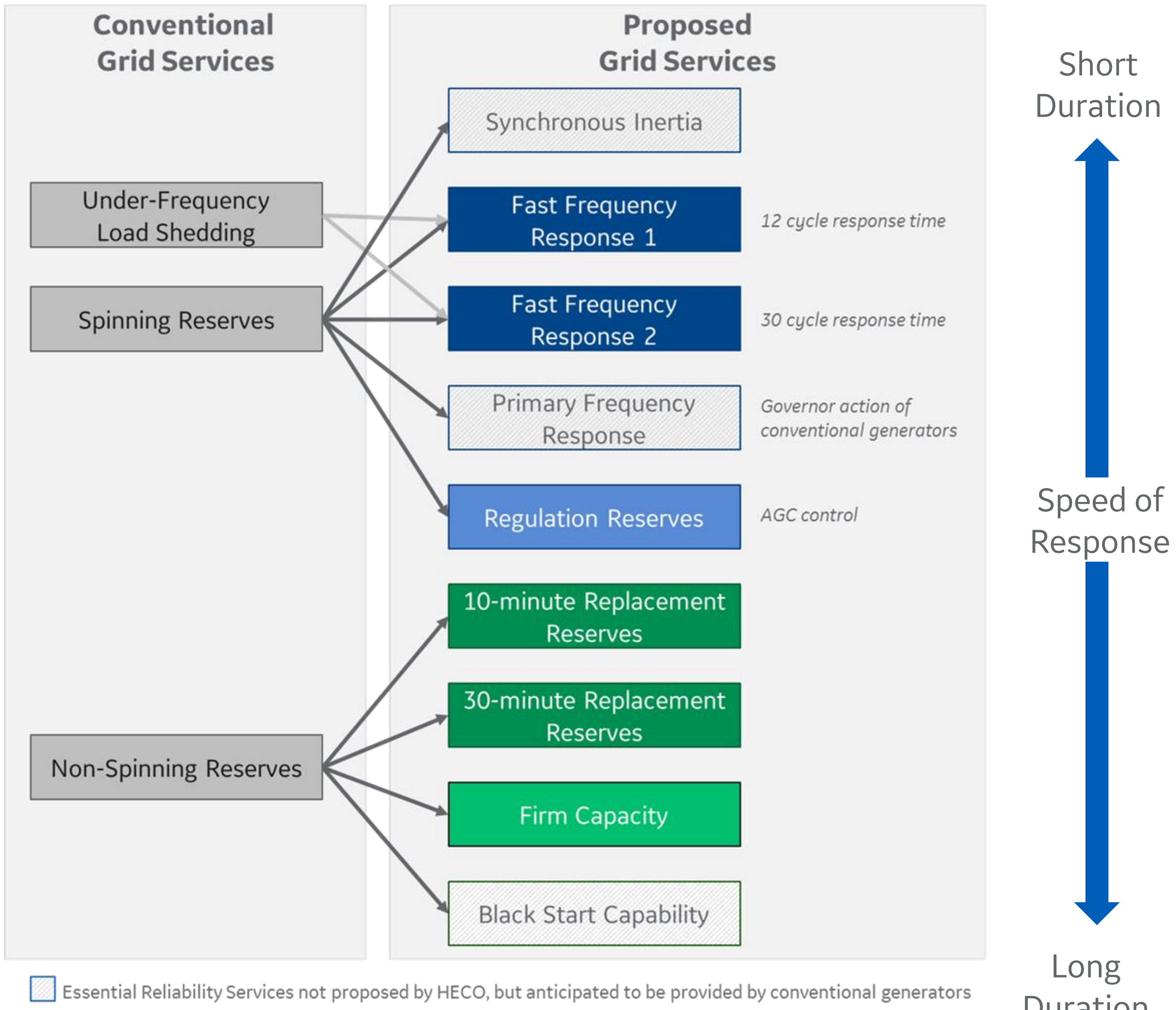
Workshop Agenda

8:15 – 8:45	Common Definitions, What's What, Matt Richwine
8:45 – 9:15	Island Grid Perspective, Matt Richwine
9:15 – 10:00	Large System Perspective, Nick Miller
10:00 – 10:30	Coffee Break
10:30 – 11:00	Market Design, Derek Stenclik
11:00 – 11:40	System Operator Experience, Sandip Sharma
11:40 – 12:00	Open Discussion & Questions

Grid Services are Evolving Across the Industry



Source: Adapted from ERCOT, Cost-Benefit Analysis of ERCOT's Future Ancillary Services (FAS) Proposal

"Grid Services" also known as *Ancillary Services* or *Essential Reliability Services*

General trend away from "ancillary" … now a primary rationale for system operator decisions (commitment and dispatch of generators),

Especially relevant for high vRE and low inertia power systems

Other grid services, not evaluated in this analysis:

- Short Circuit Strength and/or Voltage Support
- Synchronous Inertia
- Primary Frequency Response
- Ramping Reserves
- Black Start Capability

Options with managing low inertia power systems

Disclaimer: this section will cover global procurement mechanisms of synchronous inertia and FFR as examples of different strategies available, but will not cover specific market rules in each region.

Option 1 — Change operations

Option 2 — "Good Citizen" approach

Option 3 — Market Design
- Sync. Inertia
- FFR

Current practice in many regions is to determine a minimum synchronous inertia level that meets a pre-determined level of reliability recommit the system when SCED falls below expected level of system stability.

"Reliability must runs" used to secure system operations similar to other transmission constraints

Minimum Synchronous Inertia Rules

Table 6: Countries experiencing low inertia challenges

System	Ireland	UK	Nordic	Quebec	South Australia
Peak Demand, GW	6.4	53	70	39	3
Capacity from Wind and Solar	4 GW	>26 GW	10%	7%	35%
Minimum Inertia, GW*s	23	135	125	60	2
Resource Contingency Criteria, MW	500	1000	1450	1700	650
Issues	Lack of synchronizing torque, at RoCoF ≥0.5 Hz/s significant amounts of non-synchronous generation will trip[14]	At RoCoF of 0.125 Hz/s some non-synchronous generation will trip; at 1 Hz/s all non-synchronous generation will trip	Slow PFR (hydro), time to UFLS is a concern	Low inertia (hydro), high RCC, slow PFR (hydro), time to UFLS is a concern	High (1-3 Hz/s) RoCoF after RCC, at which synchronous generation may trip and UFLS may malfunction

Source: ERCOT, "Inertia, Basic Concepts and Impacts on the ERCOT Grid," 2018

Benefits of minimum synchronous inertia:

1. Easy to implement *today* – no new technology or markets required,
2. Effective at limiting RoCoF
3. Required only sparingly in most regions, most of the time, under current renewable penetrations
4. Co-benefits of other ancillary services also provided (short-circuit strength, primary frequency response, etc.)

… however, a blunt instrument to managing operations in low inertia power systems and should be viewed as a temporary mitigation

Minimum Synchronous Inertia Rules (continued)

Table 7: Mitigation measures to reduce Critical Inertia and to keep inertia above critical level

	Ireland	UK	Nordic	Quebec	South Australia	ERCOT
Monitor inertia & possible contingencies in Real-Time	✓	✓	✓	✓	✓	✓
Forecasts Inertia from DA into Real-Time	✓	✓				✓
Dynamic Assessment of Reserves based on inertia conditions and largest resource contingency		✓				✓
Limit RCC based on inertia conditions	✓	✓		✓	✓	
Synchronous Condensers (for inertia)	✓	✓			✓ (particularly looking at high inertia SCs)	
Enforce minimum inertia limit	✓	✓			✓ (for minimum inertia req.)	✓
Inertia market/auction/service inertia	✓				✓ (for above minimum inertia levels)	
Faster Responding Reserves	FFR	Enhanced Frequency Response Service		Synthetic inertia from wind	“Contingency” FFR (frequency trigger) and “Emergency” FFR (direct event detection)	Load Resources providing RRS

Note: Planned mitigation measures are shown in blue, while already-existing mitigation measures are shown in black.

Source: ERCOT, “Inertia, Basic Concepts and Impacts on the ERCOT Grid,” 2018

Limitations of minimum synchronous inertia rules:

1. Expensive, requires fuel burn for rare events.. Increasing costs with increasing frequency at high RE penetration
2. May lack transparency of which generators were selected and when (control room decision)
3. Potential for market power & gaming
4. May suppress market signals for other ancillary services
5. Locational intricacies may not cover all contingency events

AEMO Example on Minimum Synchronous Inertia

As *inertia* is reduced in an *inertia sub-network*, a larger Fast FCAS response is required to maintain an Acceptable Frequency and keep the *inertia sub-network* in a *satisfactory operating state*.

Inertia by itself cannot arrest a fall in *power system frequency* entirely, or bring it back to be within the *normal operating frequency band*; it can only reduce the rate at which *frequency* changes. Fast FCAS, however, can arrest a decline in *frequency*.

Figure 2 Relationship between Fast FCAS requirement and inertia

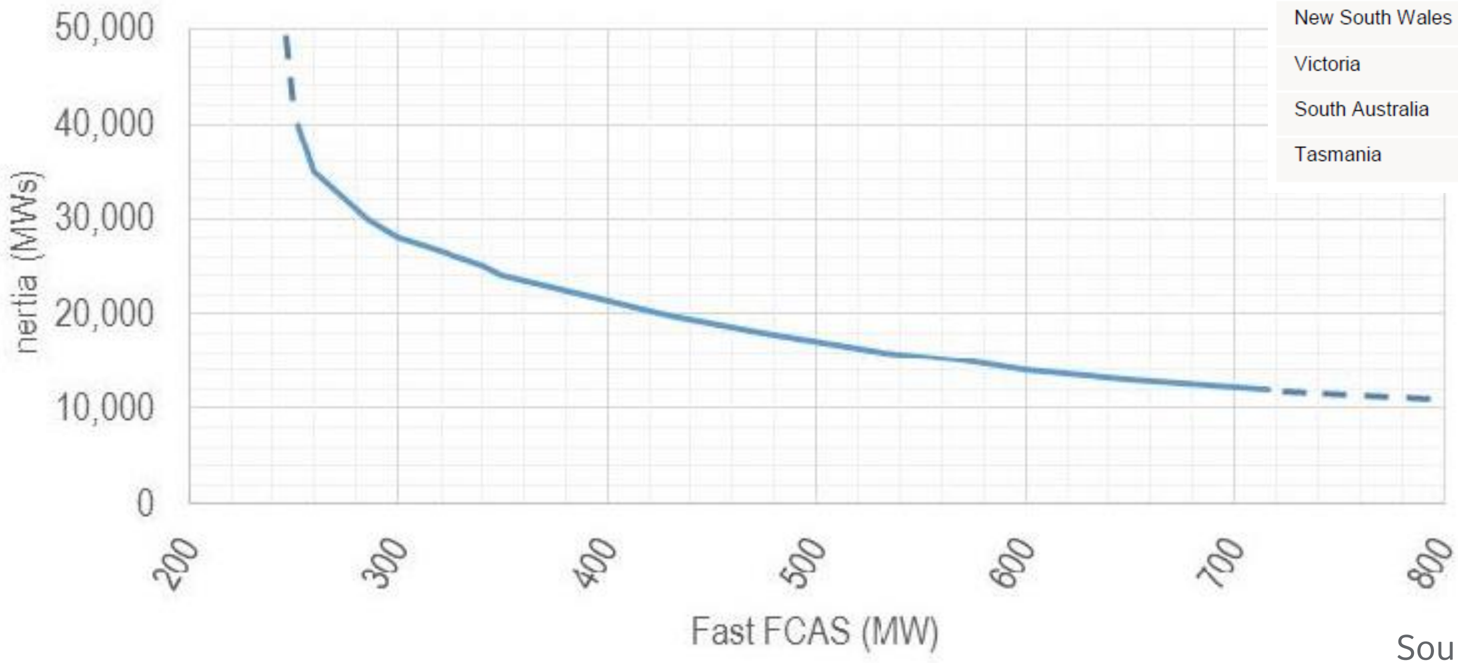


Table 2 Inertia requirements for 2018

Inertia sub-networks (Regions)	Inertia available through System Strength (MWs)[33]	Minimum threshold level of inertia (MWs)	Secure operating level of inertia (MWs)
Queensland	11,950	12,800	16,000
New South Wales	18,100	10,000	12,500
Victoria	10,900	12,600	15,400
South Australia	4,900	4,400	6,000
Tasmania	2,000	3,200	3,800

AEMO has determined minimum synchronous inertia levels by region and will recommit if necessary, payment based on top percentile of annual LMPs

Source: AEMO, *Inertia Requirements & Methodology*, July 2018

Options with managing low inertia power systems (continued)

Option 1	Option 2	Option 3
Change operations	"Good Citizen" approach	Market Design • Sync. Inertia • FFR

utilize large industrial loads that can participate in direct load response and special protection schemes...

compensation based on a fixed payment (without market), lower rates, grid code requirement,

...or because lack of participation would mean even worse load shedding

The Icelandic Example

Engage the loads and location matters

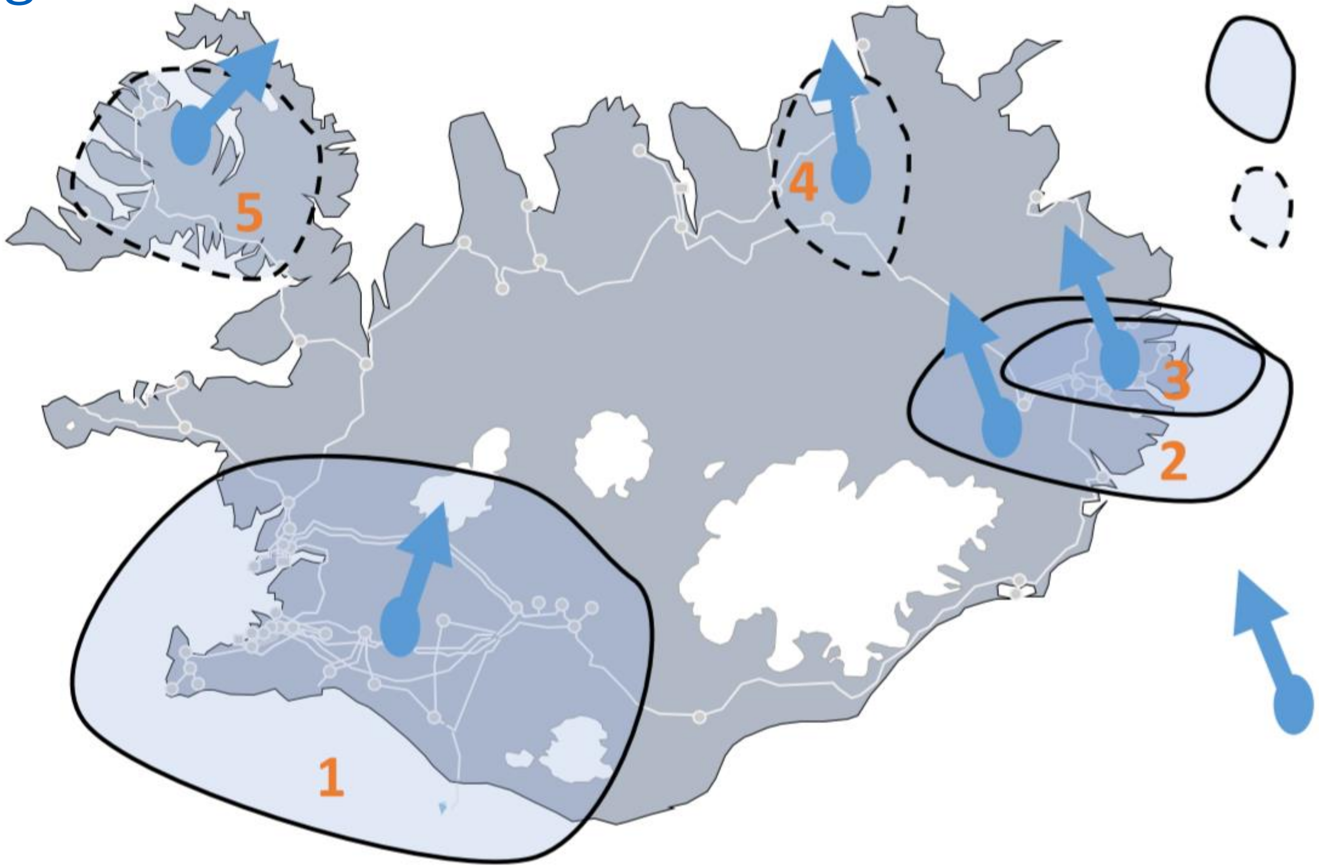


Figure 4 Regional Aggregation of Frequency and Angles

REGIONS Centres of inertia represented by aggregate frequency & angle measurement Zone Aggregate **SHARED** with all Control Units

Future control zones

Load side: Two smelters step up or down, +industrial load trip (separate from UFLS)

Generation side: geothermal fast-valving response (1-3sec) followed by hydro resources (2-20sec)

REGIONAL ANGLE validated and averaged angles merged to a single representative phasor. **REGIONAL FREQUENCY** also derived and shared with Control Units.

Source: D. Wilson, et al, "Icelandic Operational Experience of Synchrophasor-based Fast Frequency Response and Islanding Defence," CIGRE Session 2018.

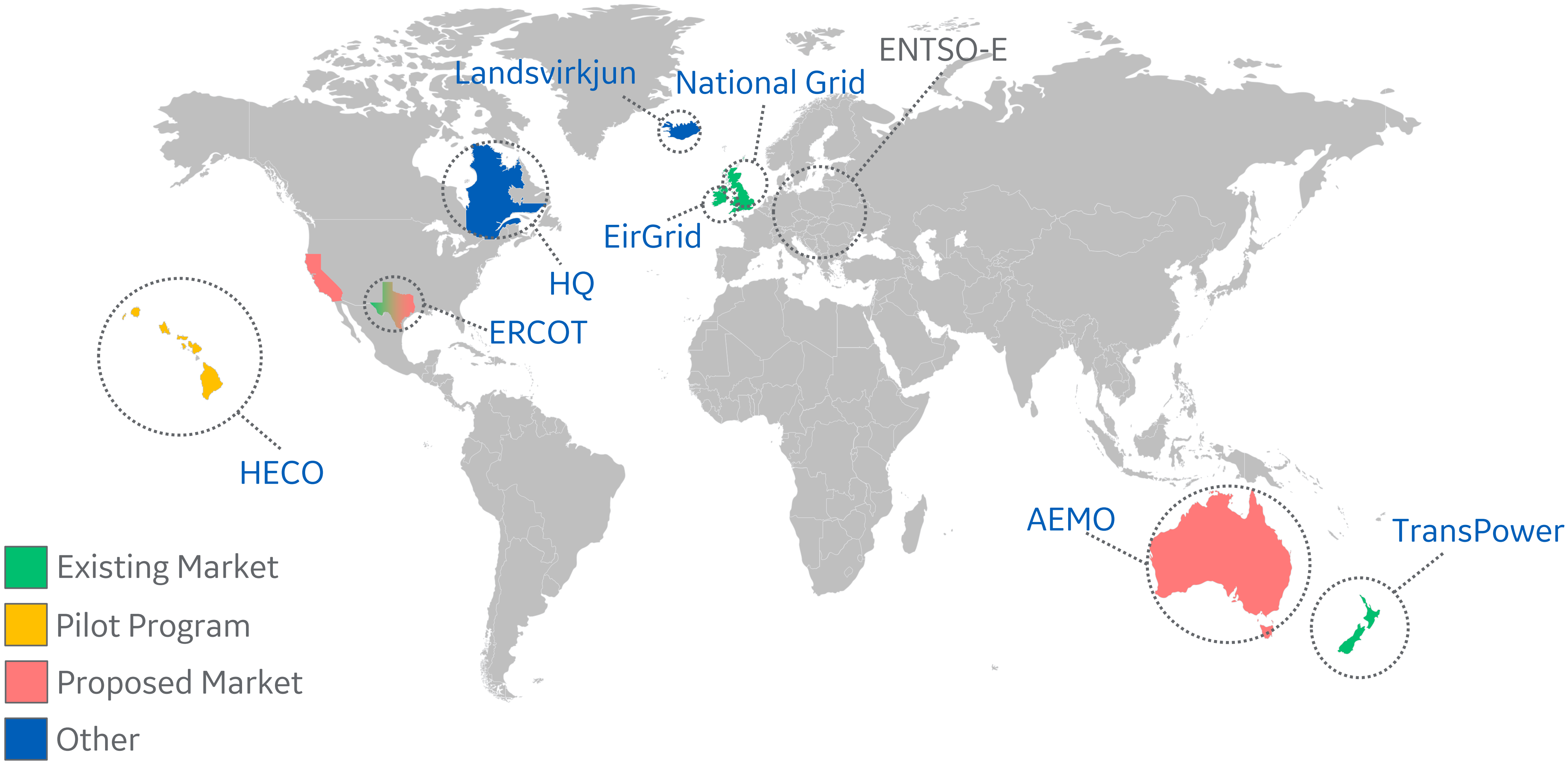
Options with managing low inertia power systems (continued)

Option 1	Option 2	Option 3
Change operations	"Good Citizen" approach	Market Design • Sync. Inertia • FFR

What is the role of Fast Frequency Response (FFR)?

1. Replace synchronous inertia?
   - Arrest frequency decline (slow RoCoF) after a contingency event
   - Avoid UFLS
   - Buy time for slower responding resources, PFR from governor response, non-frequency responsive loads, etc.
   - t = cycles to seconds
2. Replace conventional spinning reserves?
   - Stabilize and restore system frequency after a contingency event
   - Turn off synchronous generators to accommodate additional renewables
   - t = seconds to minutes
3. Both?

Where are sync. inertia or FFR markets operated today?



Review of Emerging Global FFR Programs

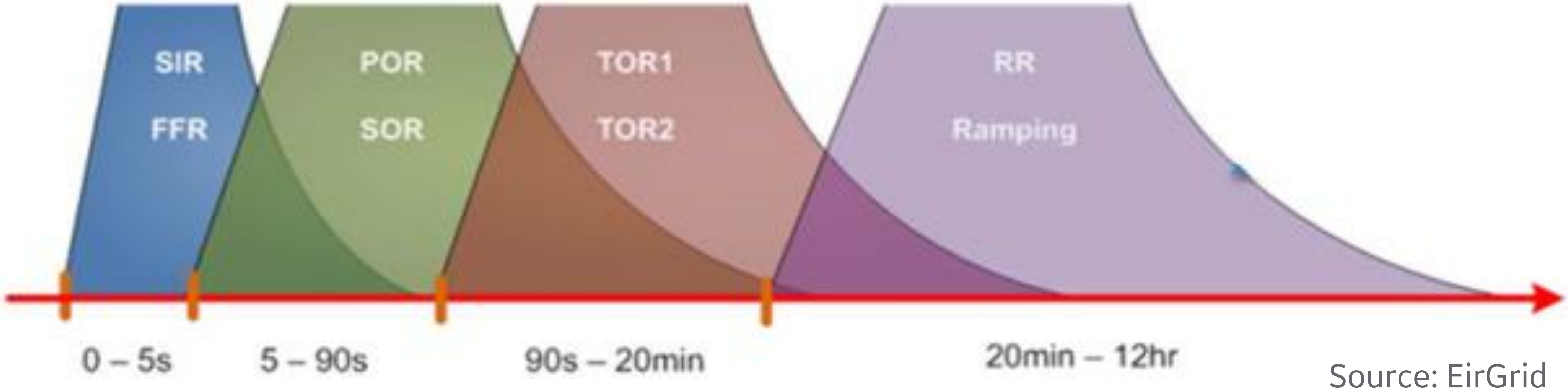
	NEW ZEALAND	UK	IRELAND	TEXAS	HAWAII	AUSTRALIA	CALIFORNIA
Grid Operator	Transpower	National Grid	EIRGRID	ERCOT	HECO	AEMO	CAISO
Reserve Product Name	Fast Instantaneous Reserve	Enhanced Frequency Response	DS3 Fast Frequency Response	FAS Fast Frequency Response	Fast Frequency Response	Fast FCAS	Frequency Response Phase 2
Status	Operating	Operating	Operating	Operating (RRS) Proposal (FFR)	Pilot	Proposal	Proposal
Market Size	~400 MW	200 MW	100 MW (TBD)	1,400 MW (RRS)	TBD	TBD	TBD
Trigger	49.2 Hz	49.9/50.1 Hz	49.8 Hz	FFR1: 59.8 Hz, FFR2: 59.7 Hz	59.7/60.1 Hz + RoCoF	TBD	TBD
Response Time	50 cycles (for DR only)	50 cycles	100 cycles	30 cycles	FFR1: 12 cycles, FFR2: 30 cycles	25 - 50 cycles	60 cycles
Response Duration	60 seconds	15 minutes	10 seconds	FFR1: 10 minutes, FFR2: up to 90min	30 minutes	TBD	TBD
Prices	$19M NZD, ~$6 NZD/MWh	12 £/MW of EFR/ h	3.09 €/MWh	N/A	N/A	N/A	N/A
Synchronous Inertia Req	N	N	Y	Y	N	Y	N
Primary Frequency Response Req	Y	Y	Y	Y	N	Y	Y

EirGrid's DS3 System Services Products

Service Name	Abbreviation	Unit of Payment	Short Description
Synchronous Inertial Response	SIR	MWs^{2}h	(Stored kinetic energy)* (SIR Factor – 15)
Fast Frequency Response	FFR	MWh	MW delivered between 2 and 10 seconds
Primary Operating Reserve	POR	MWh	MW delivered between 5 and 15 seconds
Secondary Operating Reserve	SOR	MWh	MW delivered between 15 to 90 seconds
Tertiary Operating Reserve 1	TOR1	MWh	MW delivered between 90 seconds to 5 minutes
Tertiary Operating Reserve 2	TOR2	MWh	MW delivered between 5 minutes to 20 minutes
Replacement Reserve – Synchronised	RRS	MWh	MW delivered between 20 minutes to 1 hour
Replacement Reserve – Desynchronised	RRD	MWh	MW delivered between 20 minutes to 1 hour
Ramping Margin 1	RM1	MWh	The increased MW output that can be delivered with a good degree of certainty for the given time horizon.
Ramping Margin 3	RM3	MWh	
Ramping Margin 8	RM8	MWh	
Fast Post Fault Active Power Recovery	FPFAPR	MWh	Active power >90% within 250 ms of voltage >90%
Steady State Reactive Power	SSRP	MVArh	MVAr capability*(% of capacity that MVAr capability is achievable)
Dynamic Reactive Response	DRR	MWh	MVAr capability during large (>30%) voltage dips

14 "System Service" Products, and evolving market structure for high renewable penetration & low inertia operations

EirGrid's DS3 System Services Products (continued)

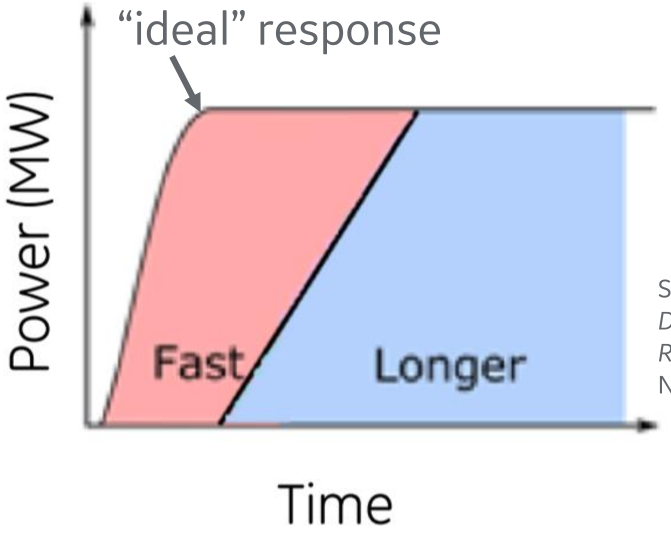


Source: EirGrid

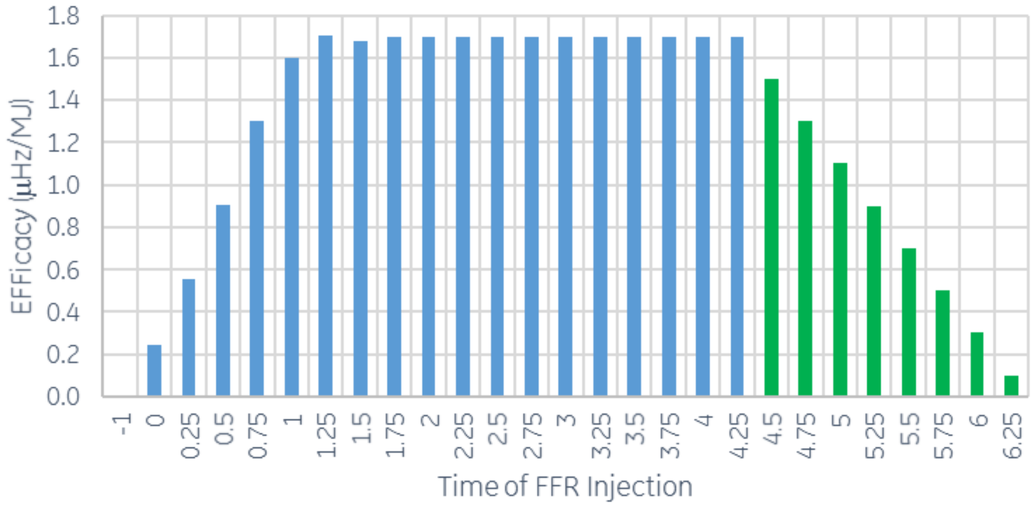
A layered approach of ***response time*** and ***duration of response***

- Allows resources to provide services they are technically capable of providing
- Does not preclude resources to provide valuable system services with strict duration requirements for example: SIR and FFR are designed to buy-time for longer duration resources to respond.
- Resources that can provide both speed and duration are able to provide multiple services
- Scalars used to provide pay-for-performance
- Limits "drawing lines in the sand"

Take everything you can get! Avoid hard thresholds



Source: GE Grid Solutions, *Discussion Paper on Frequency Response Market*, Prepared for National Grid, 2016



Source: GE Energy Consulting, *Technology Capabilities for Fast Frequency Response*, Prepared for AEMO, 2017

There may be fast resources that can only sustain a response for a short duration (seconds), that still provide significant value to the system,

Energy that can help "catch" the system at high RoCoF should be valued, even if the duration is limited,

Speed and duration of response are two separate characteristics and one does not need to preclude the other,

A layered set of services, and scalars, that assigns value to anything that can provide some support is preferred.

National Grid’s UK Enhanced Frequency Response Market

First auction completed in August 2016

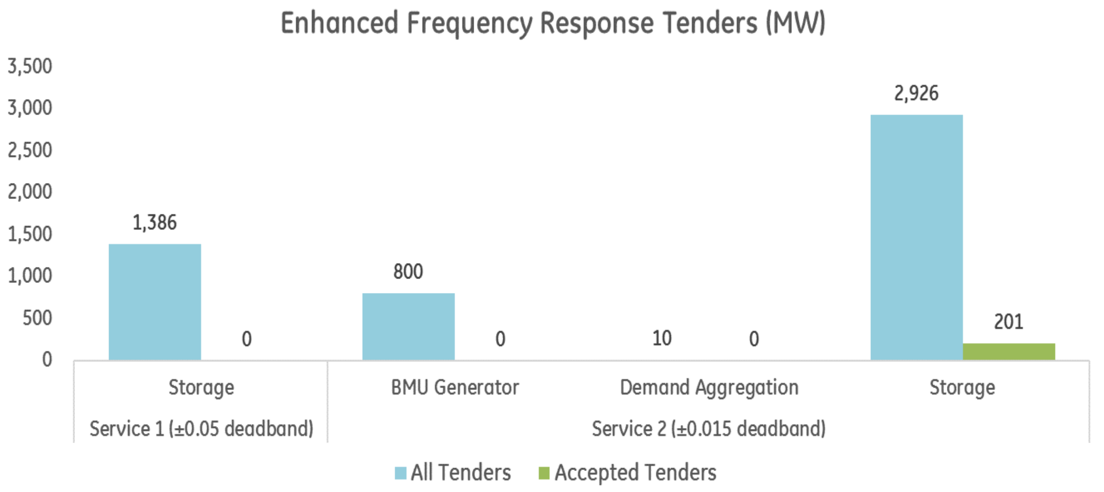
- all results are public, including individual bid quantity & price
- 4-year contracts
- 5,122 MW of EFR bid into auction,
  201 MW cleared (limit 50 MW per bidder)
- only 10 MW of DR, (0 MW DR)

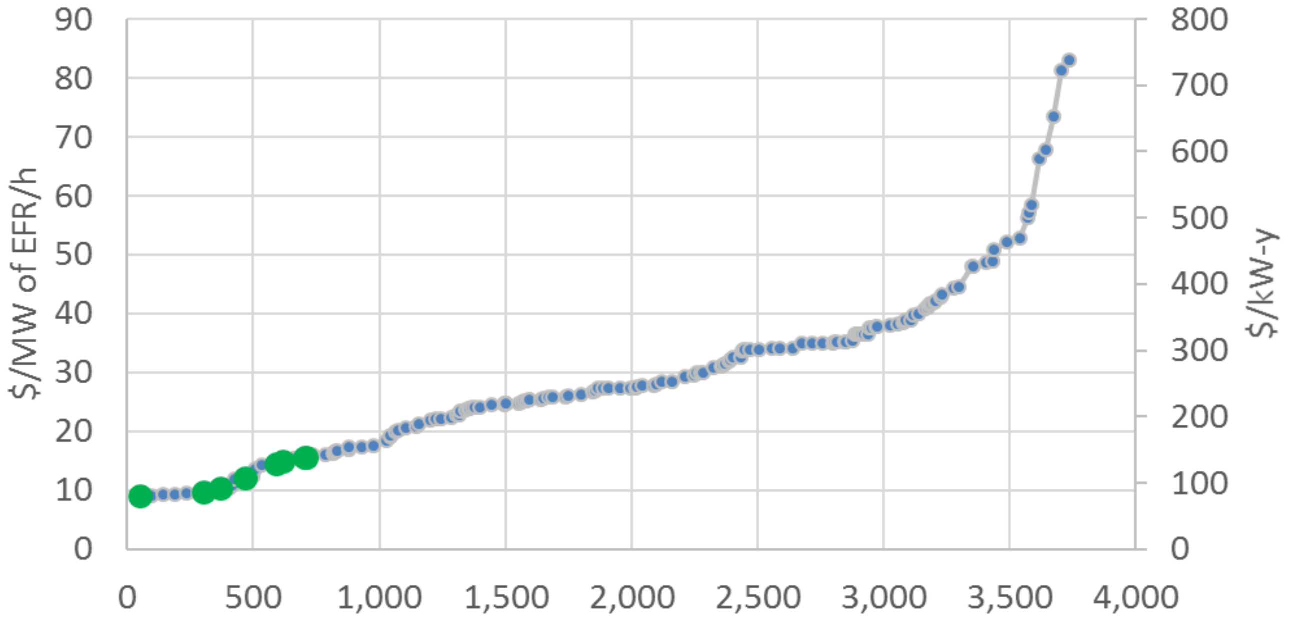
Must provide under-frequency and over-frequency response for same duration

Prefer 24/7 service, but 95% requirement for availability

Originally proposed to be a 9sec duration product, with a two products (Primary and Secondary), but merged into a single product

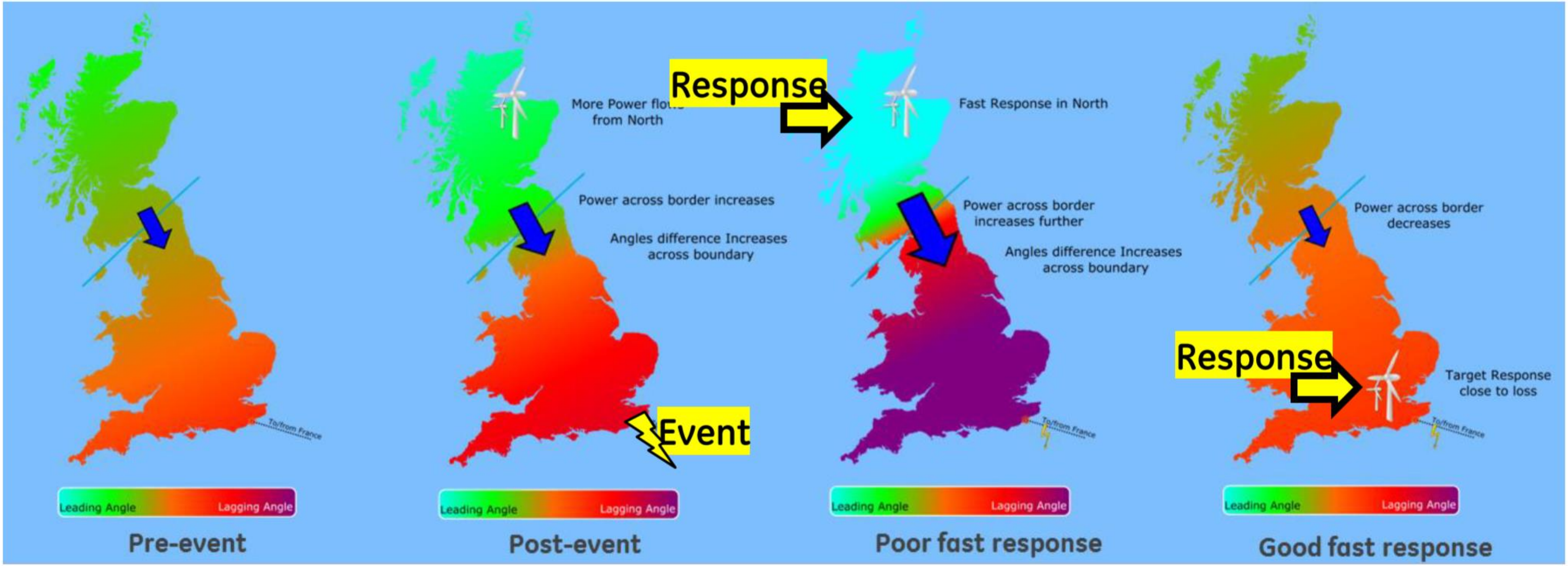
Source: National Grid, “Enhanced Frequency Response Market Information Report,” 2016





Location Matters

In larger grids ideal response is not just a function of speed and duration of response, but also location…
… dependent on inertia levels across the system and location of contingency



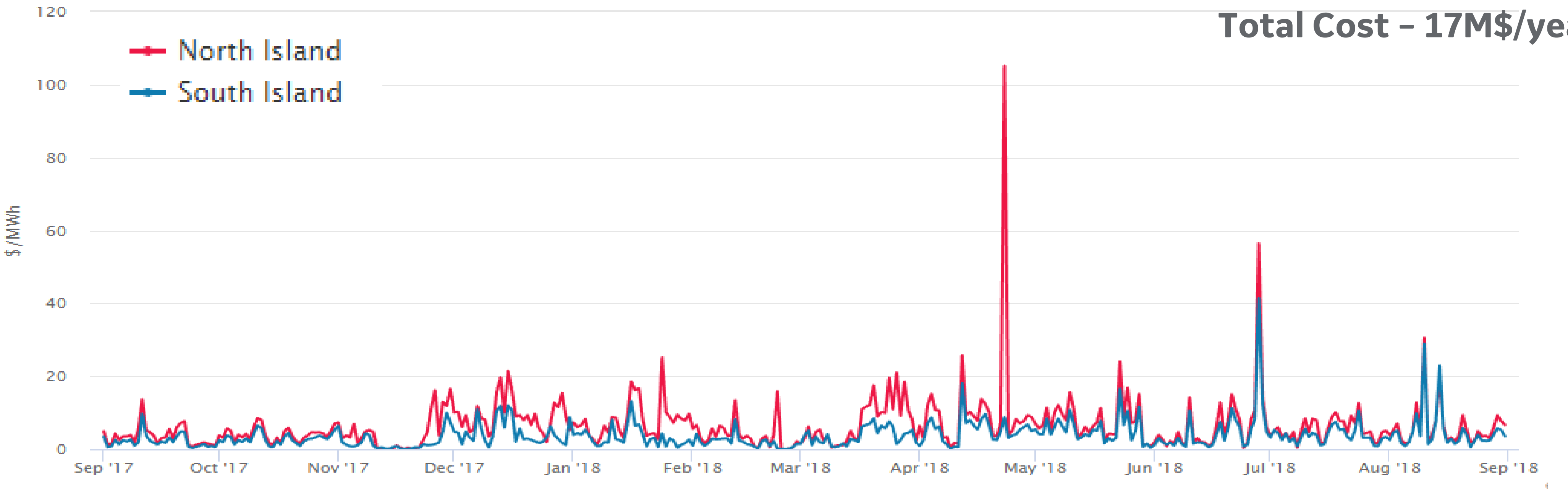
Source: GE Grid Solutions, *Discussion Paper on Frequency Response Market*, Prepared for National Grid, 2016

Transpower's NZ Fast Instantaneous Reserves

- Fast Instantaneous Reserves relies almost exclusively on demand response, ~400 MW
- Annual closed tender process with generators, distributors, large load providers and demand aggregators
- Reserve Management Tool dynamically sets the amount of contingency and FIR reserves needed
- Transparent – system data is updated every 30min on requirement, provision and bids

UK vs. NZ Examples frame a broader discussion on energy storage vs. demand response options

Total Cost – 17M$/year



Source: Electricity Authority of New Zealand, *Electric Market Information*, https://www.emi.ea.govt.nz/

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