



Integrating Grid-Forming and Grid-Following Battery Energy Storage Systems into Power Markets

Knowledge Sharing - Power Systems Operation, Protection and Control | Imperial College London

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How Great Britain's Fuel Mix Has Evolved Over the Years

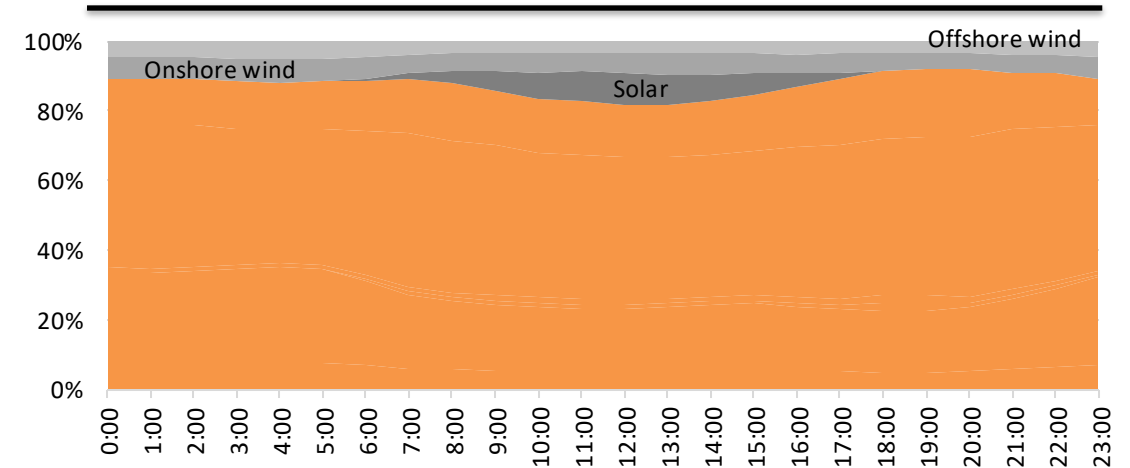
UK Generation by Fuel Type

- Fossil fuels (CCGT, OCGT, Oil, and Coal) accounted for 32% of generation in 2024, down from 56% in 2016.
- Low-carbon sources (Wind, Biomass, Nuclear, Hydro (Non-PS), and Pumped Storage) provided 54% of generation in 2024, up from 33% in 2016.
- Wind power contributed 28% of generation in 2024, up from 8% in 2016.
- Biomass supplied 8% of generation in 2024, up from 1% in 2017.
- Nuclear power made up 16% of generation in 2024, down from 24% in 2016.

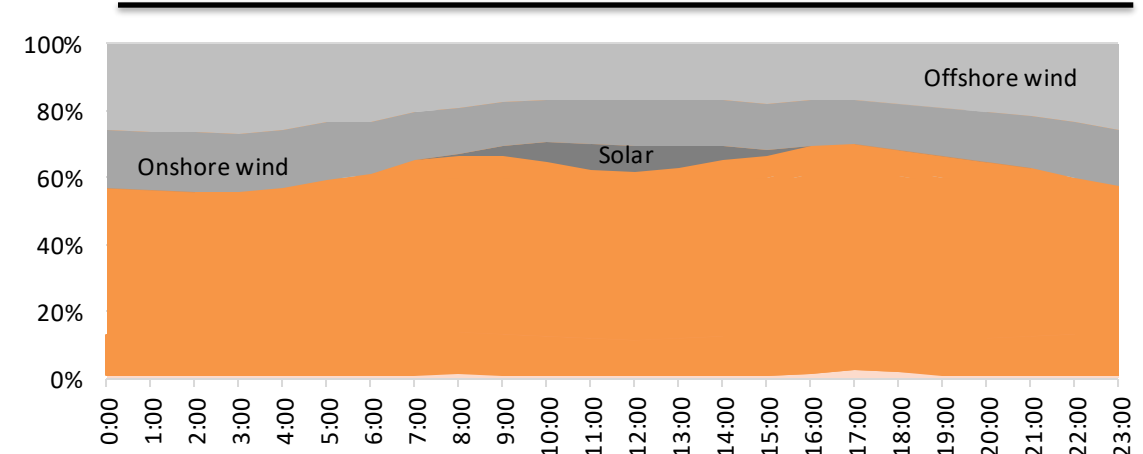
Renewable Integration and System Dynamics

- Renewable integration rapidly transforms power systems.
- Conventional generators are phasing out, leading to declining system inertia.
- Supply and demand are becoming more variable due to renewables and dynamic consumption patterns.
- These trends result in greater frequency volatility and reduced predictability across the power system.

Annual Generation Mix – Hourly Average - 2016¹



Annual Generation Mix – Hourly Average - 2025¹



¹<https://www.elexon.co.uk/>

Understanding Grid Stability



Constant Frequency

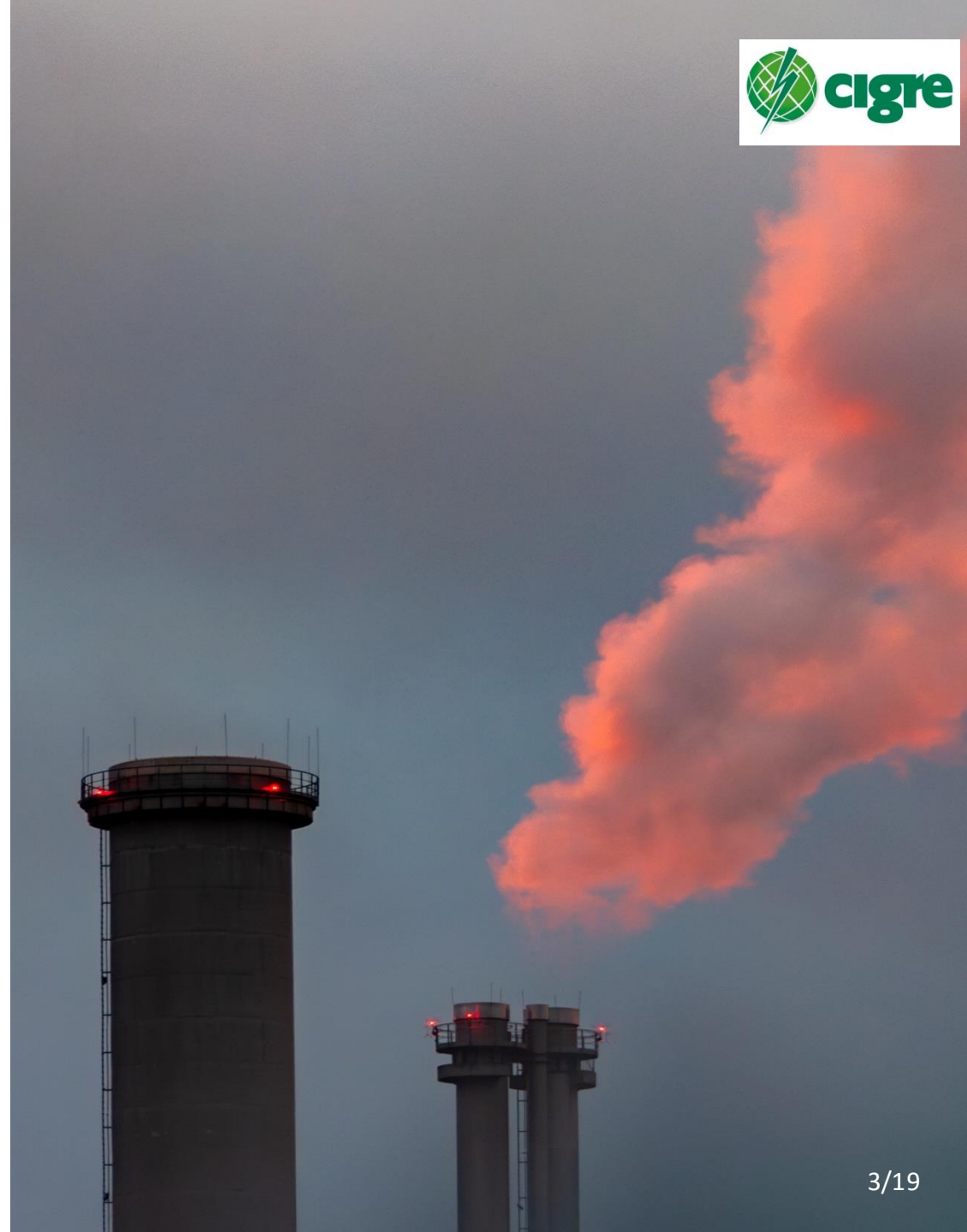
The most critical aspect is maintaining the grid's frequency (50Hz in the UK) within tight tolerances. This is the number of times alternating current cycles per second, and deviations can damage equipment.

Balance of Supply and Demand

A perfectly stable grid has the exact same amount of electricity being generated as is being consumed at any given moment.

System Resilience

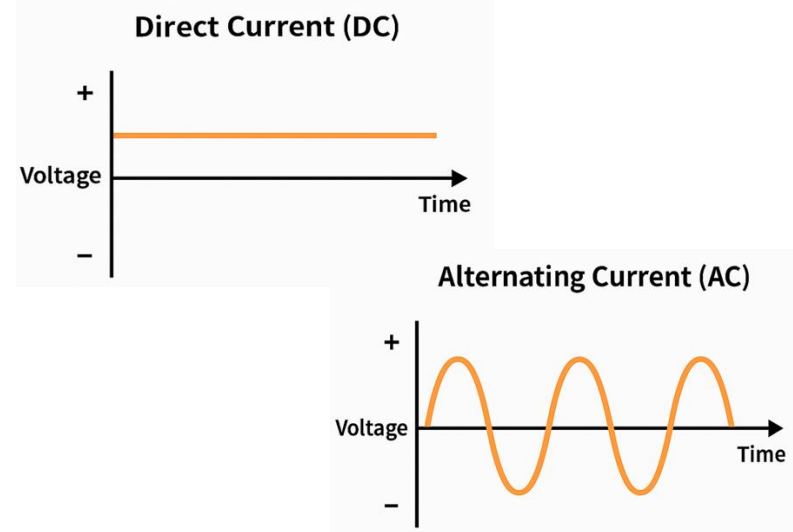
It's the system's capacity to withstand disturbances, such as generator failures or unexpected changes in demand, and return to a stable operating state.



Growing penetration of non-synchronous generation drives the need for more system inertia and frequency support

Conventional power plants use large rotating synchronous generators to produce electricity

- Hydro
- Nuclear
- Natural Gas
- Coal



Renewables use inverters to produce electricity

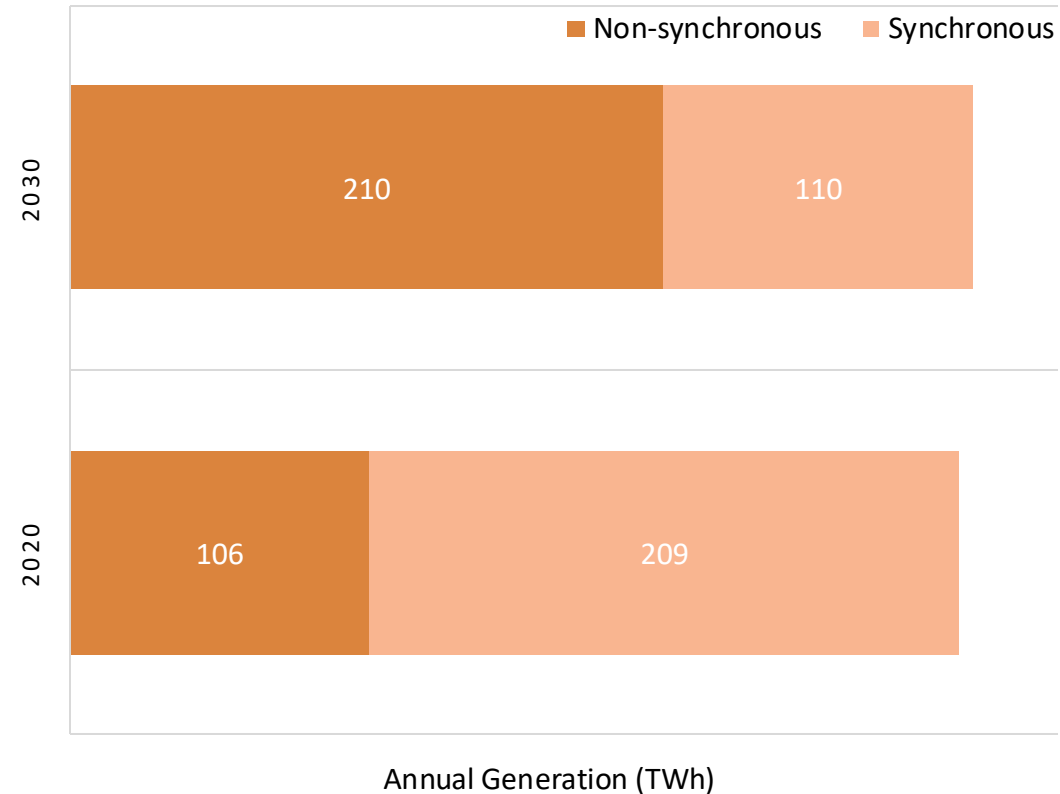


- Non-synchronous generation — such as solar PV and wind — is connected to the grid through power electronics rather than directly through synchronous generators (like traditional coal, natural gas, or hydro plants).
- This means it does not inherently provide rotational inertia, which helps stabilize grid frequency during disturbances.



Growing penetration of non-synchronous generation drives the need for more system inertia and frequency support

Expected Increase of Non-synchronous Generation



Two Main Inverter Control Philosophies



Grid-Following (GFL)

- Output current is controlled to follow the grid voltage.
- Synchronization is dependent on an external voltage source.



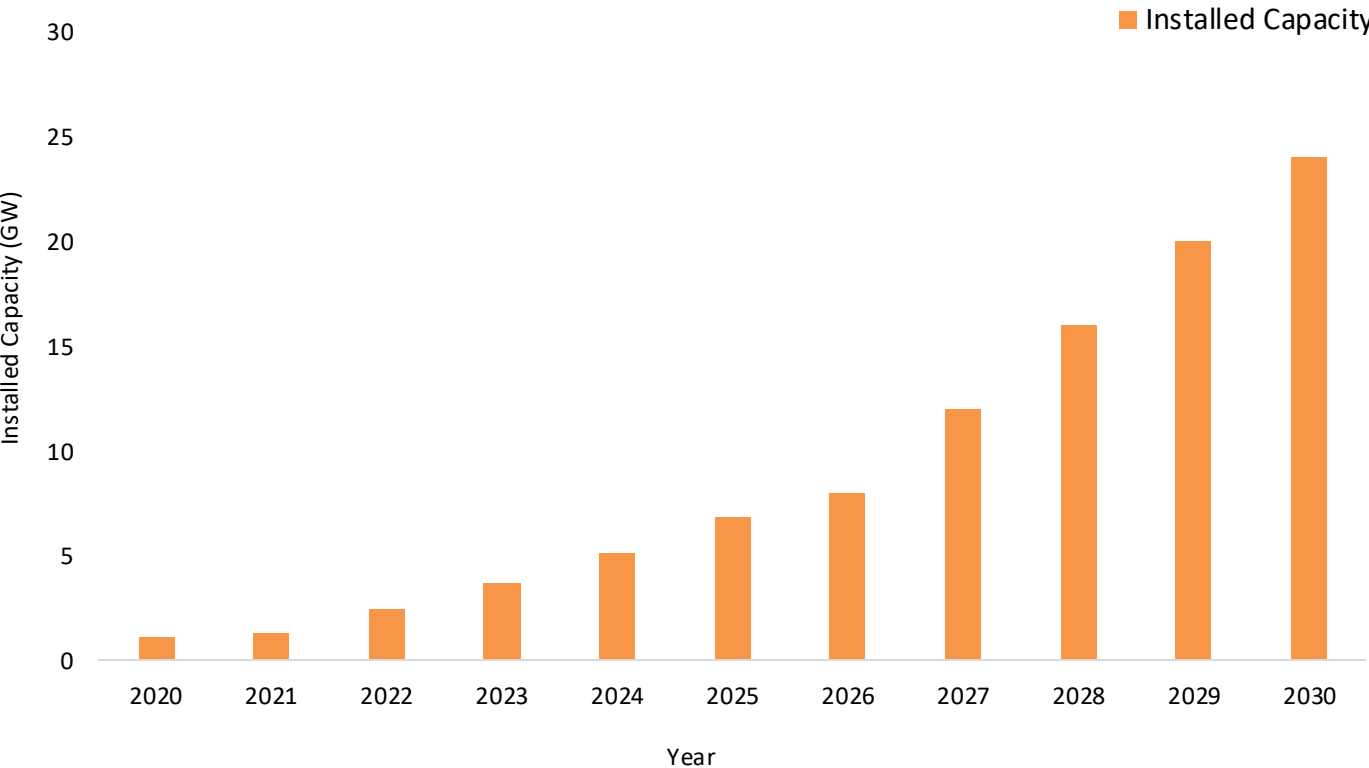
Grid-Forming (GFM)

- Output voltage is controlled independently.
- Capable of generating its own voltage waveform.

Increasing Deployment of Battery Energy Storage Capacity (GW)



UK Battery Storage Deployment – Cumulative Capacity (GW), 2020 – 2025



Commentary

The figure shows the consistent growth of installed battery energy storage capacity across Great Britain over the past years. Starting from minimal levels in 2020, deployment has surged since 2022, driven by the rapid uptake of Battery Energy Storage Systems to enhance renewable integration and grid stability. By 2023, installed capacity surpassed 3 GW, underscoring the growing importance of storage technologies in the national energy landscape. In 2025 the capacity is expected to increase to 6.8 GW while by 2030 the total installed capacity is projected to reach 25 GW.

Can we use BESS to stabilise the power grid?

Rapid Dynamic Response	BESS can respond within milliseconds, allowing immediate adjustment of active power output in response to frequency deviations or transient events.
High-Precision Power Control	Power delivery is highly controllable and can be modulated with fine accuracy to maintain system balance and stability.
Bi-Directional Operation	Batteries can both absorb and supply power, enabling seamless transition between charging and discharging modes depending on grid conditions.
Modular and Scalable Design	Their modular architecture allows deployment across a wide range of capacities and voltage levels, from small distributed systems to large utility-scale installations.
Absence of Mechanical Components	As BESS contain no rotating parts, associated wear is eliminated, resulting in reduced maintenance requirements and minimal operational latency.
High Reliability and Availability	The solid-state nature of BESS enhances system reliability and enables sustained operation with minimal downtime.
Grid-Forming Capability	Advanced control systems allow certain BESS configurations to operate in grid-forming mode, establishing voltage and frequency references and providing dynamic support during disturbances.



Grid-Following vs Grid-Forming BESS



Grid-Following

Grid-Forming

Core Capabilities Market Products & Revenue Streams	Definition	Operates as a " <i>grid taker</i> ", synchronising to existing grid waveforms with fast response capabilities	Operates as a " <i>grid maker</i> ", independently establishing grid voltage and frequency references
	Core Capabilities	• Fast frequency/voltage response • Optimal for strong grid conditions • Relies on existing system inertia	• Provides synthetic inertia and system strength • Maintains stability in low-inertia grids • Enables islanded mode operations
	Market Products & Revenue Streams	Energy Arbitrage Charging during low-price periods, discharging during peak pricing windows Frequency Regulation Primary/secondary reserves and frequency containment reserve services Capacity Markets Ensuring system adequacy through participation in capacity procurement Peak Shaving & Demand Management Commercial and industrial demand charge reduction strategies Congestion Relief Supporting transmission and distribution system optimization	Black Start Capability The ability of battery energy storage systems (BESS) to independently restart parts of the power grid following a system-wide blackout, reducing reliance on conventional generation sources. System Strength and Stability The contribution of BESS, particularly in grid-forming mode, to voltage stability, fault current provision, and overall network resilience against disturbances. Inertia Services and Microgrid Support The role of BESS in emulating rotational inertia, providing fast frequency response, and enabling stable islanded microgrid operations with high renewable penetration.

Grid-Following vs Grid-Forming BESS



Functionality	Grid-forming inverters generate and regulate grid voltage and frequency, whereas grid-following inverters synchronize their output to the existing grid voltage and frequency.
Operational Independence	Grid-forming inverters can operate either independently or in coordination with other generation sources. In contrast, grid-following inverters rely on the grid to provide a stable voltage and frequency reference.
Support Capabilities	Grid-forming inverters can actively support voltage and frequency, particularly during grid disturbances or outages, while grid-following inverters are unable to do so.
Ancillary Services	Grid-forming inverters are capable of delivering a range of ancillary services, including inertia, system strength, voltage regulation, and frequency response—services that grid-following inverters cannot provide.
Complexity and Cost	Grid-forming inverters are generally more complex and costly to design and implement than grid-following inverters.
Control Dynamics	Grid-forming inverters typically exhibit slower power control and response times compared to grid-following inverters.
Challenges	Despite their advantages, grid-forming inverters face several technical and regulatory challenges, including synchronization, protection, coordination, and compliance with evolving standards—issues that grid-following inverters largely avoid.



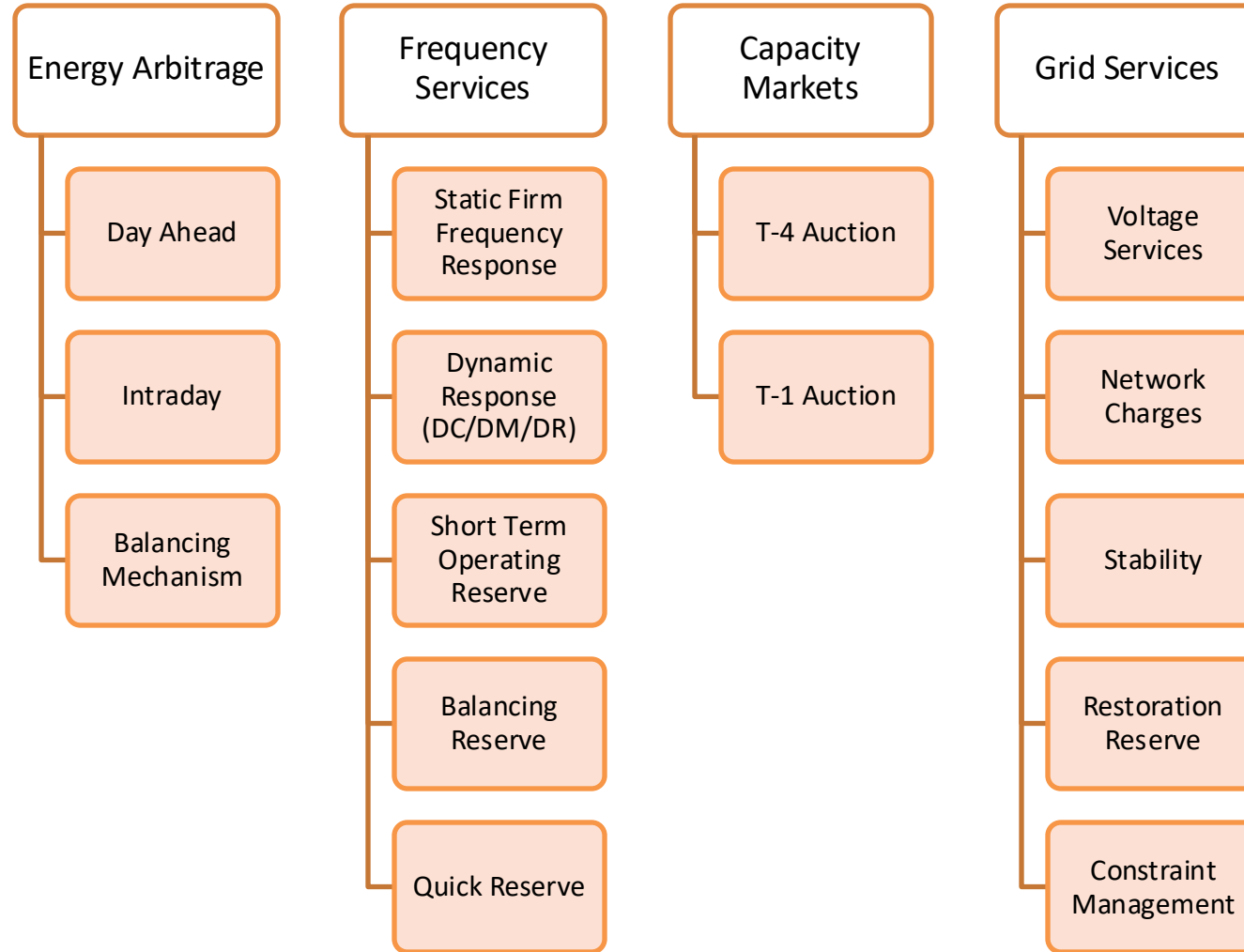
Grid-Following vs Grid-Forming: Capability Matrix



Service / Product	Grid-Following BESS	Grid-Forming BESS
Energy Arbitrage	✓ Proven, widely deployed	✓ Same as GFL
Frequency Regulation	✓ High accuracy, very fast	✓ Plus enhanced weak grid stability
Capacity Markets	✓ Reliable participation	✓ Added resilience contribution
Black Start Services	✗ Requires external voltage reference	✓ Independent grid energization
Virtual Inertia / Stability	✗ Limited capability	✓ Synthetic inertia provision
Weak Grid Support	✗ Performance degrades	✓ Optimal for low short circuit ratio conditions
Islanding Capability	✗ Grid-dependent operation	✓ Seamless islanding and resync



Revenue Streams and Market Opportunities for BESS in the UK



Revenue Streams and Market Opportunities for BESS in the UK



Energy Arbitrage

Frequency Services

Capacity Markets

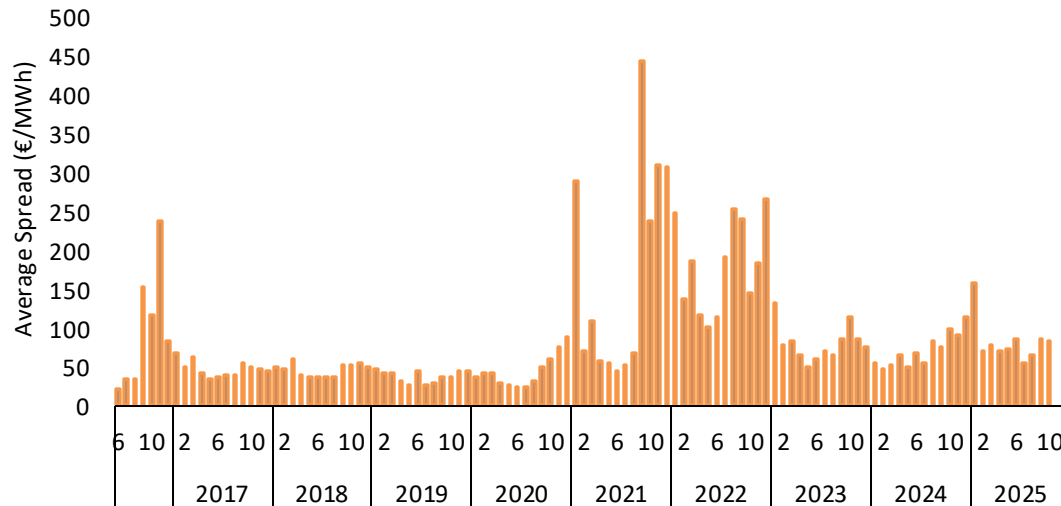
Grid Services

Energy arbitrage on the wholesale market

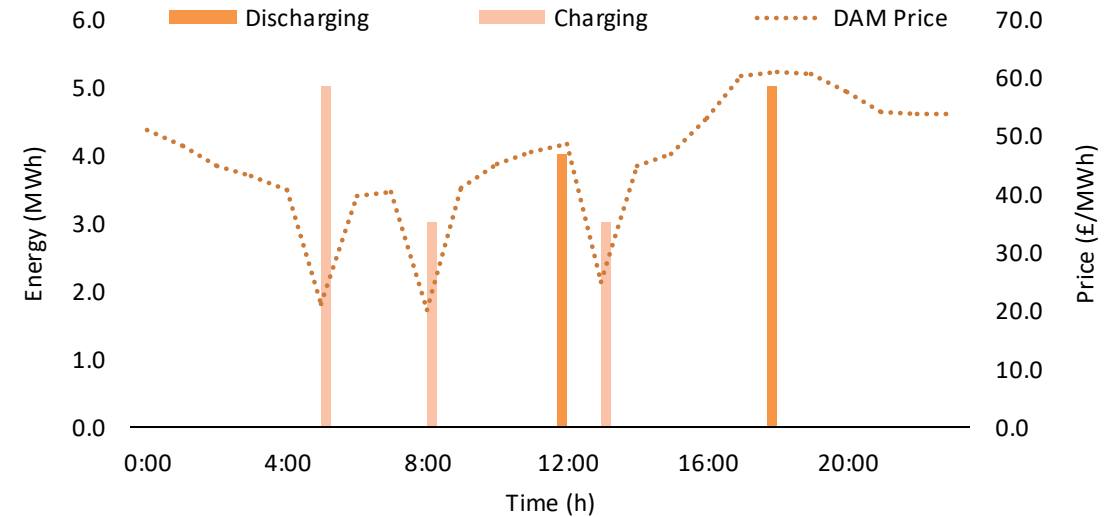
- Energy arbitrage has become the most important revenue stream on the wholesale market over the past years.
- The revenue potential from energy arbitrage is largely determined by the electricity generation mix.

- BESS profit from when charging/buying energy during low priced hours and discharge/sell that energy back to the grid during high price hours

Monthly average price spreads on the day-ahead market



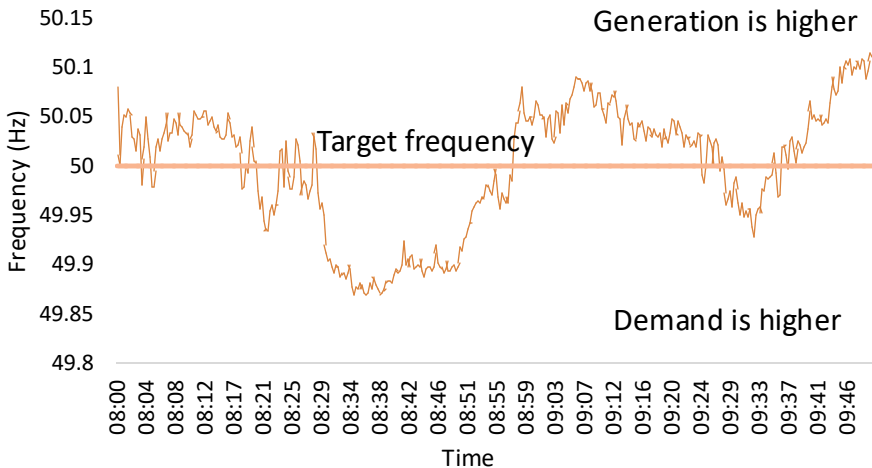
Illustrative example of BESS charging/discharging behaviour



System Frequency Monitoring

- To ensure that generation and demand remain in balance system frequency is continuously monitored in real time by the National Energy System Operator. In the GB electricity system, this balance corresponds to 50 Hertz (Hz).
- When generation exceeds demand, the frequency is observed to rise above 50Hz, while the opposite occurs when demand surpasses generation.

Rolling System Frequency (08:00-10:00, 8 Oct)



Frequency Services can be Distinguished by Several Key Factors

Static vs Dynamic

Static services (e.g., static FFR) provide a predefined response — for instance, increasing generation or reducing demand for 30 minutes when frequency drops to 49.7 Hz. Dynamic services (e.g., Dynamic Containment) offer a continuously variable response based on real-time grid frequency.

Pre- vs Post-Fault

Pre-fault services (e.g., Dynamic Regulation) act proactively to stabilise frequency before significant deviations occur. Post-fault services (e.g., static FFR) respond reactively after a disturbance.

Direction

Some services are unidirectional (e.g., static FFR), responding only to frequency rises or drops. Others are bidirectional, responding to both. Those services may be procured as a single combined product or as separate components for each direction.

Response Time

The time taken to begin and fully deliver a response varies — from as fast as 0.5 seconds (Dynamic Containment) to up to 30 seconds (static FFR).

Delivery Duration

Services with faster response times (e.g., Dynamic Containment) typically sustain delivery for shorter periods, around 15 minutes. Slower services (e.g., Dynamic Regulation) can deliver for longer durations, up to 60 minutes.

Revenue Streams and Market Opportunities for BESS in the UK



Energy Arbitrage

Frequency Services

Capacity Markets

Grid Services

Product ¹	Speed	Duration	Direction	Purpose
Dynamic Regulation	10 seconds	Up to 60 minutes	High and Low	Pre-fault service
Dynamic Moderation	1 second	Up to 30 minutes	High and Low	Pre-fault service
Dynamic Containment	1 second	Up to 15 minutes	High and Low	Post fault service
Static Firm Frequency Response	30 seconds	30 minutes	Low	Post fault service
Mandatory Frequency Response	10 to 30 seconds	30 minutes	Bundled High and Low	Designed to resolve all issues with the one service.
Commercial Frequency Response	Varies	Varies	Varies	Suite of bespoke, bilaterally arranged frequency response contracts

¹<https://www.neso.energy/industry-information/balancing-services/frequency-response-services>

Revenue Streams and Market Opportunities for BESS in the UK



Energy Arbitrage

Frequency Services

Capacity Markets

Grid Services

Capacity Market Revenues for BESS in the UK

Stable Revenue Source	Capacity markets provide a more predictable and stable income stream compared to energy arbitrage and frequency services.
Auction Structure	The UK operates two types of capacity market auctions: • T-4 Auctions: Held four years ahead of delivery, offering the bulk of capacity volume and long-term contracts (up to 15 years). • T-1 Auctions: Held one year ahead of delivery, mainly targeting existing assets.
Contract Value	Securing a T-4 contract can ensure revenue stability for a BESS project even before construction is completed.
Challenges for Existing Projects	The four-year delay before income from T-4 contracts can create financial strain for operational projects seeking immediate returns.
Price Volatility	Capacity market clearing prices have fluctuated significantly due to changes in BESS participation rates and competition from gas-fired generation.

T-1 Auction Capacity Awarded by Primary Fuel Type (GW)¹



Nuclear led capacity awards with 3.64 GW (45.8%), followed by gas at 2.37 GW (29.9%). Battery storage secured 0.73 GW (9.2%), while demand-side response (DSR) contributed 0.66 GW (8.4%). Smaller shares came from interconnectors (0.25 GW), offshore and onshore wind, and waste. Other fuel types, including hydro and coal, received no awards in this round.

T-4 Auction Capacity Awarded by Primary Fuel Type (GW)²



Gas dominated awards with 27.3 GW (63%), followed by interconnectors (6.8 GW, 16%). Battery storage and DSR each secured around 4% of capacity, while pumped storage, hydro, and nuclear contributed smaller shares. Minor allocations went to waste, diesel, and wind technologies.

¹<https://nationalenergyso-emr.my.salesforce.com/sfc/p/#8d000002dUGC/a/1700000057ZI/WSDaGWFzdcClBryKIMp3eKmolrbM0ECzVWI1FPUXOqE>

²<https://nationalenergyso-emr.my.salesforce.com/sfc/p/#8d000002dUGC/a/170000005997/VzvDwNNYe4mjfZh9KPhhABiQOIGZI8jQb8VcuGTKOV4>

Revenue Streams and Market Opportunities for BESS in the UK



Energy Arbitrage

Frequency Services

Capacity Markets

Grid Services

- Grid services currently make up a smaller share of total BESS revenues, but they are becoming increasingly important as the UK electricity system evolves.
- Ongoing reforms create new low-risk, long-term income opportunities for storage operators.
- Voltage, stability, and restoration (Black Start) services have traditionally been procured from thermal generators. However, although batteries are non-synchronous, their inverters can produce reactive power and provide virtual inertia.

Stability and Voltage Contracts

- In 2022, five BESS projects secured stability contracts.
- Blackhillock (Scotland), commissioned in 2025, became the first in the world to provide stability services.
- Three projects (2024) gained 10-year voltage contracts
- Black Start still in feasibility.

Constraint Management Services

- Allows BESS to earn by being available to trip offline during grid faults.
- Available mainly in Eastern England and Scotland.
- To date, only Wishaw has a contract; potential still emerging.
- Future congestion could make this a valuable revenue stream for flexible storage assets.



Technical & Operational Challenges



Short-Circuit Current Limitations

Grid-forming inverters provide limited fault current compared to synchronous machines, requiring comprehensive protection system redesign and coordination.

Complex System Coordination

Integration challenges with existing synchronous machines and grid-following inverters demand sophisticated control coordination strategies.

Regulatory & Standards Gap

Current grid codes and technical standards assume synchronous generator characteristics, creating barriers to deployment and operation.

Economic Viability Concerns

Business models for stability services remain underdeveloped, with limited market mechanisms for compensating grid-forming capabilities.



Market Evolution and Emerging Opportunities



Current State: GFL Dominance
Grid-following systems dominate energy and ancillary service markets with proven track records

1

Transition Period: Hybrid Markets
Retiring synchronous generation reduces natural inertia, creating demand for GFM capabilities

2

Future Grid: GFM Premium
Grid-forming assets capture value in specialized stability and resilience markets

3

New Market Products Emerging

Inertia Markets

Stability Pathfinders program pioneering synthetic inertia procurement

System Strength Services

Australia's AEMO developing frameworks for voltage support and fault ride-through

Enhanced Black Start

Premium contracts for rapid grid restoration capabilities



**Thank you for your
attention!**

