“Mainstreaming” batteries:

How to identify most competitive technologies and ensure profitable deployment

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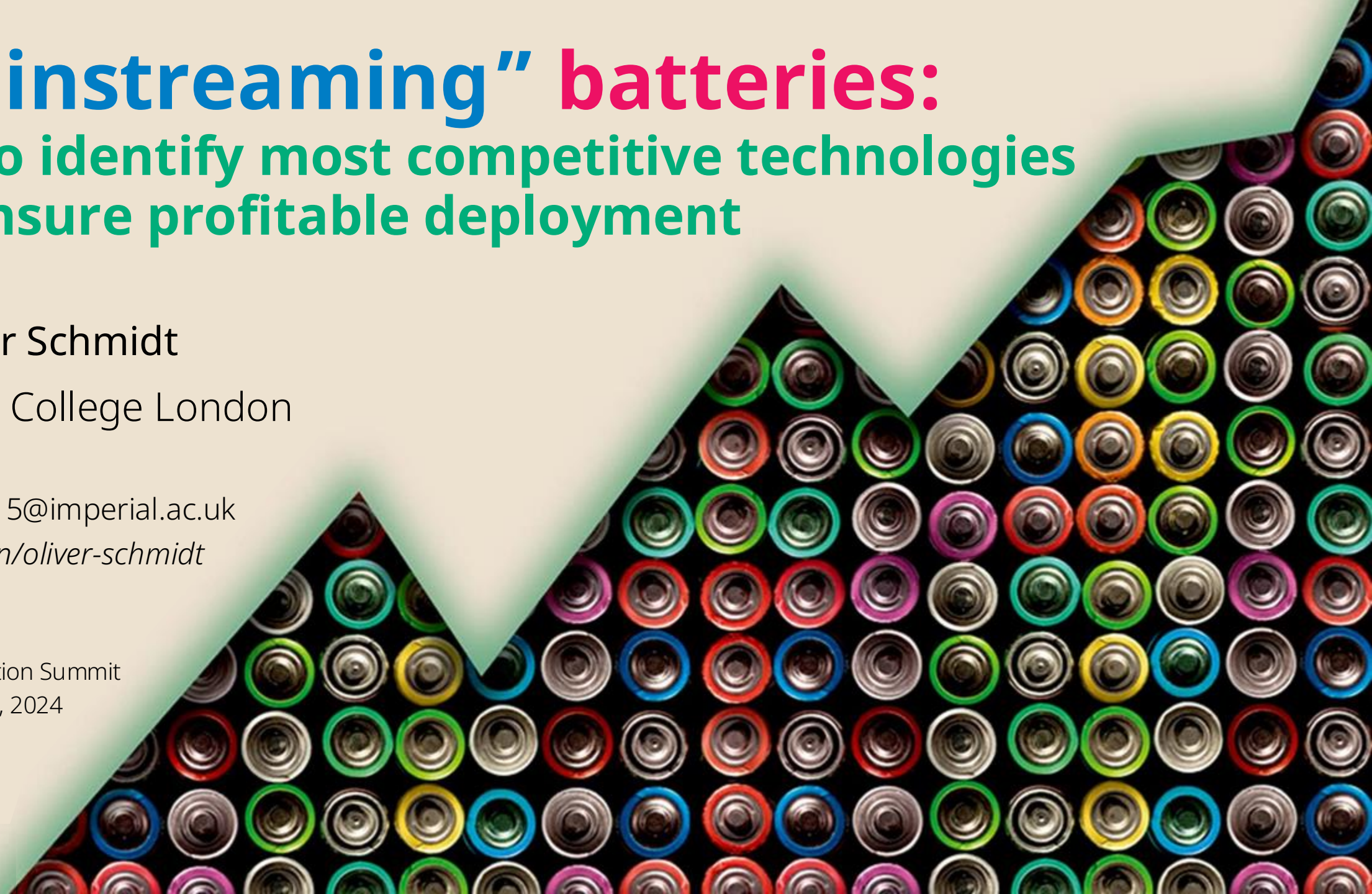
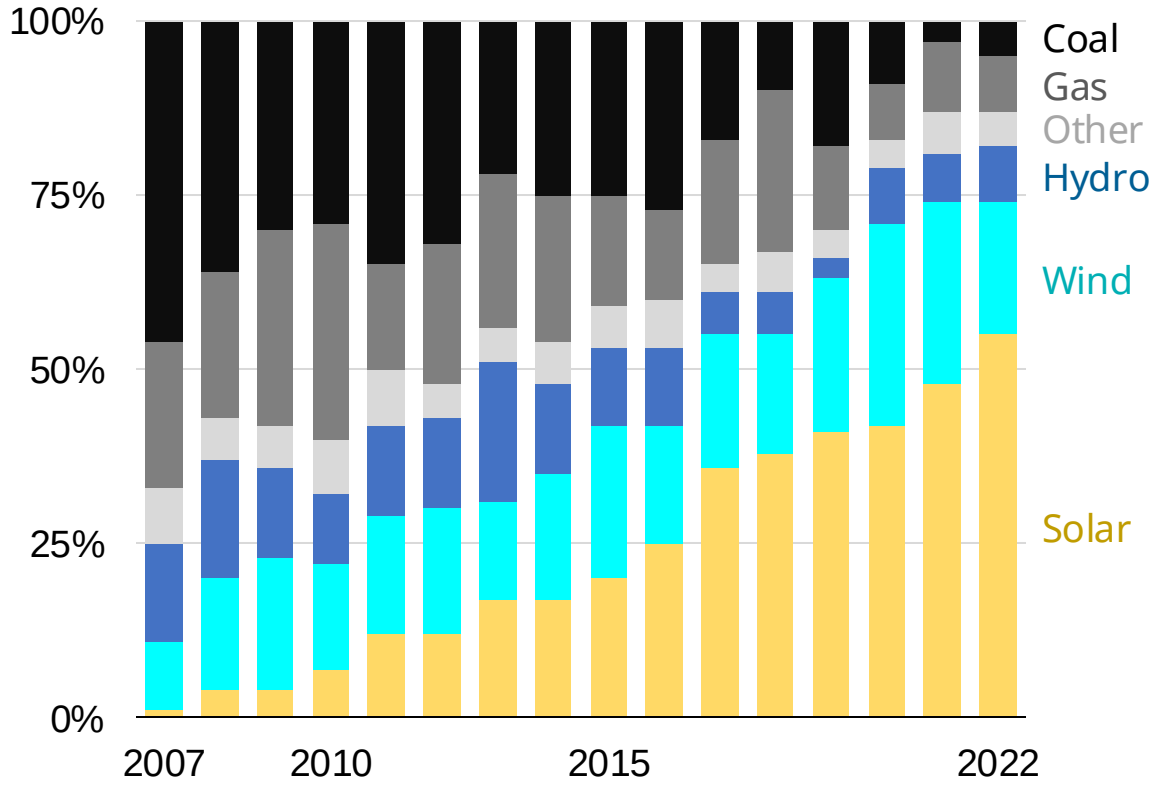


Energy Transition Summit
September 26, 2024
Dublin

The electricity sector is transforming rapidly

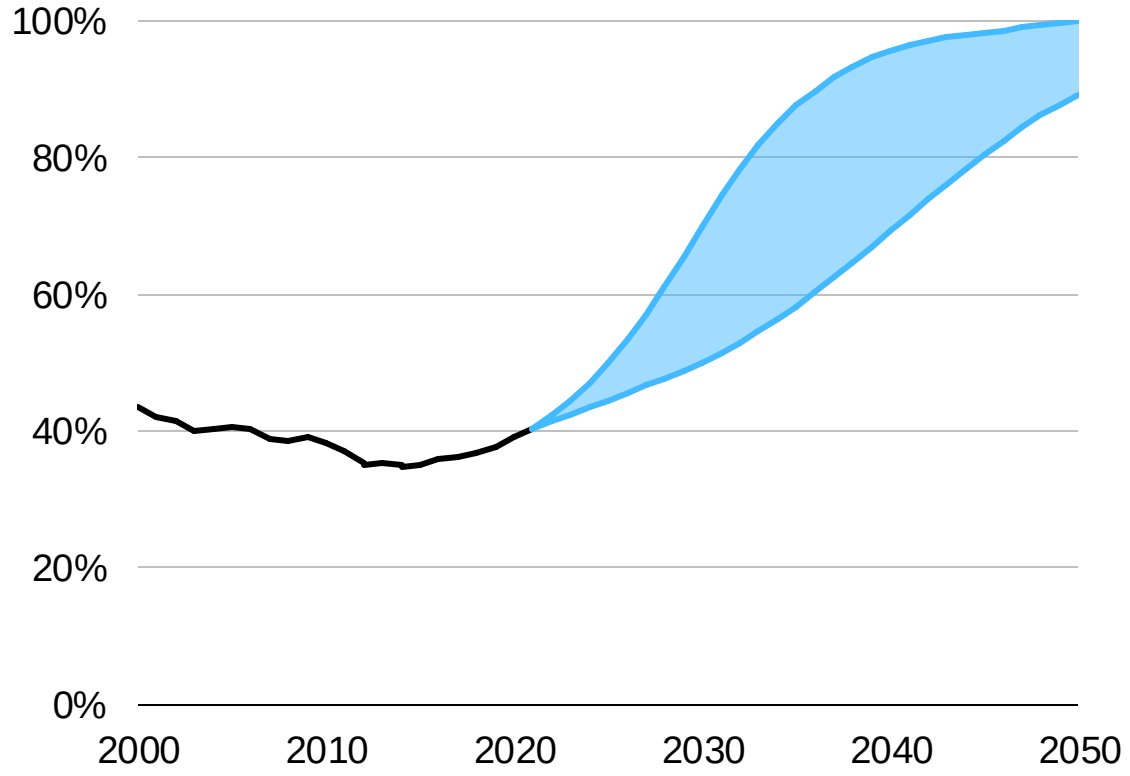
What is already happening:

Global capacity additions



What will be needed:

Electricity generation from low-carbon sources

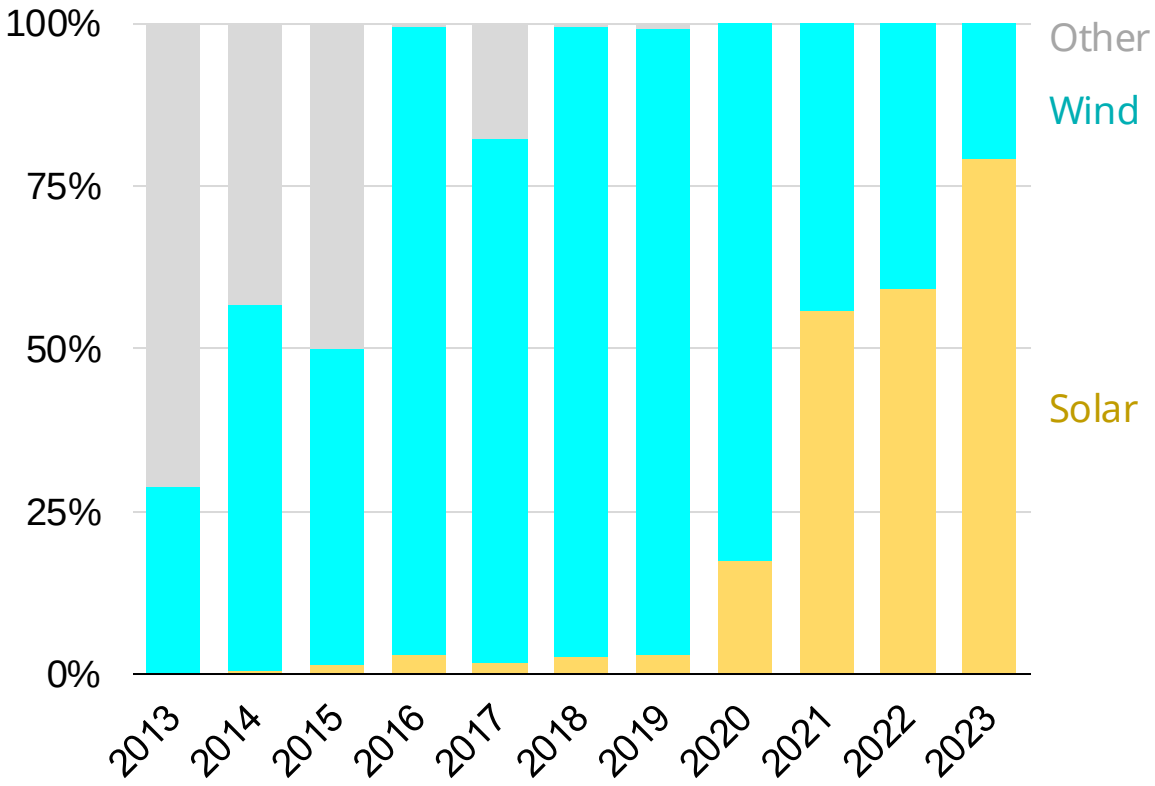


Source: BloombergNEF (2023), IPCC 6th Assessment Report (2021)

Ireland is among the leaders of this transformation!

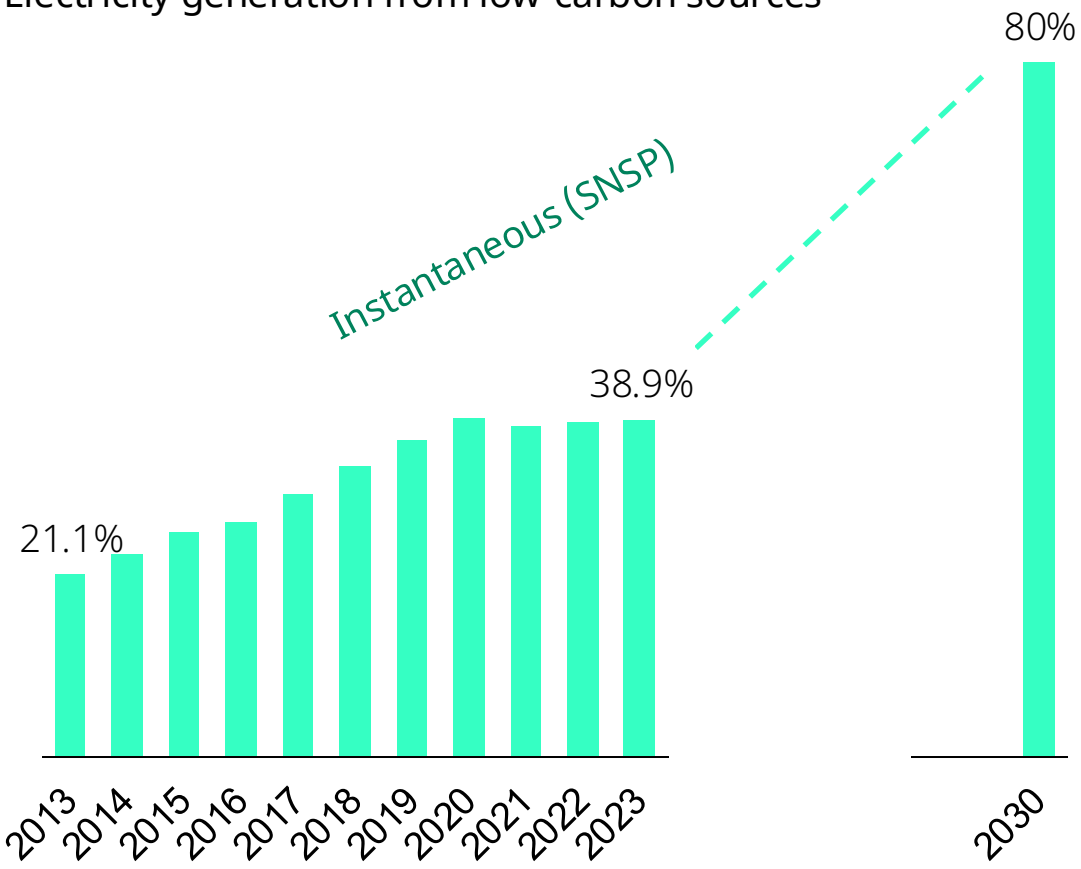
What is already happening:

Annual capacity additions



What is likely to happen:

Electricity generation from low-carbon sources



Source: EirGrid (2023), ISEA (2023), SEAI (2023)

There are many concepts and technologies for storing energy

Liquid air

- Sensible heat
- Latent heat
- Thermochemical heat

- Gravitation
- Compression
- Motion

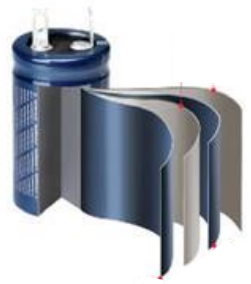
Pumped hydro

Electrolysis

- Hydrogen
- Ammonia
- Alcohols
- Hydrocarbons

- Capacitance
- Inductance

Supercapacitor



Redox flow

- Sealed batteries
- Flow batteries

Lithium ion

Lifetime cost is *the* metric for comparing these technologies

- Accounts for all cost components required to serve specific application (e.g. power conversion to enable fast response)
- Includes replacement cost to account for degradation

Cost to operate, insure and periodically service technology components

- Reflects round-trip efficiency, because more energy is purchased than discharged (respective power price depends on application)
- Also accounts for auxiliary energy (e.g. air conditioning)

Can be a cost or a value depending on the reusability or recyclability of the technology, its components and raw materials

Levelised Cost Of Storage

$$\textbf{LCOS}\left[\frac{\text{US\$}}{\text{MWh}}\right] = \frac{\textit{Costs}}{\textit{Output}} = \frac{\text{Investment} + \text{O\&M} + \text{Charging} + \text{End of life}}{\text{Energy capacity} \cdot \text{Cycles per year} \cdot \text{Lifetime}}$$

(all costs and energy output are discounted over the lifetime)

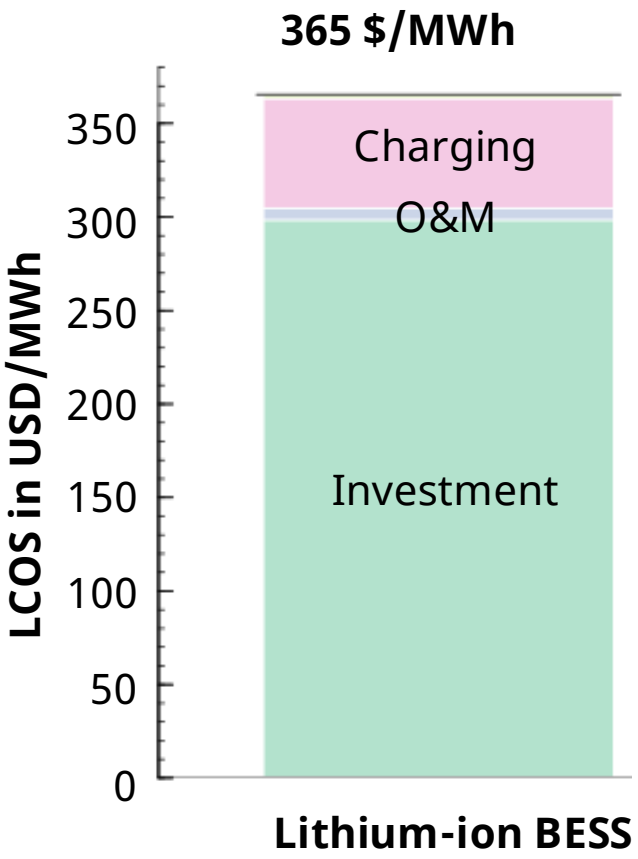
- Electricity that is discharged each cycle; should include annual degradation
- If it refers to electricity charged (against common practice), round-trip efficiency and DoD must be accounted for here

- Determined by application served by the storage system
- Can have significant impact on degradation and overall lifetime as cycle life is limiting factor for most technologies

- Option 1 - Technical: Number of years after which energy capacity degraded to e.g. 80%
- Option 2 - Economic: Pre-defined number of years, e.g. secured revenue

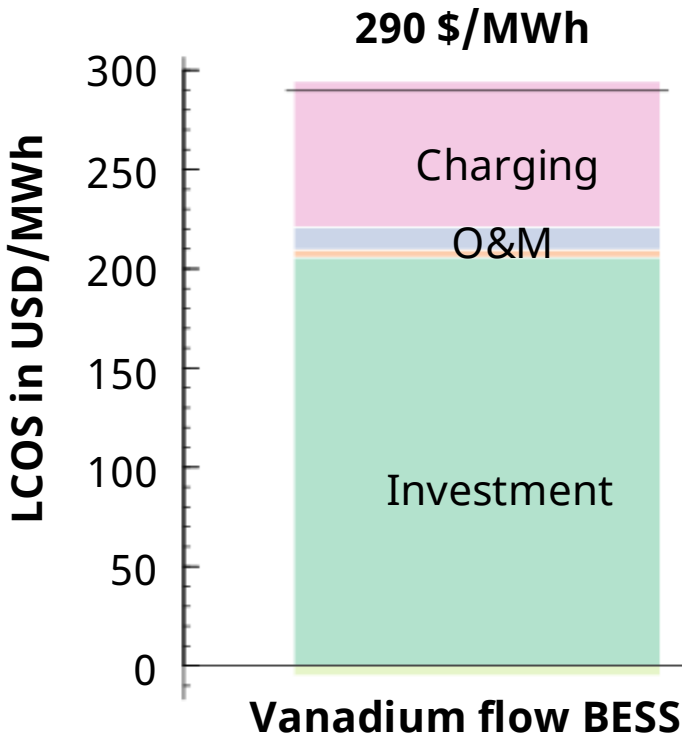
Example: For peak capacity, flow batteries beat lithium-ion

Peak capacity: 10 MW capacity, 300 cycles per year x 4 hours per cycle



Specifications

- $14.6 m
- 86% efficiency
- 3,500 cycles



Specifications

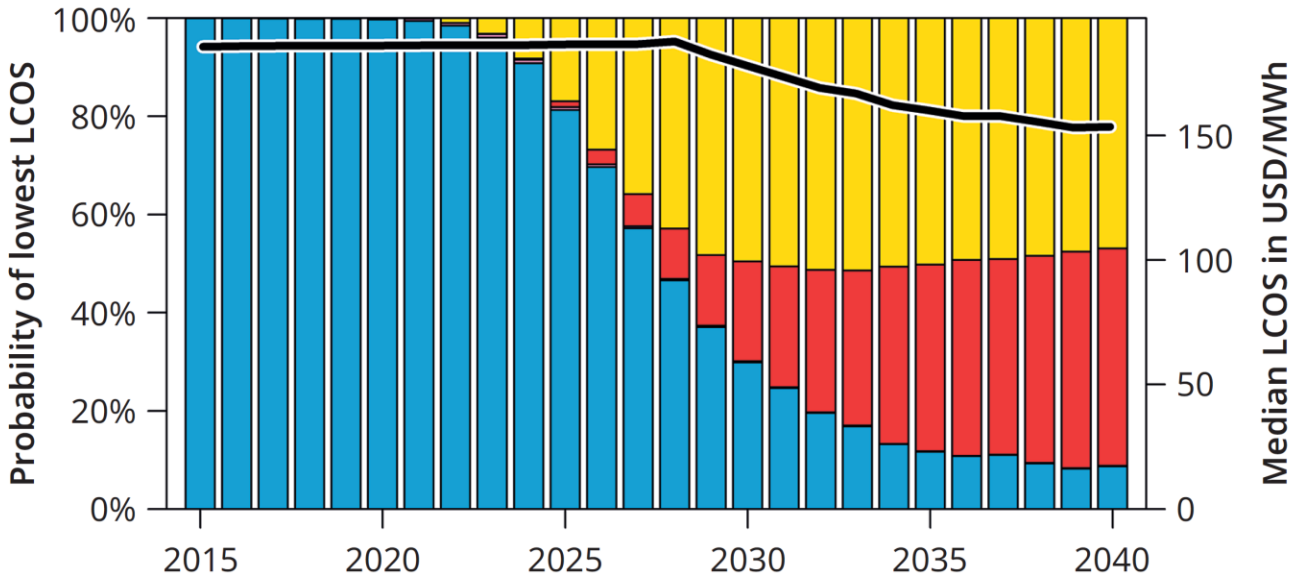
- $25 m
- 68% efficiency
- 20,000 cycles

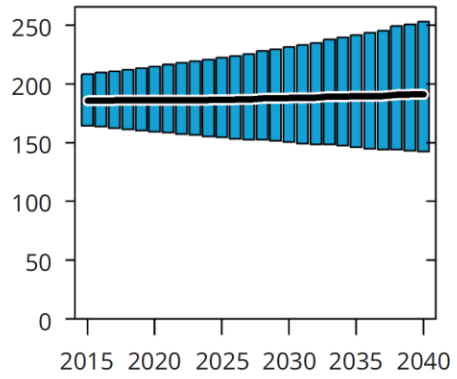
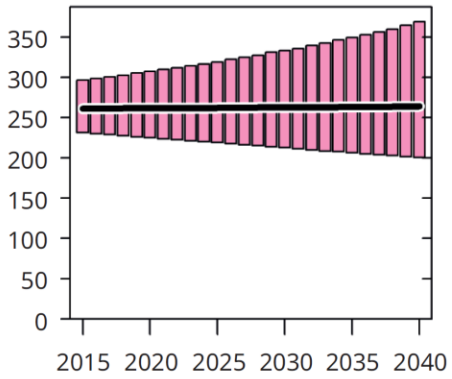
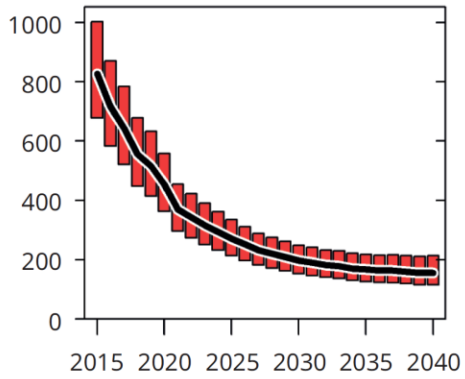
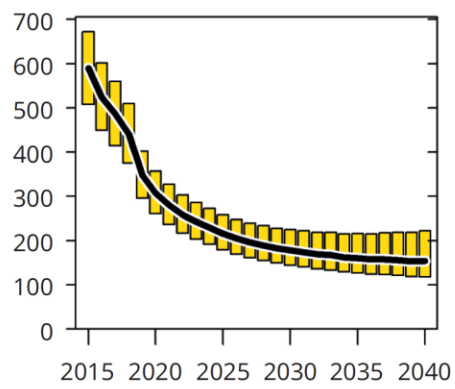
Source: Graph generated on www.EnergyStorage.ninja

The competitiveness of technologies will change over time

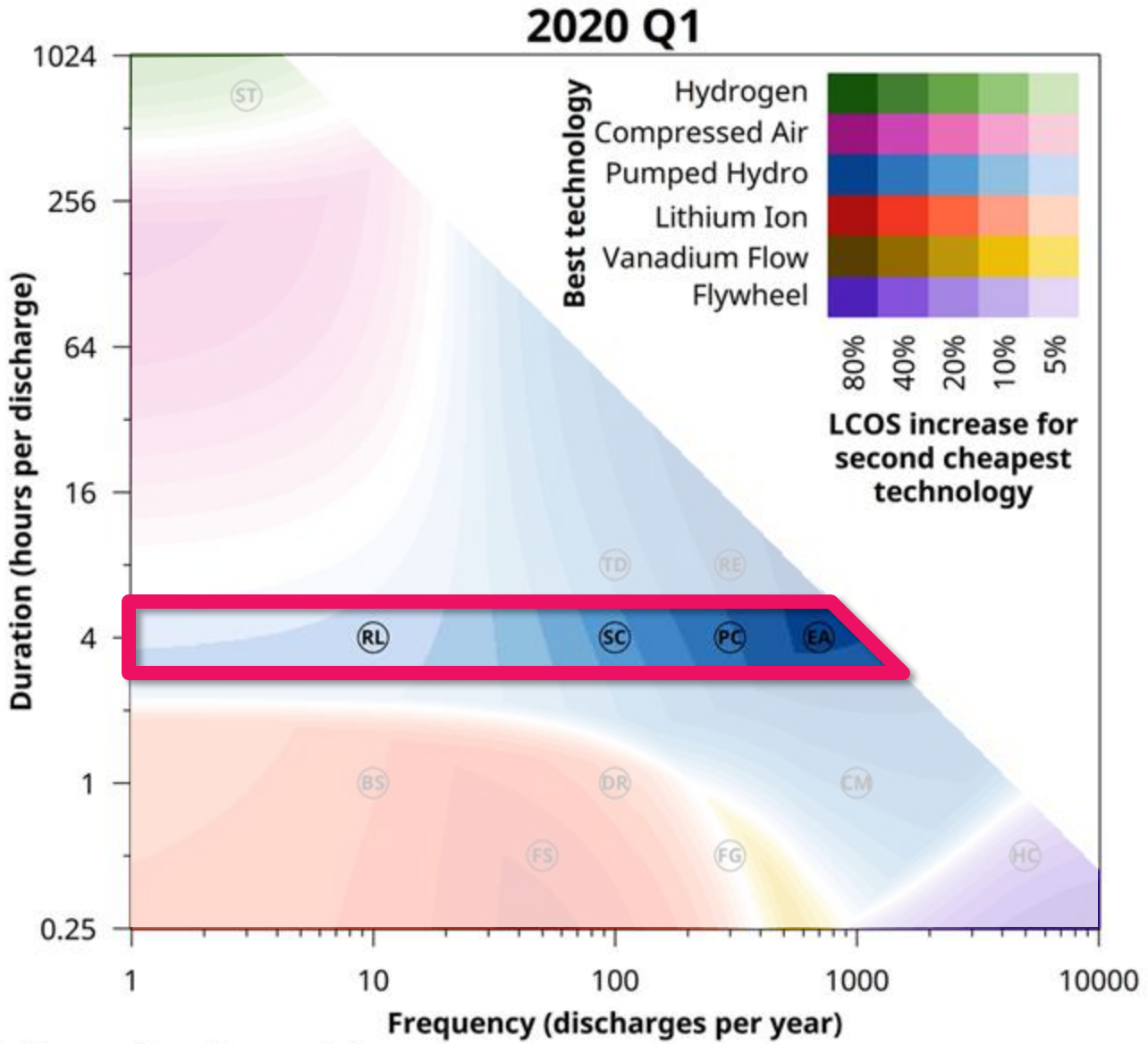
PC Peak capacity

Power capacity	10 MW
Discharge duration	4 hours
Annual cycles	300
Response time	>10 seconds
Electricity price	50 USD/MWh



	Pumped hydro	Compressed air	Lithium ion	Vanadium redox flow
Median and range of LCOS in USD/MWh				

There are dominant technologies for different requirements

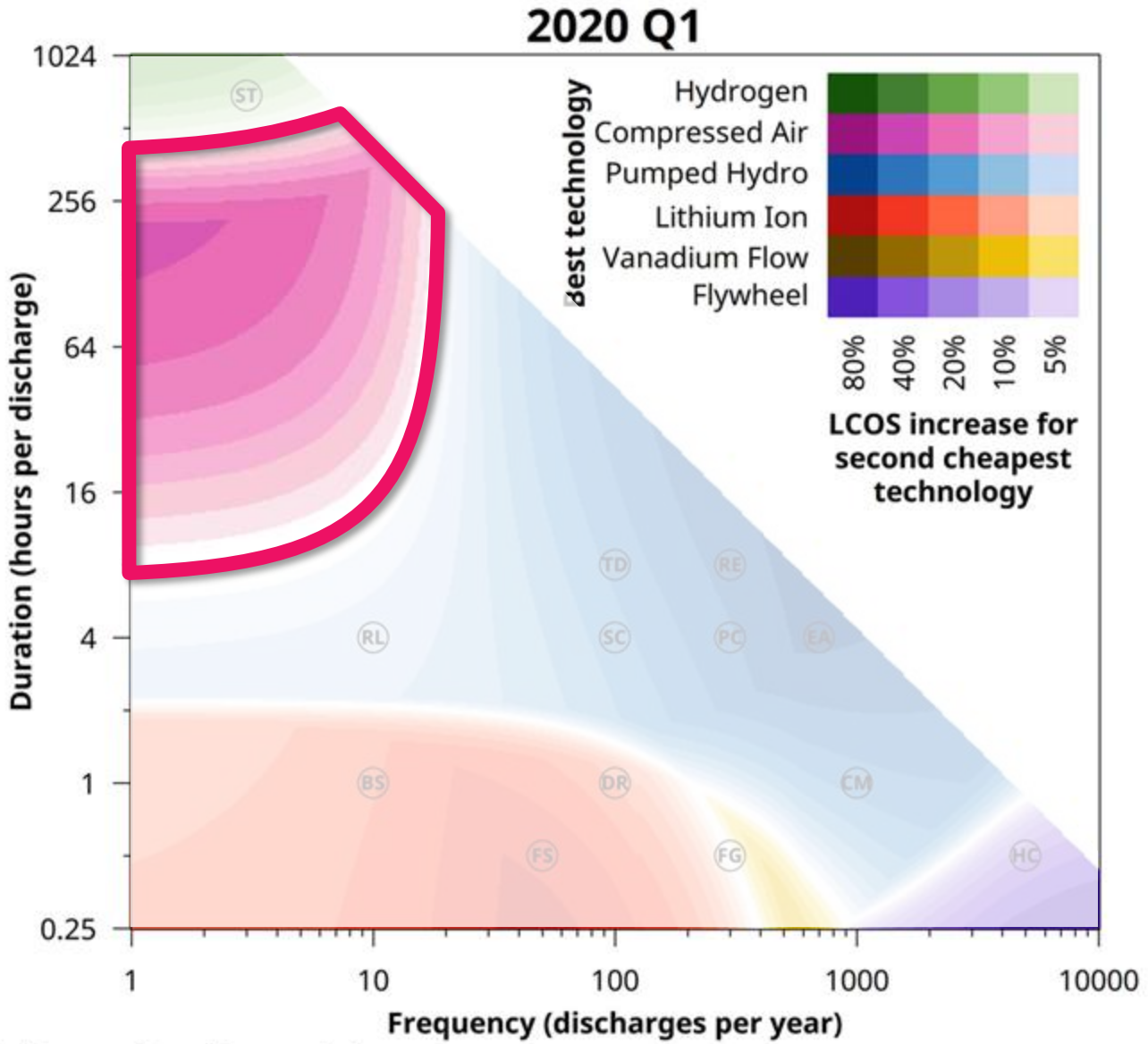


Circles denote typical power system applications:

- (ST) Inter-seasonal storage
- (RL) Power reliability
- (TD) Transmission & distribution investment deferral
- (RE) Renewables integration
- (SC) Increasing self-consumption
- (PC) Peaking capacity
- (EA) Energy arbitrage
- (BS) Black start
- (DR) Demand charge reduction
- (CM) Congestion management
- (FS) Frequency response (ramping / inertia)
- (FG) Frequency regulation (power quality)
- (HC) High cycle

Source: Graph generated on www.EnergyStorage.ninja

There are dominant technologies for different requirements



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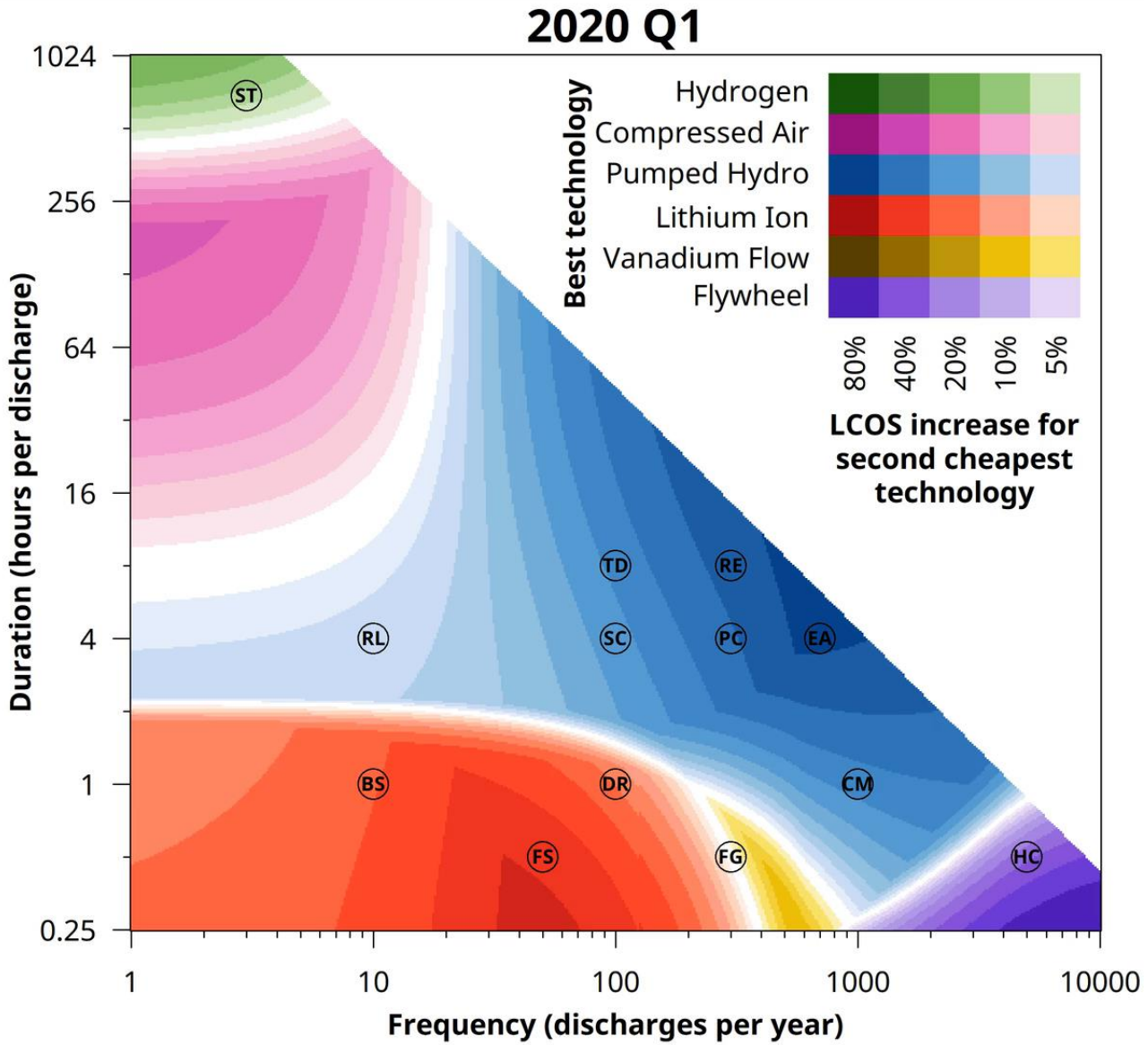
There are dominant technologies for different requirements



Circles denote typical power system applications:

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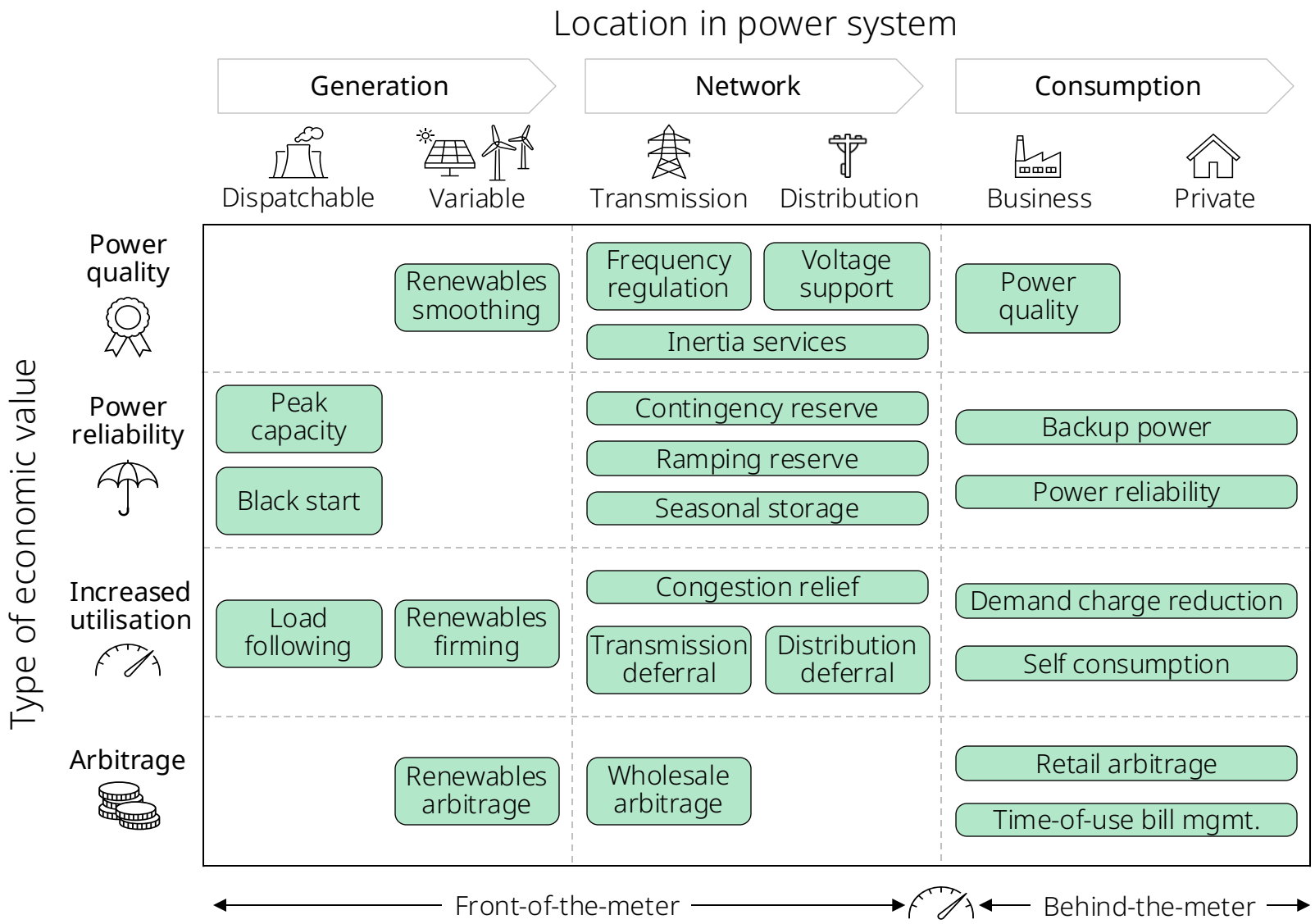
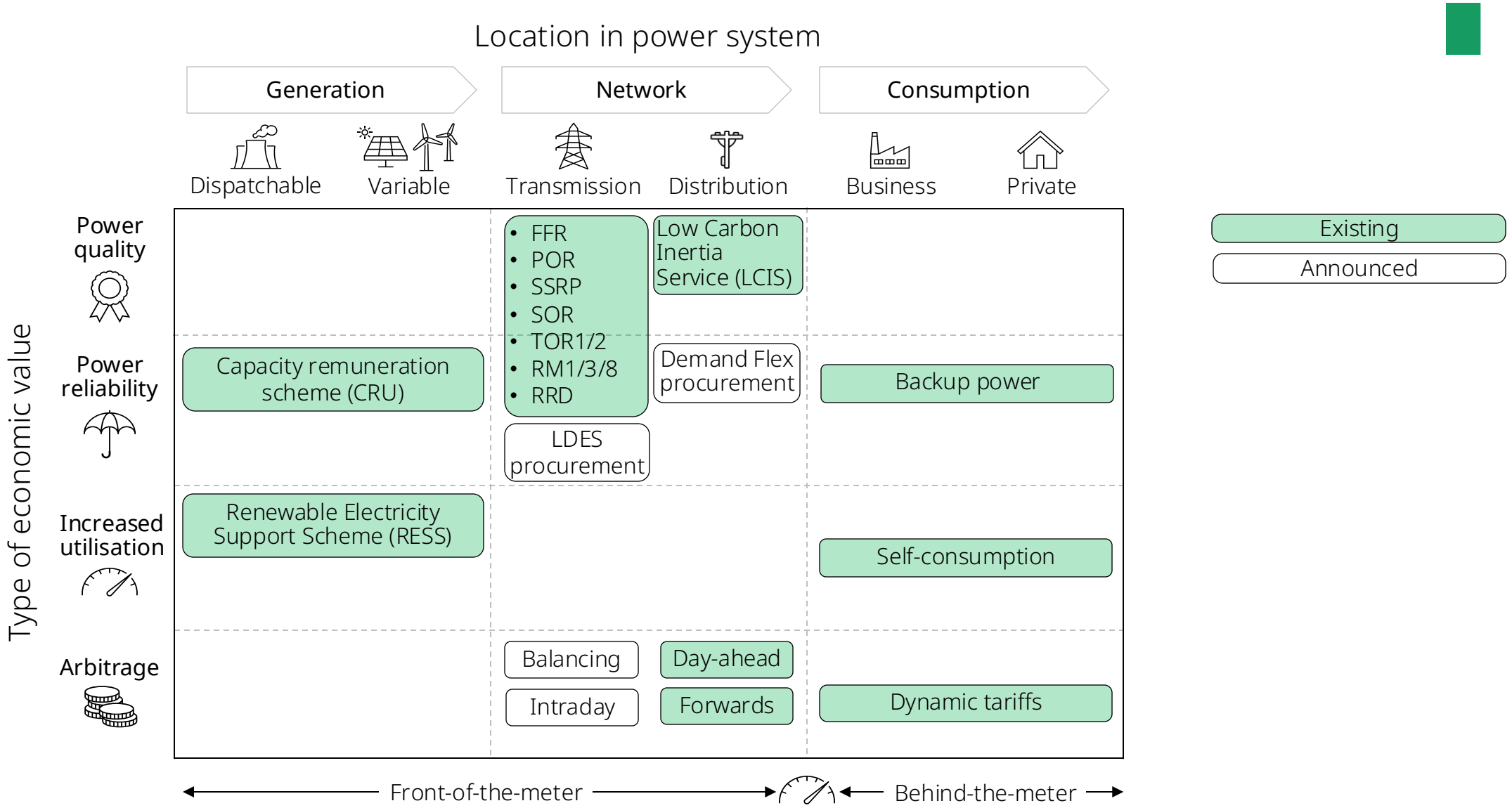
Source: Graph generated on www.EnergyStorage.ninja

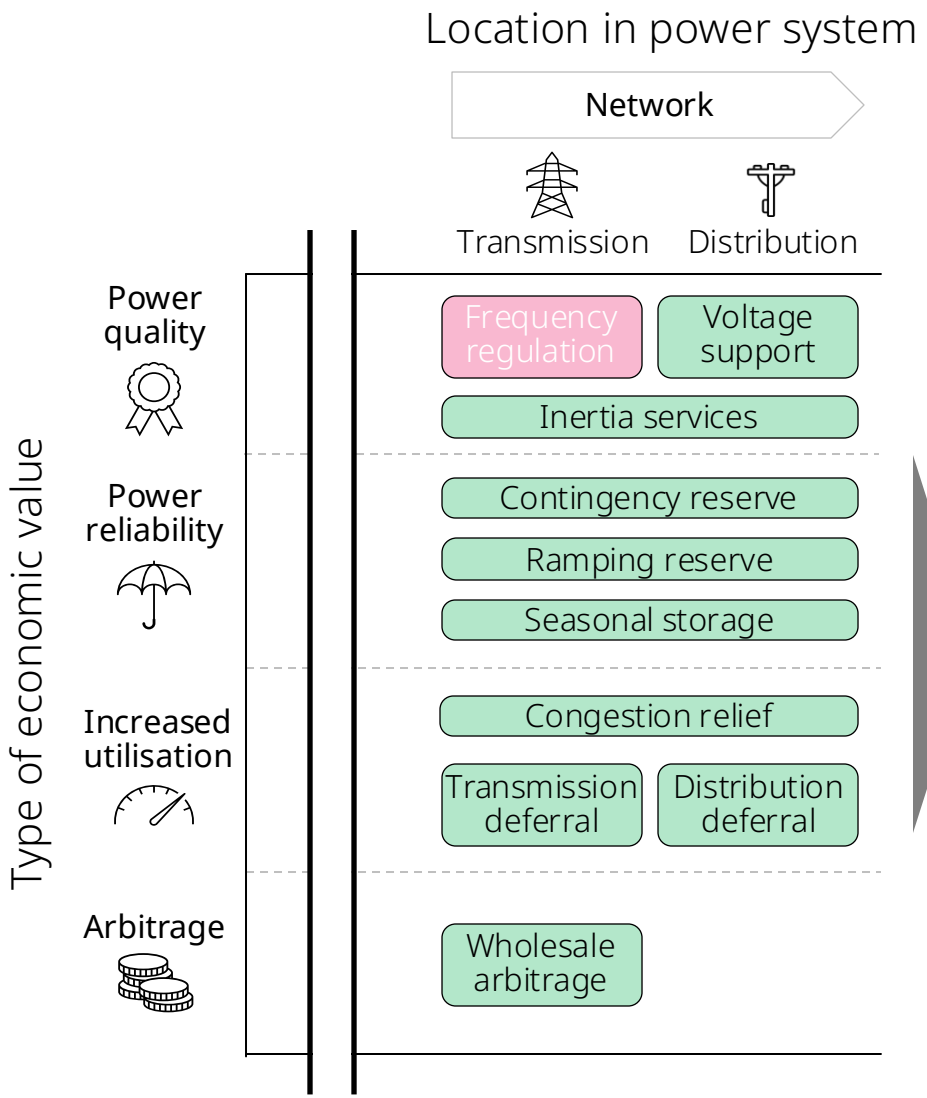
Like with technologies, there is a wide range of applications



Key applications in Ireland are DS3, energy trading and CRU

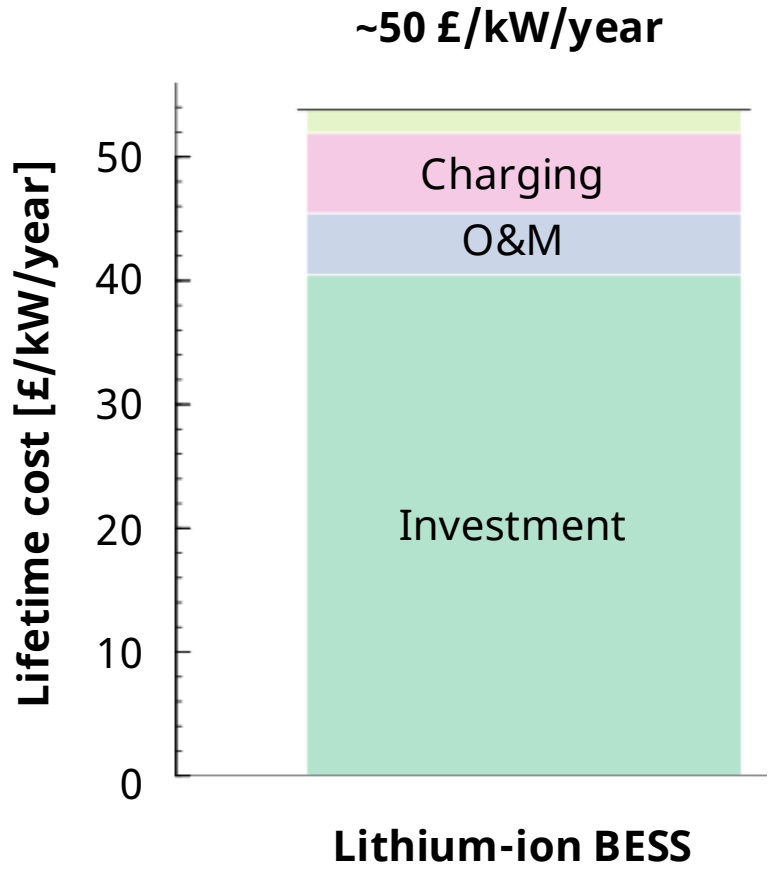


Frequency response can be provided at a cost of ~50 £/kW/yr



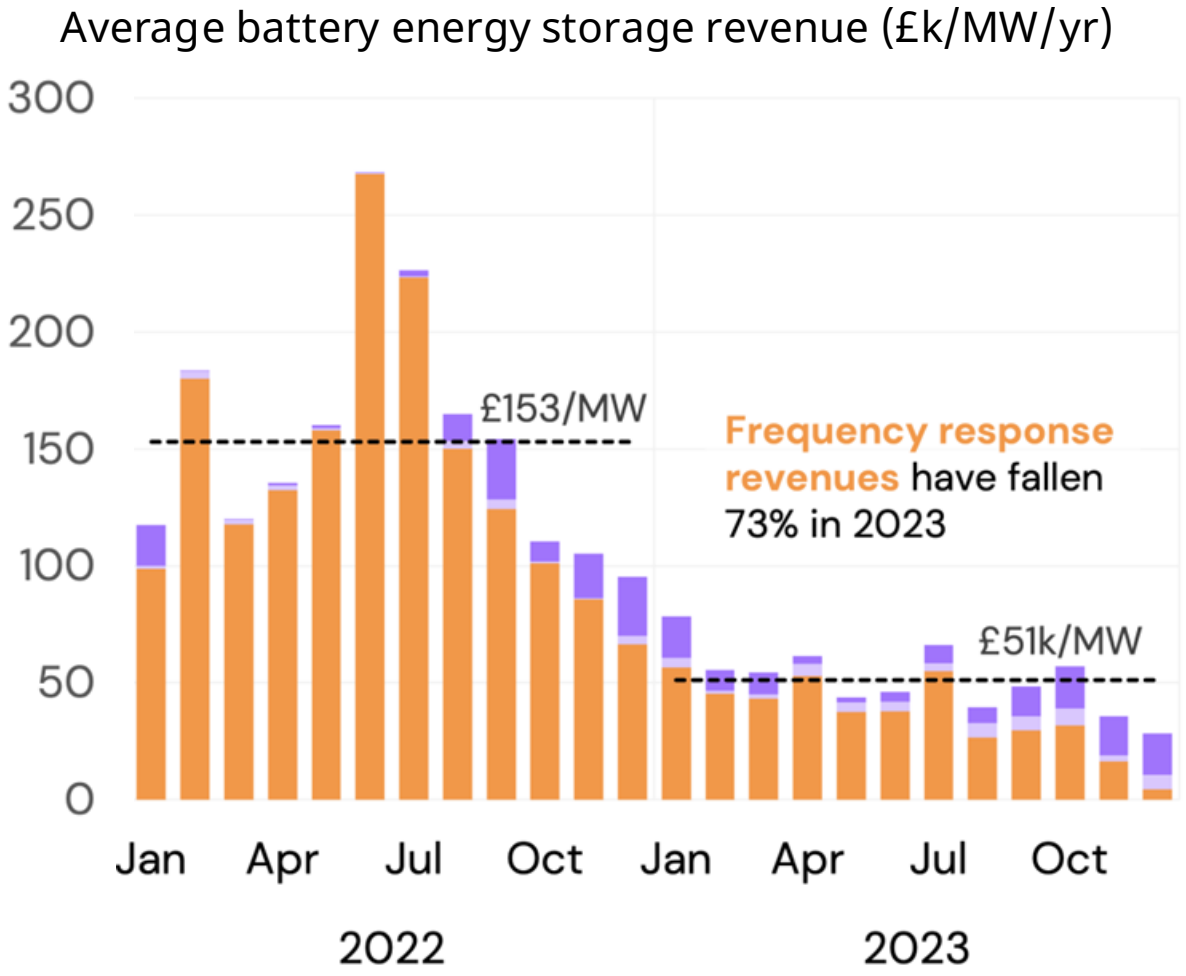
Battery specs

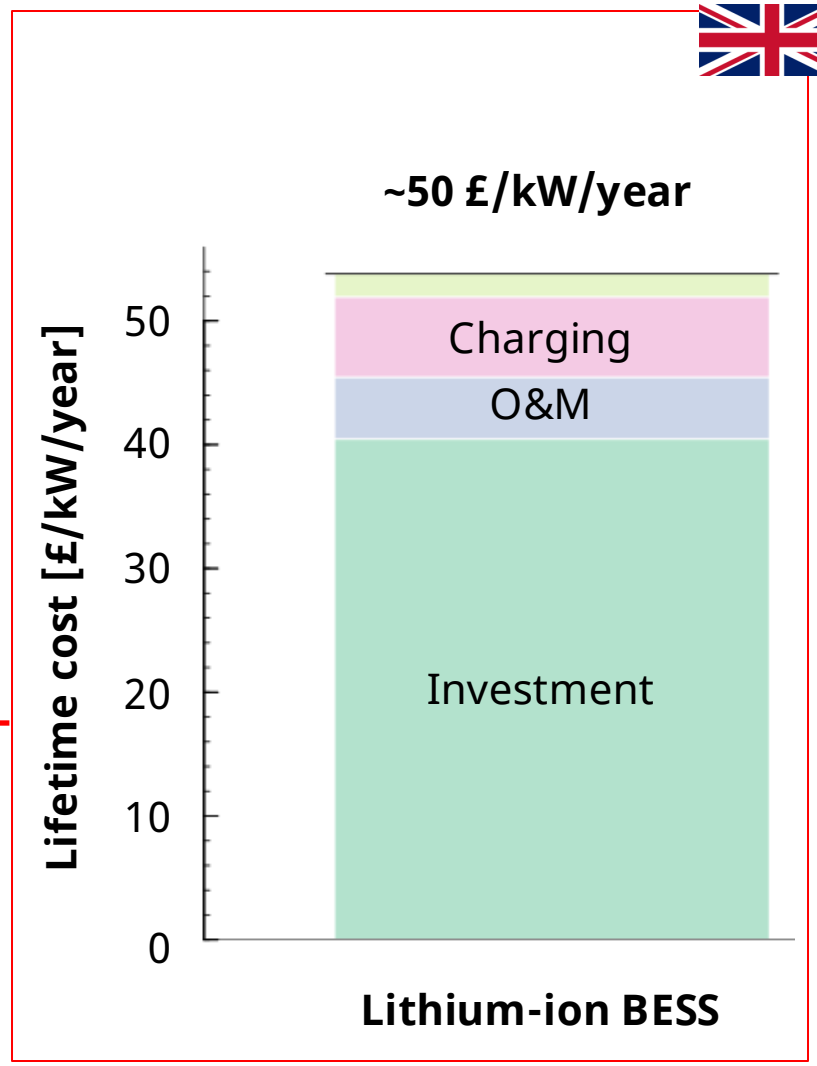
- 10 MW / 5 MWh
- £2M capex
- 85% efficiency
- 10 years lifetime
- 8% discount rate



Source: Graph generated on www.EnergyStorage.ninja

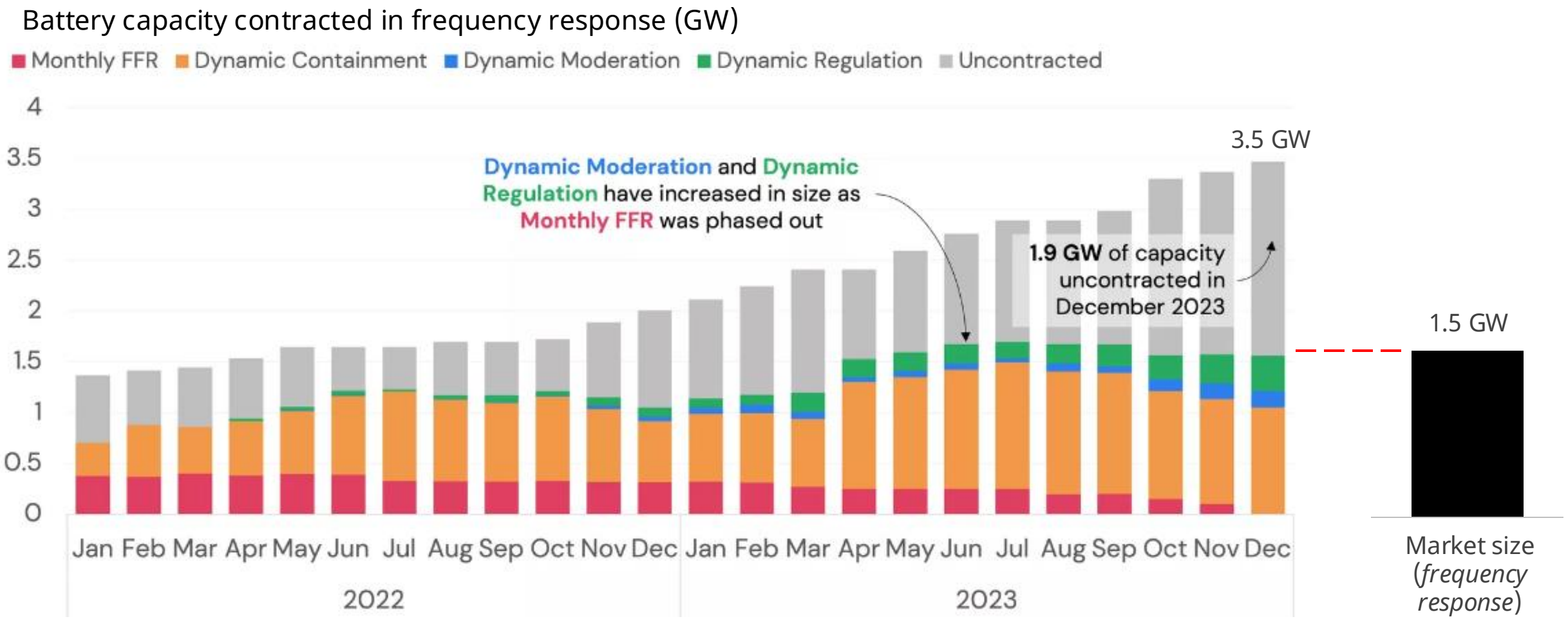
But, frequency response revenues have fallen below that





Source: Modo Energy (Jennings, 2023)

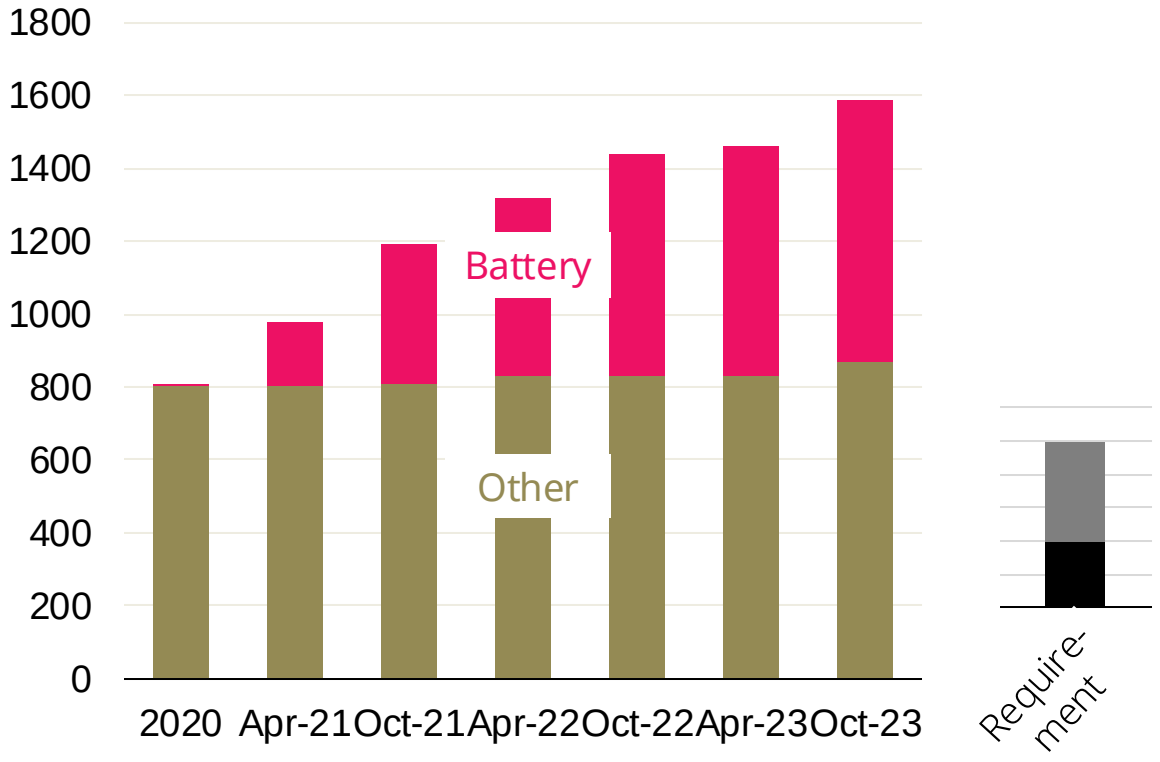
This is because frequency response markets are saturated



Source: Modo Energy (Middleton, 2023)

FFR in Ireland is saturated as well – expect <60 €/kW/year

FFR contracted volumes (MW) – DS3 Volume uncapped



FFR bids – DS3 Volume capped

"Batteries in Ireland to provide frequency response for less than 60 €/kW per year"

DS3 Volume Capped procurement in 2019

"The aim of System Services Future Arrangements (SSFA) is to introduce daily competitive auctions for system services"

Electricity Storage Policy Framework for Ireland 2024

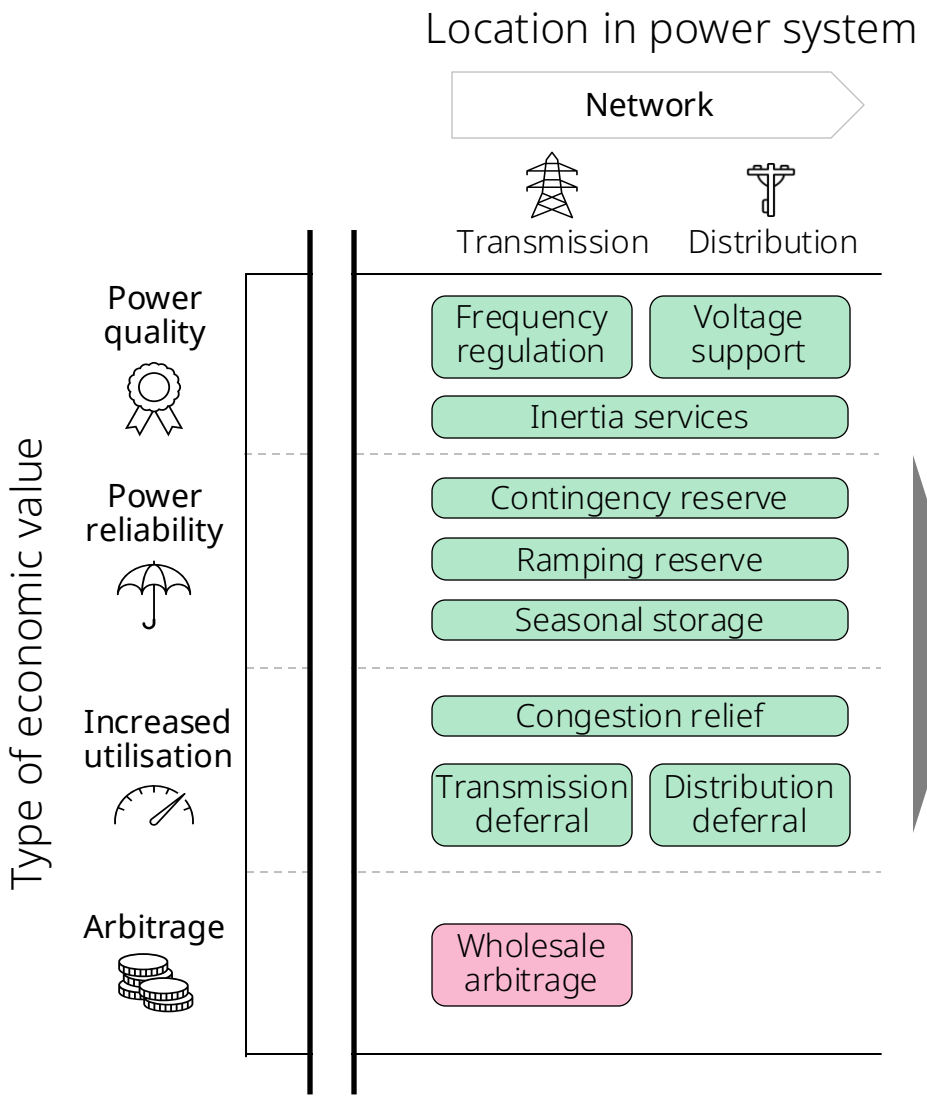
SEM committee

*"The TSS scalars should be **reduced** from October 2024. […] option to **close** the procurement of FFR-TOR2."*

September 11, 2024

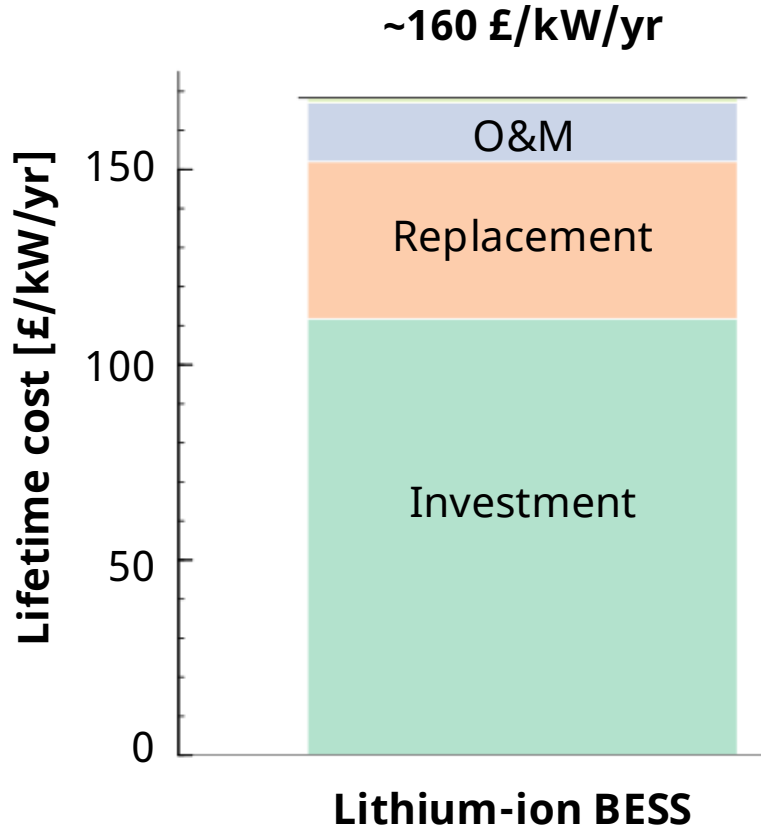
Source: EirGrid (2024), SEM Committee (2024) Everoze (2019)

Power price trading can be provided at ~160 £/kW/yr



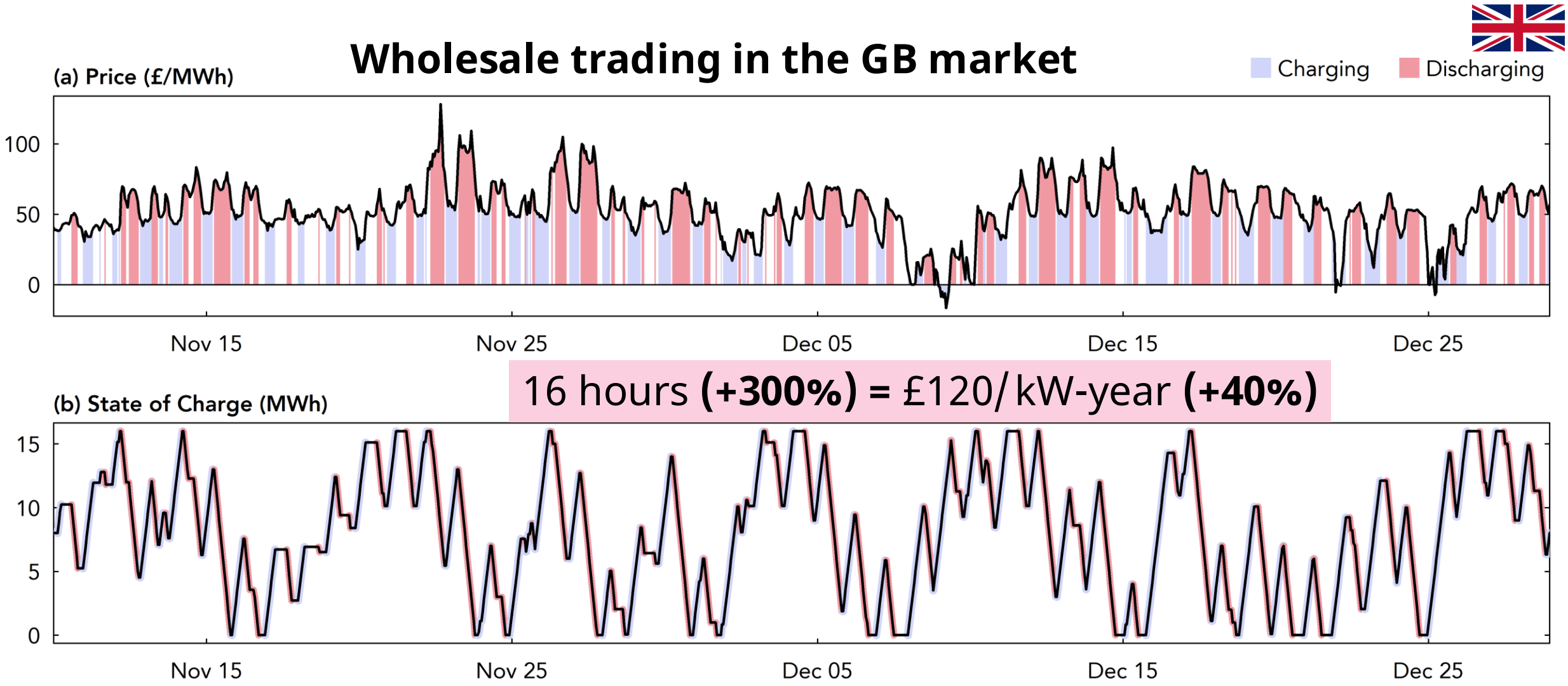
Battery specs

- 10 MW / 40 MWh
- £7.5 m capex
- 85% efficiency
- 10 years lifetime
- 5-year replacement
- 8% discount rate



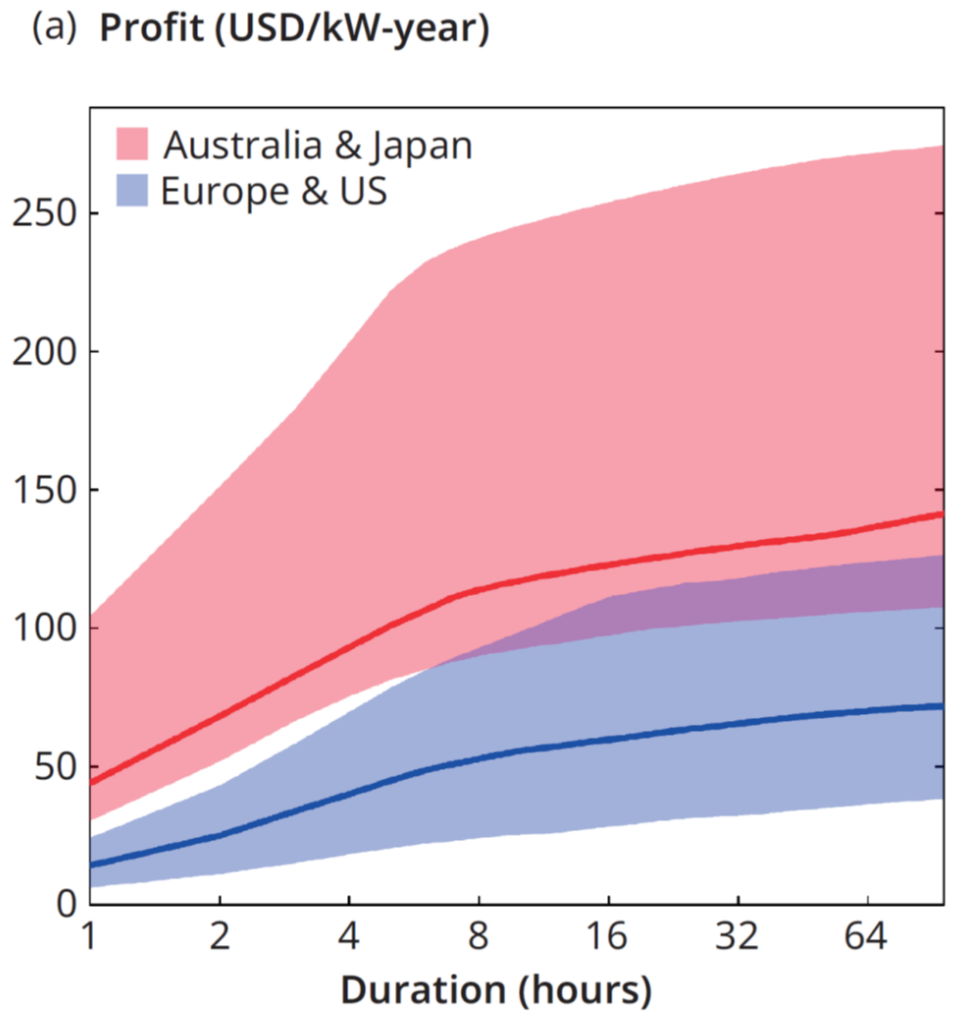
Source: Graph generated on www.EnergyStorage.ninja

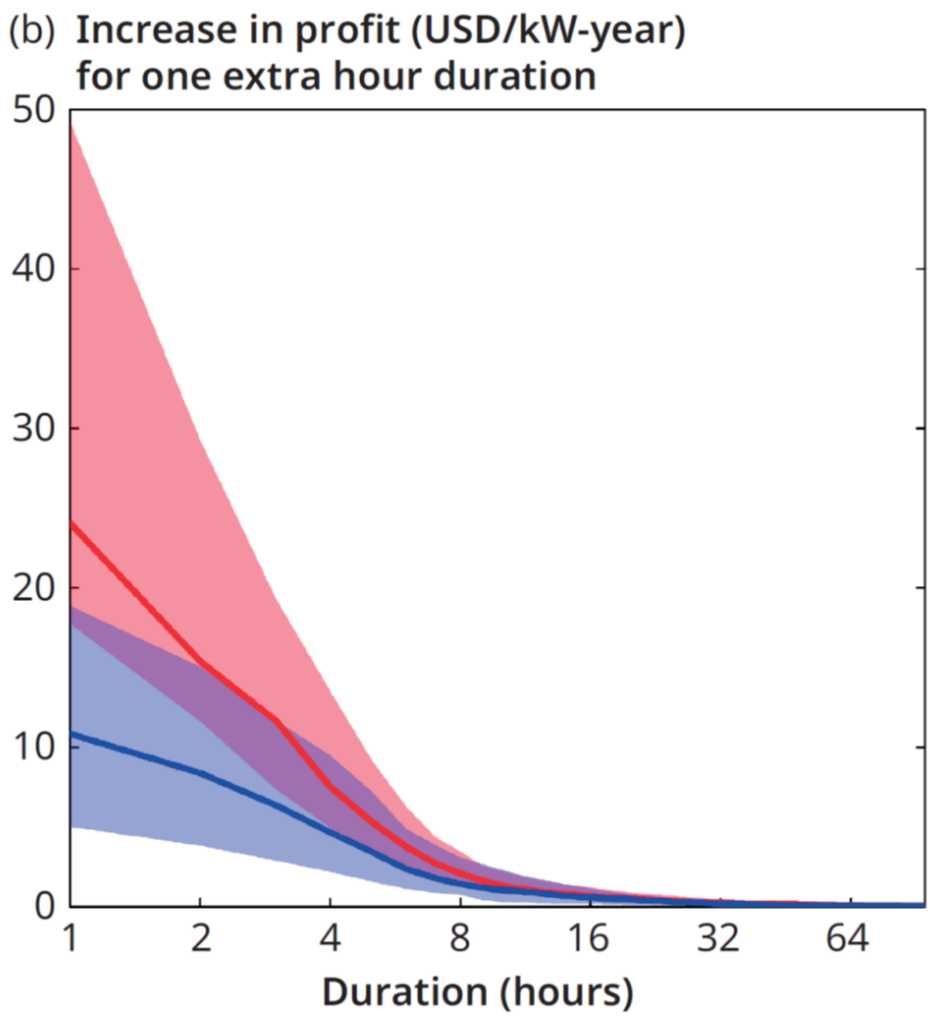
But, this is not yet profitable, even at longer durations



Source: Graph generated on www.EnergyStorage.ninja

Increasing discharge duration beyond 8 hours adds no value

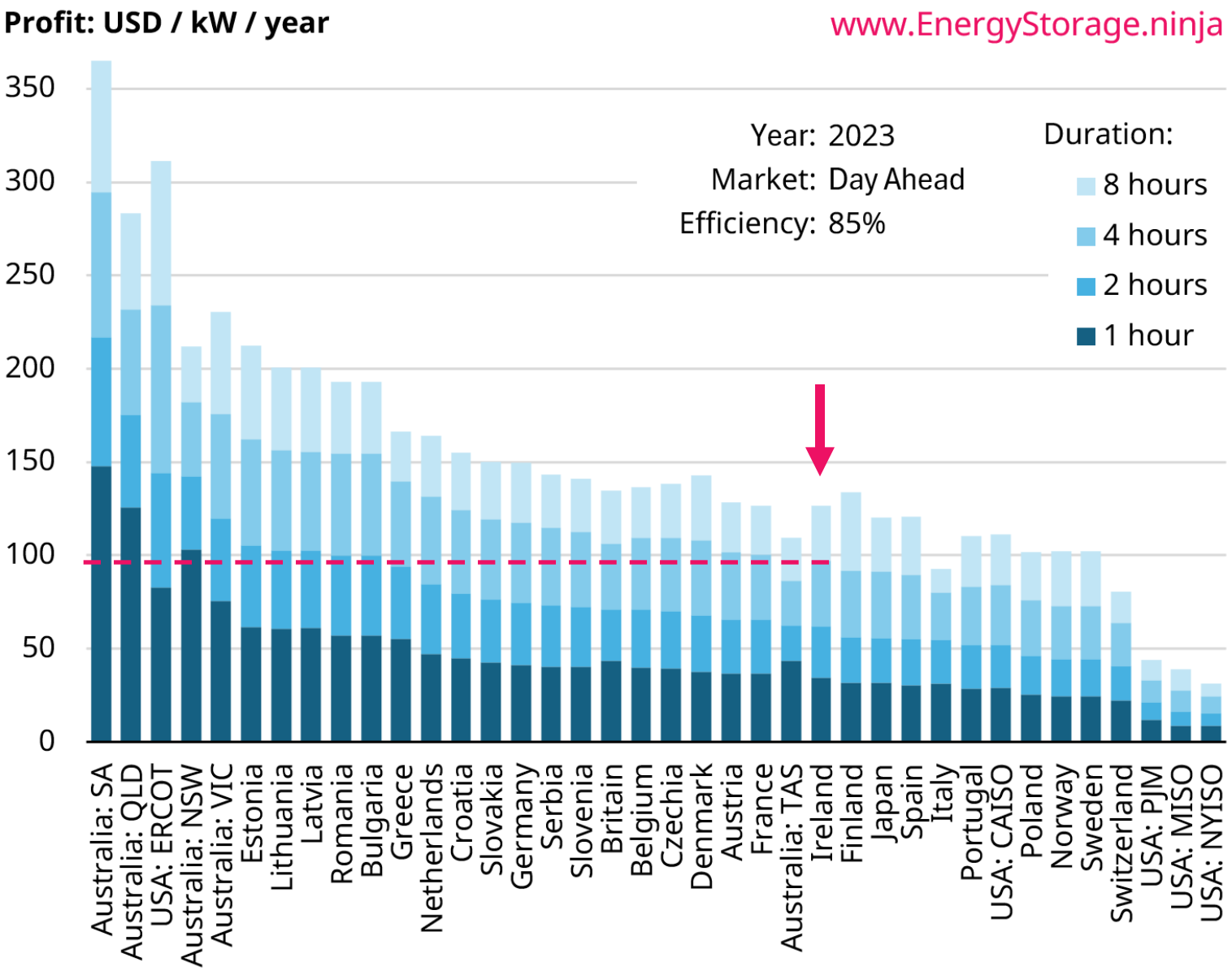




Based on day-ahead wholesale prices from 2012-19 in various markets

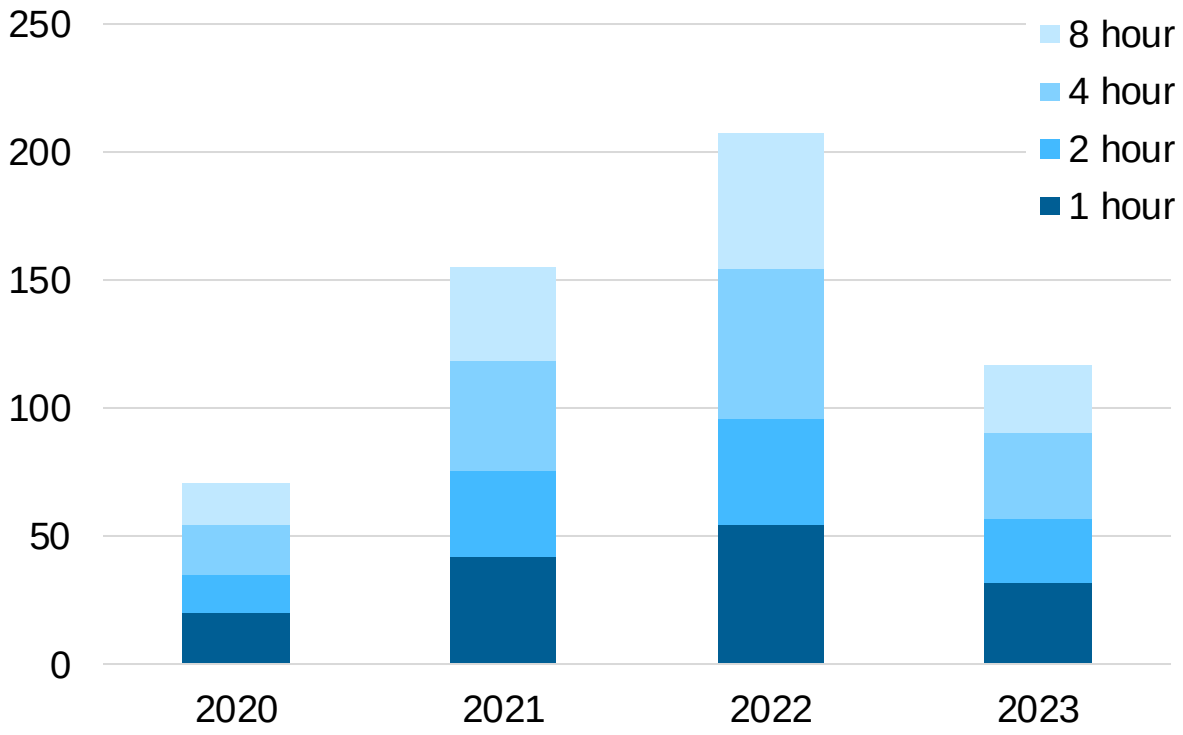
Source: Monetizing Energy Storage (2023)

Trading profits in Ireland in 2023 were even lower than in GB

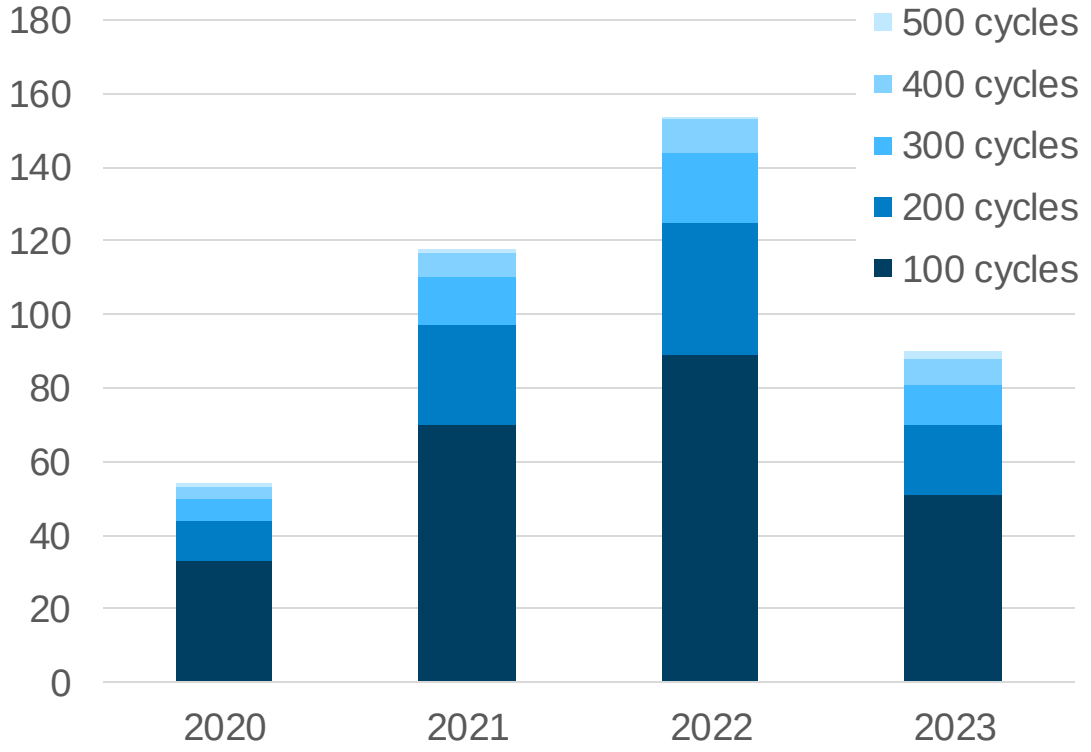


Trading profits in Ireland diminish less with longer duration

Wholesale trading profits – relative to **discharge duration**



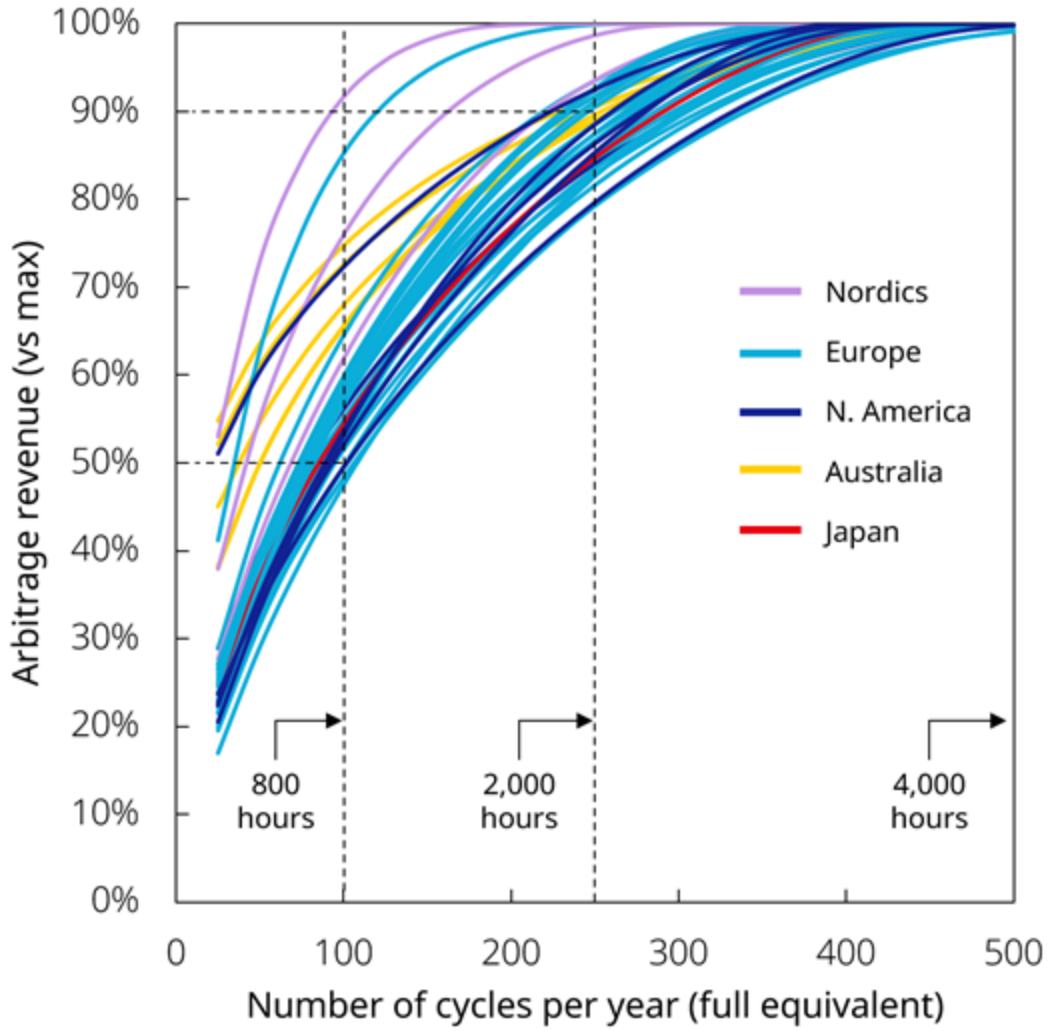
Wholesale trading profits – relative to **annual cycles**



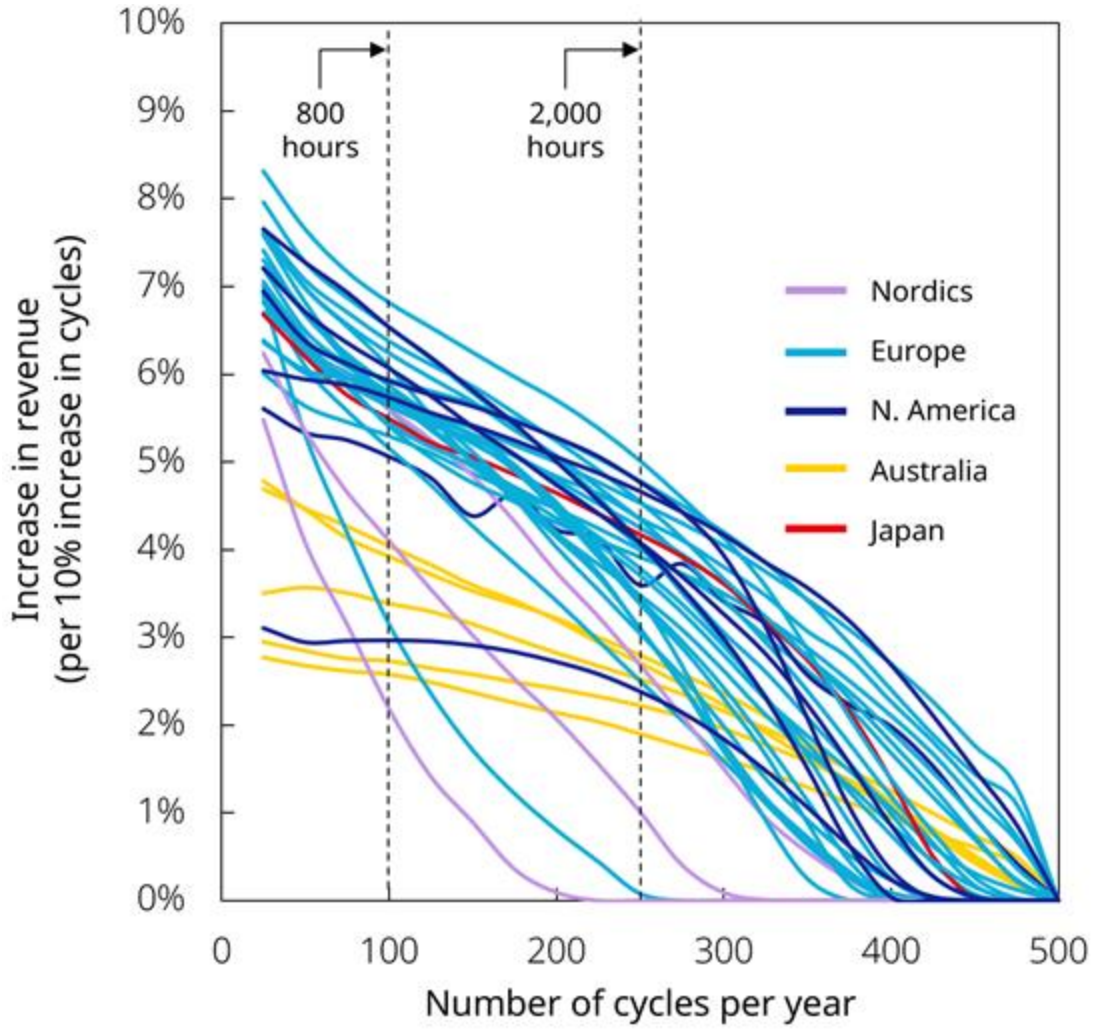
Source: Graph generated on www.EnergyStorage.ninja

90% of the value can be captured trading 25% of the year

a) Revenue (vs max)

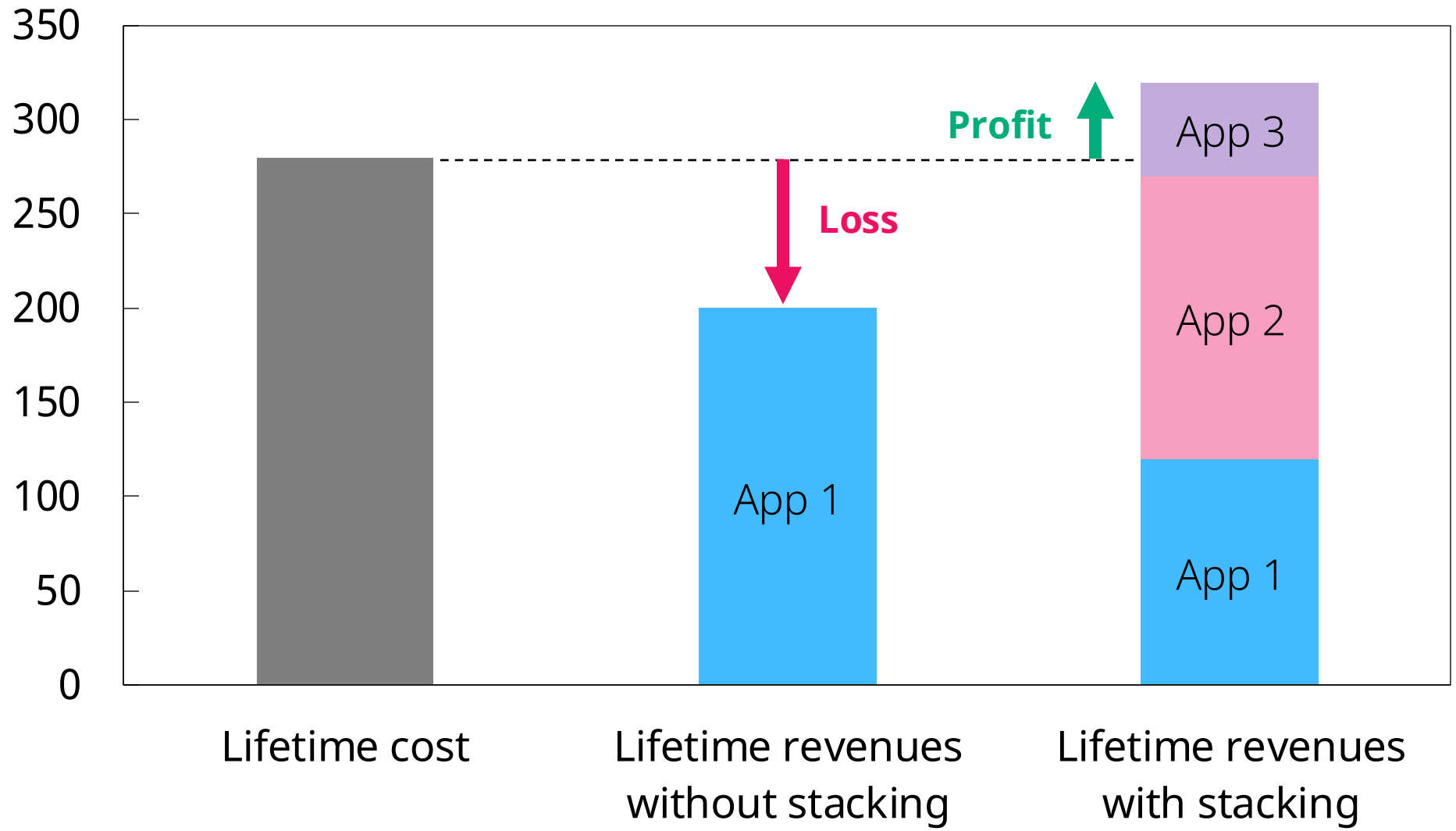


b) Increase in revenue



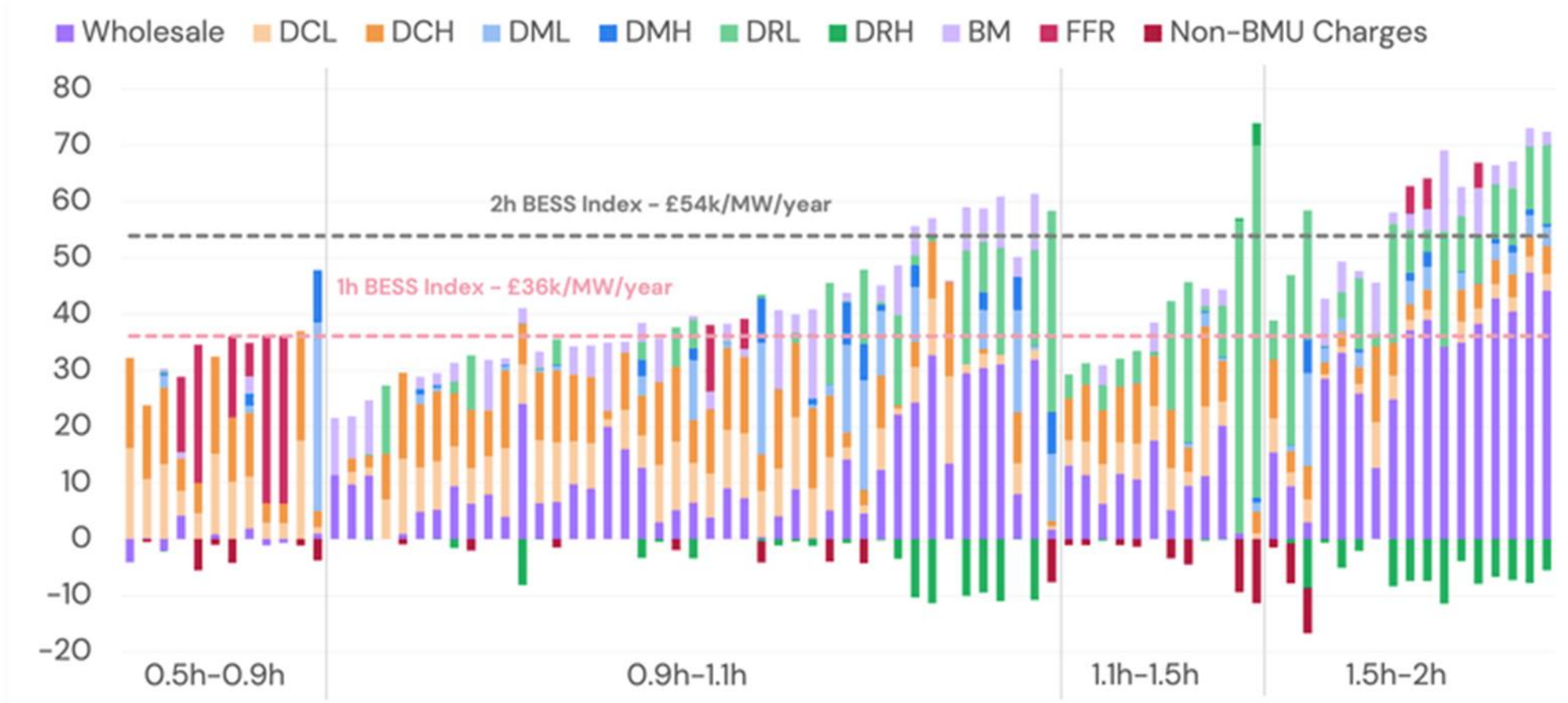
Note: Based on day-ahead wholesale prices from 2012-19 in various markets

Therefore, multiple revenue streams must be combined



In GB, complex revenue stacking is the reality

Annualized revenues of battery assets in Q4/2023 by market and duration



Each bar represents one specific battery asset

Longer duration battery = More arbitrage services (Wholesale, BM)

Source: Matt Middleton (Modo Energy, 2024)

All the insights and tools shown here are available in this book and website

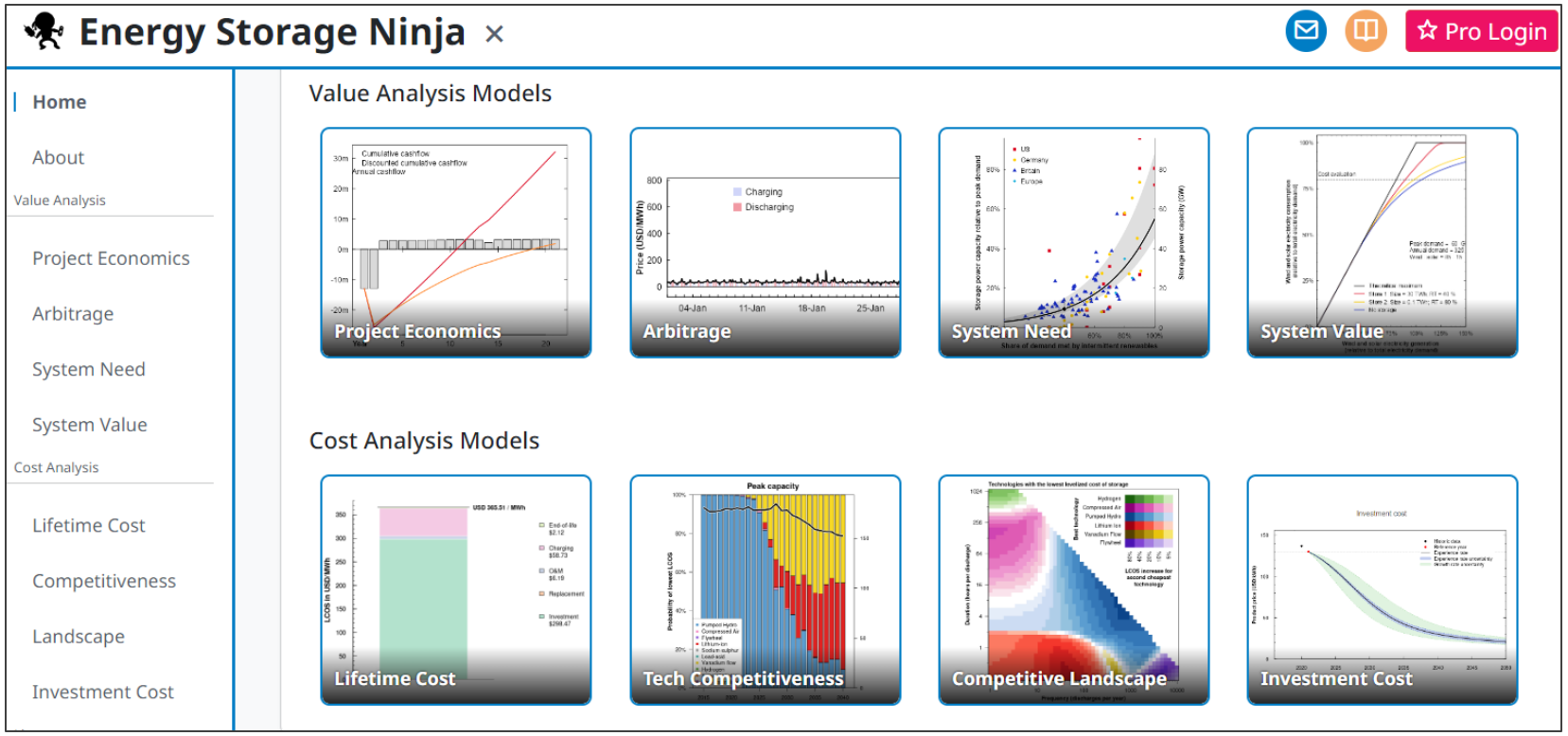
"Essential for me as an investor to navigate this complex, fast-paced energy storage industry."

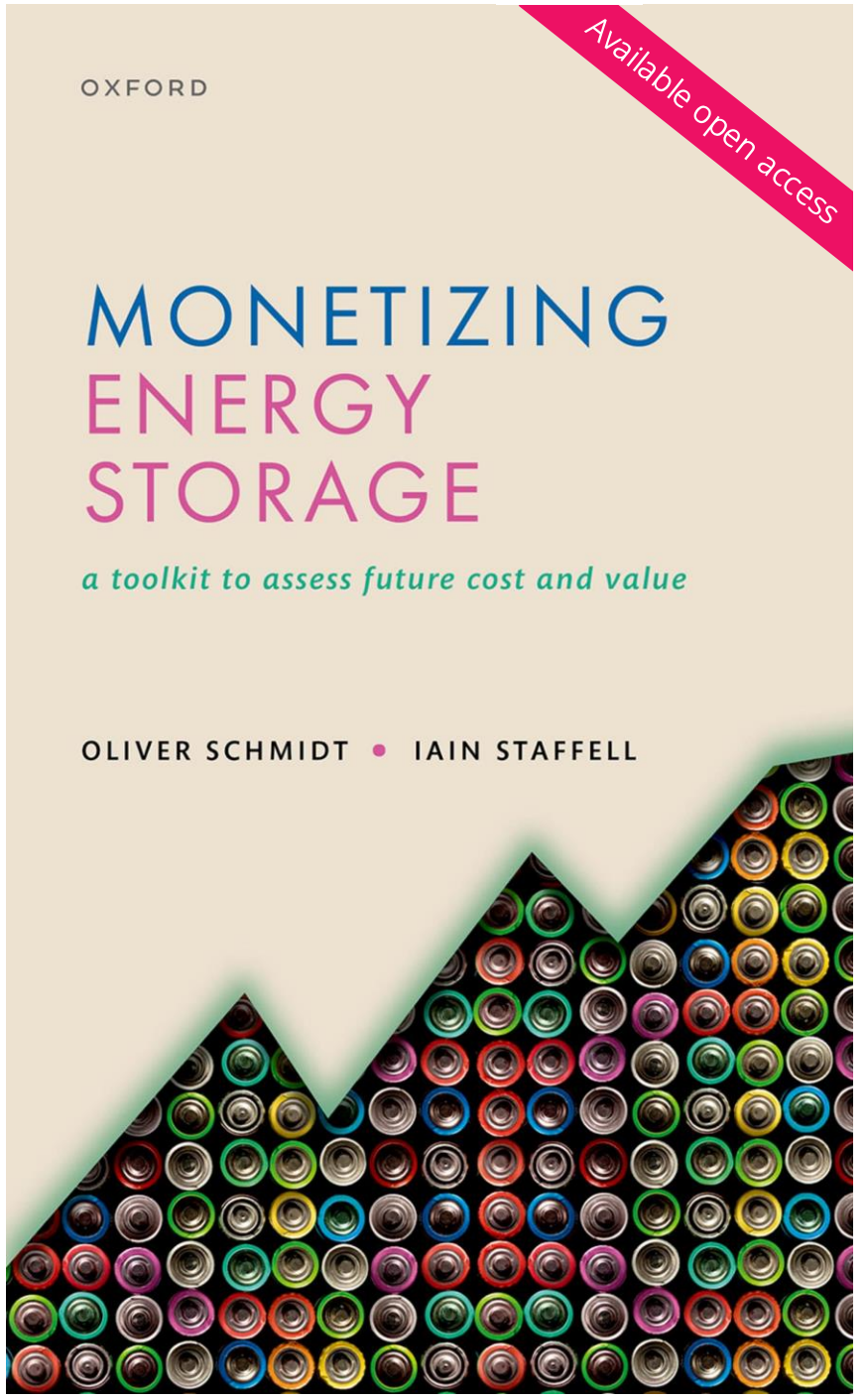
Gerard Reid, Alexa Capital

"The go-to resource… exemplary in terms of academic rigour set in a real world context."

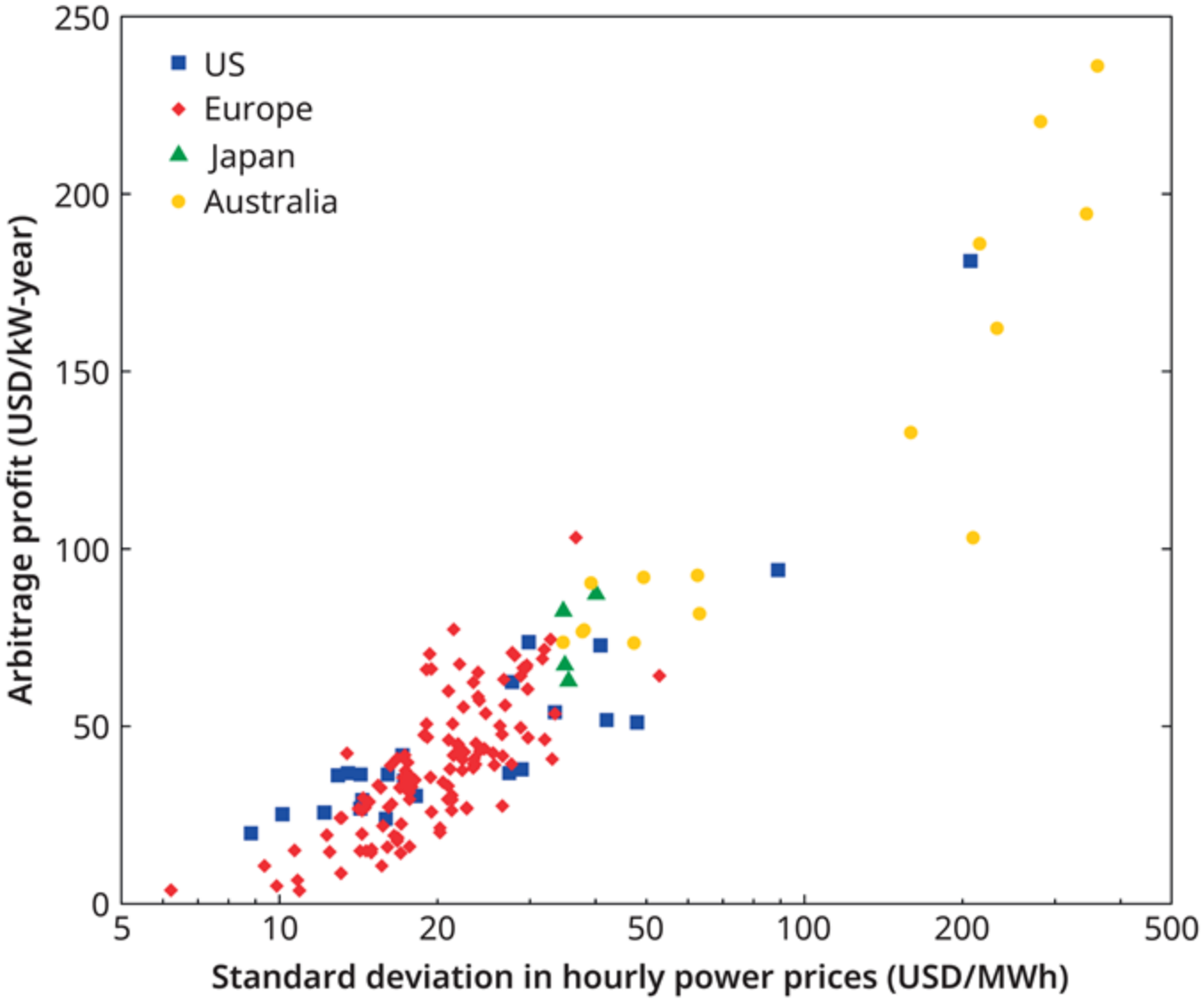
Jim Skea, Chair of the IPCC

User-friendly tools for custom analyses: www.EnergyStorage.ninja





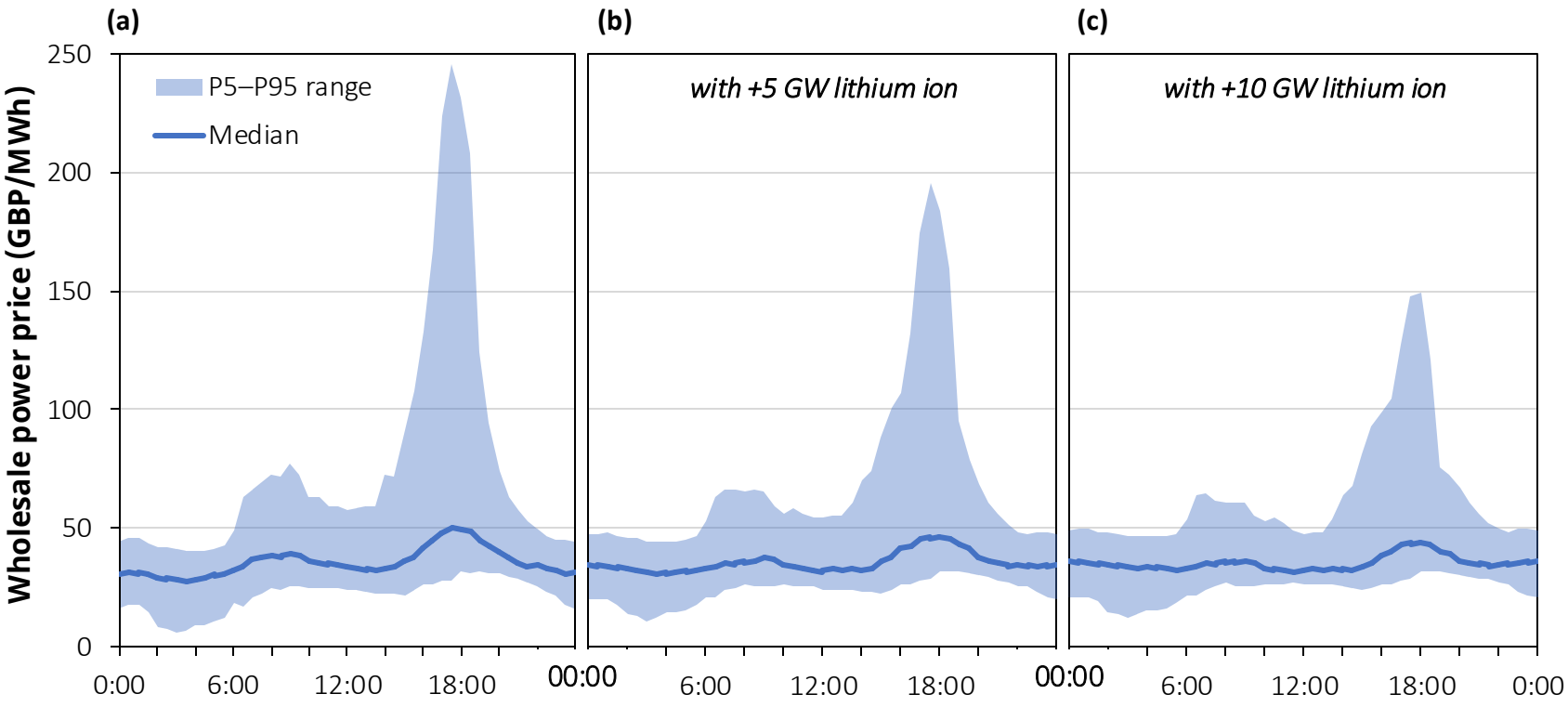
This highlights the need for storage to optimize volatility

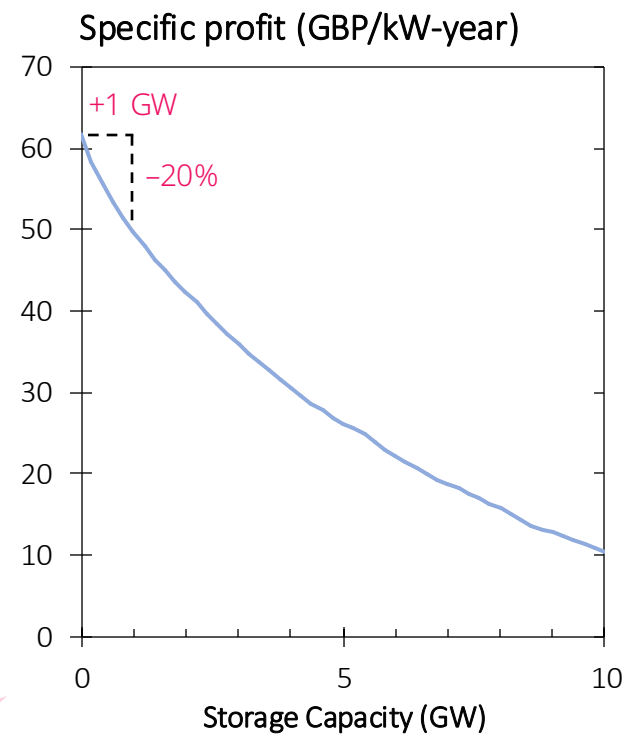


Revenues are **driven by volatility,** so instead of acting only in one market, revenues are maximized by **'skimming volatility cream' of multiple markets.**

But, 1 GW of storage already reduces abitrage profits by 20%

Day-ahead wholesale power market

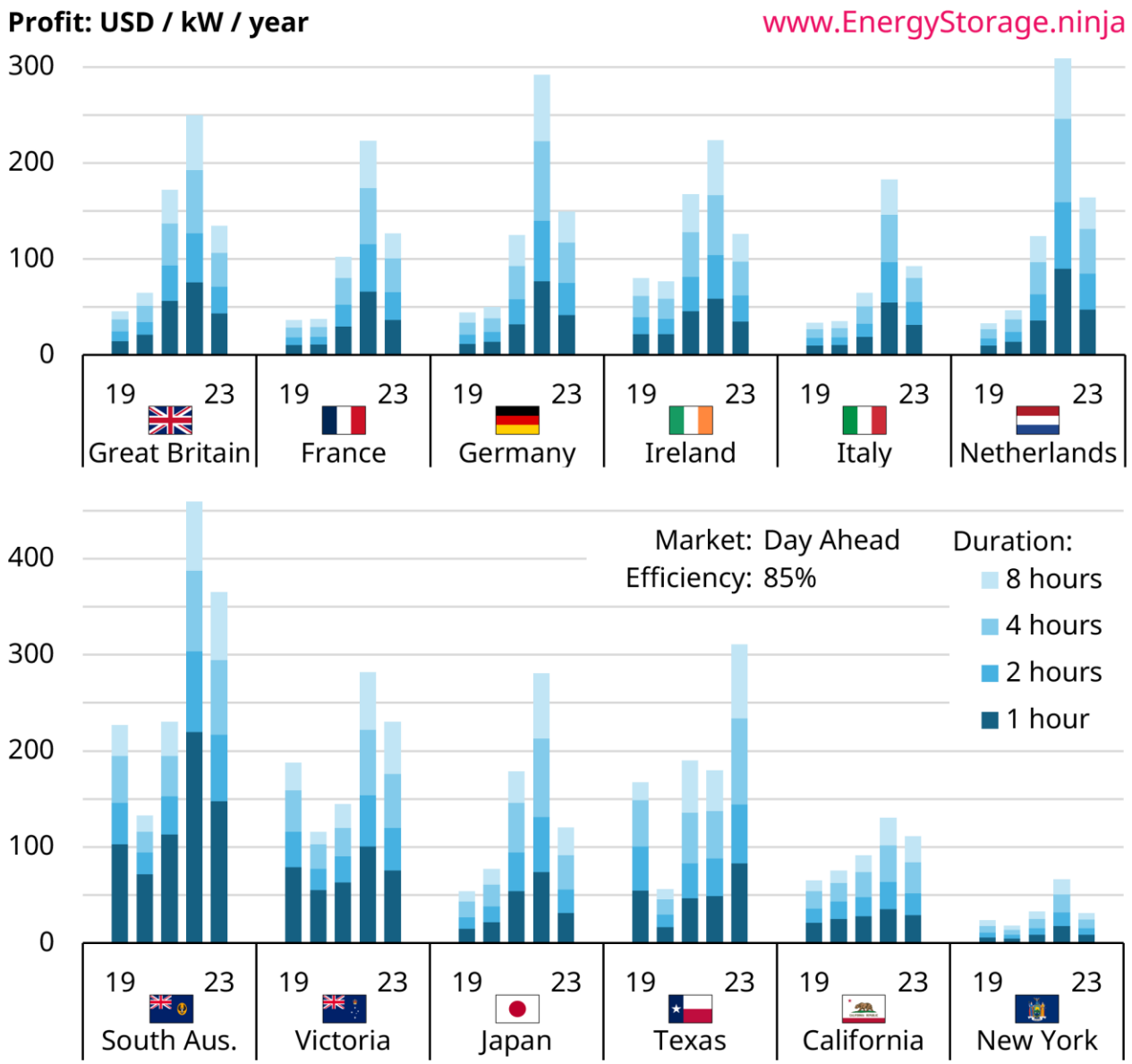




More pronounced impact likely on other wholesale markets, because

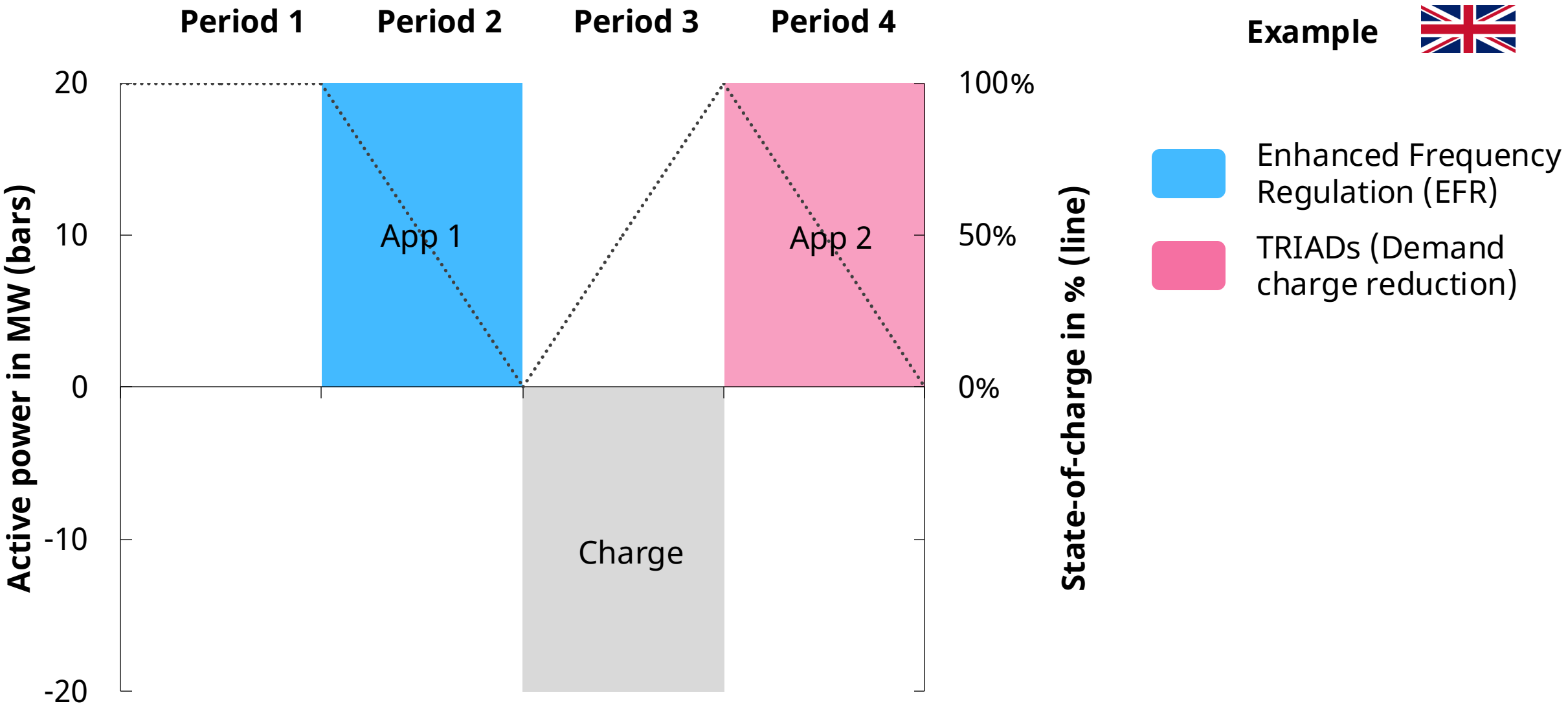
- Day-Ahead auction: ~15 GWh per hour
- Intraday auction: ~0.5 GWh per hour
- Continuous intraday: ~3 GWh per hour

Arbitrage profits in Australia are also most consistent

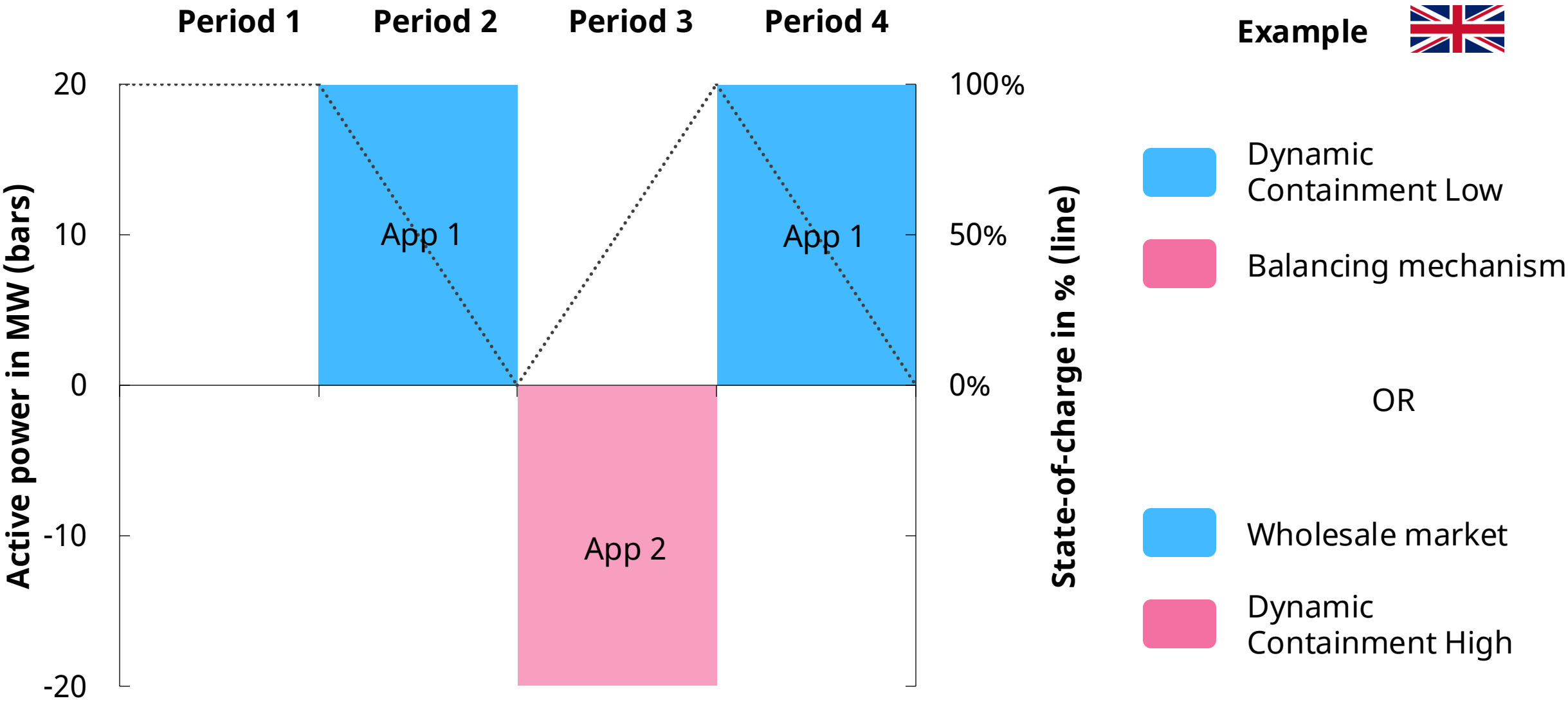


- Revenues in wholesale power trading in Europe were driven by gas price crises in 2021-2023 – generally significantly lower
- Revenues in mainland Australia (e.g., SA, VIC) are consistently high due to
  - High wind and solar penetration
  - High solar irradiation
  - Power network constraints
  - (Realtime spot market)

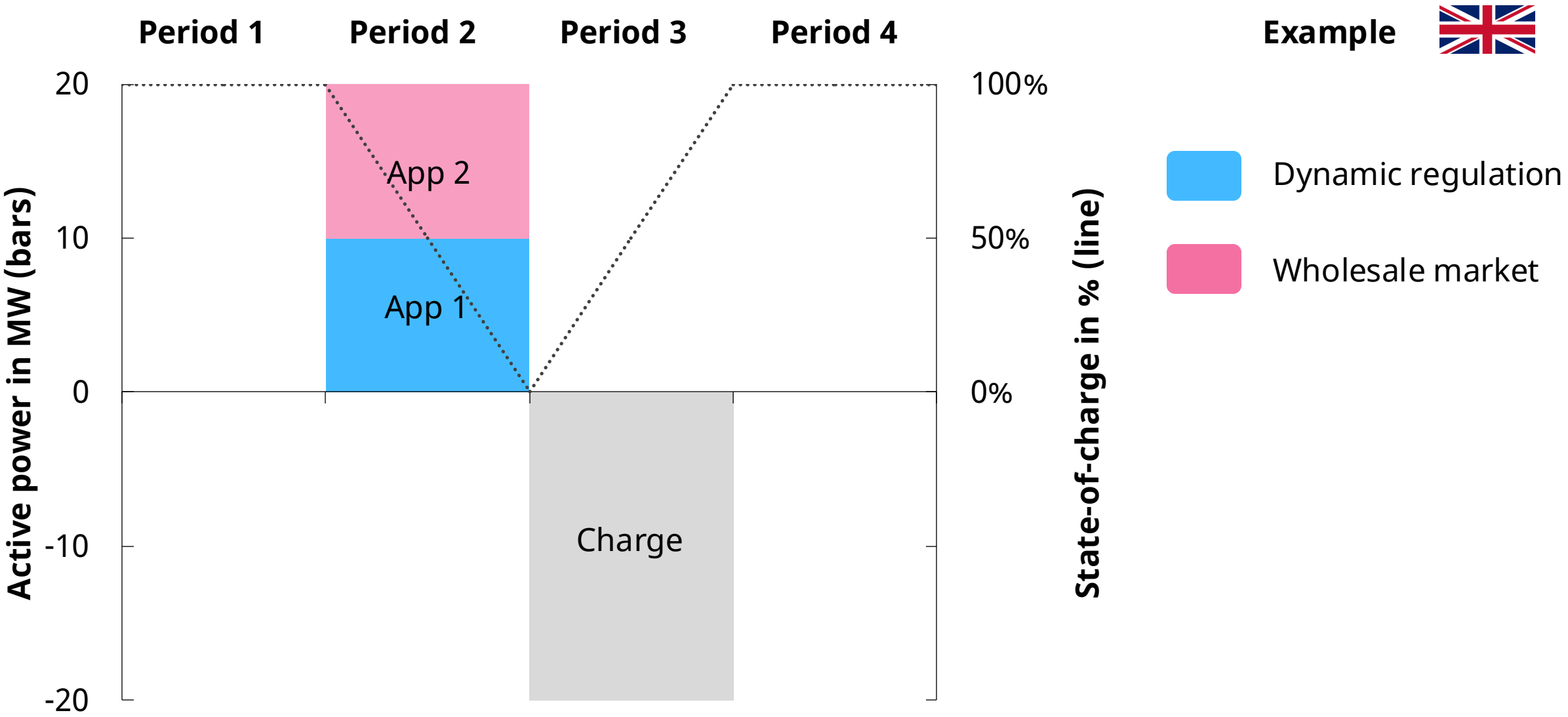
Option 1: Sequential stacking



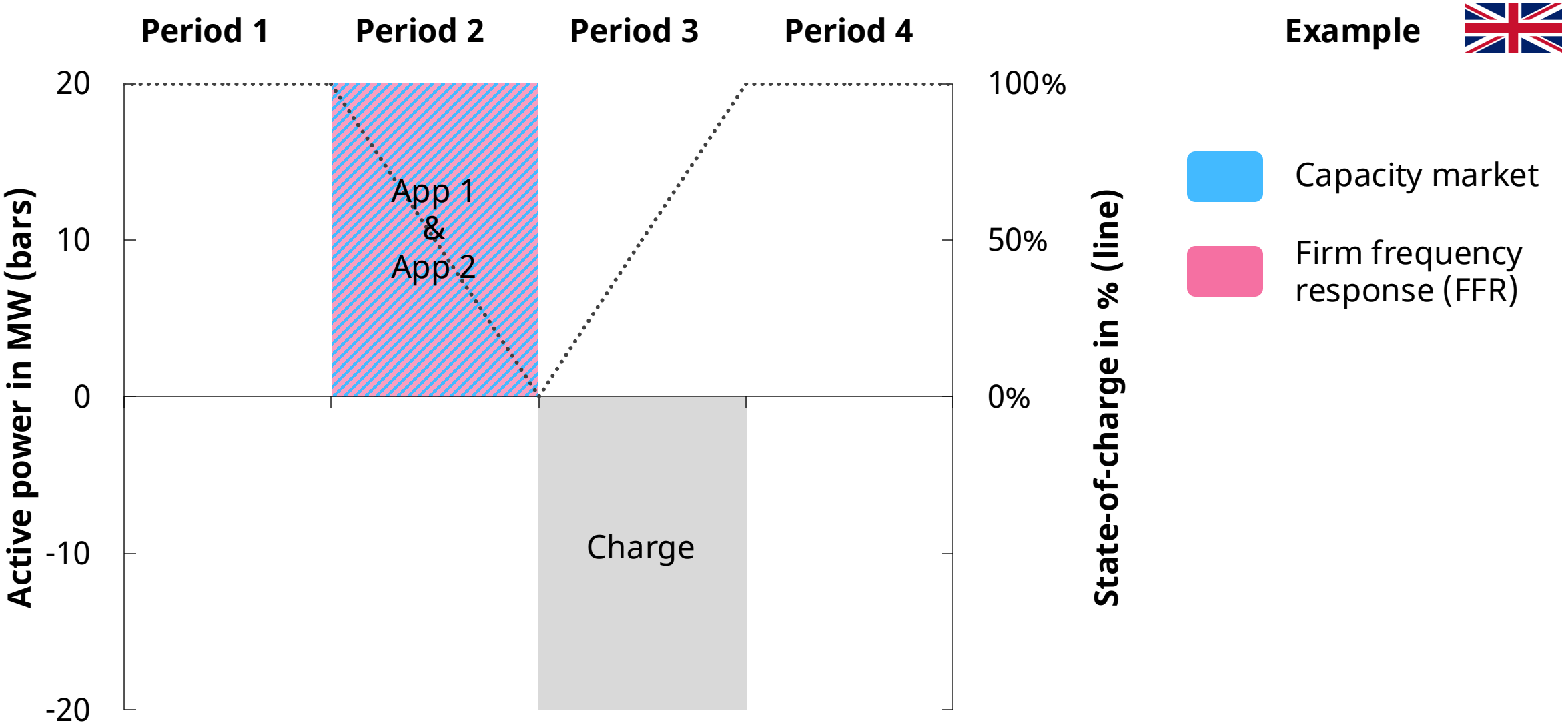
Option 2: Sequential stacking in opposite directions



Option 3: Parallel stacking

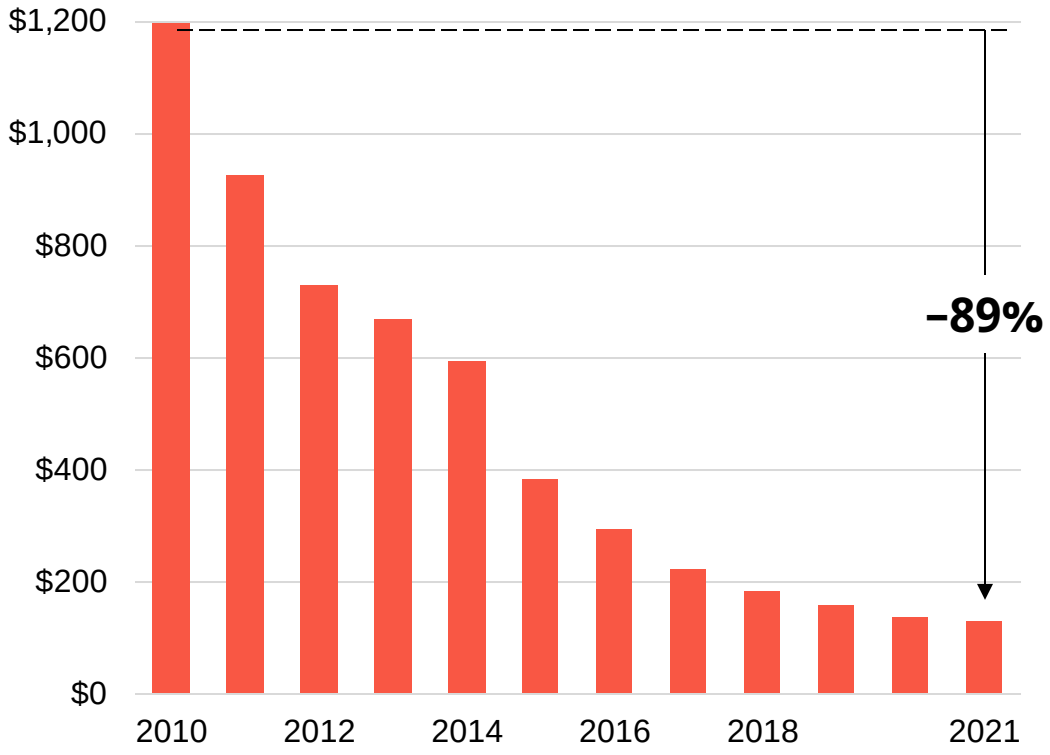


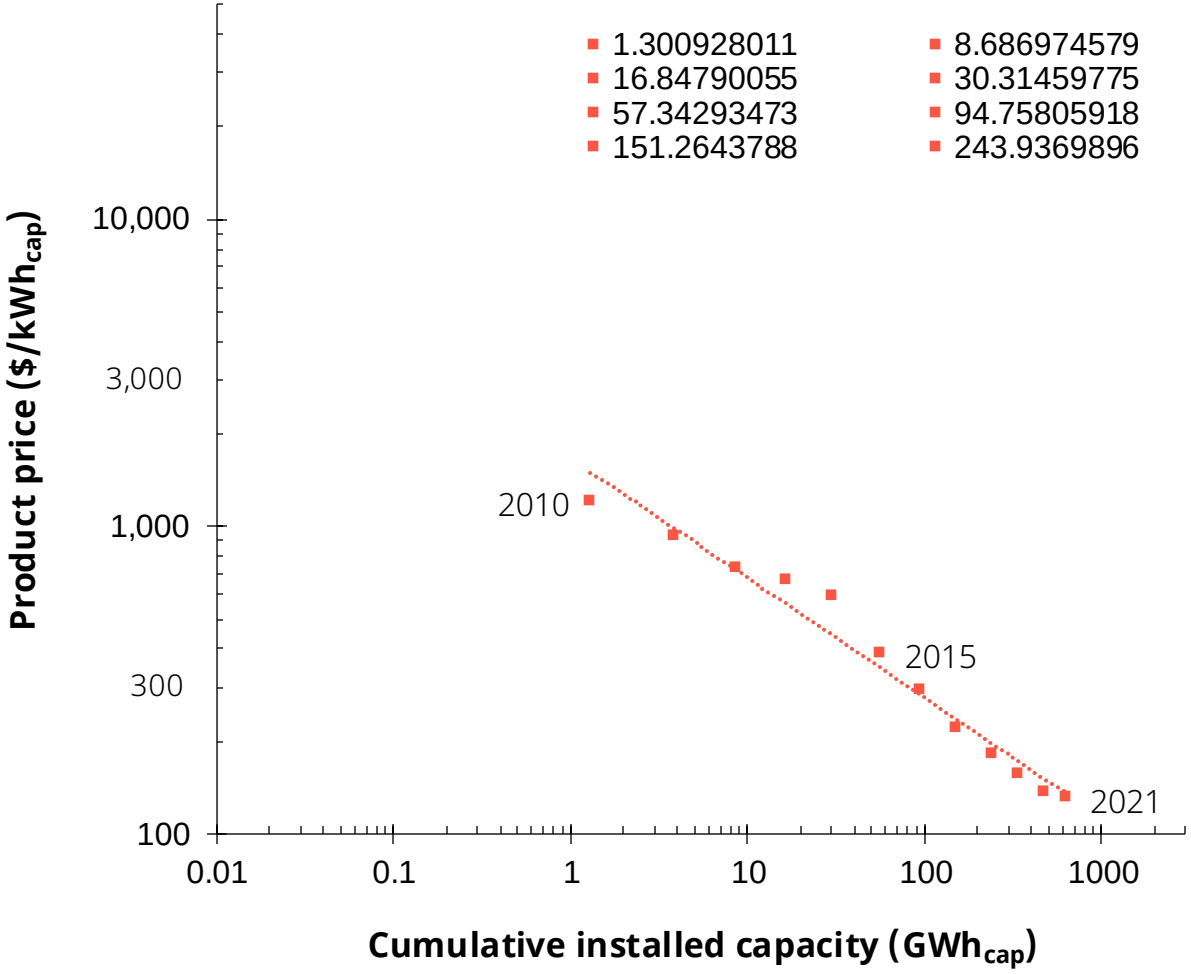
Option 4: Overlapped stacking



Falling cost is driving the uptake of lithium ion

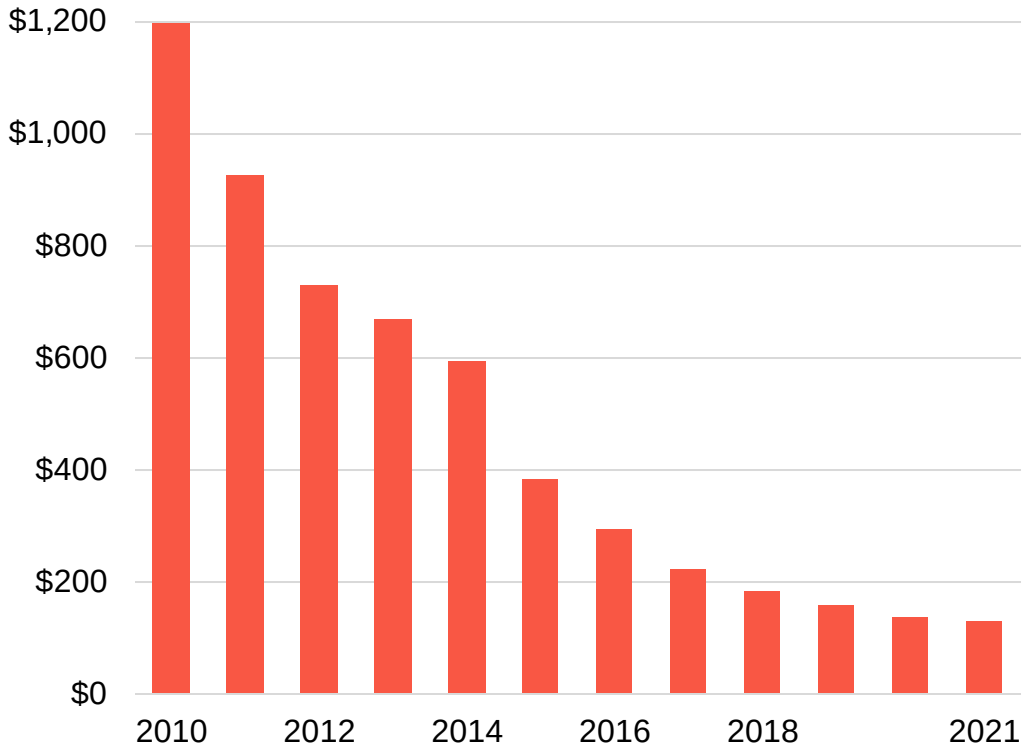
Lithium-ion battery packs ($/kWh)

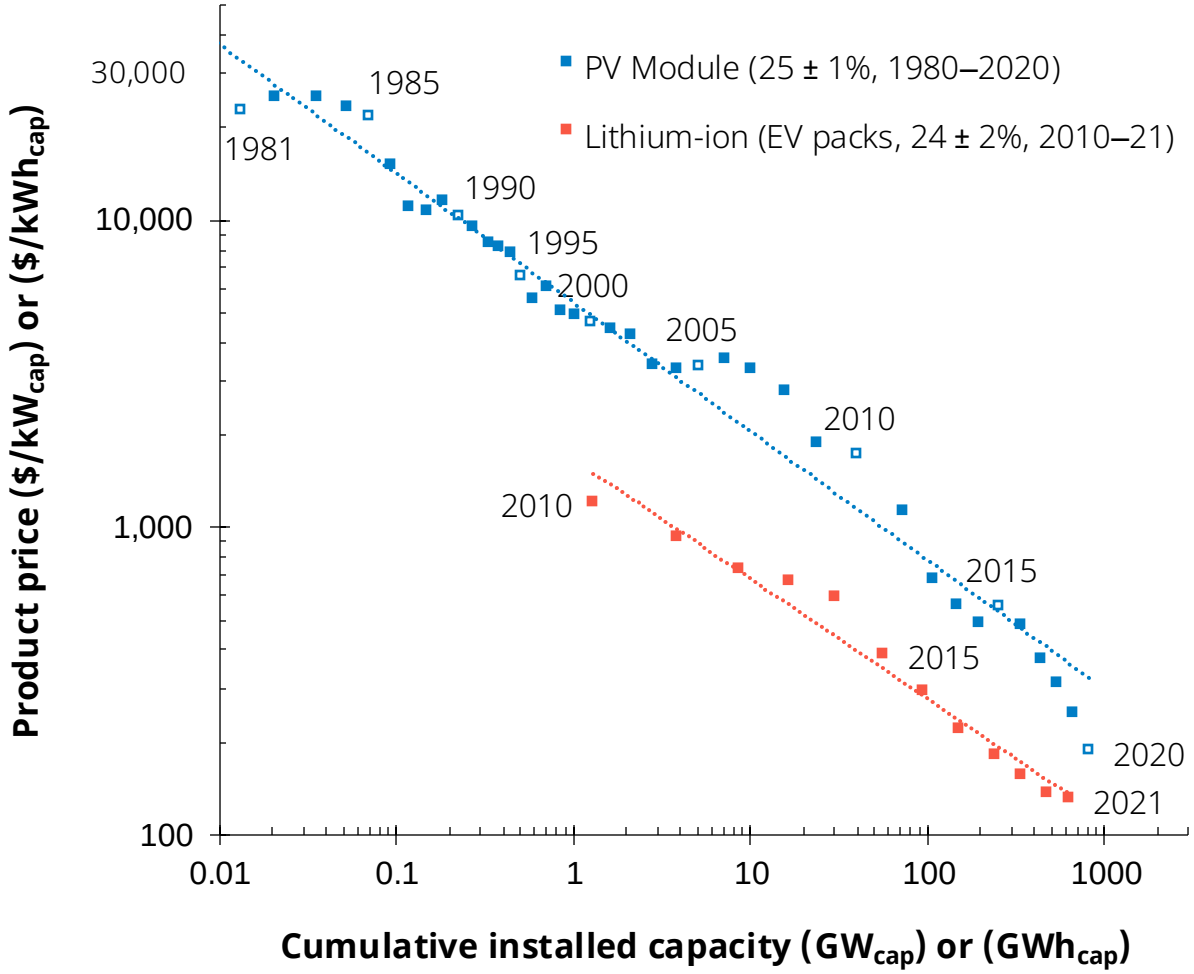




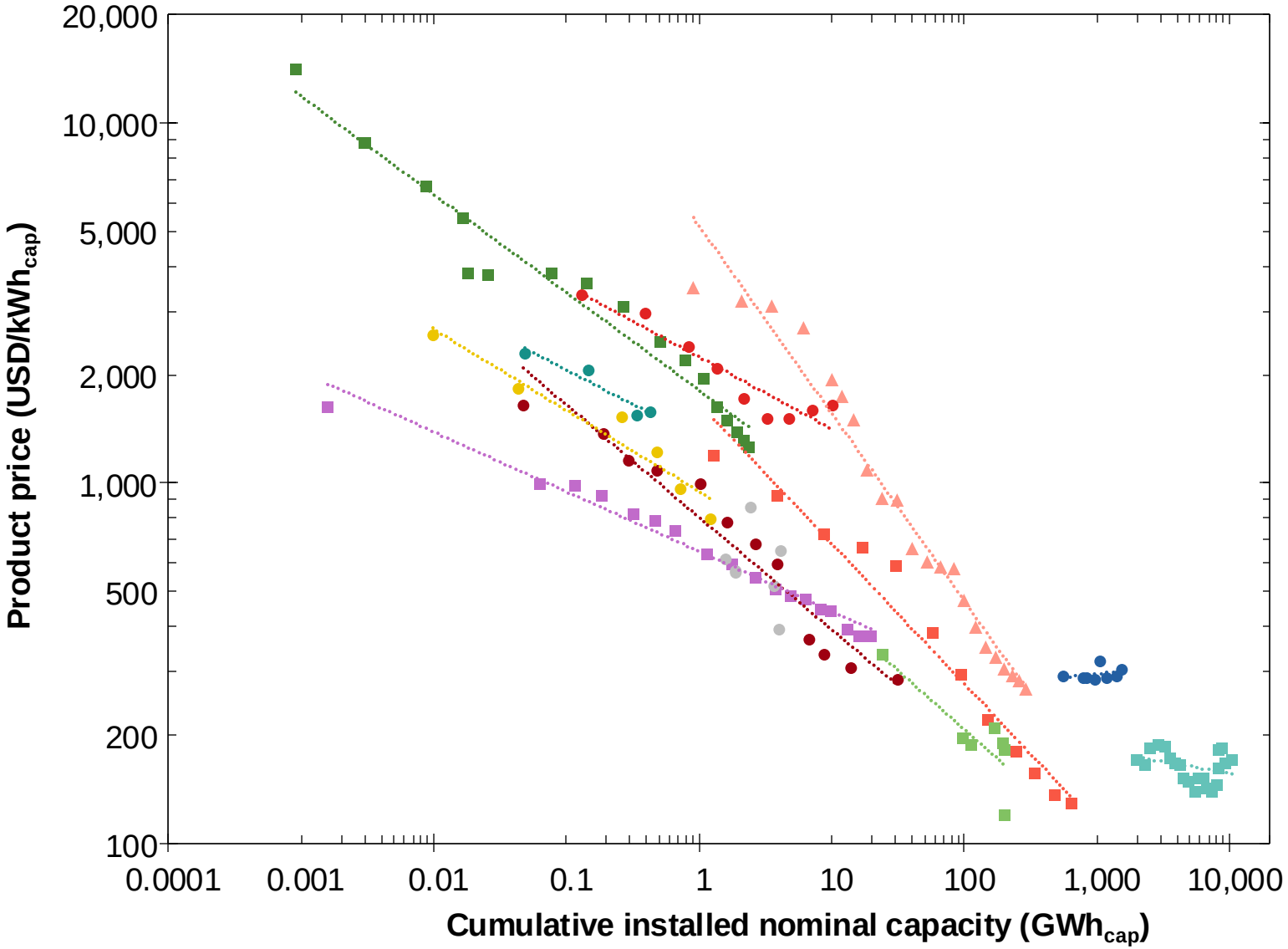
Similar to how the uptake of solar PV was driven

Lithium-ion battery packs ($/kWh)





But, most storage technologies experience cost reductions



Scope:

● System ■ Pack ▲ Cell

Technology: