# Operational and Stability Impacts of High Shares of Variable Renewables in Power Systems

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# Towards 100% Variable Renewables

- 100% wind/PV region as part of a larger non-100% wind/PV synchronous power system
  - System balancing, local stability challenges, and regional sharing of system services (reserves) capabilities
  - Reduction in local voltage support, fault level, synchronising torque, inertial support, grid strength, etc.
- Synchronous system approaches instantaneous 100% wind/PV for short (extended) periods of time
  - System-wide (frequency, voltage, rotor angle, etc.) stability concerns + network (power transfer) loading
- 100% annual energy from variable renewables
  - System adequacy, subject to access to interconnection links

# Power System of the Future

- Higher net load variability + uncertainty
- Changing system service requirements
  - New reserve + ramping products + voltage support
- Fewer conventional plant on-line
  - Increased (conventional) plant cycling
  - Reduction in synchronous inertia + synchronising torque
- Proliferation of power electronic devices
  - Voltage dip induced frequency dips in weak grid areas
  - Correct operation of protection systems + harmonic issues
- Sustainable network development
  - (Short-term) renewables curtailment
  - Increased network utilisation + active network measures
- System restoration and blackstart

# Flexibility and Stability Challenges

| No Scarcity | Evolving Characteristic | Concern | Scarcity |
|---|---|---|---|

| | Continental Europe | Ireland & Northern Ireland | Nordic System |
|---|---|---|---|
| RoCoF (dimensioning incident) | Localised concern | Inertia scarcity | Evolving characteristic |
| RoCoF (system split) | Global concern | N/A | Not analysed |
| Frequency containment (dimensioning incident) | Evolving characteristic | Evolving characteristic | Evolving characteristic |
| Frequency containment (system split) | Global concern | N/A | Not analysed |
| Steady State Voltage Regulation | SS reactive power scarcity | SS reactive power scarcity | |
| Fault Level | No scarcity | Dynamic reactive injection scarcity | |
| Dynamic Voltage Regulation | No scarcity | Dynamic reactive injection scarcity | |
| Critical Clearing Times | Evolving characteristic | Evolving characteristic | |
| Rotor Angle Margin | Not analysed | Localised concern | |
| Oscillation Damping | Damping scarcity | Damping scarcity | |
| System Congestion | Global concern | Transmission capacity scarcity | |
| System Restoration | Not analysed | Evolving characteristic | |

# Operational Constraints

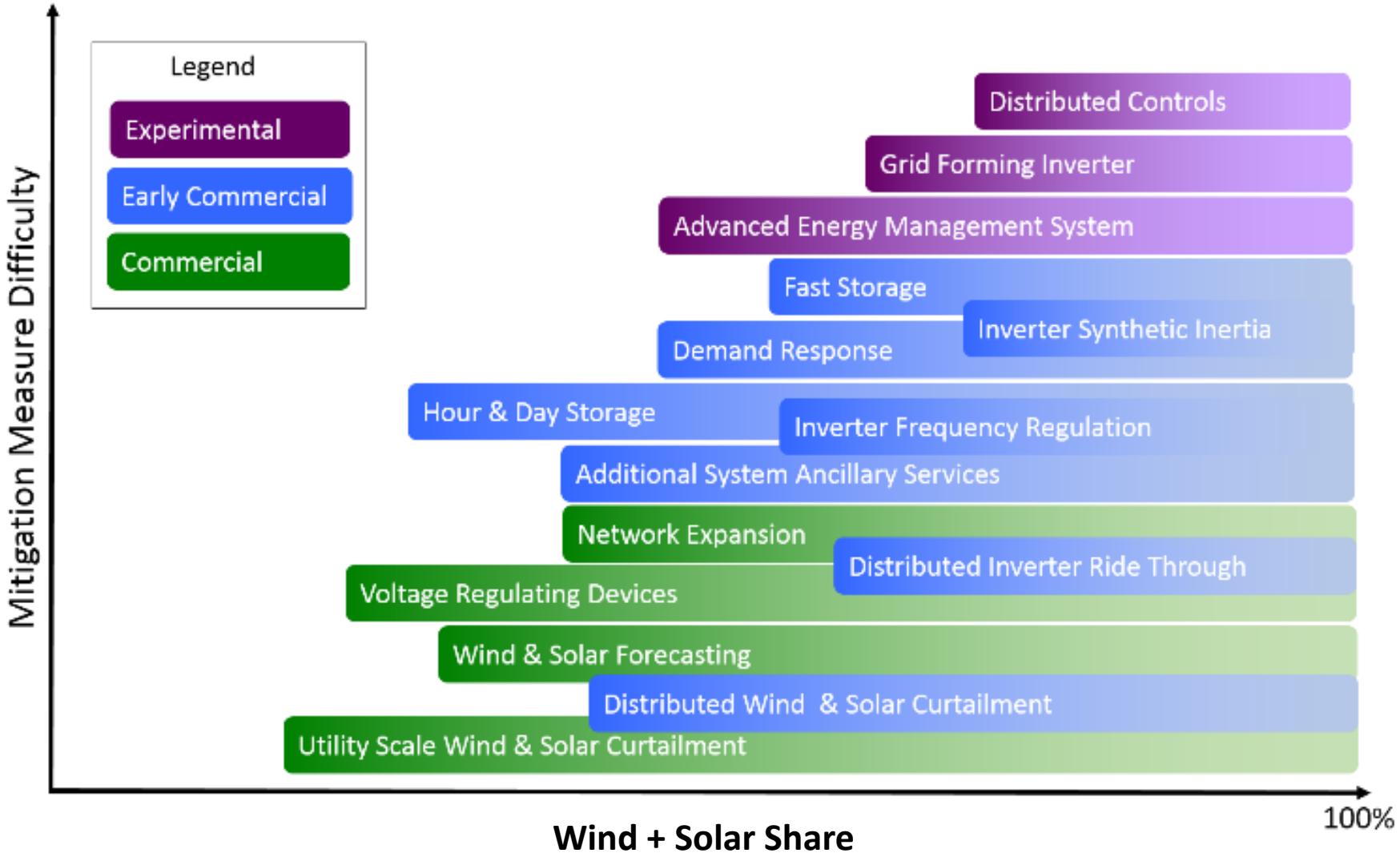
- Operational reserve + ramping requirements
  - Fast frequency, primary, tertiary reserve, ...
  - Solar PV duck/canyon curves
- Instantaneous non-synchronous share
  - Maximum wind + solar + HVDC share
- Rate of change of frequency (± RoCoF)
  - Maximum infeed / outfeed dimensioning event
  - Weather-related events, e.g. storms/hurricanes
- Minimum inertia (GWs)
  - Large, centralised units only
- Regional distribution of (must-run) units
  - Inter-regional flow limits and regional splits
  - Voltage support, synchronising torque, blackstart capability

# Potential Solutions

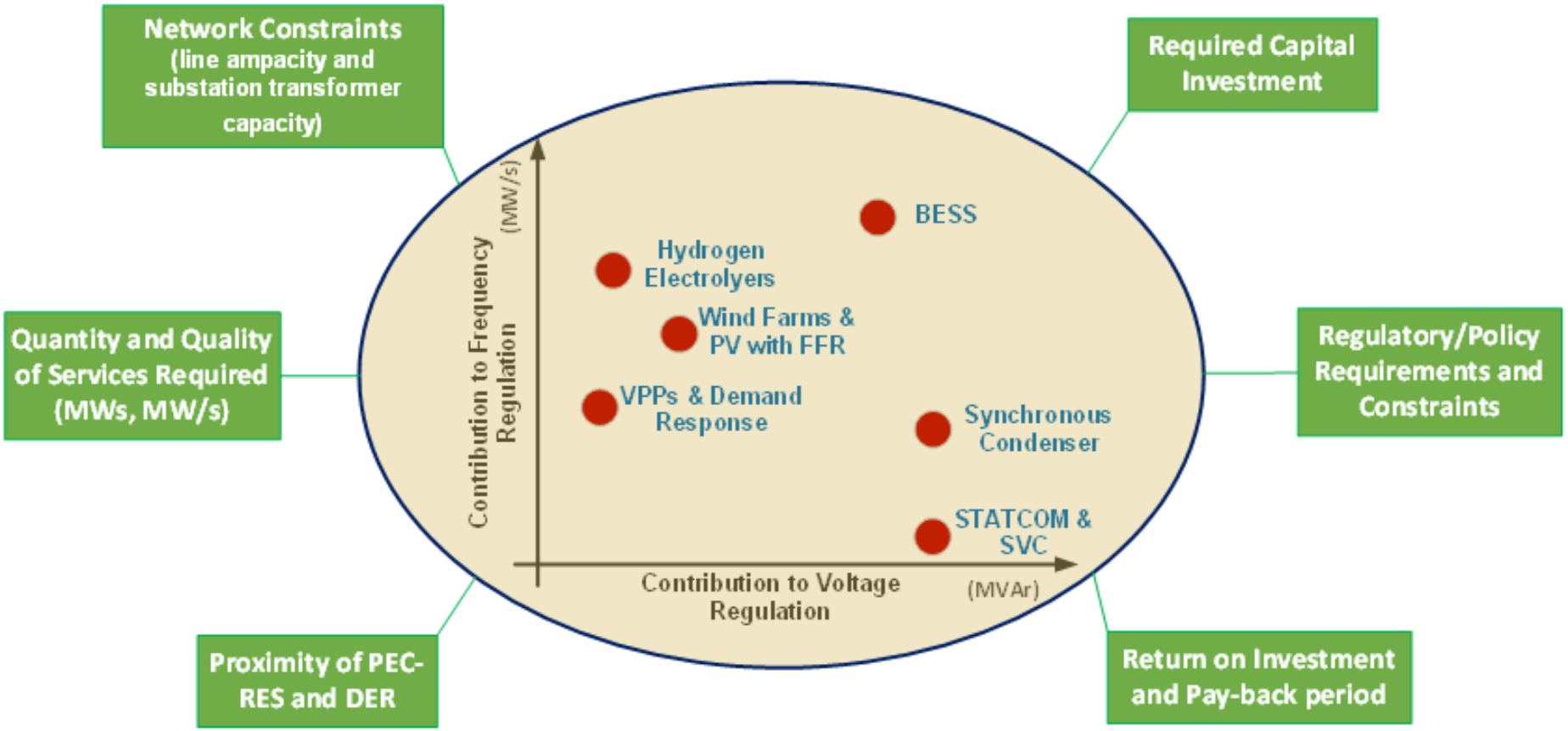
- Energy storage
  - Short-term, long-term storage (+ grid-forming capability)
- Renewable generation (+ local storage)
  - Flexibility provision, frequency control, voltage support
- Demand side response
  - Space heating, water heating, air conditioning, EVs, …
- Interconnection
  - Hybrid interconnectors, offshore energy hubs/islands, ...
- Energy systems integration
  - Municipal water pumping, wastewater treatment, desalination, power to gas, hydrogen, ammonia, …

**Power system reliability and security must be retained while respecting stability, protection, power quality, etc. issues**

# Potential Solutions



# Technology Capability Chart




**FFR**: Fast frequency response
**BESS**: Battery energy storage system
**VPP**: Virtual power plant
**SVC:** Static var compensator

# System Services Categories

| | | | |
|---|---|---|---|
| **Reserve** | Primary Operating Reserve | Secondary Operating Reserve | Tertiary Operating Reserve 1 |
| **Ramping** | Tertiary Operating Reserve 2 | Replacement Reserve (De-synchronised + Synchronised) | |
| **Reactive Power** | Steady-State Reactive Power | | |

# System Services Categories

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|---|---|---|---|---|
| **Reserve** | Primary Operating Reserve | Secondary Operating Reserve | Tertiary Operating Reserve 1 | |
| **Ramping** | Tertiary Operating Reserve 2 | Replacement Reserve (De-synchronised + Synchronised) | | Ramp Margin (1 hr + 3 hr + 8 hr) |
| **Reactive Power** | Steady-State Reactive Power | | | |
| **Inertia** | Synchronous Inertial Response | | | |
| **Fast-acting** | Fast Frequency Response | Fast Post-Fault Active Power Recovery* | | Dynamic Reactive Reserve* |

- Addition of new services to reward flexibility provision, and improve renewables utilisation, e.g. solar PV ramping, network congestion

# Zero Carbon System Services

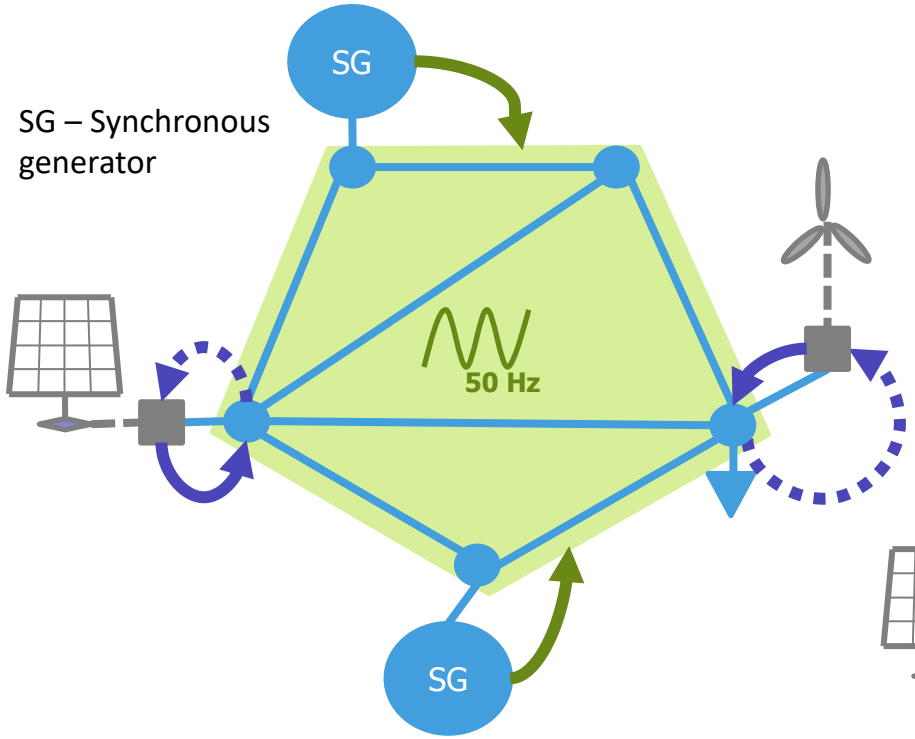
- Phase out “carbon based” system services
- Spectrum of system services
  - Frequency control, voltage control, ramping, blackstart, ...
- Low carbon inertial services (superproduct) analagous to synchronous machine capabilities
  - Synchronous inertia (stored energy)
  - Reactive power, short circuit level
  - Incorporation of locational incentives
- (Available) solution options
  - Synchronous compensators
  - Grid-forming converters (Wind, PV, BESS)
  - Type 5 (hydrostatic) wind turbines

# 100% Converter-Based Grids

Wind + Solar

- No conventional synchronous generation
  - Rotational inertia? Voltage support? Fault contribution?
  - (Power electronics) control interactions?
- What is meant by system frequency?
- Achieving load balancing with ‘local’ controls?
- Operational rules in a ‘100%’ state?
- Requirement for (new) system services?
- …
- Achievable without ‘smart grid’ communications?
- …
- System adequacy for a (near) 100% RES system?

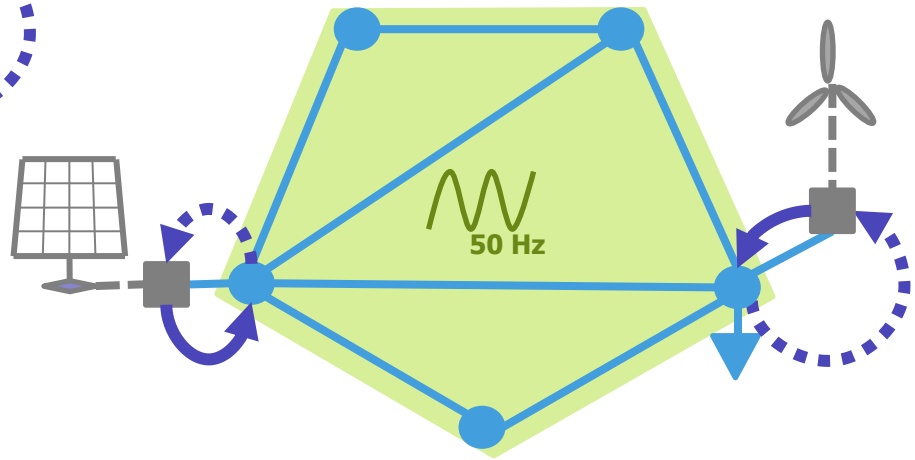
# Grid-Forming Converters




Existing (wind + solar) converters are said to be *grid-following*

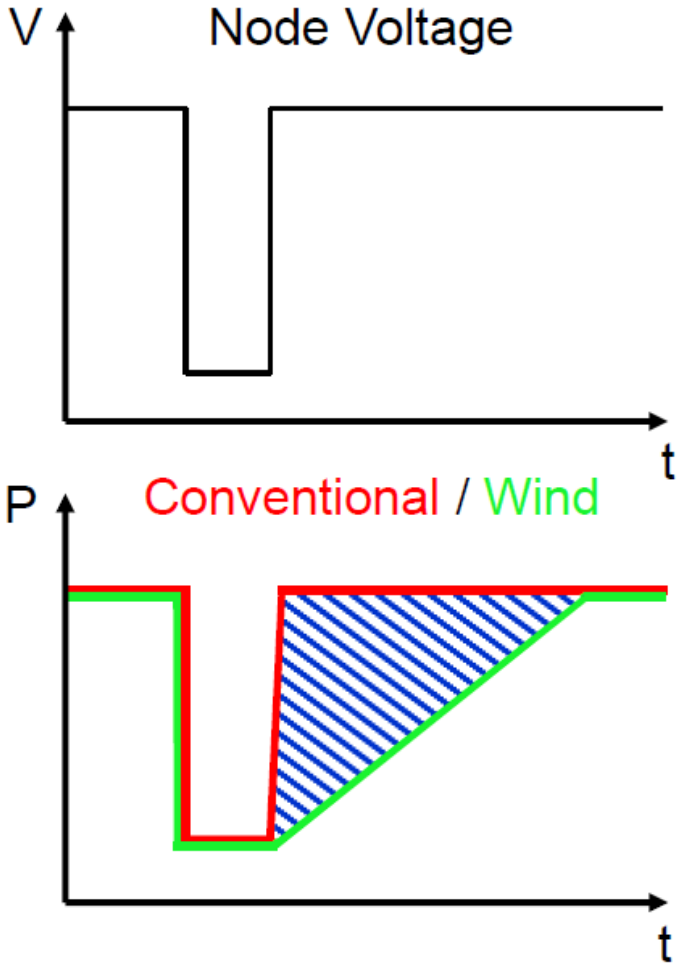
**What to *follow*?**

*Some / many* future converters need to be *grid-forming*

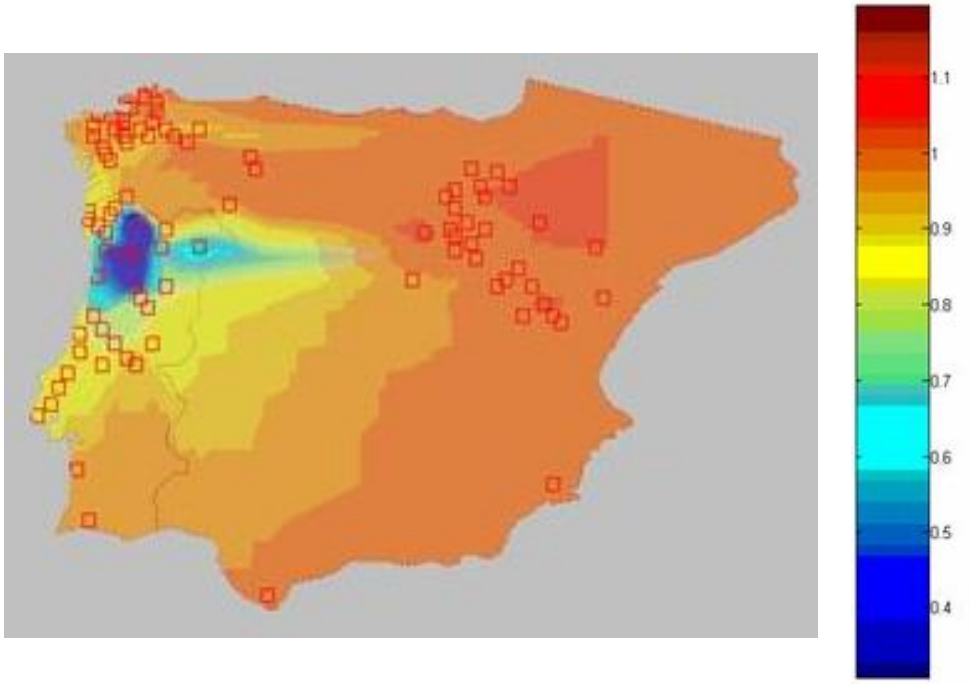



How best to incentivise / enforce sufficient grid-forming capability?

# Voltage Dip Induced Frequency Dips

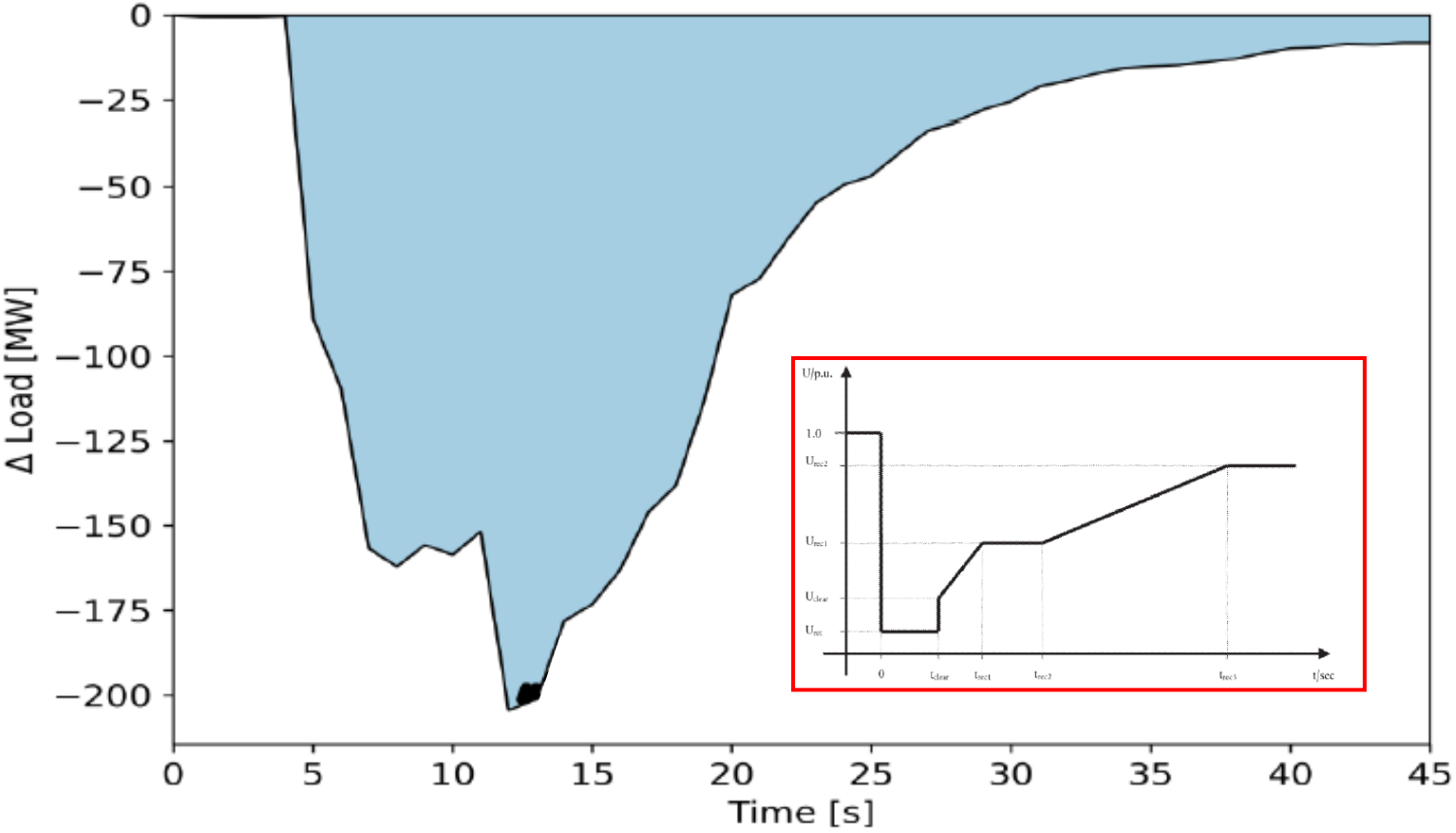



- Should wind turbines prioritise reactive power or active power during fault recovery period?



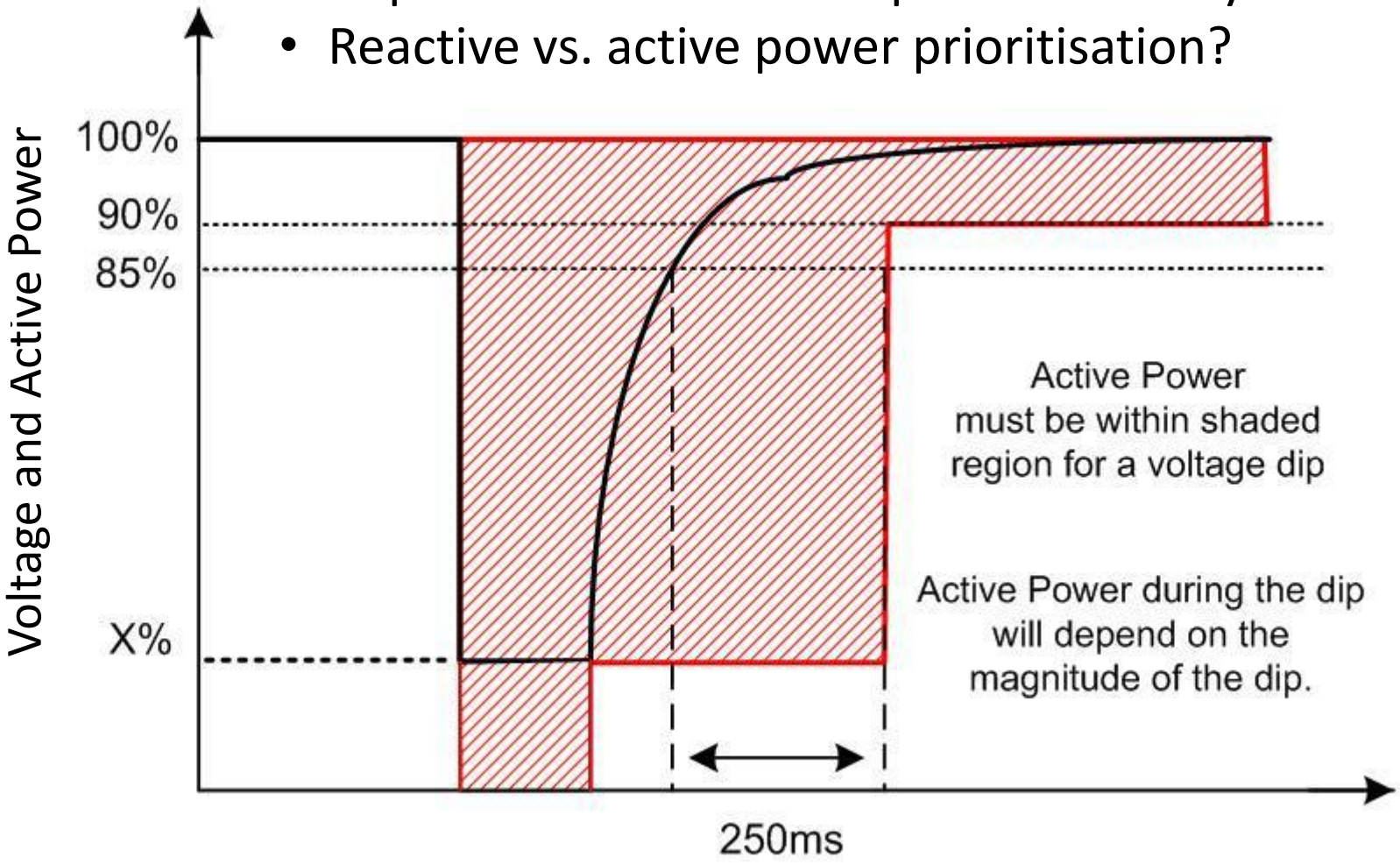
# Load Fault Ride-Through Performance?

- 220 kV network fault
- Large energy users may switch to backup supplies



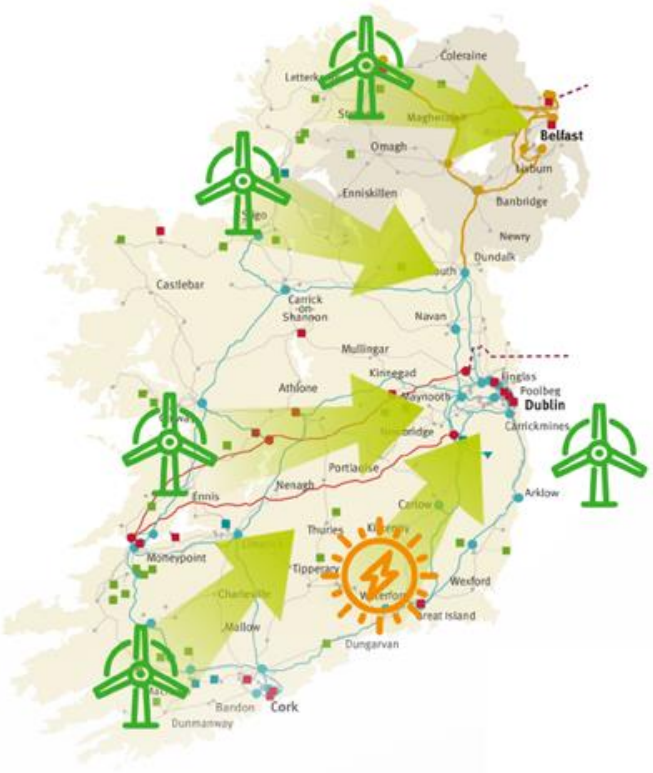
# Post-Fault Active Power Recovery

- System service activated at high non-sync shares to promote “fast” active power recovery
- Reactive vs. active power prioritisation?



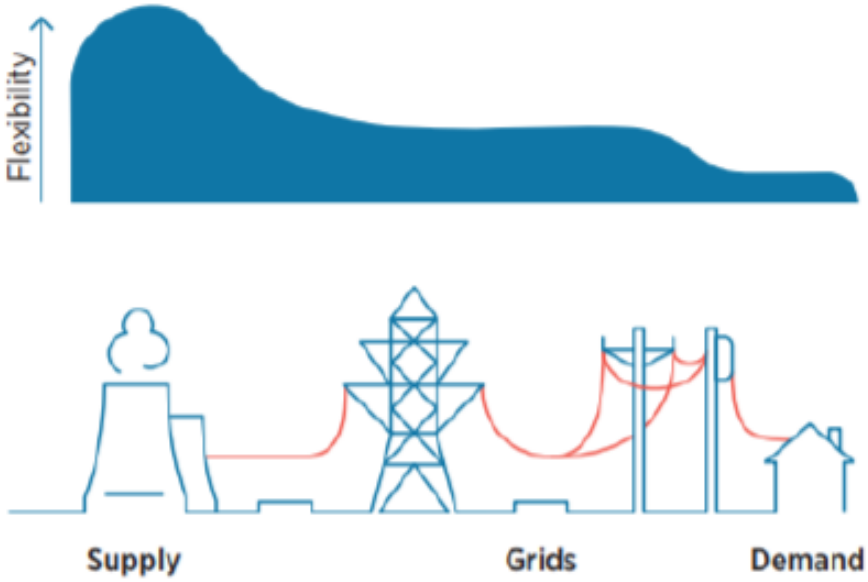
# Maximising Network Utilisation

- Thermal generation (near major load centres) displaced by renewables generation (in more remote locations)
- Network congestion and overloads on both transmission and distribution networks
- ... offshore wind and DC grids, require onshore grid connections
- Flexibility sources increasingly located on distribution/LV networks
- New line(s) construction subject to planning consent
- Utilisation of technological-based assets to maximise utilisation of existing transmission capacity

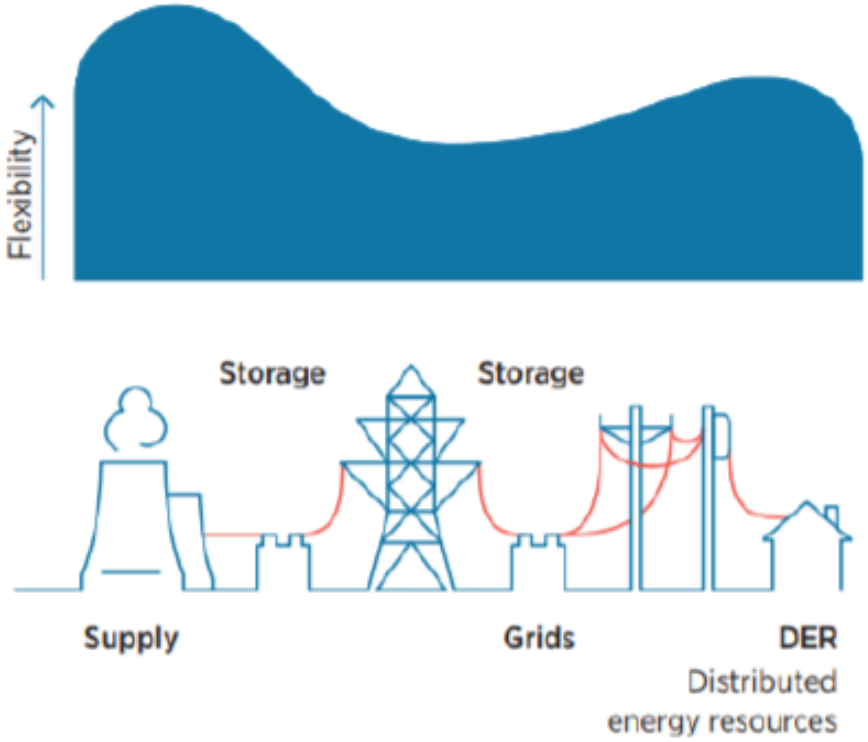


# Evolving Flexibility Provision

Flexibility providers for the **existing** power system

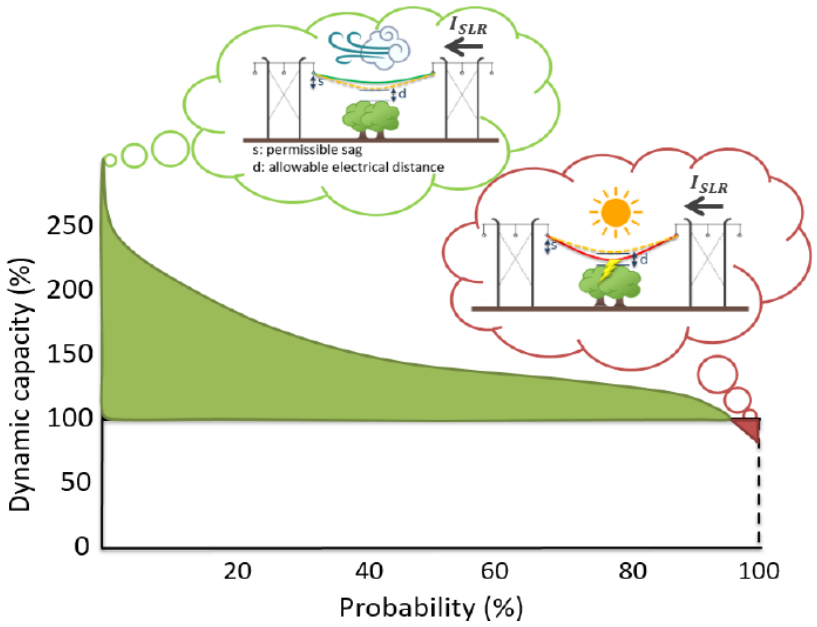



Flexibility providers for the **future** power system



# Congestion Management

- Dynamic line rating
- High temperature low sag (HTLS) conductors
- Voltage uprating (+ reconductoring)
- SVC, STATCOM, synchronous compensator, ...
- Series compensation
- Power flow controllers
- Energy storage systems
- HVDC and DC transmission
- ...
- Reactive power markets?
- Congestion relief system services?



# Conclusions

- System services, and stability & operational concerns need to be addressed by renewable sources
- Multiple technology options are available, but how best to choose an optimal flexibility portfolio?
- Faster responses required from zero carbon sources
- Scope of dimensioning events and range of operational scenarios should be broadened
- Can grid-forming capability be *robustly* supplied through system service arrangements?

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