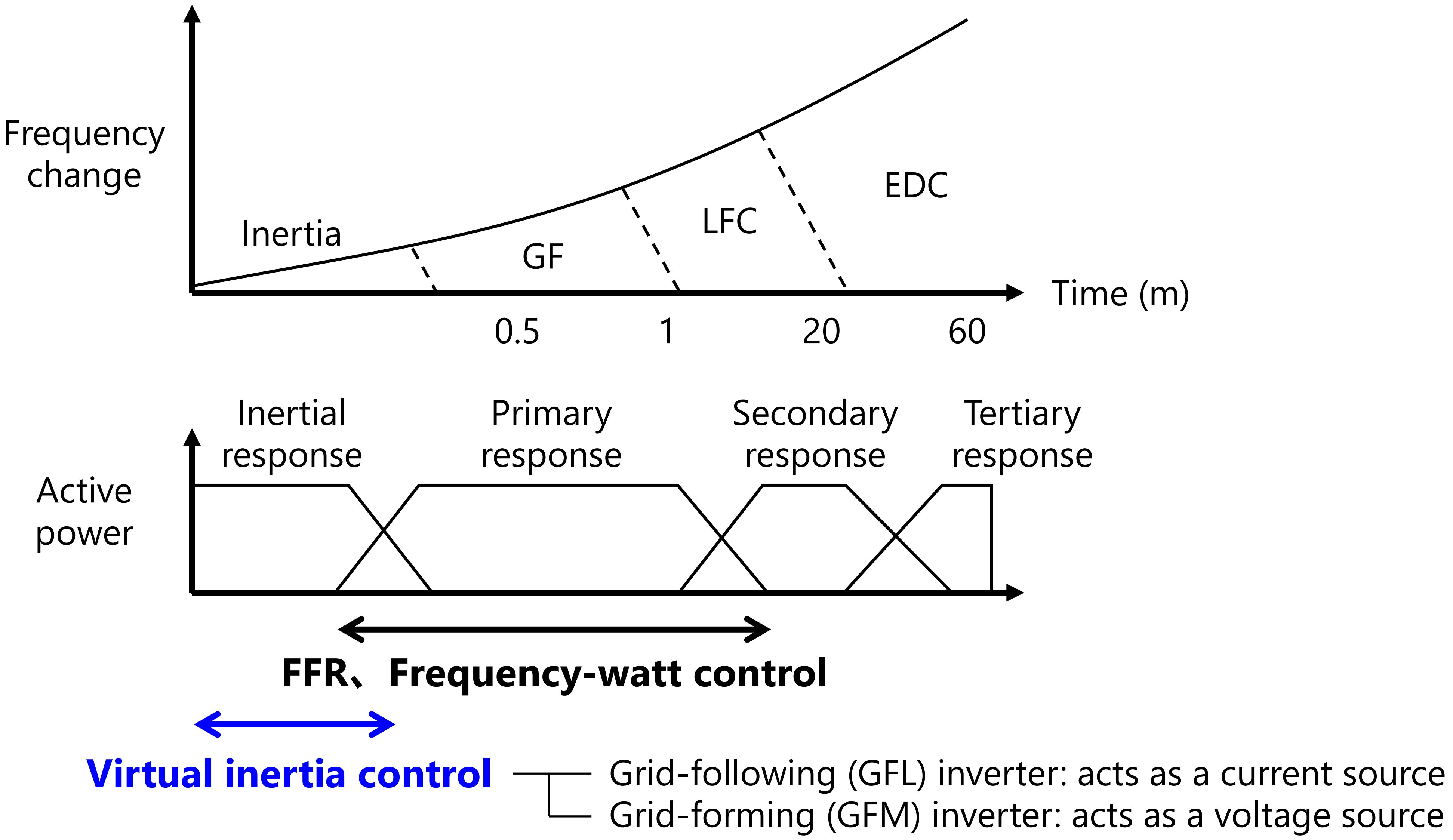
Source: NREL

IEEE STANDARDS ASSOCIATION

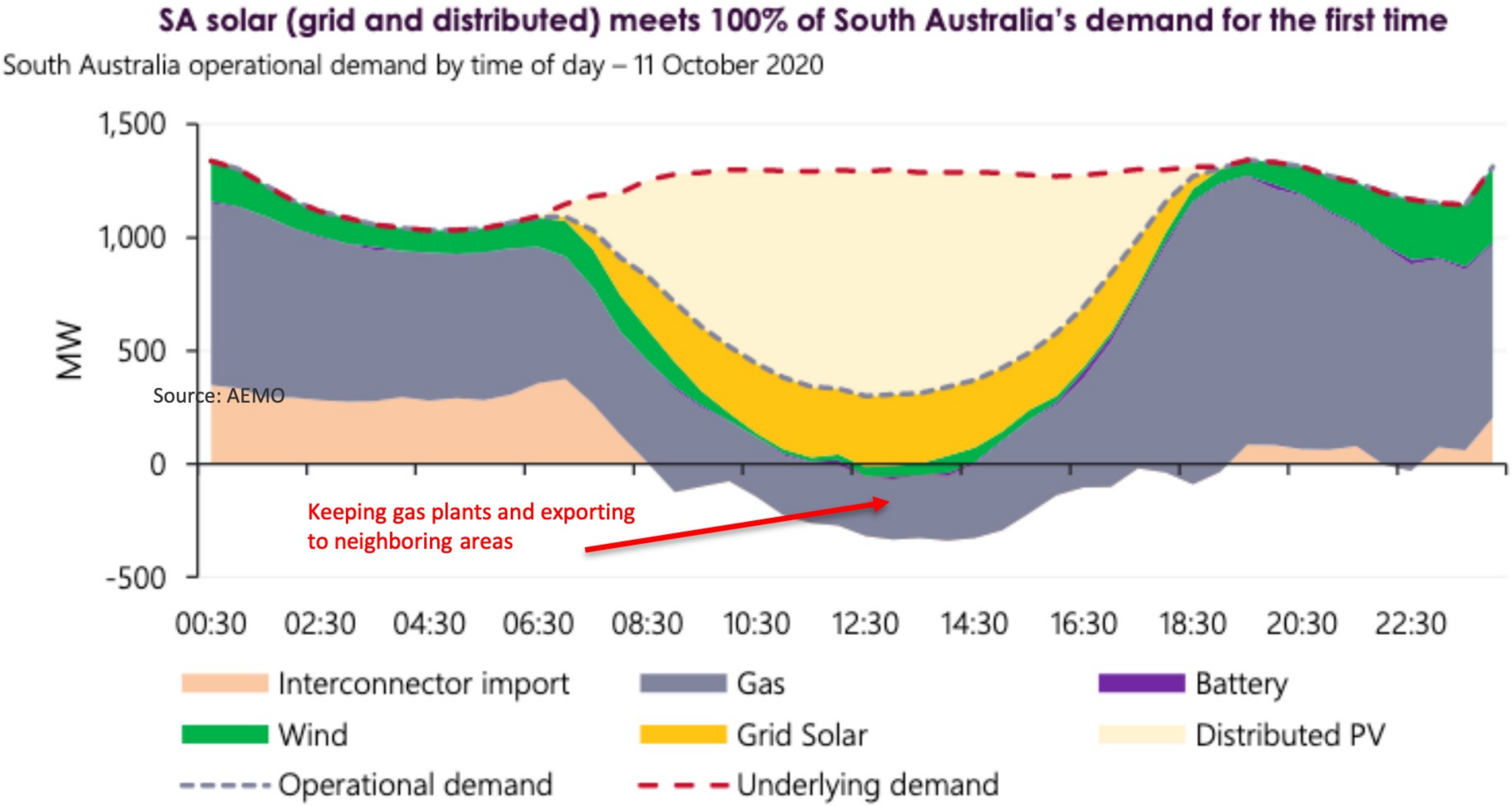
IEEE

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

Faster response is required for IBRs in low-inertia power systems



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

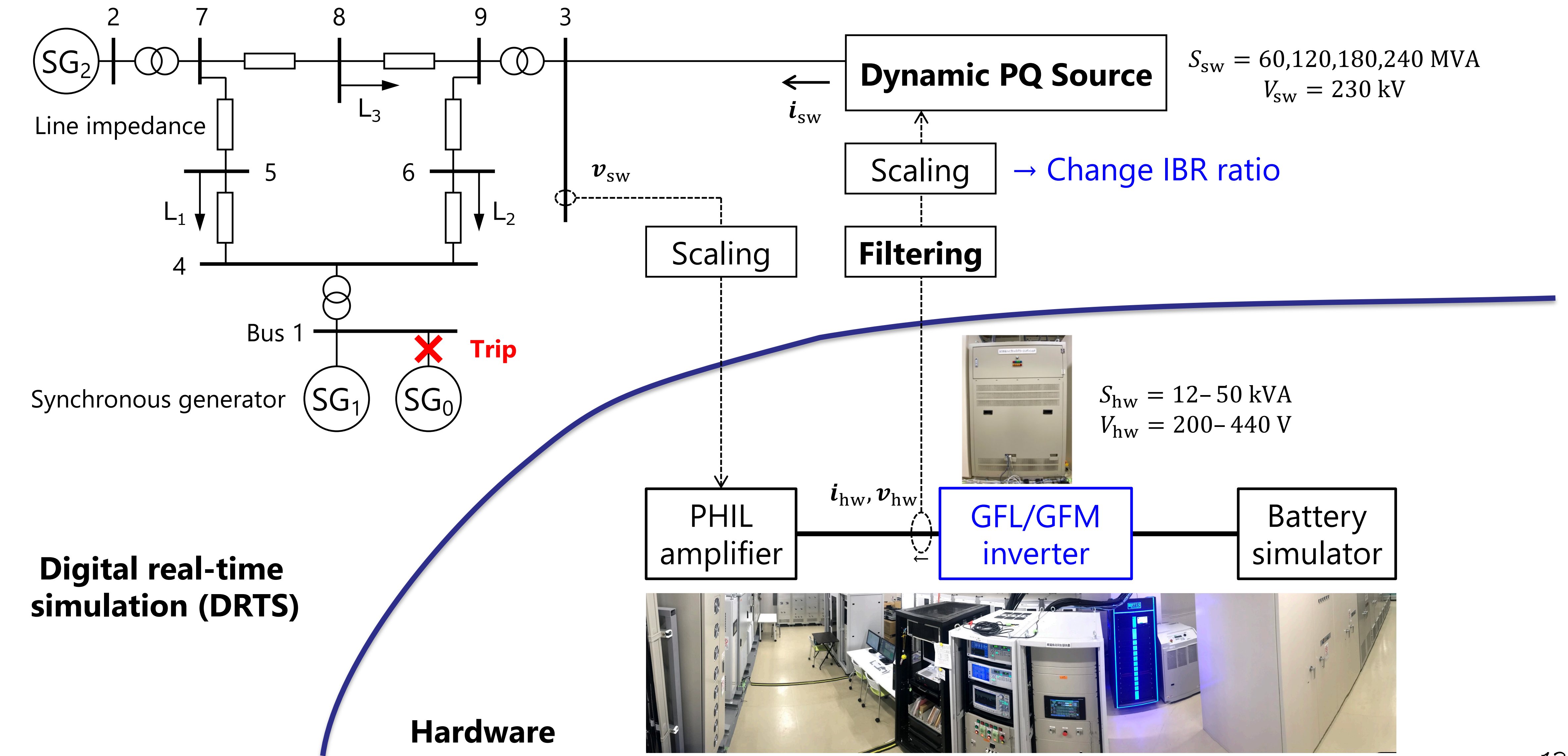
Tested five inverter prototypes with virtual inertia control

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



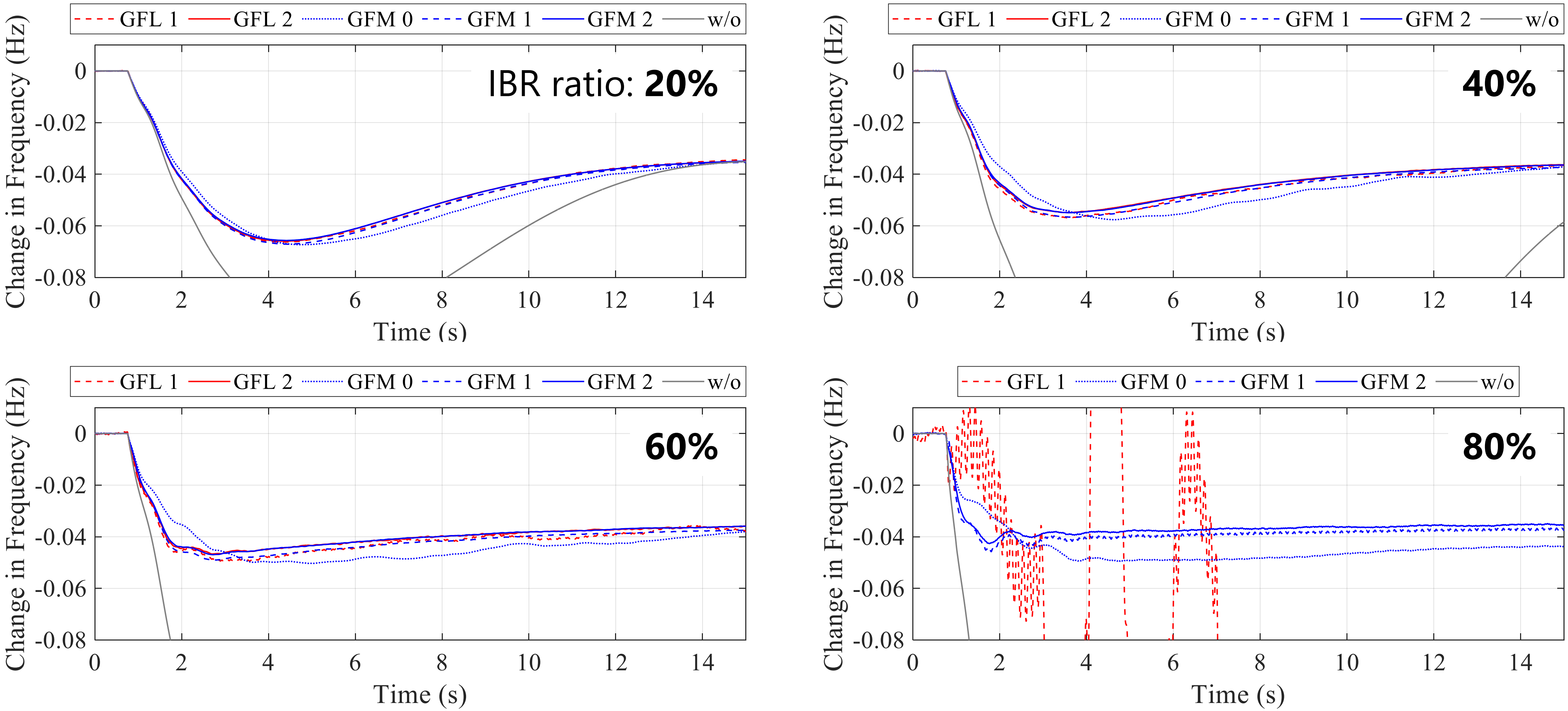

Test setup for GFL/GFM inverters using modified IEEE 9-bus system model

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 conventional 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.

Summary

- IBRs are expected to replace some of services provided by SGs
- Tested five GFL and GFM inverters from different manufacturers
  - As the IBR ratio increased, frequency change increased for conventional IBR, decreased for GFL and GFM inverters
  - GFM inverters were stable at 80%
- Working on a subsequent national R&D project for practical application of GFM inverter

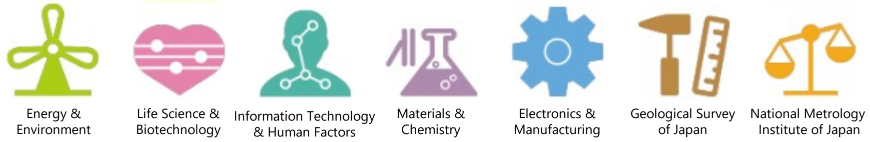
Appendix

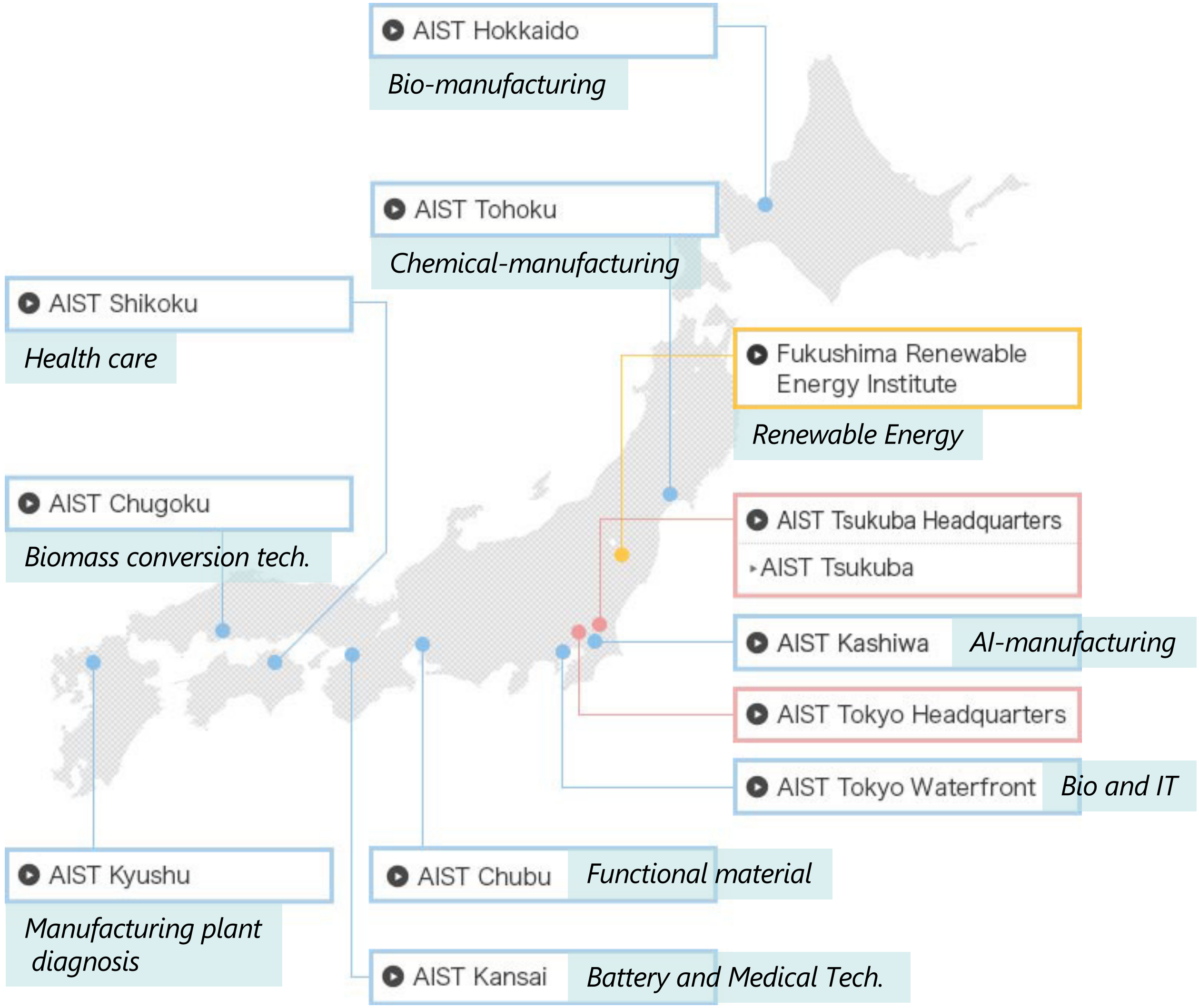
Related Works

- 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.
- H. Kikusato et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.
- 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.
- H. Kikusato et al., "Power Hardware-in-the-Loop Testing for Multiple Inverters with Virtual Inertia Controls," Energy Report 2023, 9 (supplement 10), 458-466.
- D. Orihara et al., "Contribution of Voltage Support Function to Virtual Inertia Control Performance of Inverter-Based Resource in Frequency Stability," Energies 2021, 14, 4220.
- D. Orihara et al., "Internal Induced Voltage Modification for Current Limitation in Virtual Synchronous Machine," Energies 2022, 15, 901.
- J. Hashimoto et al., "Development of df/dt Function in Inverters for Synthetic Inertia," Energy Reports 2023, 9 (supplement 1), 363–371.
- J. Hashimoto et al., "Developing a Synthetic Inertia Function for Smart Inverters and Studying its Interaction with Other Functions with CHIL Testing," Energy Reports 2023, 9 (supplement 1), 435–443.
- T. Takamatsu et al., "Simulation Analysis of Issues with Grid Disturbance for a Photovoltaic Powered Virtual Synchronous Machine," Energies 2022, 15, 5921.
- H. Hamada et al., "Challenges for a Reduced Inertia Power System Due to the Large-Scale," Global Energy Interconnection 2022, 5(3), 266–273.

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

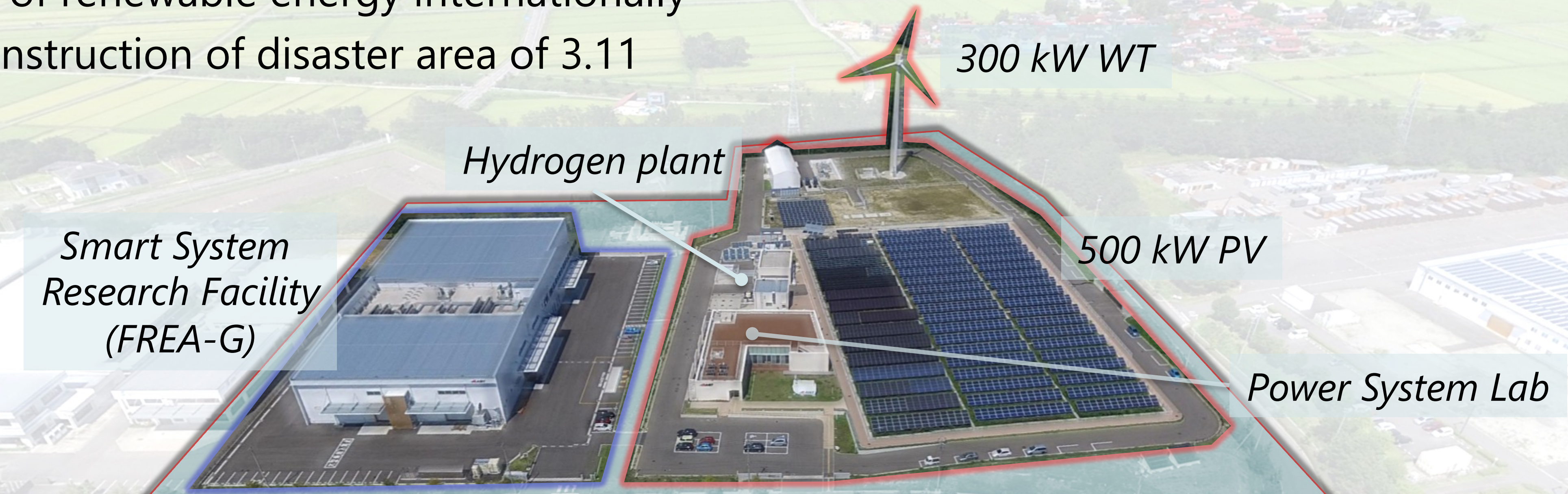




Source: AIST, JP) https://www.aist.go.jp/ , EN) https://www.aist.go.jp/index_en.html

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/

AIST FREA

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

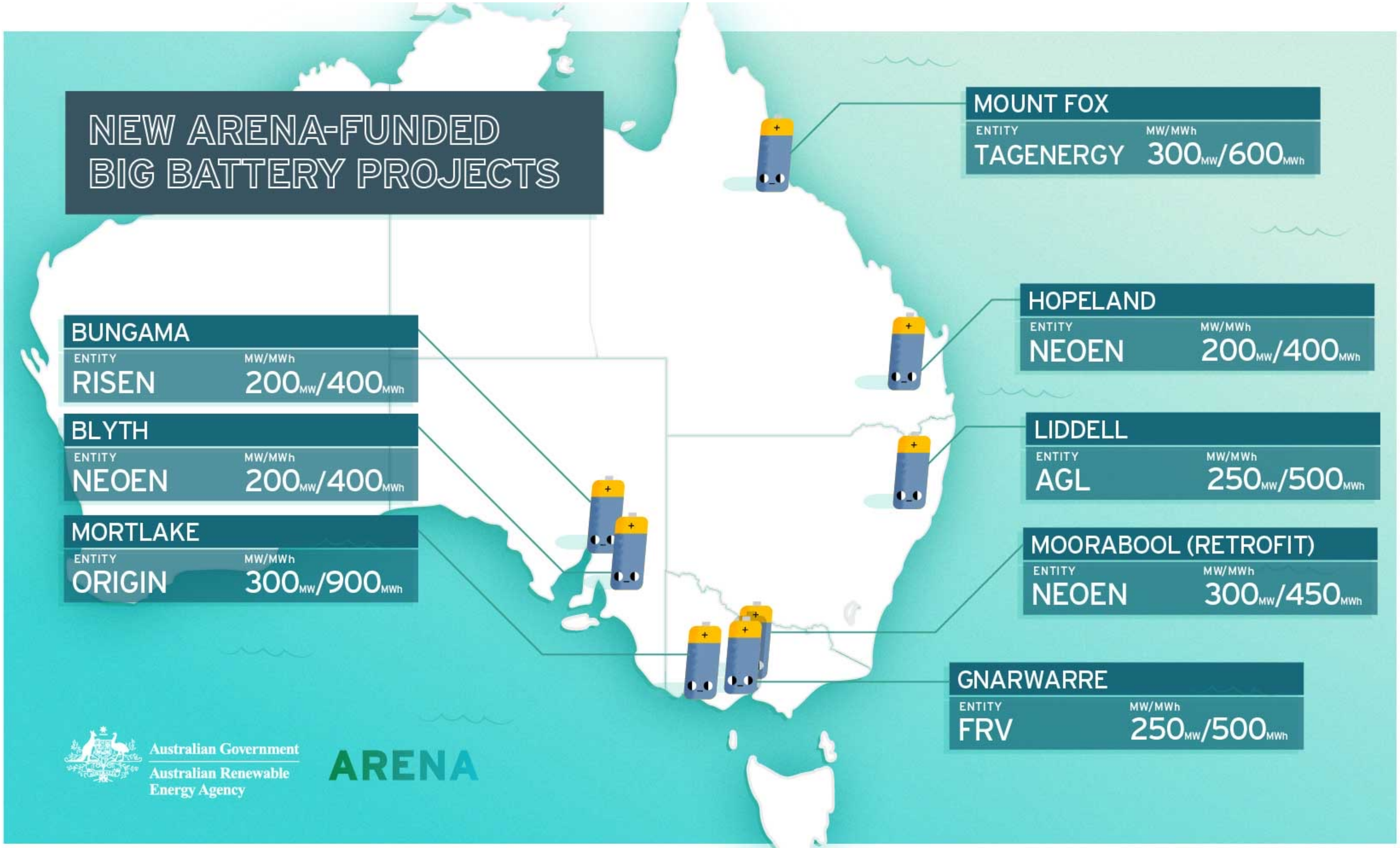
NC RfG 2.0 / Grid forming new Article

	1.0 applicable	2.0 applicable (after general transitional period)	2.0 applicable (after general transitional period + dedicated transitional period of 3 years)
Type B Type C Type D	---	Grid forming non-mandatory (unless national regulation requires it)	Grid forming mandatory
Type A	---	Grid forming non-mandatory	Grid forming non-mandatory

entsoe 6

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

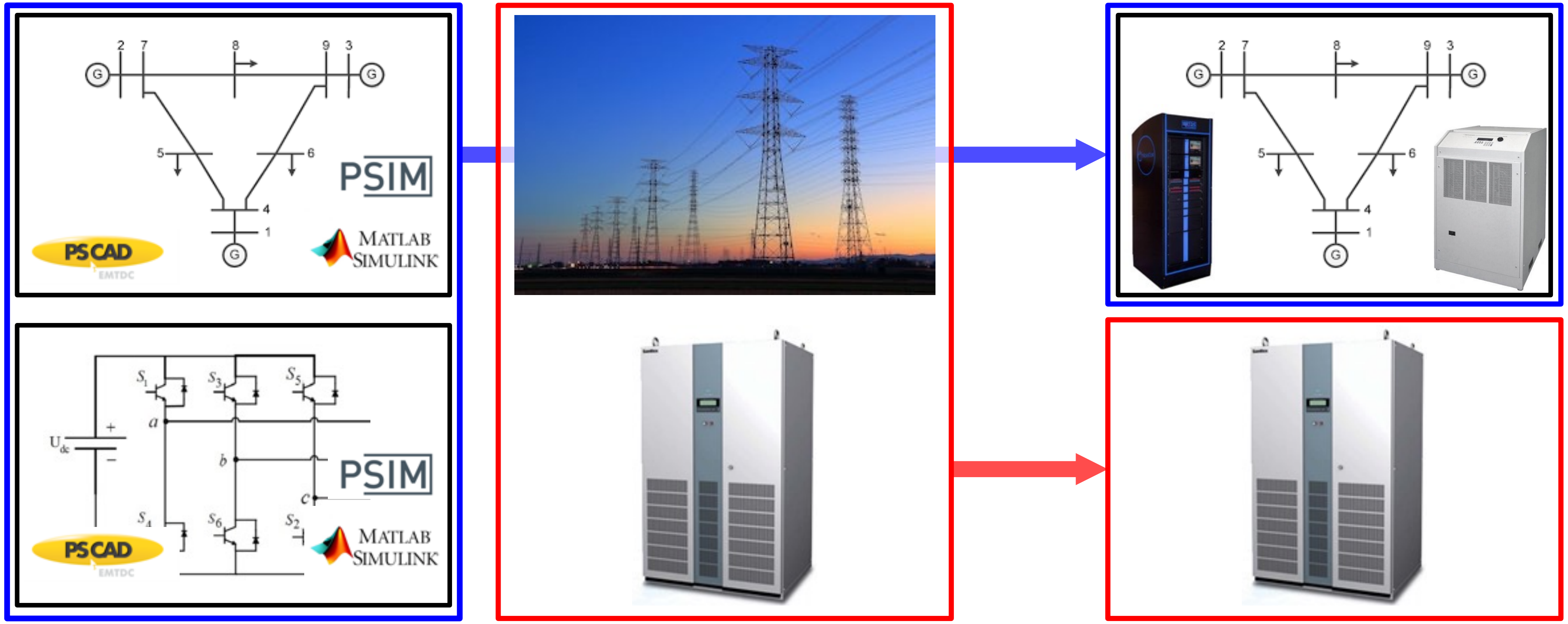
8 GFM batteries with total capacity of 2.0 GW/4.2 GWh



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/

PHIL Simulation is a Flexible and Reliable Testing Method

	Simulation	Demonstration	**Power hardware-in-the-loop (PHIL) simulation**
Grid			
GFMI			



	Simulation	Demonstration	PHIL simulation
Flexibility (Grid)	**High**	Low	High
Fidelity (GFMI)	Low	**High**	High

AIST FREA

Conducted existing conformance tests with changes in voltage magnitude, frequency, and phase angle. **GFL** inverters were mostly **conformance** in all tests. **GFM** inverters were **non-conformance** in most tests; **3 issues** were identified.

#	Test	GFL 1	GFL 2	GFM 0	GFM 1	GFM 2
1	Test for over/under-voltage trip	C*	C	N	N	N
2	Test for over/under-frequency trip	C*	C	N	N	N
3	Unintentional islanding test	C*	C*	-	N	C*
4	Test for voltage magnitude change within continuous operation region	C	C	N	C	C
5	Test for voltage phase angle change	C	C	C	N	N
6	Test for low/high-voltage ride-through	C*	C*	N	N	N
7	Test for low/high-frequency ride-through	C	C	N	N	C

C: Conformance; N: Non-conformance; -: Not conducted

* Conformance can be expected by minor changes to device configuration, control logic, etc.

Source: H. Kikusato, et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.