LDES market overview

What is the outlook for innovative LDES in Europe?

An AFRY Report for Eurelectric

June 2026

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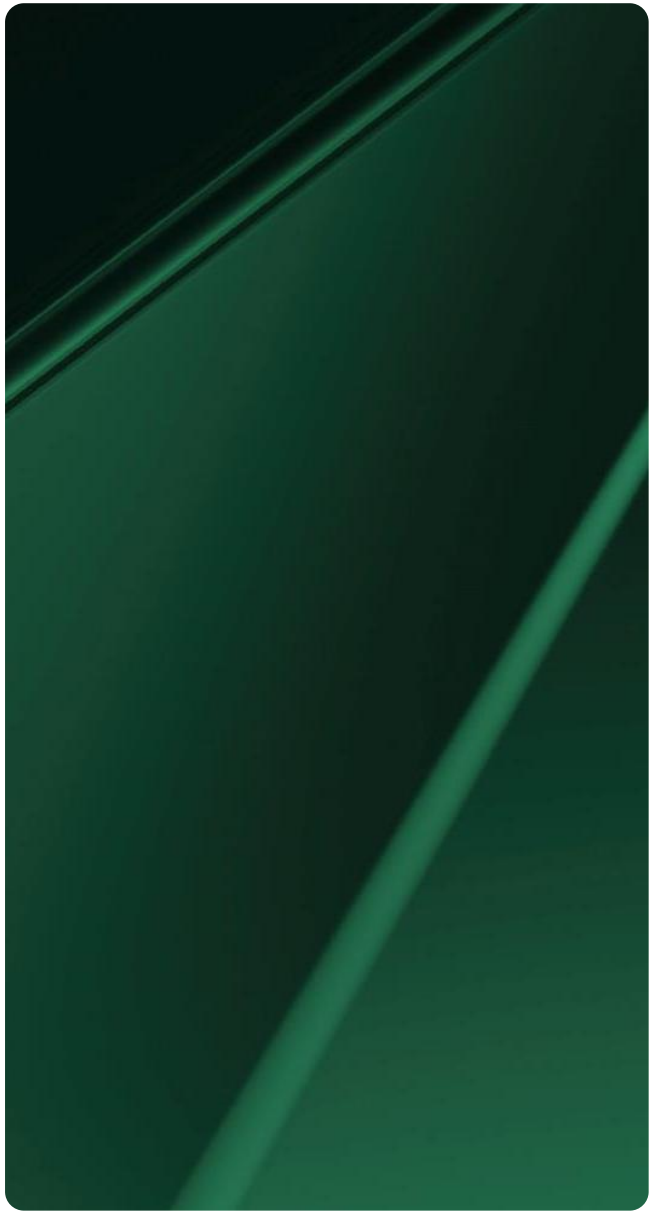
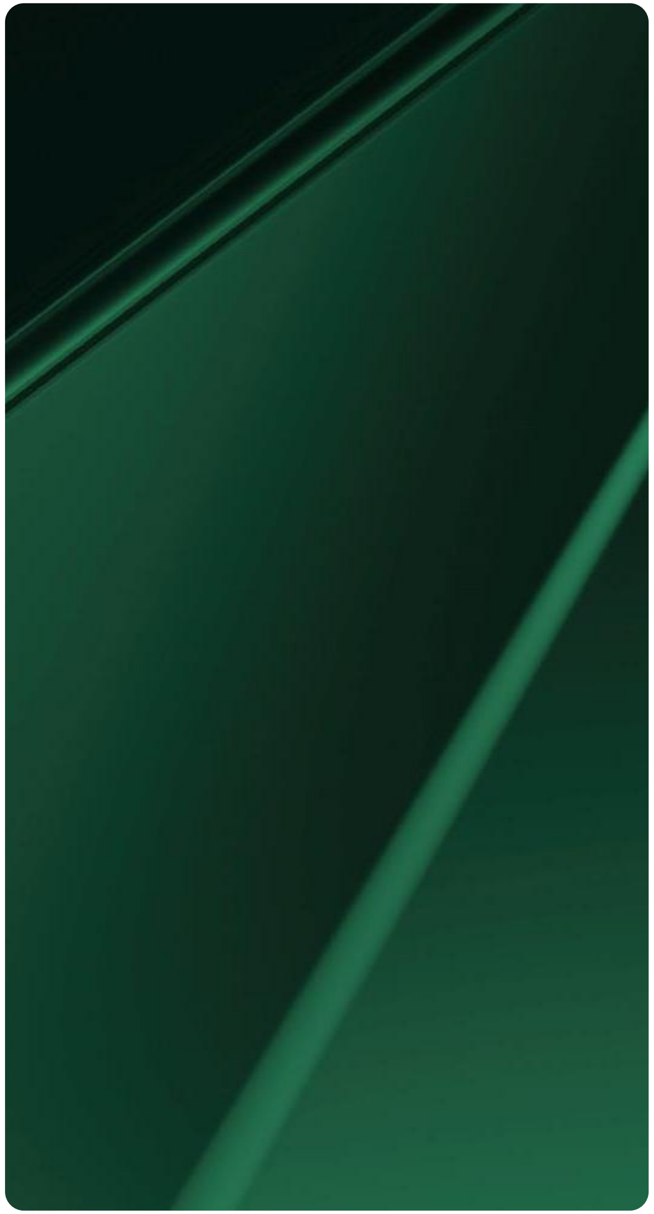


EXECUTIVE SUMMARY

Introductory note

- This report focuses *exclusively* on innovative Long-Duration Energy Storage (LDES) technologies and does not cover Pumped Hydro Energy Storage (PHES), which is a mature and widely deployed technology across Europe and a significant contribution to meeting the underlying flexibility needs.
- All monetary values presented in this report are in real 2025 money terms, unless otherwise stated.



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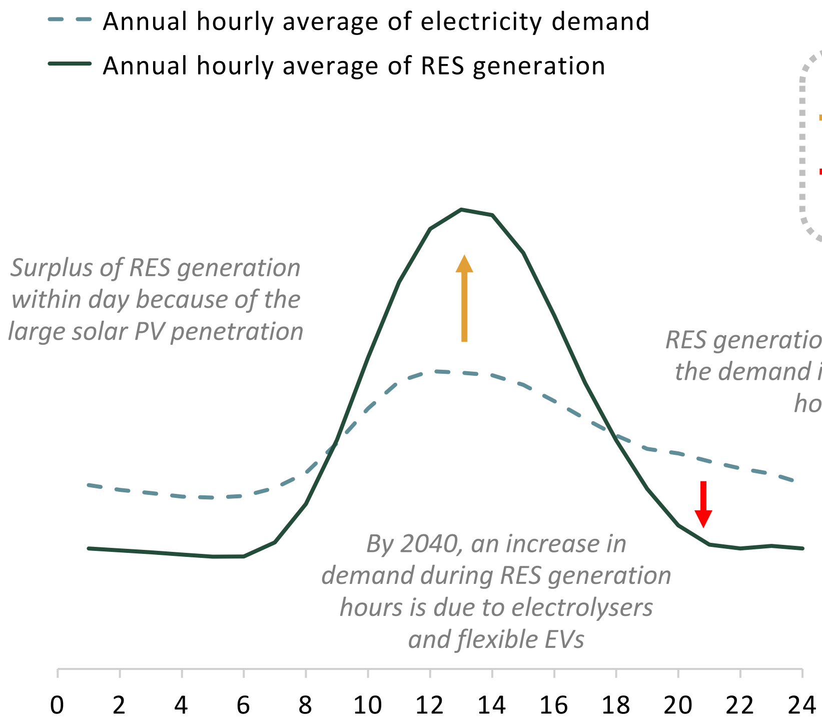
Changes in demand patterns and the expansion of intermittent renewable generation result in increased flexibility needs …

Daily[1]

Related to solar PV production variability



Surplus of RES generation within day because of the large solar PV penetration

RES generation cannot meet the demand in the evening hours

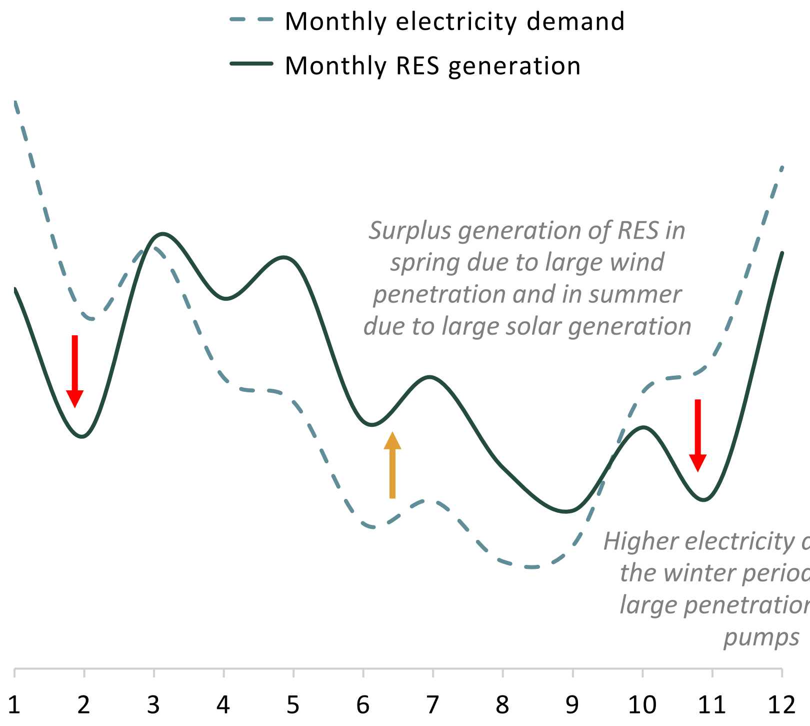
By 2040, an increase in demand during RES generation hours is due to electrolysers and flexible EVs

➡ Surplus of RES generation

➡ Demand not met by RES

Seasonal[1]

Related to demand, RES and temperature variability



Surplus generation of RES in spring due to large wind penetration and in summer due to large solar generation

Higher electricity demand in the winter periods due to large penetration of heat pumps

Notes: 1) Data for Germany TYNDP scenario 2040

EXECUTIVE SUMMARY

… with new and innovative solutions emerging to meet these

EXISTING FLEXIBILITY SOLUTIONS

- Unabated gas generation, interconnectors, hydro (including pumped storage) and battery storage.
- Challenging economics for unabated gas in the future and/or explicit operational restrictions.
- Limitations on economic pumped storage development potential.

LDES TECHNOLOGIES

- Longer duration and different types of electrochemical batteries, CAES[1], LCES[2] and hydrogen storage (in tanks or underground).
- LDES technologies can shift energy over different timescales, from daily to monthly timeframes.

LOW-CARBON THERMAL GENERATION

- Flexible low-carbon gas alternatives, including and H2-ready GTs and CCGTs, and less ‘flexible’ options with CCS.
- The potential for CCS gas could be restricted due to resource limitations, such as carbon storage capacity.
- H2-ready plants may face constraints related to hydrogen availability and infrastructure development.

DEMAND FLEXIBILITY

- The demand-side has the potential to completely change the way we use electricity and could be the key flexibility ‘resource’ in the future.
- In the short to medium term, however, it may be challenging to reveal the full scale of the demand-side flexibility needed.

Notes: 1) Compressed Air Energy System. 2) Liquid CO2 Energy System. 3) Carbon Capture and Storage.

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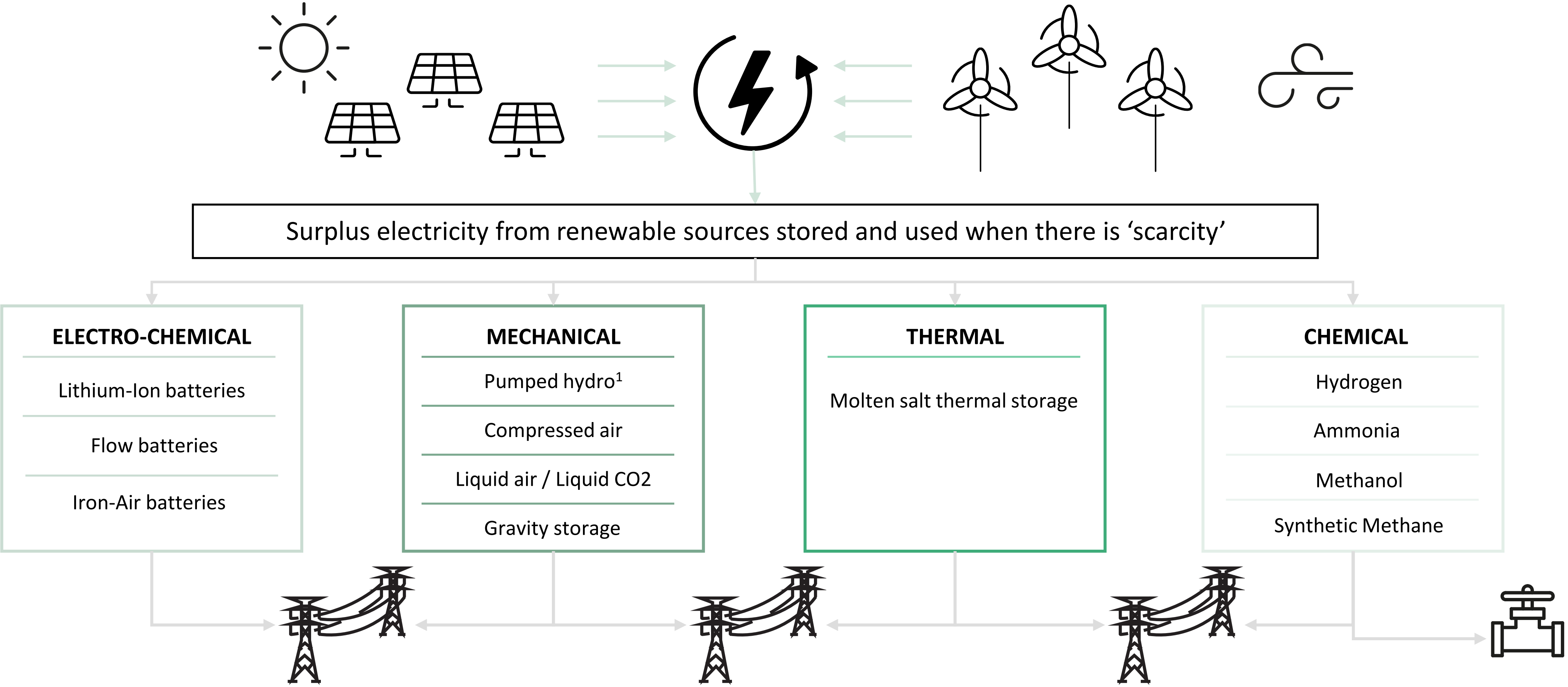
There is a range of storage technologies that can be used to provide flexibility …



Surplus electricity from renewable sources stored and used when there is ‘scarcity’

ELECTRO-CHEMICAL

- Lithium-Ion batteries
- Flow batteries
- Iron-Air batteries

MECHANICAL

- Pumped hydro[1]
- Compressed air
- Liquid air / Liquid CO2
- Gravity storage

THERMAL

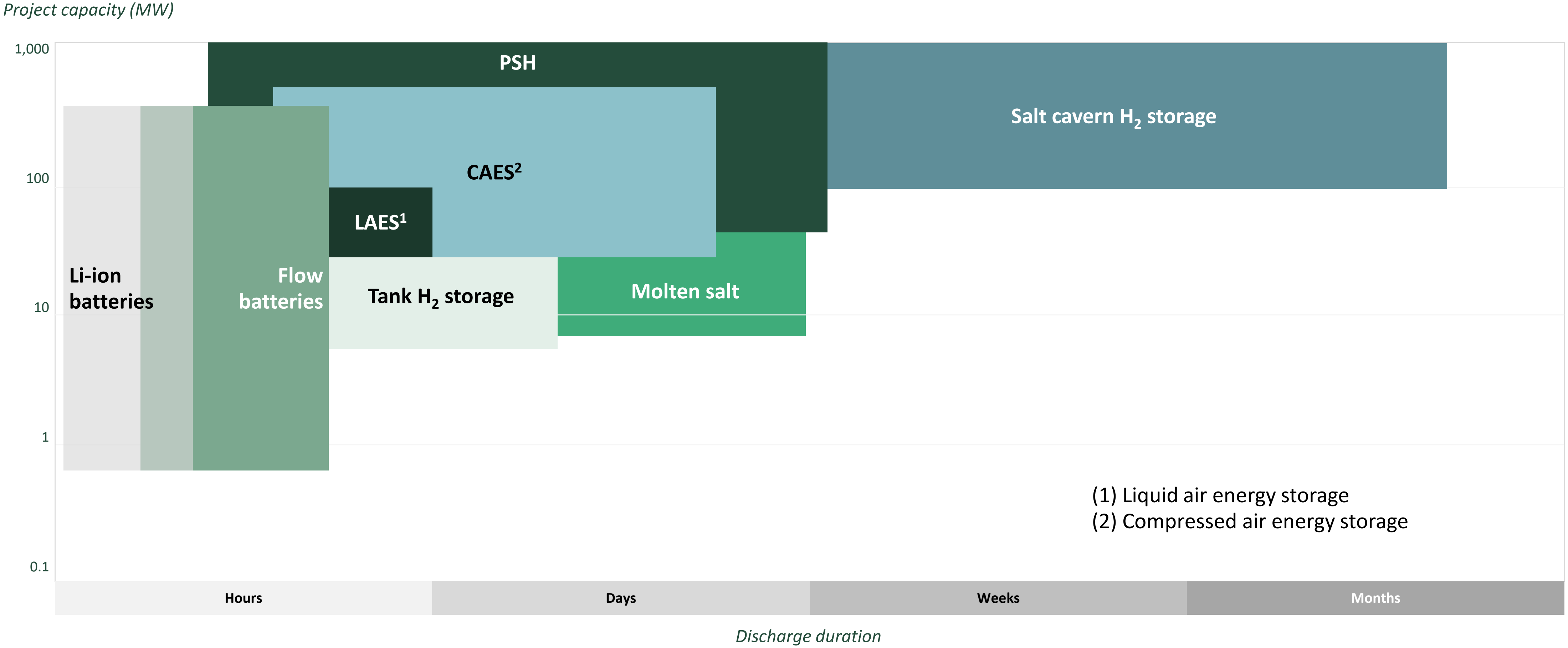
- Molten salt thermal storage

CHEMICAL

- Hydrogen
- Ammonia
- Methanol
- Synthetic Methane

Note: 1) This report focuses *exclusively* on innovative long-duration energy storage (LDES) technologies and does not cover pumped hydro storage (PHS), which is a fully mature and commercially viable technology that already contributes significantly to Europe's flexibility needs

… and these different technologies can store energy for varying lengths of time ranging from a few hours to multiple days



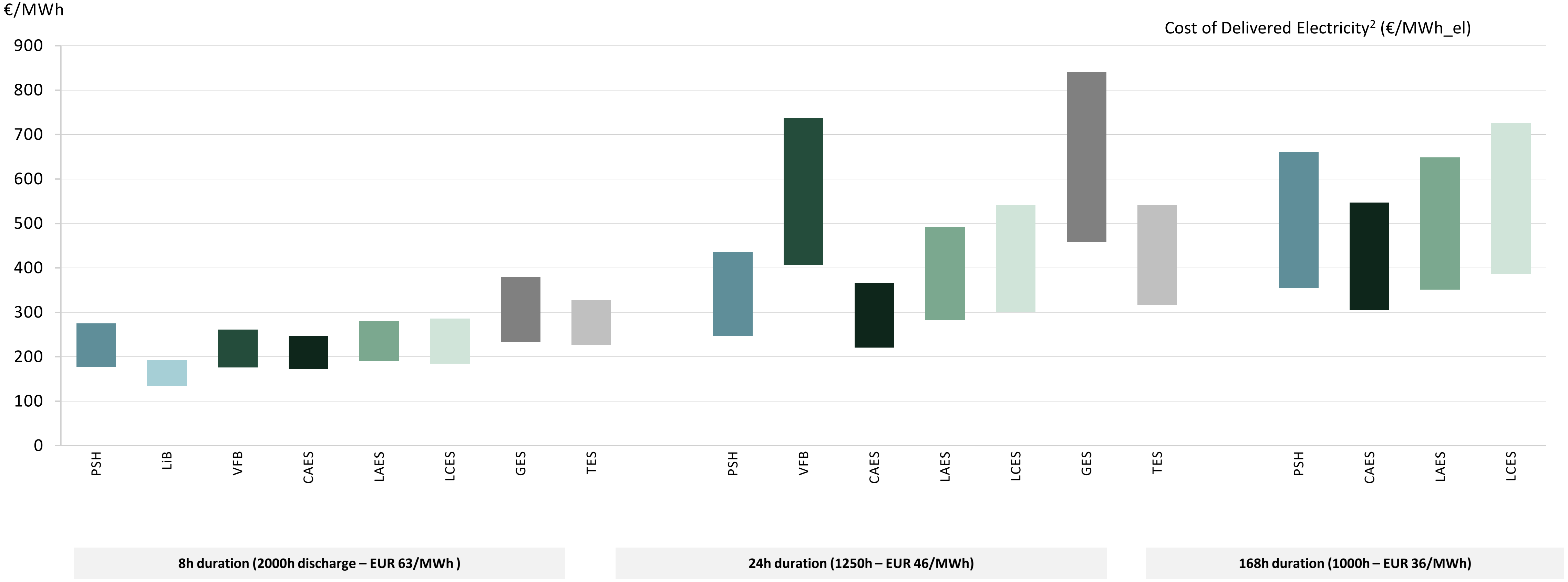
(1) Liquid air energy storage
(2) Compressed air energy storage

Source: LDES Council, UK DESNZ and AFRY analysis

EXECUTIVE SUMMARY

Lithium-ion batteries are today the cheapest option with other solutions gradually becoming cost-competitive

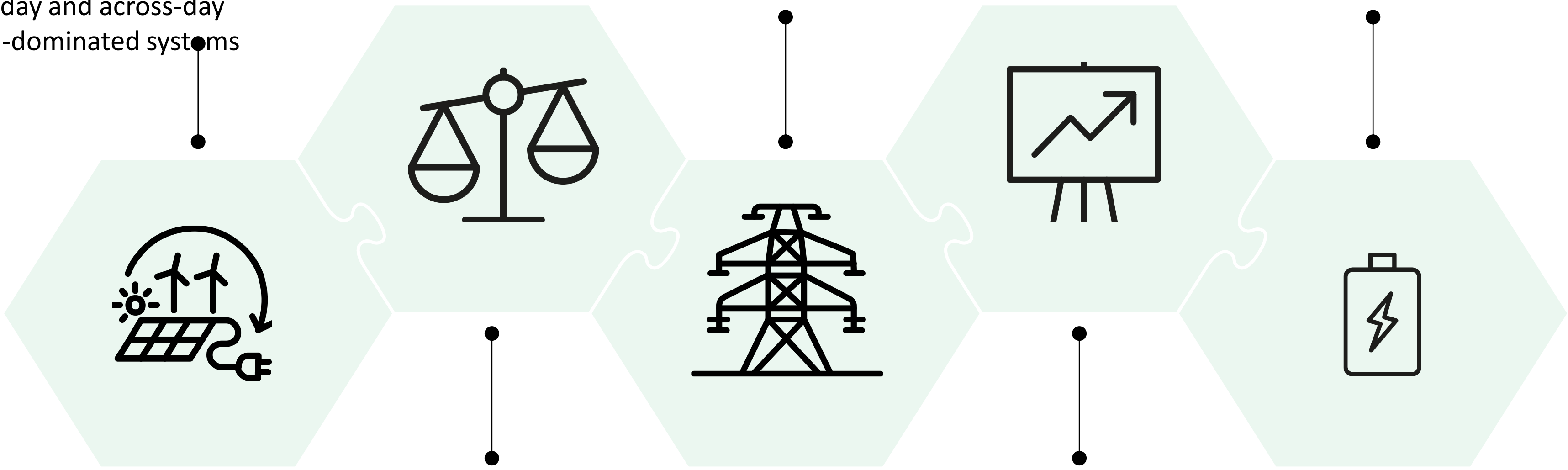
LEVELISED COST OF STORAGE[1] PROJECTIONS ACROSS SELECTED TECHNOLOGIES (2030)



Assuming 300h of discharging and an average electricity price when charging of EUR 74/MWh. This assumption is based on an annual average electricity price; however, LCOS would decrease if these technologies charge during periods of low or negative prices.

Sources: BNEF, PNNL, US DOE & AFRY analysis

LDES are expected to participate in a range of markets, offering different services to the power system



Increasing price volatility

Greater wind and solar penetration increases low-price periods, creating within-day arbitrage opportunities in solar-dominated markets and within-day and across-day opportunities in wind-dominated systems

Congestion management

LDES can help manage network congestion by storing excess generation and reducing RES ‘dispatch down’ and ‘redispatch’ costs

Co-location with RES

Co-locating storage with RES can lower costs through shared infrastructure, reduce curtailment, and in some cases enable grid access

Growing need for Balancing Energy

LDES can replace thermal generating units, providing frequency response, Balancing Capacity, and Balancing Energy

Revenue stacking

Most storage assets stack revenues across wholesale trading, Balancing Markets and system services, with the share dictated by trading strategy, storage technology, and country-specific rules

EXECUTIVE SUMMARY

LDES can help manage congestion, provide system services and ‘shift’ energy within a day and across multiple days

Great Britain 01.

Dedicated framework and emerging LDES business case

- ● Multi-day energy shifting acting as back-up capacity during low wind periods.
- ● 25-year cap & floor scheme: helps de-risk projects.
- ● Manage congestion, especially at the Scotland–England boundary.

Germany 02.

Opportunity for LDES given congestion and wind levels

- ● Multi-day energy shifting acting as back-up capacity during low wind periods.
- ● North–south grid congestion creates structural value for congestion management.
- ● An expected dedicated auction for long-duration technologies can improve revenue certainty.

Iberia 03.

Strong business case for MDES driven by solar penetration

- ● Need for 8–12 hour storage driven by solar generation.
- ● Persistent and predictable within-day price spreads supports medium duration economics.
- ● Deployment of electrolysis may flatten prices.

Finland 04.

Challenging economics for LDES despite wind levels

- ● Multi-day energy shifting acting as back-up capacity during low wind periods (limited by hydro).
- ● Hydro generation can challenge LDES economics.
- ● In ‘dry’ years LDES can act as a strategic asset.

● Sweet spot ● Differentiator ● Risks & upsides

*Note: Financial analysis of H2 – storage is not considered in this report

EXECUTIVE SUMMARY

AFRY has modelled a power scenario based on the TYNDP 2024 and informed by AFRY analysis in the short term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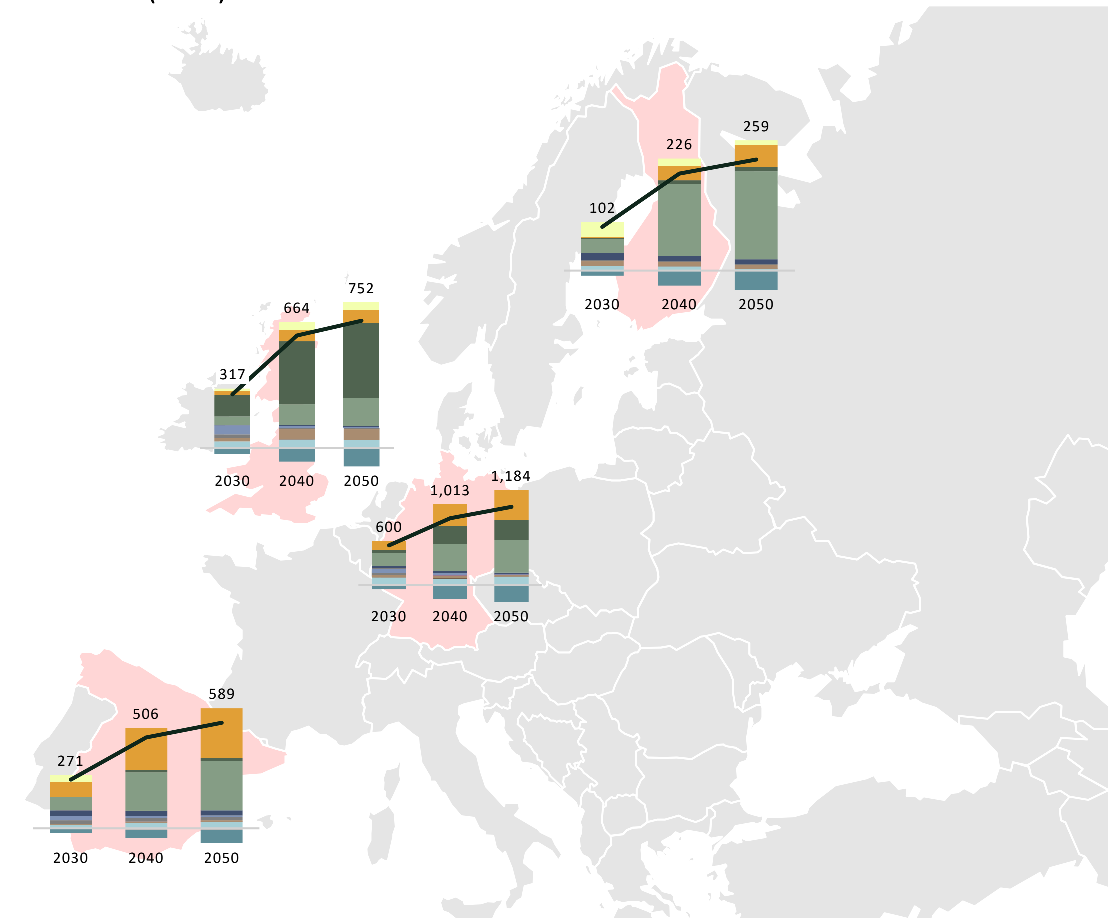
TYNDP 2024

Final Scenarios Report

January 2025

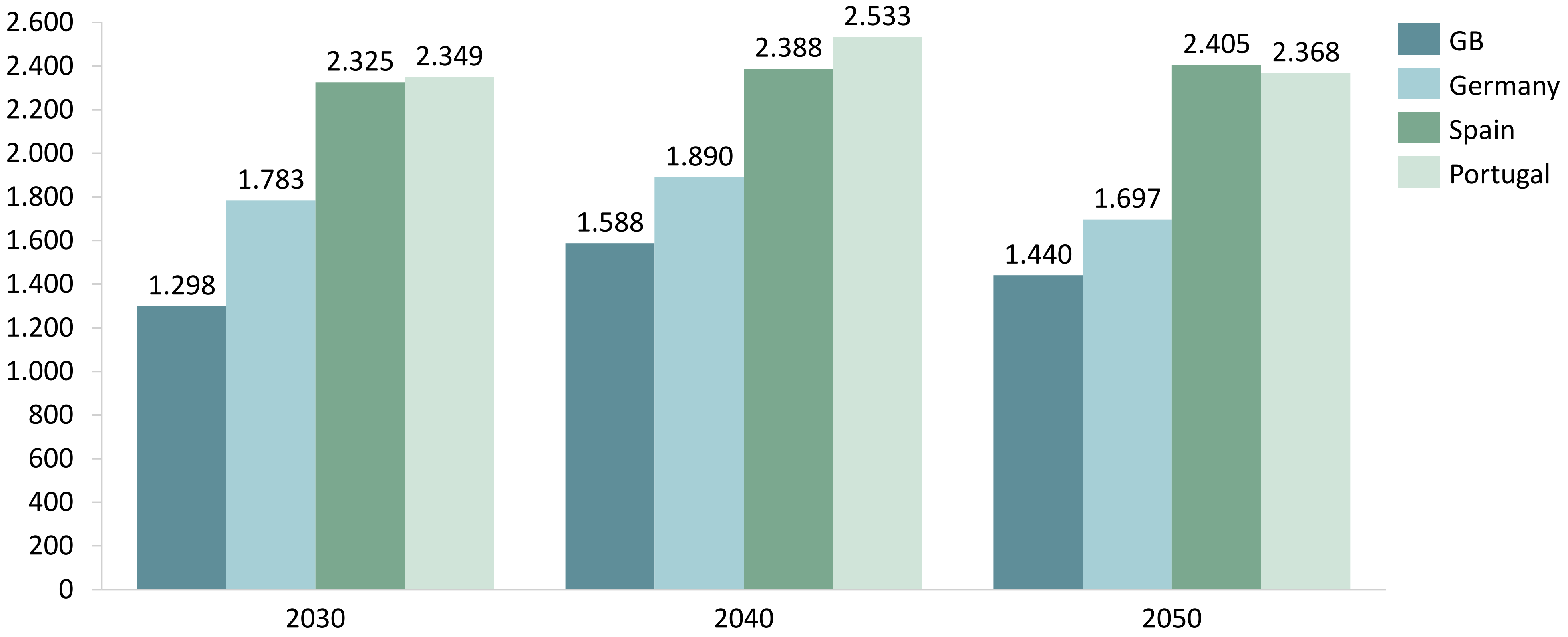
Generation (TWh)



- 🟨 Nuclear
- 🟧 Solar PV
- 🟩 Offshore Wind
- 🟩 Onshore Wind
- 🟦 Hydro
- ⬛ Coal & Lignite
- 🟦 Gas turbine
- ⬜ Storage
- 🟪 Hydrogen
- ⬛ Other Thermal
- 🟫 Other RES
- 🟫 DSR
- 🟦 Imports
- 🟦 Exports
- 🟦 Electrolyser
- — Total Demand*

We expect a significant reduction in RES curtailment with the use of LDES; this could be even higher in places with network congestion

RES curtailment avoided (MWh/MW installed-year)



*Note: We present the average RES curtailment avoided from a 'blended portfolio' of LDES technologies. This is the RES volumes that would have otherwise been curtailed and are withdrawn from the LDES units. When injected back to the grid, thermal generation can be displaced. However, because of efficiency loss the avoided thermal generation is lower.

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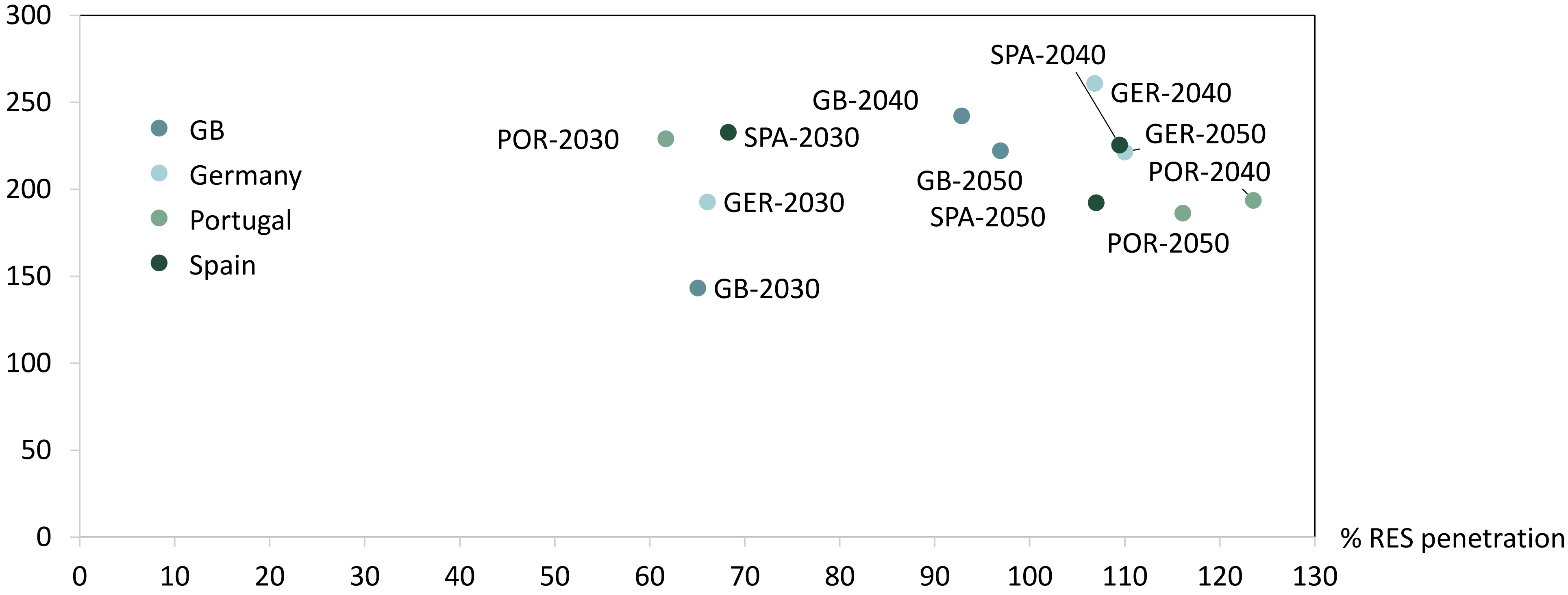
Our analysis suggests each GW of LDES can help save €150m-€250m of variable operating costs per annum

Variable cost savings (m€/GW-year)[1]



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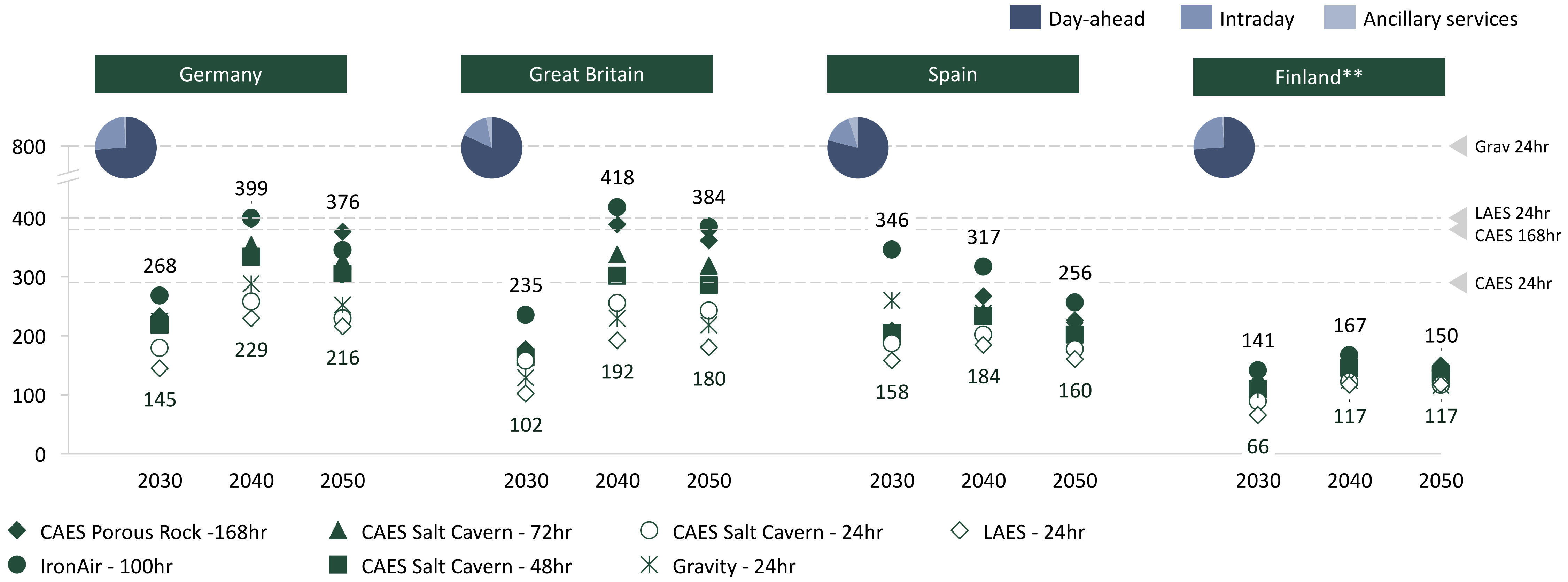
*Note: RES penetration is defined as total available RES resource (including curtailed volumes) divided by total electricity demand

1) This cost reduction estimate to the first GW of LDES installed. The 1GW of LDES reflects an 'LDES portfolio' consisting of the different LDES technologies we have assessed. The addition of LDES to the system results in gradual cannibalisation. This means the variable cost savings are not necessarily linear. We would expect an incremental reduction of the variable cost savings with each increase additional MW of LDES installed (all else being equal)

Some solutions are getting close to being ‘in the money’, most notably some >24h storage options in Germany and GB post 2040

Total gross margins* (€/kW), real 2025 LDES: 24-168hr



*Gross margins are calculated as the total revenues of selling energy – buying energy in the Day-ahead market, plus revenues of adjusting

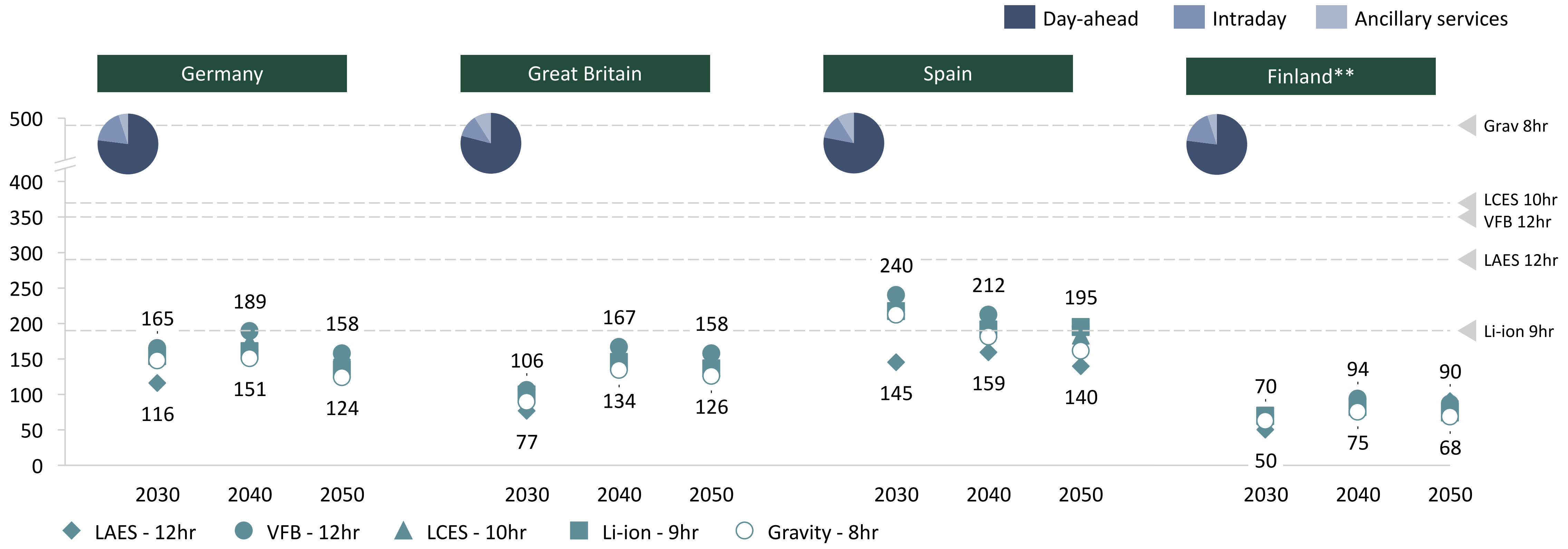
**Note: for Finland, the revenues for ID and balancing were obtained from the same share as in Germany, due to the similarities in market configurations.

*** The projected LCOS presented is that as of 2030. We recognise that the LCOS is very likely to drop going forward in line with the learning curve.

For more information, refer to the Annex

Iberia, as a solar-dominated region, is the most attractive market for LDES with 8-12 hr duration

Total gross margins* (€/kW), real 2025 LDES: 8-12hr



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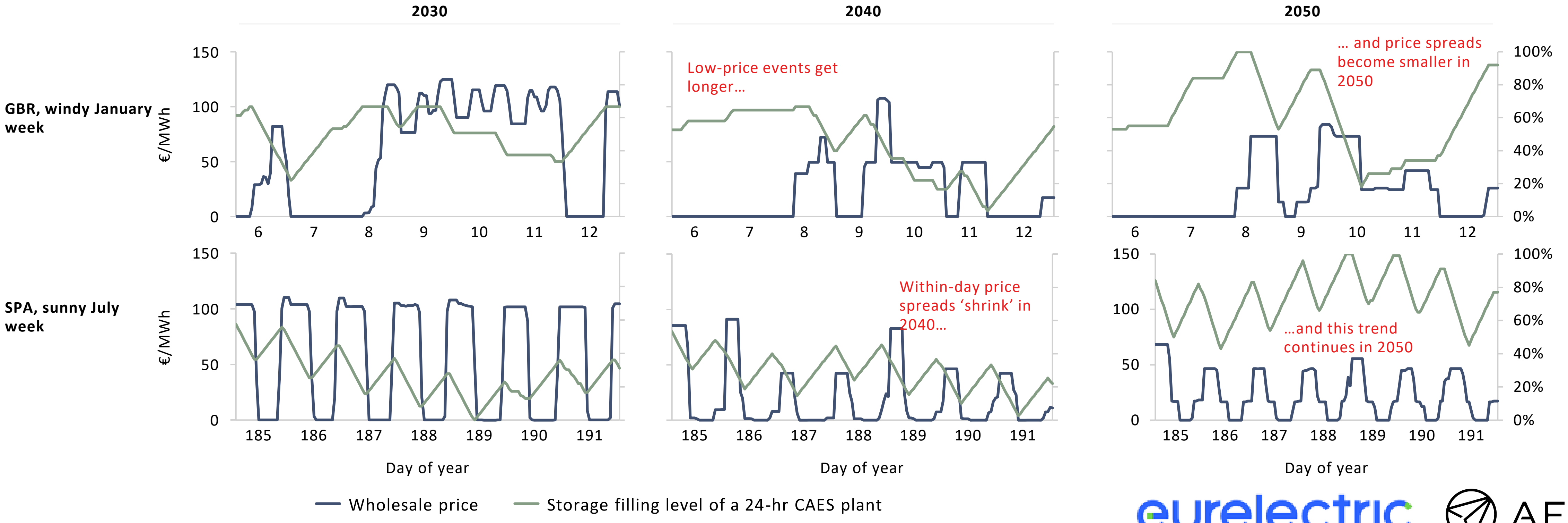
The underlying market price formation can help explain the LDES operation and captured margins

- In GB, longer low-price events in 2040 and 2050 enable more low-cost charging, which results in higher gross margins than 2030. Higher wind output in 2050 leads to 'longer' low-price events, but also smaller price spreads. This, in turn, results in lower margins in 2050 compared to 2040
- In Spain, the within-day price spreads 'shrink' going forward . This, in turn, leads to a reduction in LDES gross margins out to 2050

HOURLY SNAPSHOTS OF WHOLESALE PRICE AND STORAGE FILLING LEVEL IN 2030, 2040 AND 2050



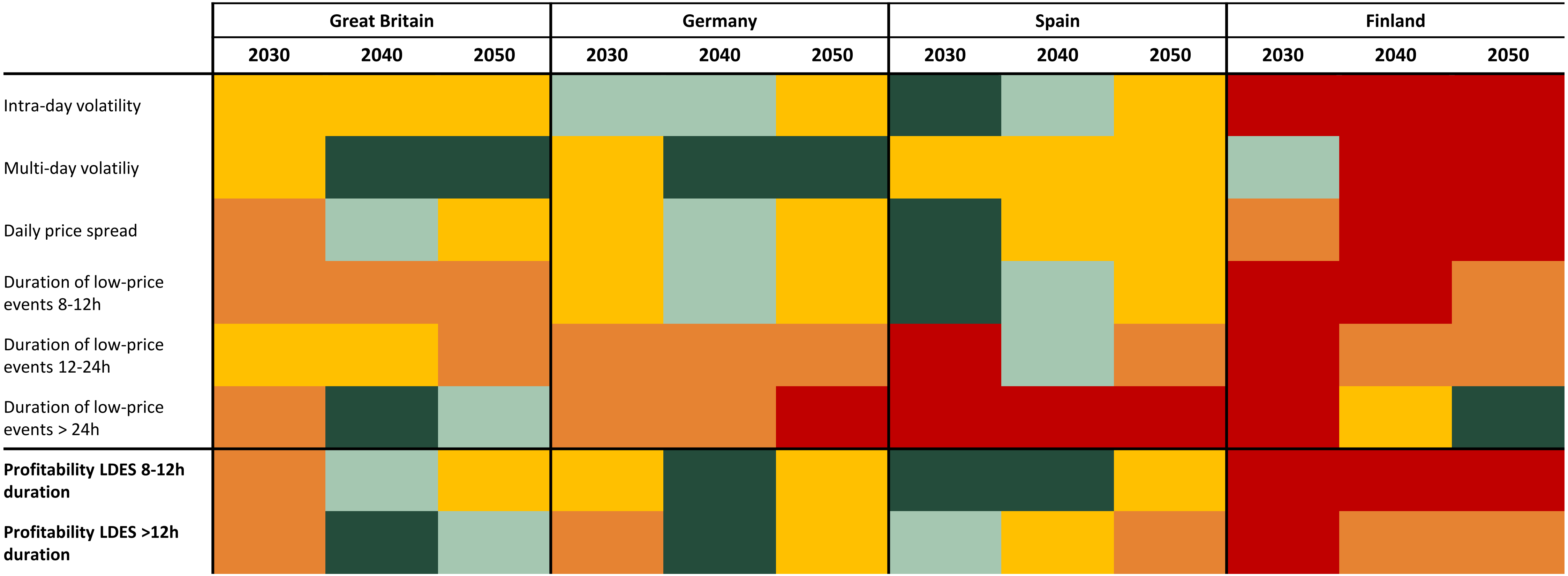
Low-price events get longer…

… and price spreads become smaller in 2050

Within-day price spreads 'shrink' in 2040…

…and this trend continues in 2050

Within-day price volatility coupled with more frequent extended low-priced events result in different opportunities for LDES



	Great Britain			Germany			Spain			Finland		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Intra-day volatility	🟨	🟨	🟨	▨	▨	🟨	🟩	▨	🟨	🟥	🟥	🟥
Multi-day volatiliy	🟨	🟩	🟩	🟨	🟩	🟩	🟨	🟨	🟨	▨	🟥	🟥
Daily price spread	🟧	▨	🟨	🟨	▨	🟨	🟩	🟨	🟨	🟧	🟥	🟥
Duration of low-price events 8-12h	🟧	🟧	🟧	🟨	▨	🟨	🟩	▨	🟨	🟥	🟥	🟧
Duration of low-price events 12-24h	🟨	🟨	🟧	🟧	🟧	🟧	🟥	▨	🟧	🟥	🟧	🟧
Duration of low-price events > 24h	🟧	🟩	▨	🟧	🟧	🟥	🟥	🟥	🟥	🟥	🟨	🟩
Profitability LDES 8-12h duration	🟧	▨	🟨	🟨	🟩	🟨	🟩	🟩	🟨	🟥	🟥	🟥
Profitability LDES >12h duration	🟧	🟩	▨	🟧	🟩	🟨	▨	🟨	🟧	🟥	🟧	🟧

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Daily[1]

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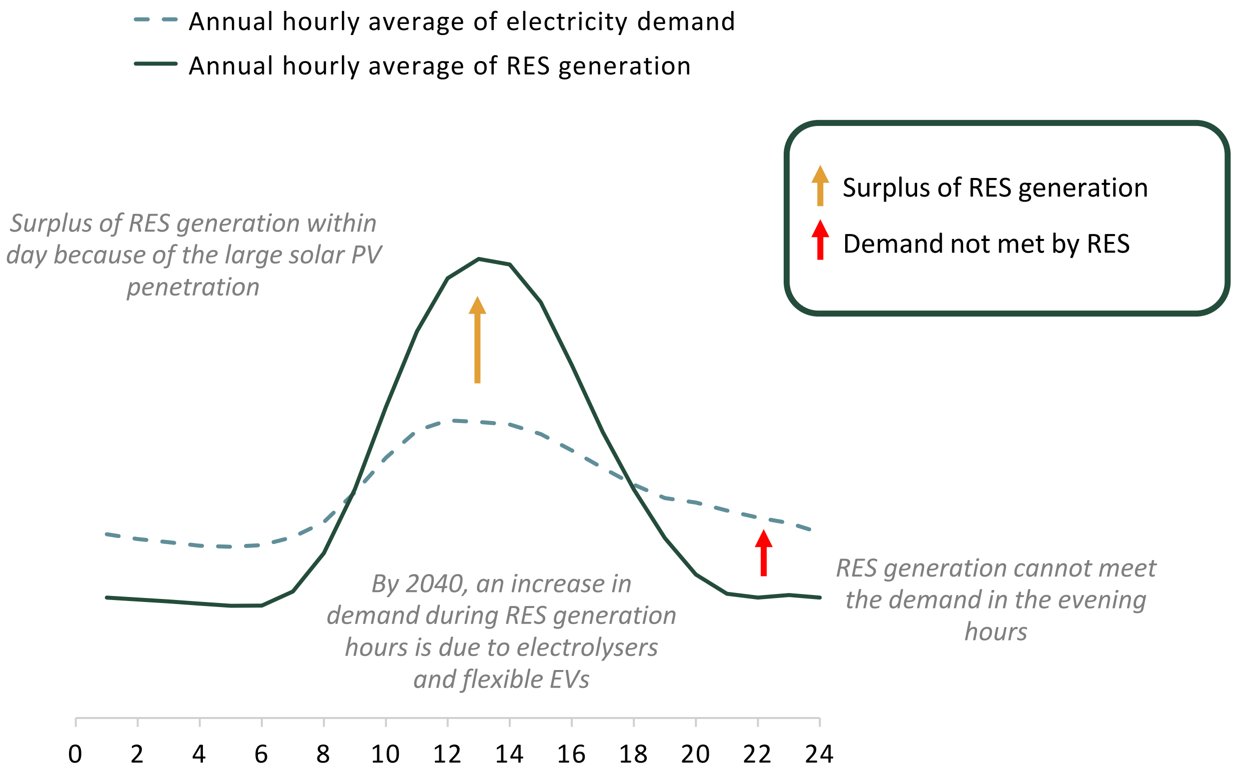

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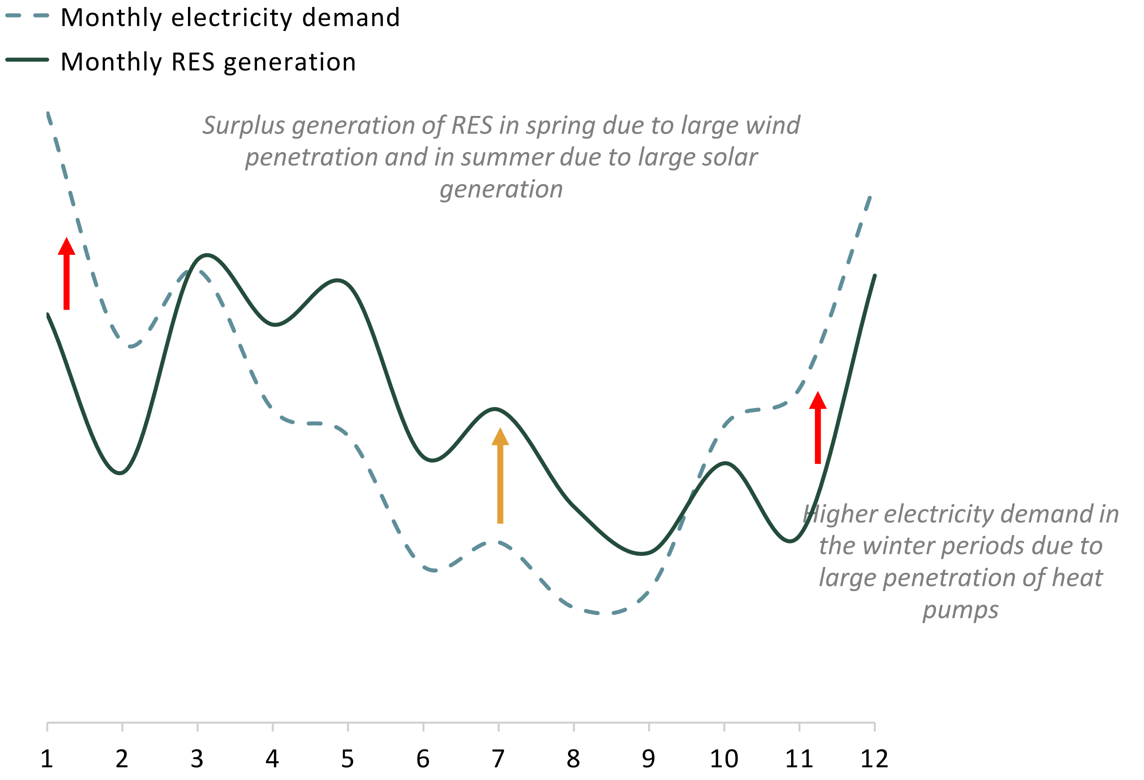

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Storage can capture income from various markets in line with its ability to manage a range of system needs

Value pools for Power LDES

Markets	Description
Traded markets	– Storage can capture value by trading (buying and selling) in the ex-ante markets . As storage relies predominantly on hour-to-hour (or day-to-day for longer durations) price volatility, forward market are less attractive and trading is centred around closer to real-time markets, such as the Day-Ahead and intraday. Storage can then also be used in the TSO-led Balancing Markets where prices are (typically) even more volatile. – Multi-day and within-day price volatility are key drivers for storage (driven by high solar and/or wind) with time-shifting across multi-period 'lows' and 'highs' expected to become more common in the future (mostly driven by wind rather than solar PV).
Systems services	– Storage can also provide system services, most notably frequency response and reserve. The potential scale of income from these is jurisdiction-dependent. Still, reserve markets are typically 'thin' and can be very quickly oversupplied. Even though the need for reserve and frequency response may increase, supply may increase at a much faster pace. – There is the possibility for additional income from the introduction of new system services, such as 'synthetic' inertia and reactive power injection/absorption.
Congestion management	– Storage can reduce congestion through withdrawing renewable generation that cannot be accommodated locally when the grid is congested, and injecting to the grid in different periods, when there is no network congestion. – In some places, there are explicit congestion markets, and in others congestion is managed via the Balancing Market. LDES can be particularly helpful in managing congestion given longer duration.
Hedging & other contracts	– It is very common for storage to have hedging contracts in place, such as tolling agreements or agreements that guarantee a floor revenue in exchange for some revenue sharing beyond a certain level. – Capacity markets are used in several European markets, including GB and Spain, to ensure generation adequacy. Storage can participate, typically based on some pre-defined de-rating factors. LDES will typically have a higher de-rating factor. – Several countries are also considering (or are already in the process of) introducing explicit tenders to procure LDES capacity.

LDES TECHNOLOGIES

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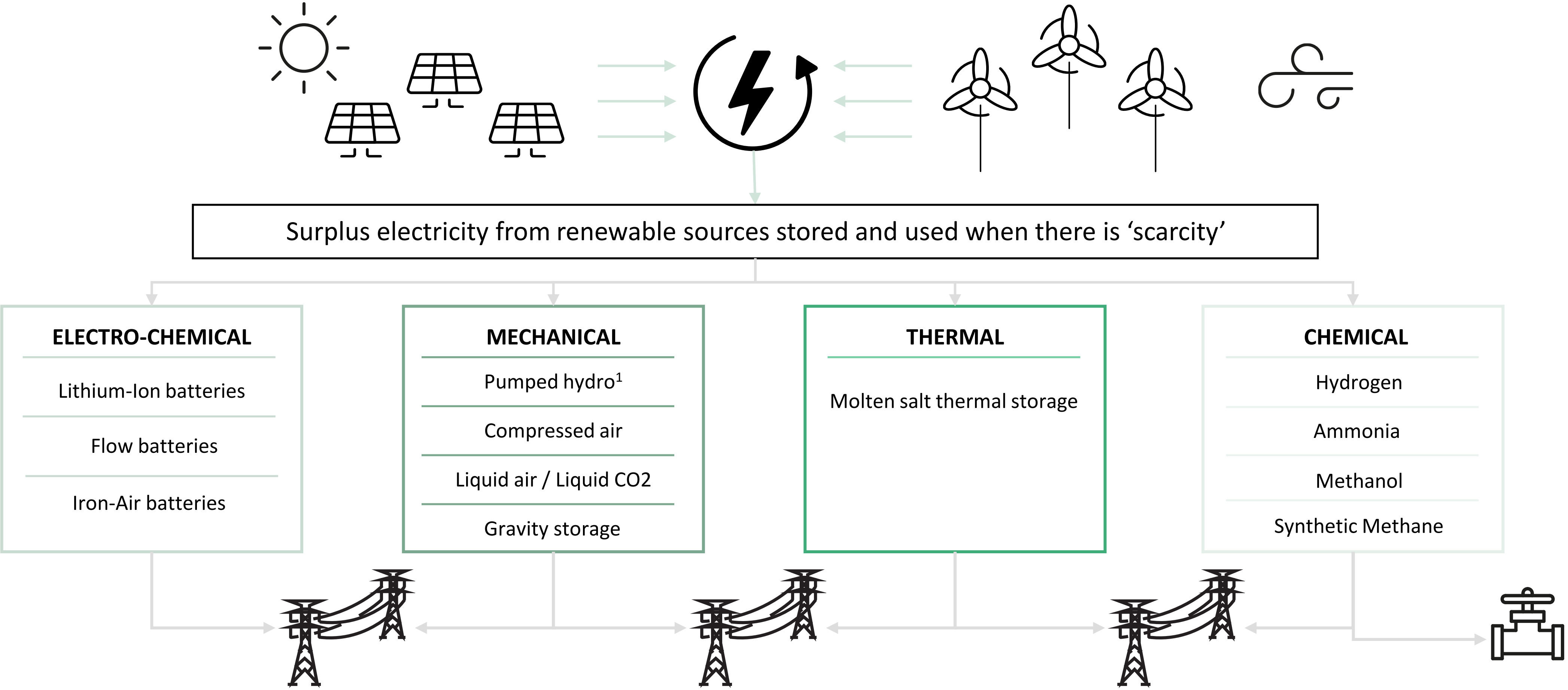

Surplus electricity from renewable sources stored and used when there is ‘scarcity’

ELECTRO-CHEMICAL

- Lithium-Ion batteries
- Flow batteries
- Iron-Air batteries

MECHANICAL

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- Compressed air
- Liquid air / Liquid CO2
- Gravity storage

THERMAL

- Molten salt thermal storage

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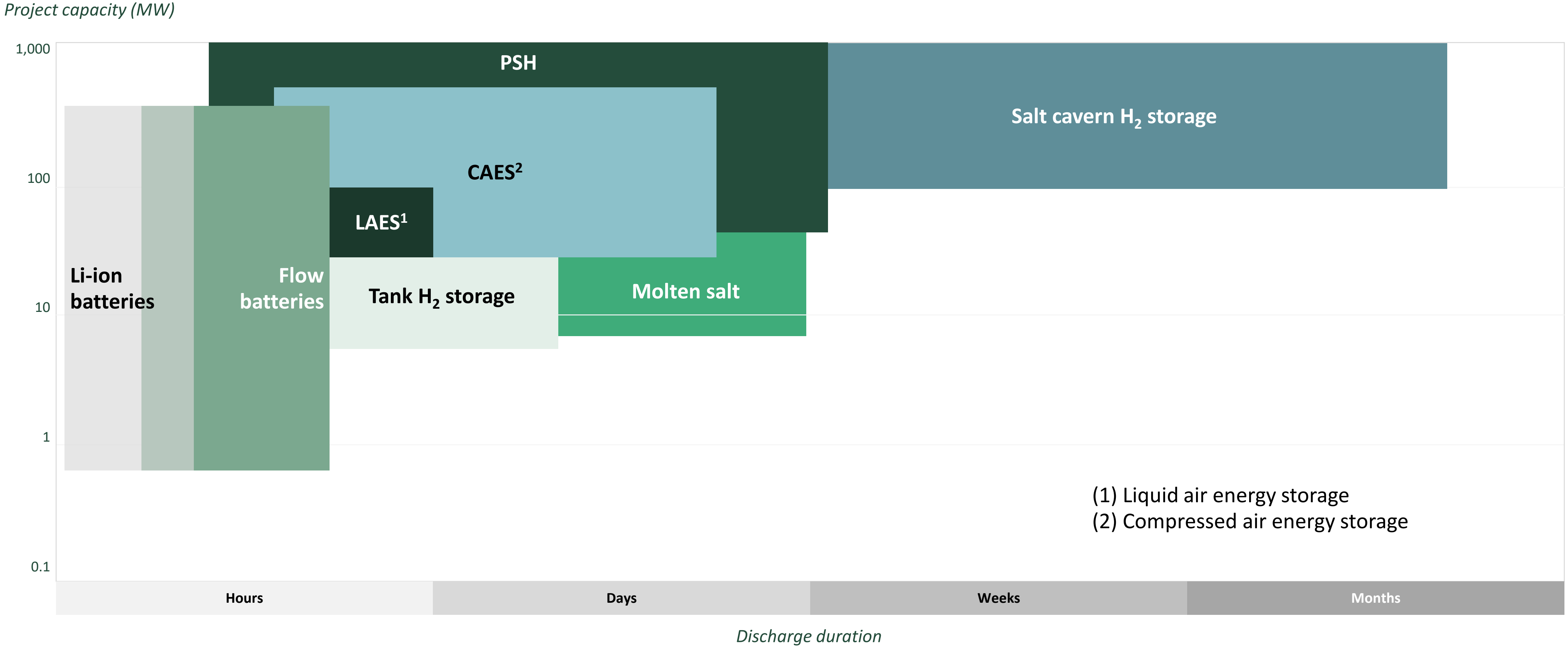


Source: LDES Council, McKinsey, Navigant Research, UK DESNZ and AFRY analysis

Storage solutions have different characteristics, are at different stages of commercial maturity and can be used to address various system needs (1/2)

	Focus technologies	Use cases	Round-trip efficiency	Services	Maturity
ELECTROCHEMICAL	Lithium-ion batteries (LiB)	INTRADAY	85%	POWER, AS[2]	Commercial[3]
	Flow batteries (VFB)	INTRADAY	70%	POWER, AS	Commercial
	Iron-air batteries (IAB)	INTRADAY, MULTIDAY[1]	40%	POWER, AS	Pre-commercial
MECHANICAL	Pumped storage hydro (PSH)	INTRADAY, MULTIDAY	80%	POWER, AS	Mature
	Compressed air (CAES)	INTRADAY, MULTIDAY	65%	POWER, AS	Commercial
	Gravity energy storage (GES)	INTRADAY, MULTIDAY	80%	POWER, AS	Pre-commercial

Notes: 1) Either weekly or monthly 2) Ancillary services 3) Lithium-ion batteries of short/medium duration (up to 4hr) are considered a mature technology, however longer durations are in commercial stage.

Storage solutions have different characteristics, are at different stages of commercial maturity and can be used to address various system needs (1/2)

Focus technologies

		Use cases	Round-Trip Efficiency	Services	Maturity
MECHANICAL	Liquid CO2 (LCES)	INTRADAY MULTIDAY	75%	POWER AS	Pre-commercial
	Liquid air energy storage (LAES)	INTRADAY MULTIDAY	60%	POWER AS	Pre-commercial
THERMAL	Thermal energy storage (TES)	INTRADAY MULTIDAY	50%	POWER AS HEAT	Commercial
CHEMICAL	Hydrogen tank (H_2 tank)	INTRADAY MULTIDAY	35%	POWER HEAT	Mature[2]
	Underground H2 storage[1]	MULTIDAY SEASONAL	35%	POWER HEAT	Commercial[3]

Notes: 1) Either in salt cavern (UG SC) or in depleted field (UG Depl.). 2) Referring to the sole storage tank, not to the entire value chain (production of molecule, storage and conversion to power) 3) Commercial for Salt Cavern, Pre-Commercial for Depleted Fields.

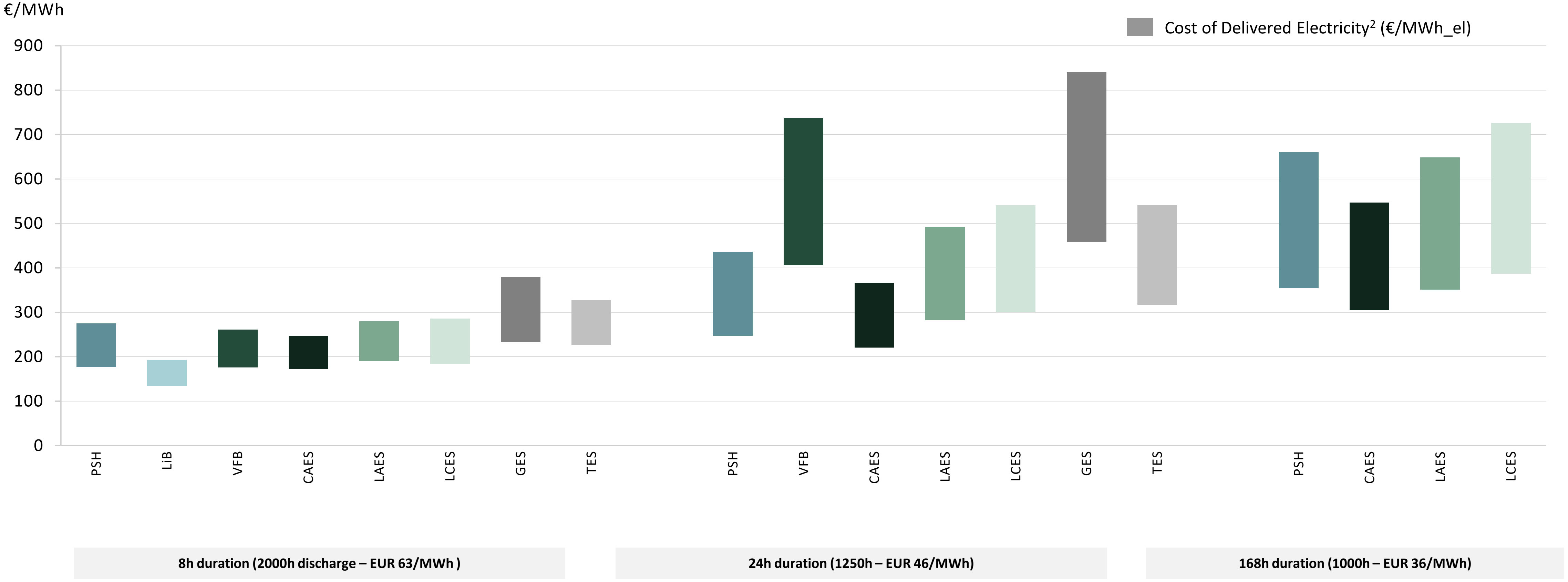
Longer duration energy storage (LDES) units are better suited for shifting energy across multiple periods and for congestion management

	DURATION	USE CASE	TECHNOLOGY TYPE
Short Duration Energy Storage (SDES)	< 8 hours	Balancing needs and within-day energy shifting (limited to the storage duration).	Lithium-ion, Fly wheels, Super capacitors, V2G.
Long Duration Energy Storage (LDES)	Over 8 hours	Balancing needs, within-day energy and across-day energy shifting and congestion management.	Lithium-ion, Pumped-hydro-storage, CAES,LAES, VFB, Hydrogen tank storage (up to 720h), Gravitational storage, Thermal energy storage.

Note: Duration refers to the length of time taken for the storage to fully empty when starting from 100% full, outputting at maximum rate. This classification is not and international standard but has been defined as such for the purpose of this work.

Lithium-ion batteries are today the cheapest option with other solutions gradually becoming cost-competitive

LEVELISED COST OF STORAGE[1] PROJECTIONS ACROSS SELECTED TECHNOLOGIES (2030)



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LDES TECHNOLOGIES

Flow batteries and CAES seem to be ‘ahead’ of other emerging LDES technologies – however, this can quickly change given pace of improvement

Type	Maturity	Current usage	Future	AFRY Comment
Flow batteries	Commercial	Rongke Power has delivered 175MW/ 700 MWh (2024) and 200MW/ 1000MWh projects (2025) in China.	FlexBase Group started construction in 2025 on a data centre combined with a 0.8GW/1.6GWh battery in Switzerland.	Most large-scale development are in China.
Iron-air batteries	Pre-commercial	Several small pilot projects in Europe and the US with durations of 100+ hours.	US DoE supported the development of 85MW 100-hour iron-air storage project (COD by 2028).	Projects generally remain at the pilot stage and require further support to scale up the technology.
CAES	Commercial	During the 2020s, more than 810MW/3600MWh of CAES capacity has been deployed in China.	Additionally, 0.7GW/ 4.2GWh and 0.7GW/ 2.8GWh projects are under development in China.	China’s five-year plan highlights the need to rapidly expand new-type energy storage, with investment signalling CAES as one of the priorities.
Gravity energy	Pre-commercial	Pilot projects only so far in Europe and the US.	An 18MW/ 36MWh plant is expected to be built in Texas; a 25MW/ 100MWh project is under development in China.	Further support is needed to scale up the technology; it is still unclear if gravity storage can be competitive.
LAES	Pre-commercial	A 50MW/300MWh project is under development in GB (2026 COD) with governmental support.	A 300MW/3.2GWh project has been announced in GB.	Further cost reductions may be needed to ensure the technology becomes competitive.
Liquid CO2	Pre-commercial	Pilot 2.5MW/ 4MWh project operating in Italy.	Projects for 20MW/ 200MWh are under development in Italy and the US.	Energy Dome developing its project in Italy with support from Google.
Underground H2 storage	Commercial	Uniper operates a pilot in Germany for 500 MWh H2.	Serveral projects in GB are under development, located in Cheshire and Dorset.	Development of the H2 supply chain remains in early stages, with the industry facing challenges and an overall slowdown in projects.

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LDES, as is the case, with all storage applications is expected to be active in a range of markets and offer different services to the power system

Increasing price volatility driven by RES	More wind and solar results in more frequent low-priced periods. Within-day and across-day arbitrage opportunities exist across Europe with greater potential for within-day energy shifting in solar-dominated and across-day energy shifting in wind-dominated countries.
Growing need for Balancing Energy and system services	As thermal generating units decommission, there is a need for additional and alternative provision of reserve and other system services. LDES solutions are well suited to provide frequency response, reserve capacity and Balancing Energy.
Congestion management	All European countries are facing network constraints as renewable build-out is outpacing transmission upgrades. LDES can absorb excess generation in constrained zones and re-inject electricity later, reducing renewables curtailment and redispatch costs.
‘Revenue stacking’	Most storage units ‘stack’ income from the above – wholesale trading across different timeframes, Balancing Market and system services. The share of the different income streams depends on ‘trading’ strategy, type of storage technology and jurisdiction.
Co-location with renewables	Storage can also be co-located with renewables. This can then mean relatively lower capital and/or operating costs (shared infrastructure), helping reduce curtailment and resulting in a ‘firmer’ profile. In some cases, adding storage may be the only way to ensure grid access.

Short duration storage (<8h) is being widely developed across Europe – what types will we need in the future in addition to short duration storage?

Region	Key renewable technology	Energy storage use cases
Northwest Europe: UK, Germany, Netherlands, Belgium	Balance of offshore wind, onshore wind and solar PV (though wind dominates in energy terms).	Long duration (over 12 hours) storage to manage Dunkelflaute (multi-day wind lulls combined with high demand) – some scope also for medium duration storage for within-day energy shifting.
Central Europe: Austria, Switzerland, Czechia, Poland	A mix of onshore wind, solar PV; significant hydro capacity.	Short to medium duration storage for within-day energy shifting and to a lesser extent longer duration storage to manage across days energy shifting.
Nordics: Norway, Finland, Sweden, Denmark	A mix of offshore wind and onshore wind; significant hydro capacity.	Long duration (over 12 hours) storage to manage Dunkelflaute (multi-day wind lulls combined with high demand) combine with 'dry' hydro conditions.
Southern Europe: Spain, Portugal, Italy, Greece	A mix of onshore wind, solar PV; more limited offshore wind.	Short to medium duration storage for within-day energy shifting and to a lesser extent longer duration storage to manage across days energy shifting.

LDES can help manage congestion, shift energy across multiple days (removing the need for controllable capacity) and provide within-day energy shifting in solar-dominated markets

Great Britain

- **Sweet spot:** Multi-day energy shifting with LDES acting as back-up capacity during low wind periods in the longer term.
- **Key differentiator:** The 25-year cap & floor scheme can help de-risk LDES projects whilst retaining some upside through partial market exposure.
- **Additional edge:** Potential for LDES to be used to manage congestion, especially at the Scotland–England boundary.

Germany

- **Sweet spot:** Multi-day energy shifting with LDES acting as back-up capacity during low wind periods in the longer term.
- **Key differentiator:** The presence of north–south grid congestion creates structural value for congestion management.
- **Market evolution:** A dedicated LDES auction can improve long-term revenue certainty.

Iberia

- **Sweet spot:** Need for 8–12 hour storage capability driven by a more predictable solar generation profile (excess generation during the day and no output during the night).
- **Key differentiator:** Persistent and predictable within-day price spreads support medium duration storage economics.
- **Future risk:** Widespread deployment of electrolysis may result in 'flatter' prices and less scope for some LDES technologies.

Finland

- **Sweet spot:** Hydro limits the role for storage to manage volatility.
- **Key differentiator:** Hydro can challenge LDES economics.
- **Longer-term upside:** In 'dry' years LDES can act as a strategic asset.

*Note: Financial analysis of H2 – storage is not considered in this report

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GERMANY

LDES in Germany can act as ‘back-up’ to manage Dunkelflaute events and can be an important tool for managing congestion and RES dispatch down

USE CASES FOR LDES

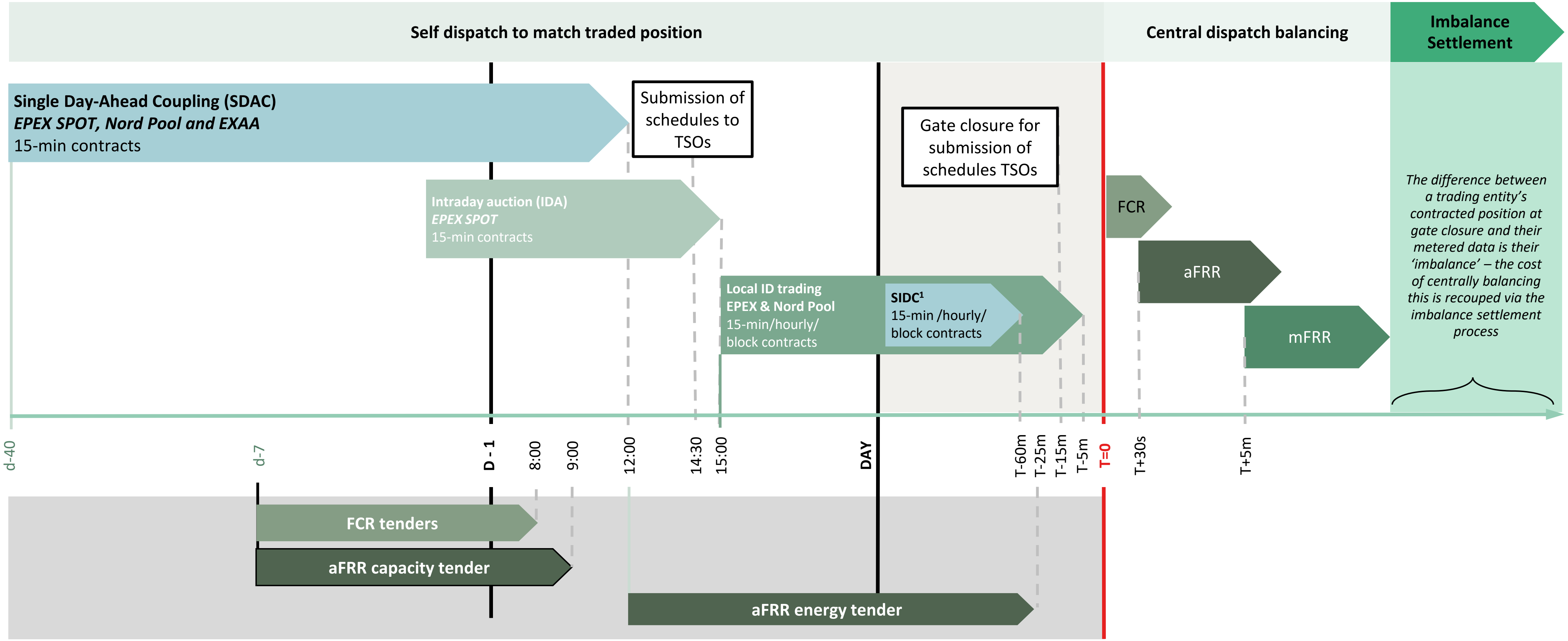
Energy shifting	Today, storage is predominantly used for providing frequency response, reserve and within-day energy shifting. Going forward, there is increased scope for LDES in Germany – ‘back-up’ to manage ‘Dunkelflaute’ events that need multi-day energy shifting (or controllable generation). LDES can ‘charge’ during extended low-priced periods, storing low-cost renewable electricity, and discharge during extended high-priced periods.
System services & Balancing Energy	LDES can also provide frequency response and reserve – aFRR and mFRR Balancing Capacity are an important revenue stream for German storage. These markets are, however, thin and the value in these can quickly disappear. In addition to responding to intraday volatility, storage can also offer flexibility in the form of Balancing Energy.
Grid congestion management	Wind generation is concentrated in the north when most of the demand is in the south – the network does not have sufficient capacity to accommodate this generation-demand disparity and congestion in north-south corridor is frequent. Storage can help reduce redispatch costs and wind curtailment by absorbing surplus generation in the north at times when there is network congestion and injecting to the grid at low wind periods. There is also scope for ‘virtual cables’ through the deployment of storage in different location on the grid. The BMWK Electricity Storage Strategy has also recognised storage as an important tool for alleviating congestion[1].
Co-location with RES	Co-location of storage with RES helps reduce RES curtailment and can ‘firm up’ generation profiles that may be more appealing to industrial and commercial consumers. Germany’s Innovation Tenders actively support PV+storage hybrid projects.
Industrial flexibility	According to the BMWK hydrogen white paper, salt caverns are expected to play a key role for meeting future long-duration industrial needs, supporting industrial decarbonisation while ensuring continuity of operations during periods of low wind and solar generation.

Source: EEX, EPEX Day-Ahead, EPEX spot, BMWK Electricity Storage Strategy, BMWK hydrogen storage white paper.

Note: 1) SDES can alleviate congestions for a few hours at times of peak generation; however, for persisteng congestion during long periods (days), LDES are required.

GERMANY

Storage operators optimise asset operation across the different energy markets and for the provision of system services



Self dispatch to match traded position

Central dispatch balancing

Imbalance Settlement

Single Day-Ahead Coupling (SDAC)
EPEX SPOT, Nord Pool and EXAA
15-min contracts

Submission of schedules to TSOs

Intraday auction (IDA)
EPEX SPOT
15-min contracts

Gate closure for submission of schedules TSOs

Local ID trading
EPEX & Nord Pool
15-min/hourly/ block contracts

SIDC[1]
15-min /hourly/ block contracts

FCR

aFRR

mFRR

The difference between a trading entity's contracted position at gate closure and their metered data is their 'imbalance' – the cost of centrally balancing this is recouped via the imbalance settlement process

FCR tenders

aFRR capacity tender

aFRR energy tender

Note: Single Intraday Coupling (SIDC) is the Pan-European continuous cross border intraday market. NEMOs can offer local trading within Germany outside the SIDC timeframe. SIDC also starts at 15:00 D-1; Source: AFRY analysis

GERMANY

Markets for ex-ante energy trading and for system services are well established in Germany

			MARKET RULES	VALUE FOR LDES
Traded markets		Day-Ahead trading Intraday trading	– Part of the EU's Single Day-Ahead Coupling (SDAC). Main NEMOs: EPEX SPOT, Nord Pool and EXAA. Contracts cover delivery for 15-minute periods for all hours of the next day. – Intraday auction (IDA) through EPEX SPOT with 15-minute contracts up to 15:00 D-1. Local ID trading through EPEX and Nord Pool, and SIDC[1] 15-minute/hourly/ block contracts from 15:00 D-1 to Gate closure.	– Trading in the closer to real-time ex-ante markets (Day-Ahead and intraday) is fundamental for storage, including LDES. – With more intermittent RES added on the system price volatility is expected to increase in the Day-Ahead and intraday markets.
Systems services	Frequency related	FCR aFRR mFRR	– Balancing products designed to manage frequency within seconds (FCR), < 5min (aFRR), <15min (mFRR). – Well established markets for Balancing Capacity (reservation) and Balancing Energy (activation).	– Markets for Balancing Capacity are rather 'thin' and can very quickly be oversupplied by storage. – However, with more RES added so will the needs for Balancing Capacity and Balancing energy.
	Non-frequency related	Inertia procurement* Market-based black start Reactive power provision Capacity reserve Redispatch / §13k EnWG	– An inertia 'market' has now been introduced – this takes the form of regulated payment to inertia (including synthetic inertia) providers. – Black start and reactive power are procured by the TSOs via bilateral contracts. – Redispatch is currently not market-based.	– Demand for inertia from innovative providers will continue to increase as conventional synchronous units decommission. – The development of a separate market-based redispatch may present additional opportunities for LDES. Strategically located assets can help reduce RES dispatch down.
Capacity Markets		Capacity payments*	– Capacity market has been announced for 2028.	– LDES will be in a position to participate in the capacity market - the applicable de-rating factors will be important for LDES.

Notes: 1) Single Intraday Coupling (SIDC) is the Pan-European continuous cross border intraday market. NEMOs can offer local trading within Germany outside the SIDC timeframe. SIDC also starts at 15:00 D-1; Source: AFRY analysis 2) Markets with an * are still in development and not yet available for LDES

GERMANY

Storage can respond to changes in system frequency in both directions

	Frequency Containment Reserve (FCR)	Automatic Frequency Restoration Reserve (aFRR)	Manual Frequency Restoration Reserve (mFRR)
Speed of response	<30 secs	<5 min	<15 min
Symmetry	Symmetric	Separate upward and downward products	Separate upward and downward products
Lead-time ahead of delivery	**Balancing market**: six daily auctions each for 4-hour block	**Balancing capacity market**: six daily auctions each for 4-hour block **Balancing energy market**: Auctions for every 15-min block takes place 25min before delivery	**Balancing capacity market**: six daily auctions each for 4-hour block **Balancing energy market**: Auctions for every 15-min block takes place 25min before delivery
Product types	4h products	**Balancing capacity market**: 4h products **Balancing energy market**: 15 min	**Balancing capacity market**: 4h products **Balancing energy market**: 15 min
Minimum bid size	1MW	1MW	1MW
Reserve capacity payment	Pay-as-Clear €/MW for the contract period	Pay-as-Bid €/MW for the contract period	Pay-as-Bid €/MW for the contract period
Reserve energy payment	None	Pay-as-Cleared €/MWh if activated	Pay-as-Cleared €/MWh if activated

COMMENTS

- **FCR is the ‘fastest’ balancing product**, designed to stabilise grid frequency within seconds, and activated automatically and symmetrically to counteract frequency deviations immediately.
- **aFRR** works on a slower timescale than FCR and is used to **restore the balance between generation and load** after the initial frequency containment. It is activated automatically but with a response time <5 minutes. Products are typically contracted for longer periods and procured through national or regional markets.
- **mFRR** is a slower, **manually activated reserve** used to restore system balance over longer time frames. Unlike FCR, aFRR and mFRR can be asymmetric, providing either upward or downward regulation. It is procured via tenders or markets with flexible contract durations (often ranging from hours–days).

Source: Regelleistung.net

GERMANY

Storage can trade directly in the markets or through intermediaries

Direct market access

- Main route-to-market for large German utilities (e.g., RWE, Uniper, Axpo, EnBW).
- Large battery operators register directly with EPEX Spot for day-ahead/intraday trading and with TSOs (TenneT, 50Hertz) for balancing services.
- EPEX Market Coupling: Germany participates in EU Single Day-Ahead Coupling (SDAC) and Single Intraday Coupling (SIDC), enabling LDES operators to exploit price spreads between Germany, Netherlands, France, and Nordics.
- Example: RWE's battery storage portfolio actively bids into German ancillary services markets.

Access through intermediaries

- Smaller storage operators often enter into tolling agreements (5-7 years) with major utilities:
    - Example – Statkraft Germany and Axpo Deutschland act as intermediaries, buying flexibility from storage operators and marketing it in wholesale and balancing markets.
- Specialised BESS optimisers focus on offering route-to-market for 3rd party storage assets.
- Established trading houses offer route-to-market for renewables and storage.
- Next Kraftwerke*: Germany's leading aggregator of small assets, operating a Virtual Power Plant (VPP) with >10,000 decentralised assets, including batteries and flexible loads. They pool storage assets to provide FCR, aFRR, and congestion management services.

* Next aggregates small assets, residential assets, V2G. No LDES are aggregated by Next at this point, since these are expected to be large assets

GERMANY

Policy incentives are used currently to incentivise LDES

Market conditions	Key points
Investment landscape	• Growing interest in LDES due to rising renewable penetration and grid flexibility needs. • **Pumped-storage hydropower (>9 GW) dominates the current LDES capacity in Germany.** • Projects exploring flow batteries (Fraunhofer ICT 2MW/20MWh), CAES (Huntorf plant), hydrogen storage (H2CAST Etzel), LAES, though still emerging. High upfront CAPEX remains a key constraint. • Expanding pipeline includes hydrogen salt-cavern storage (BMWK), with H2CAST Etzel hydrogen cavern pilot progressing to injection stage.[1]
Public support	• Incentives such as the extension of BMWK Electricity Storage Strategy (2023) double grid-charge exemption to 2029 promote long-duration hydrogen and heat storage.[2] • **Long-duration dispatchable capacity auction (mid-2026):** Auction with a long-duration (“Langfristkriterium”) requirement, targeting plants able to generate electricity continuously over extended periods; expected to mainly attract hydrogen-ready gas-fired generation, with delivery no later than 2031.[3] • **Technology-open capacity auction (mid-2026):** Initial step toward a technology-neutral capacity market, aimed at securing dispatchable capacity for the early 2030s, with awarded projects required to be operational by 2031.[3]
Financing models	• Most common model constitutes stacking revenues from traded market arbitrage with system services. • Germany's EEG Innovation Tenders support solar PV plus battery storage projects, offering 20-year contracts with guaranteed revenue via market premiums, promoting grid stability and renewable integration. • **The launch of the Capacity mechanism (from 2028) is expected to be highly beneficial for LDES**: Revenue certainty and long tenures ensure bankability; stacking with other revenue sources is possible, ensuring enough upside is captured; de-rating factors support longer-duration assets.
Barriers & risks	• **Revenue uncertainty due to reliance on Day-ahead price spreads and expected remuneration from 2028 capacity market.** • Long lead times for salt-cavern conversion (6–12 years). • Regional constraints: porous formations in southern Germany deemed unsuitable, limiting local storage access. • Technology maturity risks for VFB, LAES, and advanced CAES.

Sources: 1) Storag ETZEL, BMWK , EWI, BMWE; 2) https://interreg-baltic.eu/project-posts/energy-equilibrium/publication-of-the-german-electricity-storage-strategy, 3) BMWE - German power plant strategy

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IBERIA

Medium duration storage (8h-12h) can complement solar PV generation

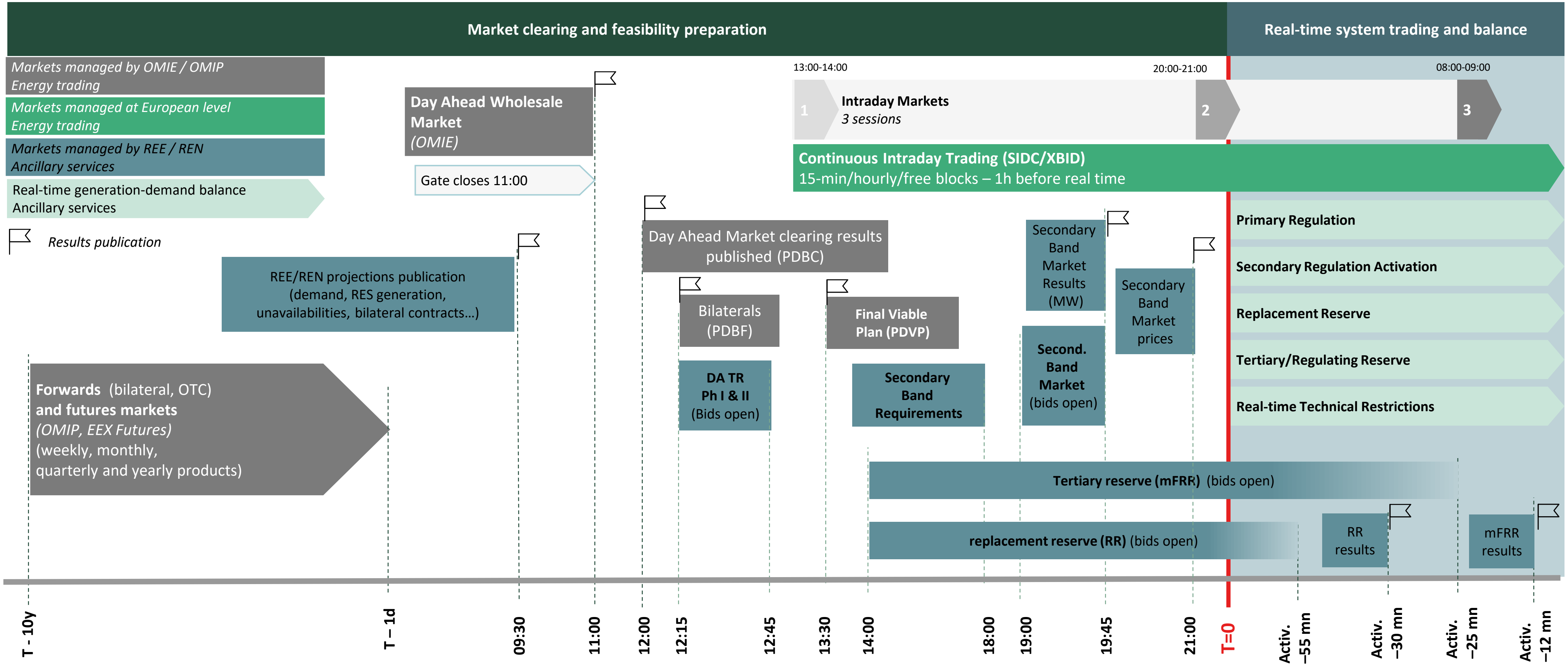
USE CASES FOR LDES

Energy shifting	The Iberian peninsula is largely solar-dominated and **SDES and MDES (8-12hour duration) can help balance within-day price fluctuations**. The deployment of solar PV capacity leads to frequent periods of low prices during daytime, while peak prices are still set by thermal or hydro generation. This results in fairly consistent **price spreads on a daily basis.** As the share of renewable energy sources increases the operation of the grid becomes more complex, and there is an enhanced need for real-time balancing and position adjustments among market participants. This will result in increasing volumes traded in closer to real-time markets.
System services & Balancing Energy	Grid operators warn of rising need for frequency response, inertia, voltage control, especially after the Iberian blackout (April 2025), where CCGTs, and especially hydro and pumped storage were key for restoring the service. **LDES can also support system stability**, potentially benefiting from revenues from new services, including (synthetic) inertia, dynamic reactive power, fast ramping, etc.
Grid congestion management	In Iberia, the deployment of LDES can support the grid as a **complement to the installation of cross-border capacity**: based on the information published on the cost-benefit studies carried out by the French regulator, it is highly unlikely to develop all the interconnection assumed in NECP. Less interconnection means more opportunities for storage to integrate renewables and provide security of supply.
Co-location with renewables and PPAs	In a world with significant solar cannibalisation, market actors are increasingly looking for baseload-style PPAs, but solar alone cannot provide 'firm' output and short-duration batteries are insufficient. LDES can help 'firm up' delivery profiles, turning solar into a baseload product.
Flexible demand solutions	The expected increase in electricity demand due to electrification, the large deployment of renewables generation, and the expected closure of thermal capacity will lead to a need of firm and flexible solutions to be installed in the Iberian system. Currently, this is provided by hydro and pumped storage. Going forward, LDES technologies can also help as we transition to a world with more of that flexibility coming from demand side response.

Source: AFRY analysis

IBERIA

In Iberia, power is traded over different timescales – the balancing process is the final phase to manage energy at real-time scale



Market clearing and feasibility preparation

Real-time system trading and balance

Markets managed by OMIE / OMIP
Energy trading

Markets managed at European level
Energy trading

Markets managed by REE / REN
Ancillary services

Real-time generation-demand balance
Ancillary services

Results publication

Forwards (bilateral, OTC)
and futures markets
(OMIP, EEX Futures)
(weekly, monthly,
quarterly and yearly products)

REE/REN projections publication
(demand, RES generation,
unavailabilities, bilateral contracts…)

Day Ahead Wholesale Market
(OMIE)

Gate closes 11:00

Day Ahead Market clearing results published (PDBC)

Bilaterals
(PDBF)

DA TR
Ph I & II
(Bids open)

Final Viable
Plan (PDVP)

Secondary
Band
Requirements

Secondary
Band
Market
Results
(MW)

Second.
Band
Market
(bids open)

Secondary
Band
Market
prices

13:00-14:00 | 20:00-21:00 | 08:00-09:00

1 **Intraday Markets**
3 sessions
2
3

Continuous Intraday Trading (SIDC/XBID)
15-min/hourly/free blocks – 1h before real time

Primary Regulation

Secondary Regulation Activation

Replacement Reserve

Tertiary/Regulating Reserve

Real-time Technical Restrictions

Tertiary reserve (mFRR) (bids open)

replacement reserve (RR) (bids open)

RR
results

mFRR
results

Sources: REN, OMIE | SDAC: Single Day-Ahead Coupling; SIDC/XBID: Single Intraday Coupling; OMIE: Iberian Market Operator; REE: Spanish TSO

IBERIA

Markets description, timings and suitability for a storage business plan

	Market	Description	Clearing	Responsible	Market Gate Closure Time
Traded markets	**Day-ahead**	Wholesale market.	Marginal price	OMIE	12 (CET):00 D-1
	Intraday auctions	Market participants are allowed to adjust their resulted day-ahead market positions in 3 intraday market auctions coupled at European level (Intraday Capacity Auctions -IDA-).	Marginal price	OMIE	3/4 hours before real time
	Continuous intraday (XBID)	Market participants are allowed to adjust their positions closer to real time.	Pay-as-bid	OMIE	1h before real time
	DA[1] TR[2] Phase I	Additional production needed for the secure functioning of the electricity system.	Pay-as-bid	REN	1h after DA results
	DA TR Phase II	Change in DA schedule to re-establish the generation/demand equilibrium after phase I.	Pay-as-bid	REN	1h after DA results
	Real time TR	During real time operation, the TSO might need to contract regulating reserve offers out of the merit order due to technical restrictions.	Pay-as-bid	REN	Real time
Systems services	**Primary reserve (FCR)**	*Mandatory regulation with response t<30s.*	*Non-remunerated*	*REN*	*Real time*
	Secondary band	Availability to provide secondary reserve through the effective provision of secondary energy. Only the units approved by the TSO can participate.	Marginal price	REN	19:45 D-1
	Secondary activation (aFRR)	Regulation with response t<30s. It shall be maintained for at least 15mins until it can be replaced by mFRR.	Same price as regulating reserve	REN	Real time
	Tertiary regulation (mFRR)	The TSO shall use regulating reserve to reconstitute the secondary reserve. Response t<15mins. Two types of bids; scheduled (15min) and direct activations (16 - 30min).	Marginal price	REN	Real time
	Replacement reserves	The TSO use RR to settle imbalances in the generation/demand equilibrium after the last intraday session before real time or restore/maintain the level of secondary and tertiary regulation.	Marginal price	REN	1/2 hours before real time
	Voltage Control	*Compulsory and non-remunerated service for generators.*	*Non-remunerated*	*REN*	*Real time*
Capacity Markets	**Capacity market mechanism***	Approved by the Spanish government to come online in 2026. Three type of acutions: main (A1) for new capacity with 15-year contracts; adjustment (A2) for existing capaicty at a 1-year; transitory (A3) to cover investments with COD 2028, 2029.	Pay-as-bid	REE auctions; CNMC supervisor	

Notes: 1) Day-Ahead (DA); 2) Technical Restrictions (TR); 3) TSO: Transmission System Operator; ; Markets with an * are still in development and not yet available for LDES

IBERIA

The main market access pathways for LDES are through direct trading and through intermediaries

Direct market access

- Storage assets can bid directly into the day-ahead and intraday markets through OMIE (Iberian market operator), capturing arbitrage and price signals in the MIBEL (Spain-Portugal) wholesale market.
- Storage can participate through direct access as a provider of regulation and reserve services (e.g., frequency control, tertiary and secondary reserves) by qualifying as a balancing service provider.
- LDES are expected to participate directly in the upcoming capacity market mechanism by submit bids offering firm capacity.

Access through intermediaries and aggregators

- Hybridisation strategies: storage can be aggregated physically or virtually with renewable portfolios to maximise market revenues, minimize volatility and potentially share one grid access point.
- Smaller storage plants may access markets collectively through aggregators or virtual power plants (VPPs), enabling participation in wholesale and flexibility services.

Digital Optimisation & Cross-Border Market Coupling

- Spain participates in the European Cross-Border Intraday Market (XBID), enabling continuous trading with other EU countries.
- In terms of balancing services, Spain is part of PICASSO for aFRR balancing, and MARI for mFRR services, linking balancing bids across Europe.

IBERIA

The Spanish market presents attractive conditions for LDES, but a series of features prevent these assets from being profitable on a merchant basis

Market conditions	Key points
Investment landscape	– Storage capacity currently installed in the Spanish system, pumped storage (PHS) and solar CSP, are mature technologies that provide flexibility to the system. Batteries are starting operations in Spain, with less than a 100MW installed. In Portugal, PHS constitutes 90% of the country's storage capacity. – Portuguese and Spanish Governments announced several CAPEX subsidy rounds with the aim of incentivizing several GW of storage projects. The majority of these projects include lithium-ion batteries, compressed air energy storage (CAES), and emerging technologies such as green hydrogen and thermal storage. – In the short-term low capex PHS projects could the most competitive LDES technology in the market, following their cost, lifetime and their LCOS value.
Public support	– Spain has already granted c. €1bn in subsidies for hybrid power plants with storage, standalone batteries, pump storage and other technologies. Furthermore, Portugal has equally organized or announced subsidies for c. €160m for hybrid solar PV power plants. These subsidies should attract according to AFRY's estimations several GW of storage capacity, highly impacting the storage context in the Iberian Peninsula. – Recent CAPEX grants in Iberia has resulted in the first LDES pilot projects, specially around heat storage.
Financing models	– Most common model constitutes stacking revenues from traded market arbitrage with system services. – The launch of the Capacity Market mechanism (expected soon) is expected to be highly beneficial for LDES: revenue certainty and long tenors ensure bankability; stacking with other revenue sources is possible, ensuring enough upside is captured; de-rating factors support longer-duration assets, – LDES can enhance the bankability of solar PPAs by enabling solar generation to function as a reliable, firm baseload product.
Barriers & risks	– Some future risks involve an increased competition due to the deployment of SDES, demand flexibility and interconnectors, limited volumes in the intraday and flexibility markets, and regulatory risks due to changes in incentive schemes. – The large-scale deployment of electrolysers can have a negative impact on LDES revenues, since they lead to a flattening of within-day and multi-day price spreads, which is key for LDES revenues.

Source: AFRY analysis

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FINLAND

Expected future market developments may create opportunities for LDES in Finland

USE CASES FOR LDES

Energy shifting	– LDES can have an important role in Finland as multi-day (1-2 week) back-up storage for periods in winter with no wind generation and high demand (Dunkelflaute). However, currently, this is not incentivized by, e.g., a capacity mechanism. During the rest of the year, LDES could benefit from trading in the day-ahead and intra-day markets, although their economic viability presents certain challenges: The current day-ahead market volatility is not enough by itself to make LDES profitable in most cases and intraday market size is still small. Future trends in the day-ahead and intra-day market and the interaction among these markets can improve the case for MDES and LDES. E.g. pumped hydro could greatly benefit from an increase in ID volumes and could, for instance, buy at low cost from ID and sell at high prices to DA.
Ancillary services	– Currently, hydro power, demand response and energy storages are the most important qualified capacity providers in most of the ancillary service products. – In the medium to long term, imbalance settlement will be a growing market as RES generation and power demand increase. In this context, aFRR and mFRR present the most attractive markets for LDES.
Colocation with RES and PPA integration	– Energy storage can be integrated into PPA structures providing support for regulatory compliance (e.g. RNFBO) and enhance contract flexibility. – New legislation has been implemented from the beginning of 2026, which enables hybrid co-location of generation and storage behind one grid connection. This removes a major regulation barrier for any storage project, including LDES.
Industrial decarbonisation	– LDES are not expected to become the leaders for industrial flexibility and decarbonisation, since Hydrogen will lead these functions. Hydrogen enables deep decarbonisation in sectors where electrification alone is insufficient, including: Steel and metals production, chemical and fertilizer industries, refining and new industrial parks.

Source: AFRY analysis.

FINLAND

Storage operators optimise asset operation across the different energy markets and for the provision of system services

		MARKET RULES	VALUE FOR LDES
Traded markets	Day-Ahead Arbitrage Intraday Arbitrage	– The Nordic day-ahead market (SDAC) is a spot market where prices are set through an implicit cross-border auction at 12:00 CET. It is traded jointly with the rest of the Nordics as part of the Single Day-Ahead Coupling, and bids are now 15-minute MTUs. – The intraday market (SIDC) functions as a continuous spot market traded jointly with the rest of the Nordic region and 25 European countries. Bids are submitted in 15-minute products.	– LDES can perform price arbitrage in the day-ahead market, although it presents low volatility. – Currently, the intraday market in Finland is not yet very large. In the future, an increase in intraday volumes could create a significant arbitrage opportunity, leading to situations where electricity could, e.g., be bought cheap from intraday and sold at a higher price to the day-ahead market.
Ancillary services	Frequency related: FFR FCR-D FCR-N aFRR mFRR	– FRR and FCR-D are capacity markets only, where capacity is remunerated on a pay-as-clear basis. If bid is accepted, generator must respond automatically to frequency deviations outside limits. – FCR-N is a capacity market only, where both capacity and energy are remunerated. Works on a pay-as-clear basis. Generator must respond automatically to frequency deviations if bid is accepted. – aFRR and mFRR are both separated into capacity and energy activation markets were both capacity and energy are remunerated. If the capacity bid is accepted by the TSO in the capacity market, the generator must participate in the subsequent activation markets. If the bid is accepted, the generator must be available for automatic activation by the TSO.	– Hydro power, energy storages (BESS) and demand response are the most important qualified capacity providers in most of the ancillary service products. – FFR, FCR-D and FCR-N markets require fast activations, and participation is therefore dependent on specific LDES characteristics. – aFRR and mFRR represent the most attractive markets for LDES, however attractiveness mostly for aFRR and mFRR depends on the ramp rate of each LDES: – aFRR is expected to become the main balancing energy product in the future due to the TSOs decision to increase aFRR volumes. Nonetheless, it is expected that SDES will participate more in the aFRR market that LDES. – Despite an expected reduction in activated mFRR volumes, LDES will monetize mostly from trading in this market.
Capacity Markets	Capacity payments	– Currently, no capacity market exists or has been announced in Finland.	

Notes: 1) Single Intraday Coupling (SIDC) is the Pan-European continuous cross border intraday market.
2) FCR-D and N= Frequency Containment Reserve for Disturbances and for Normal Operation, respectively

FINLAND

The different Finnish AS markets have different requirements for participation, regarding e.g., minimum bid size, activation time and duration

Main target market of LDES (aFRR, mFRR)

	FFR	FCR-D	FCR-N	aFRR	mFRR
Purpose	Slow down/prevent large frequency drops Frequency interval: <49.5/49.6/49.7 Hz	Limit the frequency to 49.9 or 50.1 when the frequency goes outside normal range Frequency interval: Up: <49.9-49.5 Hz Down: >50.1-50.5 Hz	Continuous frequency regulation within normal range of 49.9-50.1 Hz	Automatically restores frequency to the normal range (49.9-50.1 Hz).	Manually (semi-automatically) releases aFRR and maintains balance until balance restored in the power market
Minimum bid size	1 MW	1 MW	0.1 MW	1 MW	1[3]/5 MW
Activation time[1]	0.7/1.0/1.3 sec	30sec	3min	5min	15min
Duration	5-30sec	20min	1 h	1 h	1 h
Control	Local automatic control	Local automatic control	Local automatic control	Centralised TSO control	Centralised TSO control
Product direction	Up regulation	Separate up & down markets	Symmetric up/down	Separate up & down markets	Separate up & down markets
Market size[2]	≤ 60 MW	FCR-D up: 304 MW FCR-D down: 293 MW	126 MW	~65 MW	mFRR up: 880-1300 MW mFRR down: 575 MW

Note: 1) Maximum time to reach full activation 2) Based on Fingrid's AS obligations 2025 3) Limited number of bids
Source: Fingrid

FINLAND

Investment in LDES in Finland is risky since its profitability would require significant changes in the DA and ID markets

Market conditions | **Key points**

Investment landscape

- Long duration storage projects in Finland are relatively scarce, with **few pumped hydro projects under development**:
    - Pyhäsalmi: planned underground pumped-storage hydroelectric facility being developed in the former Pyhäsalmi mine, with a 75 MW capacity and 530 MWh of storage.
    - Noste Project: Suomen Voima Oy plans to develop three small pumped-storage plants in Northern Finland, with a combined capacity of 150-300 MW.
    - Kemijoki Project: Kemijoki Oy is planning a 550 MW pumped storage plant.
- Finland aims to lead Europe's hydrogen economy and produce **10% of EU green hydrogen by 2030**. Hydrogen is considered central to decarbonisation, new industrial growth, and export strategy. As part of the hydrogen targets, Finland plans to establish national hydrogen network; integrate into Nordic–Baltic hydrogen corridors; enable industrial hydrogen clusters throughout Finland.

Public support

- To avoid Dunkelflaute, the government has introduced recent schemes to incentivize long-term flexibility. This is aimed at minimizing loss of load risks or very high price spikes. One scheme that supports non-fossil flexibility mechanism, is currently in progress, however, it is more directed towards gas engines.

Financing models

- Most common model constitutes stacking revenues from traded market arbitrage with ancillary services.
- Energy storage can be integrated into PPA structures providing support for regulatory compliance (e.g. RNFBO) and enhance contract flexibility.

Barriers & risks

- The high capex of new LDES technologies, the low volatility in the day-ahead market, and the size of the intraday market make the economic case for LDES not viable. A long-term investment would require 1) an in increase of longer volatility fluctuations or 2) increasing volumes in the intraday market (or aFRR or mFRR energy markets).

Sources: AFRY analysis

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GREAT BRITAIN

Energy shifting and the provision of system services are the two main value streams for storage systems

USE CASES FOR LDES

Energy shifting	In the near-term, arbitrage use case for GB LDES are focused on within-day energy shifting with less frequent multi-day opportunities. Medium- to long-term, as renewables penetration and curtailment increase — especially at the Scotland-England border — LDES that can hold energy across days will capture more episodes of deep zero/negative-to-peak spreads, provided siting and network charges do not erode margins.
Ancillary services	Multi-hour energy holding and sustained delivery make LDES a strong fit for Quick Reserve (pre-fault), Slow Reserve (post-fault), and Balancing Reserve; the GB design uses capacity and activation payments and is explicitly intended for up-to-60-minute+ responses. Additionally, advanced inverter-based LDES can contribute via grid-forming capabilities in the new stability and reactive markets. LDES can also be more relevant where sustained post-fault regulation is valuable and as procured volumes trend up.
Grid congestion management	LDES sited in constrained zones (esp. Scotland–England boundary) can absorb surplus and support local redispatch.
Colocation with RES and PPA integration	Curtailed generation can be turned into firm, peak-timed exports, materially improving capture while easing local constraints. Under point of interconnection limits, **the degree of complementarity in hybrid operation is highly dependent on configuration and dispatch strategy**; in cases where the battery predominantly charges from on-site generation and revenues are accounted for separately, the site's value can often approximate the sum of the standalone RES and storage cases.
Industrial flexibility	Industry needs access to firm, low-carbon power and dispatchable heat. LDES lets sites and clusters shift multi-hour to multi-day energy at scale, smoothing renewables, cutting peak imports, monetising flexibility markets, and de-risking production. The biggest gains come when LDES co-optimises power and heat: e.g., charging from cheap/windy periods, discharging through power-to-heat (e-boilers, large HPs) into thermal storage (hot water tanks, steam accumulators, molten salt/ceramic bricks), or back to the grid when power scarcity prices spike.

Source: European Parliament, European Commission, ACER

GREAT BRITAIN

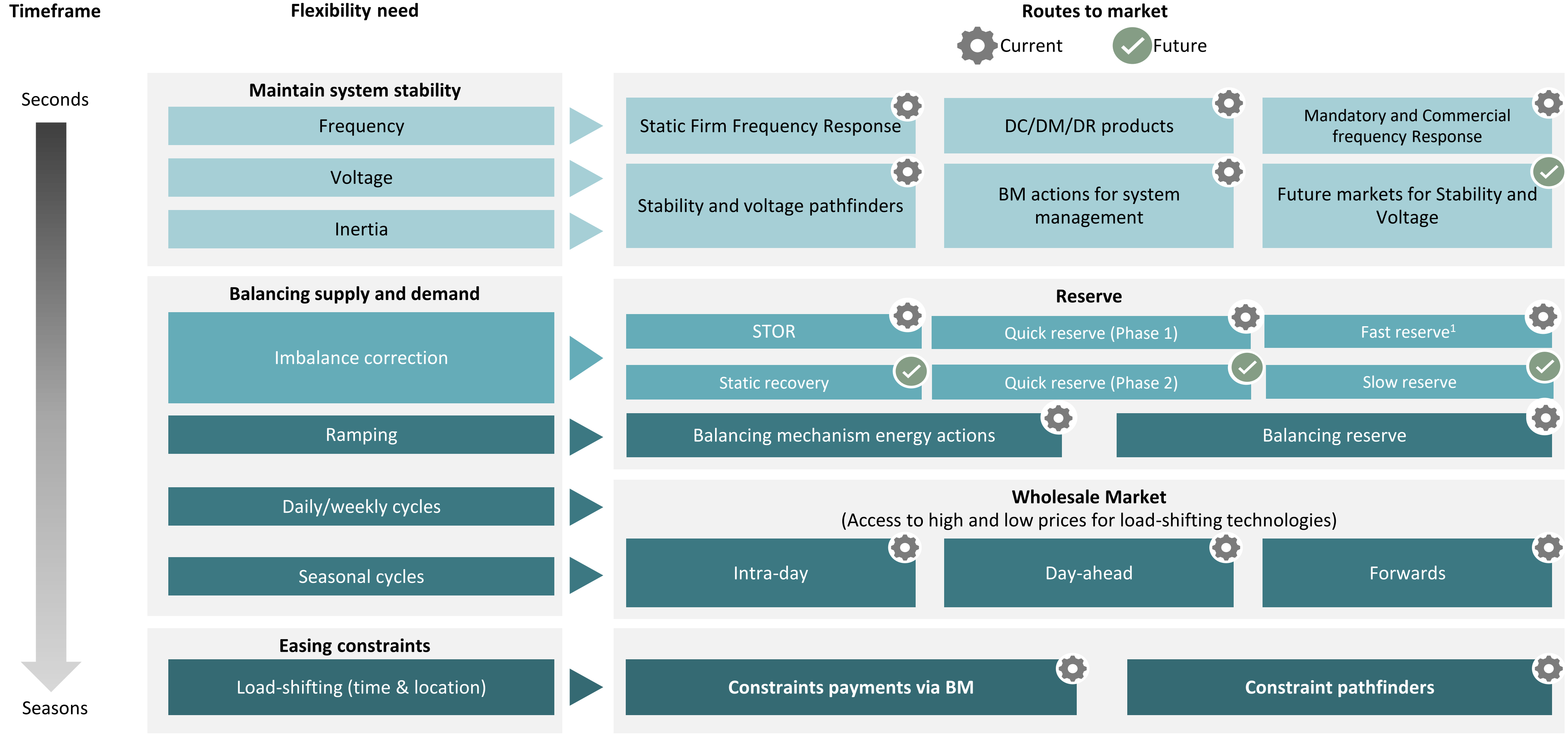
Storage can capture income from a range of sources – wholesale energy markets, the BM, system services and the capacity market

	DESCRIPTION	RISKS AND OPPORTUNITIES
Wholesale trading	– National pay-as-clear market with day-ahead and within-day trading. – Revenues stem from market arbitrage, scheduling to charge at time of low power prices, and discharge at time of high prices.	– LDES can benefit from a largely wind-driven volatility, that allows for multi-day and longer energy shifts.
Balancing Mechanism	– Real-time pay-as-bid mechanism used by the ESO to maintain system stability. – Market is used to solve national imbalances as well as locational constraints.	– Location can become a significant driver of value; LDES located behind constraints can take a ‘constraint management’ trading strategy. – Grid expansion reduces BM volumes, though uncertainty exists over when grid reinforcements will come online.
Ancillary services	– ESO contracted services for rapid generation or consumption, voltage regulation and inertia. – Day-ahead procurement for 4-hour windows*. – Stringent technical requirements mean BESS assets are well suited for service provision.	– AS markets have begun to saturate following large deployment of BESS assets relative to AS market size. – It is expected that ESO requirements for AS will grow as renewable capacity is deployed.
Capacity market	– Participants who hold a CM contract are remunerated an annual sum based on their ‘derated’ capacity. – ‘Derating factors’ are calculated by the ESO and reflect the reliability of an asset’s capacity.	– Derating factors have fallen for shorter duration storage, but LDES still can capture relevant revenues. – However, recent changes to the calculation of this factor will act to support CM revenues going forward.

CM: Capacity Market; AS: Ancillary Services; DA: Day Ahead: ID: Intraday; BM: Balancing Mechanism
*This is ongoing following NG ESO reserve and response reform

GREAT BRITAIN

Flexibility providers can monetise their services through several different routes to market



Timeframe: Seconds → Seasons

Flexibility need

Routes to market

⚙ Current ✓ Future

Maintain system stability

- Frequency
- Voltage
- Inertia

→ Static Firm Frequency Response ⚙ | DC/DM/DR products ⚙ | Mandatory and Commercial frequency Response ⚙

→ Stability and voltage pathfinders ⚙ | BM actions for system management ⚙ | Future markets for Stability and Voltage ✓

Balancing supply and demand

- Imbalance correction
- Ramping
- Daily/weekly cycles
- Seasonal cycles

Reserve

STOR ⚙ | Quick reserve (Phase 1) ⚙ | Fast reserve[1] ⚙

Static recovery ✓ | Quick reserve (Phase 2) ✓ | Slow reserve ✓

Balancing mechanism energy actions ⚙ | Balancing reserve ⚙

Wholesale Market
(Access to high and low prices for load-shifting technologies)

Intra-day ⚙ | Day-ahead ⚙ | Forwards ⚙

Easing constraints

- Load-shifting (time & location)

→ **Constraints payments via BM** ⚙ | **Constraint pathfinders** ⚙

Fast Reserve is due to phase out in spring 2026, at which point Quick Reserve will be fully implemented

GREAT BRITAIN

NESO have multiple tools for managing system security known as ‘ancillary services’ (AS)

	Fast reserves | pre-fault	**Fast reserves | post-fault**	**Primary reserves | Quick Reserve**	**Primary reserves | Balancing reserve**	**Tertiary reserves | Slow Reserve**
Services	Dynamic Moderation (DM) Dynamic Regulation (DR)	Dynamic Containment (DC)	Quick Reserve (QR)	Balancing Reserve (BR)	Slow Reserve (SR)
Objective	Respond to sudden imbalances, keeping frequency within operational limits.	Operate ‘post-fault’ to help contain frequency within statutory limits.	This reserve service will be pre-fault, responding to rapid imbalances, especially in low inertia periods.	To secure, at the day ahead stage, the availability of dispatchable units for use in the BM.	Operate post-fault and to provide NESO with access to firm, bi-directional energy to displace large losses on the system.
Market type	Capability payment only, auctions are held daily for day-ahead delivery in EFA blocks. All three auctions clear simultaneously at 14:30 the day before delivery.		Daily auction (D-1) Availability and utilisation payments.	Daily auction (D-1) Availability payments. Utilisation paid through the BM.	Daily auction (D-1) Availability and utilisation payments.
Up/down	Symmetric up *and* down regulation.		Asymmetrical, up *or* down regulation.	Positive and/or Negative.	Asymmetrical, up *or* down regulation.
Product granularity	30min	30min	30min	30min	30min
Min quantity	1MW	1MW	1MW	1MW	1MW
Pricing mechanism	Pay-as-clear. Activation not compensated.		Availability payments pay-as-clear, whilst utilisation payments pay-as-bid.	Availability payments pay-as-clear, whilst utilisation payments pay-as-bid (through the BM).	Firm service: Availability + Utilisation. Optional service: Utilisation. Availability: pay-as-clear. Utilisation: pay-as-bid.
Response time	DM: <1 sec DR: <10 sec	<1 sec	<1min	Maximum ramp time of 10 min	<15min
Min. running time	DM: 30min DR: 60min	15min	5-15min	30min	30-120min

[1] The launch of SR has been delayed due to implementation challenges within NESO’s processes and systems. Until SR is operational, Reserve requirements will be met through STOR.

Note: MFR and Static Firm Frequency Response (SFFR) remain part of the system but are less frequently used. NESO continues to update the ancillary services framework. Details on current plans and progress can be found at https://www.neso.energy/publications/markets-roadmap

GREAT BRITAIN

Revenue sharing contracts have been viewed as the preferred route-to-market for battery assets

COMMON ROUTE-TO-MARKET CONTRACT TYPES FOR BATTERY ASSETS

Most market providers engage in this contract type

Description	Revenue model	Optimisers asset access
Revenue sharing contracts Allows the optimiser to optimise the asset's dispatch against multiple routes to market to allow for revenue stacking.	Revenue is shared by parties. Determined by contractual obligations.	Partial access.
Revenue floor contracts Contract provides the asset owner a guaranteed revenue determined by a floor price which is received even in the occasion of prices falling below it.	Contractually determined optimiser fee.	Full access.
Tolling agreements Provides the optimiser the authority for the asset's dispatch to maximise its revenues.	The optimiser pays the asset's owner a monthly charge fixed and/or variable reflecting the utilization.	Full access.
Market access agreements Provides the owner with the energy market access via dispatch platform license developed by the optimizer. The owner is then responsible for operations and maximizing value.	Contractually determined optimiser fee.	Partial access.

Notes: more information on rules for stacking different ancillary services can be found in the Annex

COMMENTARY

- Maximising revenue from flexible assets involves stacking revenues across multiple markets, with operators making daily decisions on whether to participate in ancillary services or wholesale energy markets. These decisions also consider technical constraints such as ramp rates and maintenance costs for gas engines, or cell degradation for batteries, making revenue stacking a complex task.
- Some battery owners may not have these optimisation and trading capabilities. Instead, they procure those services from specialised aggregators, who maximise the value of the project using a proprietary dispatch platform. An alternative may be to procure a specialised dispatch platform licence.
- Almost all storage is managed through revenue sharing or floor contracts with the former being most common.
- Tolling contracts are less common:
  - Octopus did one of the first tolling agreements with Gresham House back in June 2024, which was a 2-year deal (1.6hr), market speculations are that it was around £57/kW/yr.
  - Penso Power executed a 7-year toll with Shell at a fixed price for a 100MW/330MWh battery – the strike price is confidential, but AFRY believe it could be around £65-70/kW/yr.
- In our view, utilities with deep pockets are most likely to offer tolls, which they can use as part of their trading and risk management strategy. They should be particularly useful to utilities with a large share of RES assets.

GREAT BRITAIN

LDES remains in the early stages of deployment, seeing government support opportunities but also scaling challenges for the different technologies

MARKET CONDITIONS

Investment landscape	LDES market is dominated by PHS systems, with 2.8GW of capacity installed currently. Other LDES technologies are generally in early stages with limited investments.
Public support	The government believes that long-duration energy storage has a key role to play in integrating high penetrations of renewable energy in the GB system. NESO estimates that up to 15.3GW of capacity is needed to reach net zero targets.
Financing models	The revenue structure for LDES can come from stacking DA, ID and BM actions and capacity payments. Additionally, there is the opportunity to build hybrid-PPAs with generation assets.
Long-term contracts	The Long Duration Energy Storage (LDES) cap and floor scheme is intended to de-risk investments and ensure economic deployment. 25-year contracts by default, with revenue assessments done on an annual to 5-year basis.

BARRIERS & RISKS (*SHORT AND LONG TERM*) [*2026-2050*]

- Most technologies are in pilot stages, still requiring to scale up to become competitive.
  LDES projects present high capital costs, forcing upfront expenditures that can make projects risky and unattractive to investors.
- Projects must achieve a minimum availability to receive floor payments.
  Ofgem scrutinize costs very closely during the Project Assessment phase before they enter the cap-and-floor scheme. This is placed in order to reduce inefficient or unjustified costs when setting the cap-and-floor.
- The behaviour of the revenue stack can be uncertain, with energy revenues being cannibalised as LDES is deployed, and the risk of network reinforcement impacting BM revenues.
- Projects outside the scheme will require contracts to make them economically viable; this will require to find a structure that makes them competitive versus short and medium duration storage.

GREAT BRITAIN

The Long Duration Energy Storage (LDES) cap and floor scheme is intended to de-risk investments and ensure economic deployment

MOTIVATION AND OBJECTIVES OF THE SCHEME

- The government believes that long-duration energy storage has a key role to play in integrating high penetrations of renewable energy in the GB system.
- The characteristics of long-duration storage technologies make them risky investments that are currently unattractive to investors.
- The scheme, administered by Ofgem, aims to provide a framework that de-risks LDES investments and ensures economic deployment.
- Some of the scheme details presented here are still being developed.

KEY COMPONENTS OF THE SCHEME

1	**Eligibility:** Projects must be a minimum of 100MW for more mature technologies and 50MW for less mature technologies and hold a duration of a minimum of 8 hours for application to the scheme.
2	**Motivation:** LDES will allow to better utilise domestically produced electricity by allowing us to store excess electricity for times of high demand, minimising waste.
3	**Assessment Process:** The scheme has three stages for application; eligibility assessment, project assessment and post-construction review.

Source: Department for Energy Security and Net Zero (DESNZ), Clean Power 2030 Action Plan: A New Era of Clean Electricity, 2024. Ofgem, Long Duration Electricity Storage: Technical Decision Document, March 2025.

KEY METRICS

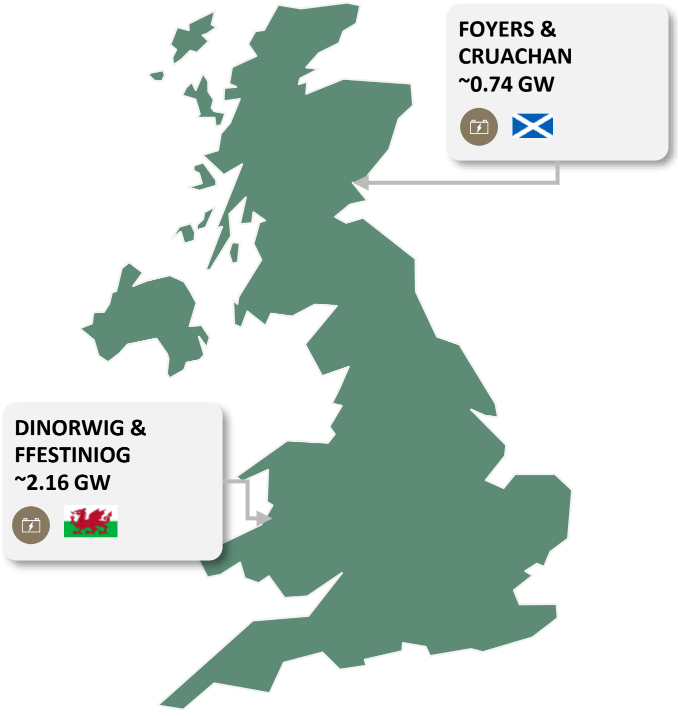
~2.9GW
Currently Installed

Pumped Hydro

2.7-7.7GW
LDES capacity expected to be procured under the scheme by 2035

~11.5-15.3GW
LDES capacity required to reach net zero according to National Electricity System Operator

LOCATION OF EXISTING LDES ASSETS



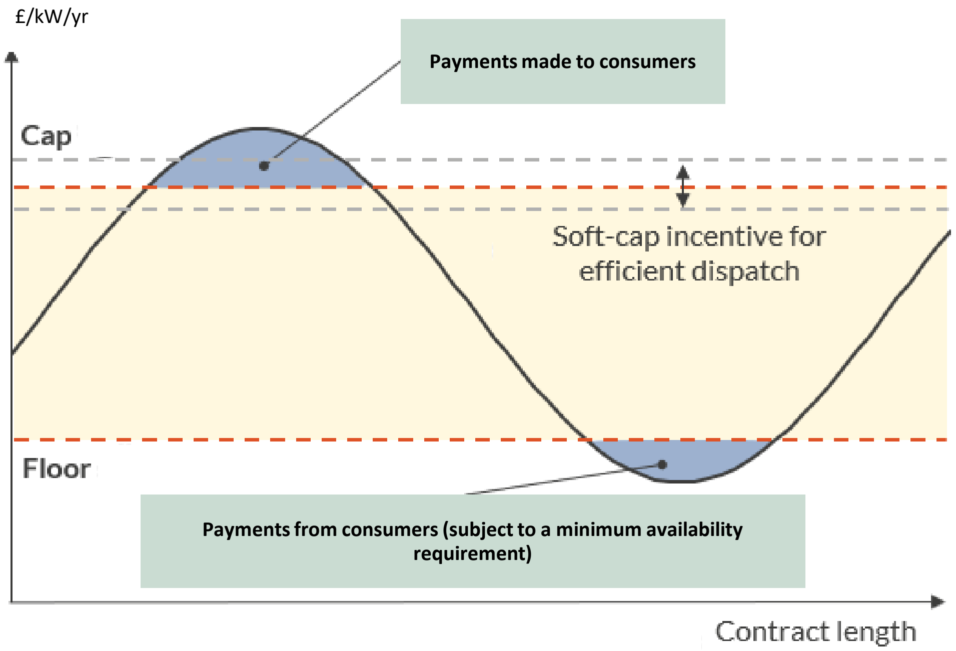
FOYERS & CRUACHAN
~0.74 GW

DINORWIG & FFESTINIOG
~2.16 GW

GREAT BRITAIN

Successful projects will be awarded a regime that ensures project revenues can only vary between pre-defined cap and floor values

GROSS MARGINS UNDER CAP AND FLOOR ARRANGEMENT



Source: Ofgem, Long Duration Electricity Storage: Technical Decision Document, March 2025

KEY TERMS OF THE REGIME

Key terms	Description
Implementation	- Implemented through special conditions in the LDES operator's licence. - Payments to/from projects will be settled through adjustments to project network charges.
Regime duration	- 25 years by default, though variations will be considered (minimum 20 years). All capital costs to be recovered over this period.
Revenue cap and floor payments	- Revenue assessments are made every year, or every 5 years (individual project preference). - The 'soft cap' means that revenues are not stopped at the cap, allowing LDES to make high revenues – but they are not allowed to keep all the revenues. - Revenues earned above the cap over the entire project life up to that point are returned to consumers. This is done through lower network charges on electricity bills. - Where revenues fall below the cap over the entire project life up to that point, a payment is made from consumers to the project.
Incentives / constraints / penalties	- Projects must achieve a minimum availability to receive floor payments. - Ofgem is considering including financial penalties for cost management.

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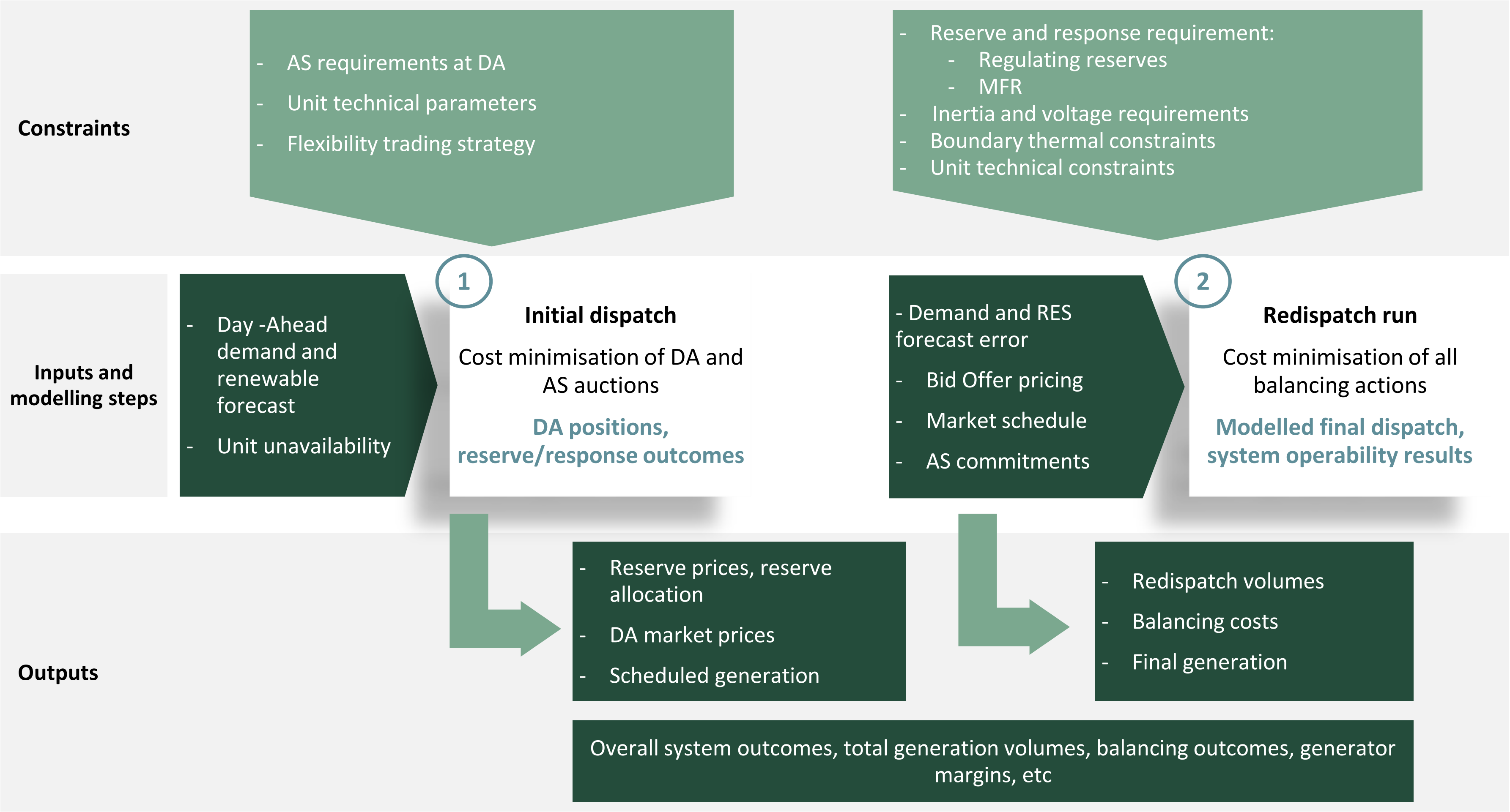
We have modelled the ex-ante energy markets, reservation of balancing capacity and the activation of energy in the balancing timeframe



Constraints

- AS requirements at DA
- Unit technical parameters
- Flexibility trading strategy

- Reserve and response requirement:
  - Regulating reserves
  - MFR
- Inertia and voltage requirements
- Boundary thermal constraints
- Unit technical constraints

Inputs and modelling steps

- Day -Ahead demand and renewable forecast
- Unit unavailability

1

Initial dispatch

Cost minimisation of DA and AS auctions

DA positions, reserve/response outcomes

- Demand and RES forecast error
- Bid Offer pricing
- Market schedule
- AS commitments

2

Redispatch run

Cost minimisation of all balancing actions

Modelled final dispatch, system operability results

Outputs

- Reserve prices, reserve allocation
- DA market prices
- Scheduled generation

- Redispatch volumes
- Balancing costs
- Final generation

Overall system outcomes, total generation volumes, balancing outcomes, generator margins, etc

*Note: The modelling does not capture network constraints within a price area. As discussed, there are additional benefits from the use of LDES to help manage congestion.

‘Longer’ duration storage is better suited to wind-dominated systems, and ‘medium’ duration storage is a better fir for solar-dominated systems

- We expect **most of the LDES margins to be captured from trading in the ex-ante energy markets** – a large part of the volumes are expected to be bought and sold in the Day-Ahead market given its liquidity. With the addition of more intermittent RES the frequency and duration of low-priced periods increases – LDES can ‘charge’ from the grid at a low cost (and at the same time storing surplus renewable generation) and can then discharge over extended high-priced periods when there is less renewable generation available, displacing thermal generation in the process.
- As is the case for short duration storage, LDES can also help with ‘flexibility’ provision – being ‘reserved’ to provide Balancing Capacity, trading closer to real-time in the intraday market and also being activated (in both directions) in the Balancing Market. Our **analysis suggests that up to 30% of the overall margins can come from intraday trading, provision of system services and activation in the Balancing Market**.
- GB and Germany appear to be attractive markets for >24h LDES assets. Some LDES technologies may not even need explicit support from 2040 onwards, assuming some cost reduction when compared to current cost levels.
- Solar PV dominated markets, like Iberia, are a better fit for ‘shorter’ durations (8-12hr).
- In general, the ‘rule of thumb’ is this: longer-duration storage is best suited to wind-dominated markets (typically greater opportunities to charge over extended low-price periods and support the system during multi-day wind lulls) with limited alternative resources to manage such events (such as reservoir hydro), and medium-duration storage is a better fir for solar-dominated systems (storing the excess solar PV generation during the day and using it during the night).
- There is already significant solar PV capacity in Iberia – this means expected margins for storage are high even in the short-term (2030) – as more flexibility is added on the system, storage margins slightly drop.
- In markets like GB and Germany we reach a critical mass of offshore and onshore wind by 2040 and LDES economics improve drastically.

RESULTS – SCENARIO OVERVIEW

Our analysis is based on the TYNDP 2024 Distributed Energy scenario with net-zero reached by 2050

	Adapted TYNDP		TYNDP 2024 – Distributed Energy[1]			
	2030		2040		2050	
	Capacities	Demand*	Capacities	Demand*	Capacities	Demand*
GER	255GW RES 40GW Storage 2.5GW Electrolysers	577TWh	630GW RES 90GW Storage 37GW Electrolysers	865TWh	771GW RES 132GW Storage 79GW Electrolysers	870TWh
GBR	80GW RES 22GW Storage 2.5GW Electrolysers	305TWh	218GW RES 26GW Storage** 29GW Electrolysers	554TWh	249GW RES 28GW Storage** 34GW Electrolysers	605TWh
SPA	102GW RES 12.5GW Storage 0.7GW Electrolysers	282TWh	268GW RES 19GW Storage 56GW Electrolysers	318TWh	300GW RES 23GW Storage 70GW Electrolysers	358TWh
FIN	15GW RES 1.3GW Storage 0.3GW Electrolysers	97TWh	118GW RES 1.9GW Storage 30GW Electrolysers	146TWh	200GW RES 3.9GW Storage 63GW Electrolysers	155TWh

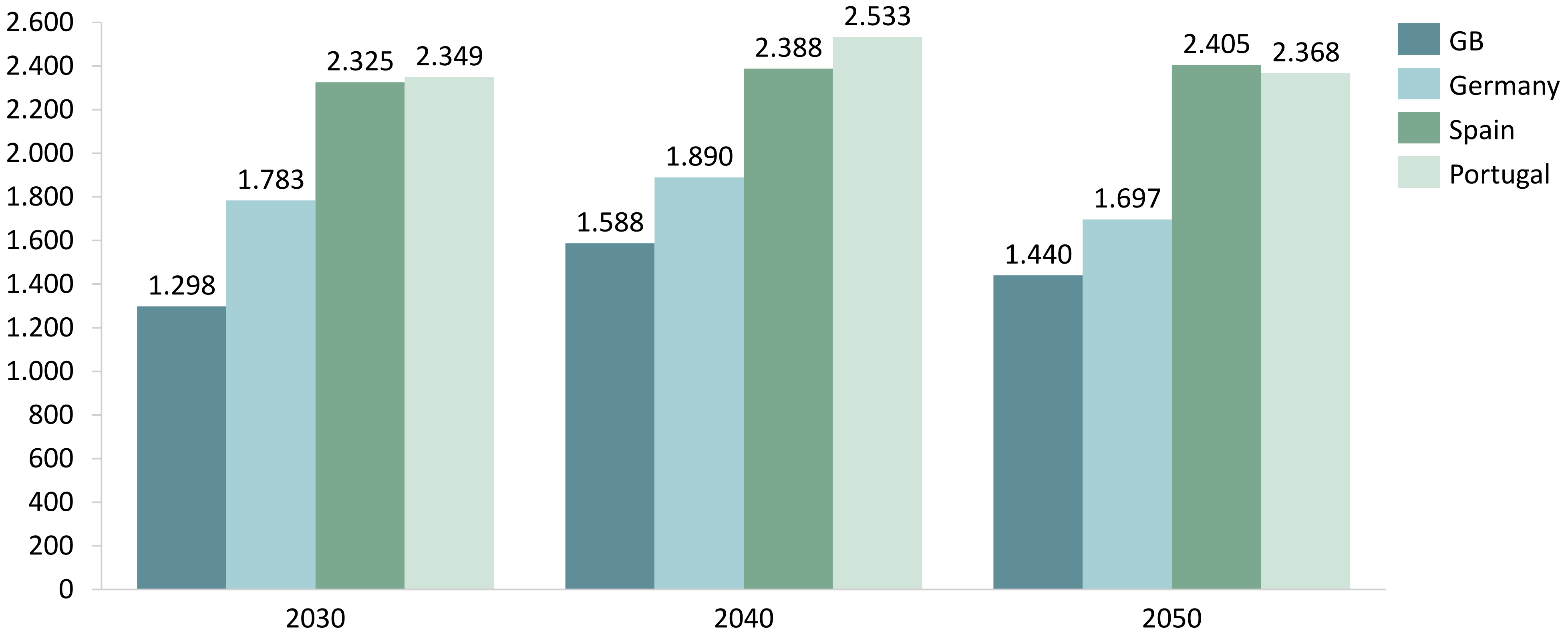
*Note: Input demand does not include demand from electrolysis, as this is an output of the model. Refer to the Annex to see the demand split per category and references.

**Note: Storage includes batteries and pumped storage. In GB, the 2030 National Trends has higher storage than 2040 Distributed Energy. The values for storage were adjusted in 2040 and 2050 to be consistent with the expected storage for 2030. For more information, refer to the Annex

1) Source: https://2024.entsos-tyndp-scenarios.eu/visualisation-platform/

We expect a significant reduction in RES curtailment with the use of LDES; this could be even higher in places with network congestion

RES curtailment avoided (MWh/MW installed-year)



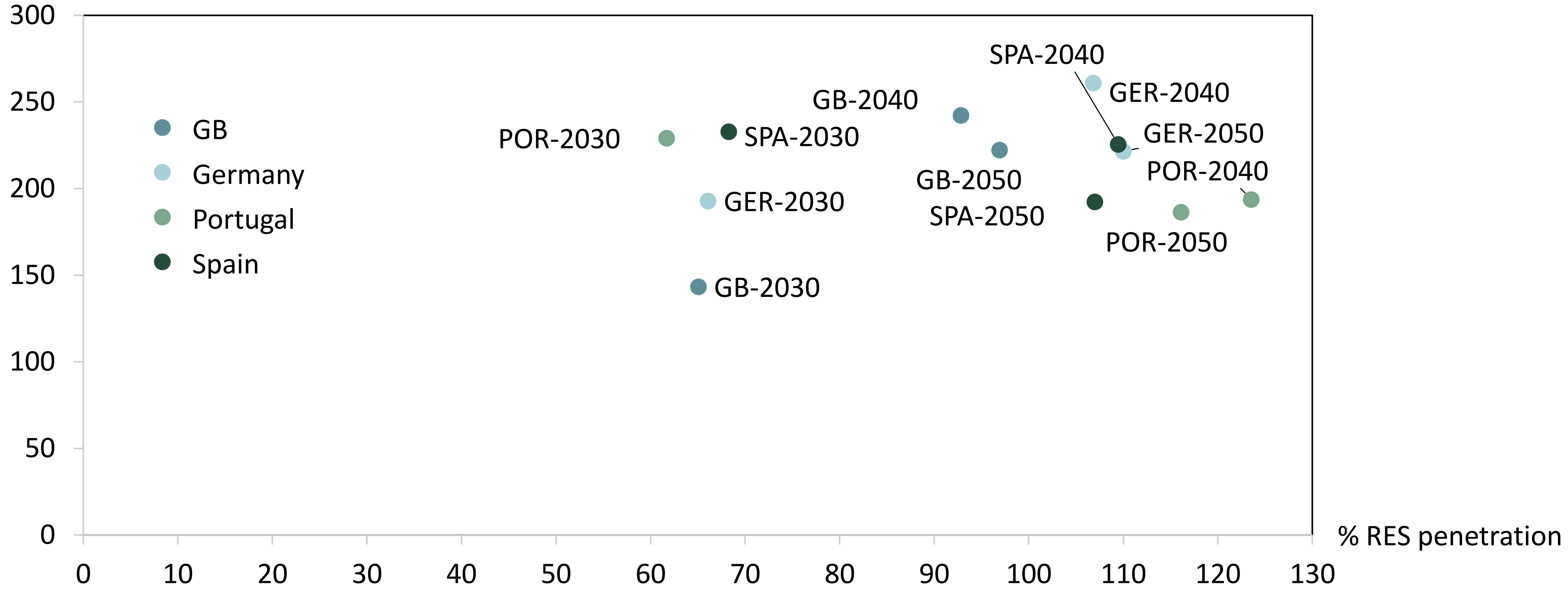
	GB	Germany	Spain	Portugal
2030	1.298	1.783	2.325	2.349
2040	1.588	1.890	2.388	2.533
2050	1.440	1.697	2.405	2.368

*Note: We present the average RES curtailment avoided from a 'blended portfolio' of LDES technologies. This is the RES volumes that would have otherwise been curtailed and are withdrawn from the LDES units. When injected back to the grid, thermal generation can be displaced. However, because of efficiency loss the avoided thermal generation is lower.

RESULTS – VARIABLE OPERATING COSTS AVOIDED

Our analysis suggests each GW of LDES can help save €150m-€250m of variable operating costs per annum

Variable cost savings (m€/GW-year)[1]



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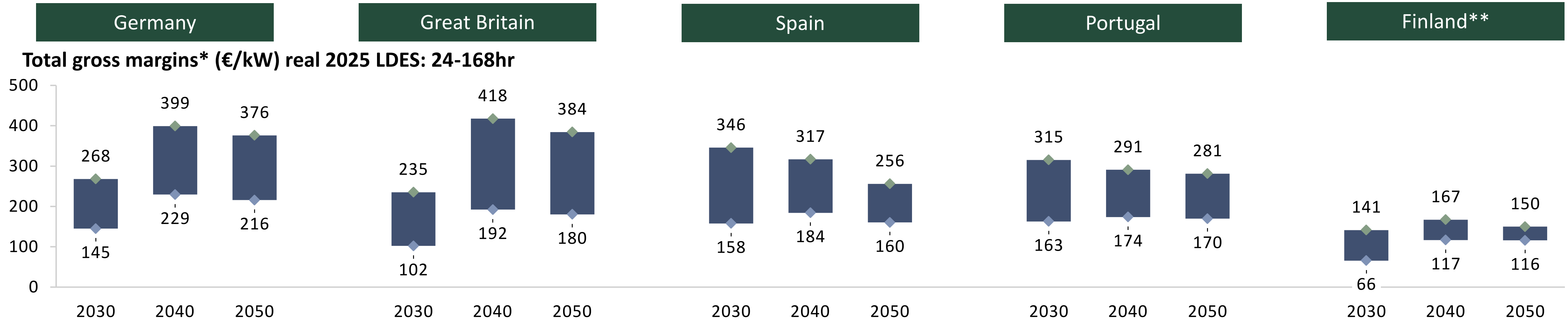
*Note: RES penetration is defined as total available RES resource (including curtailed volumes) divided by total electricity demand

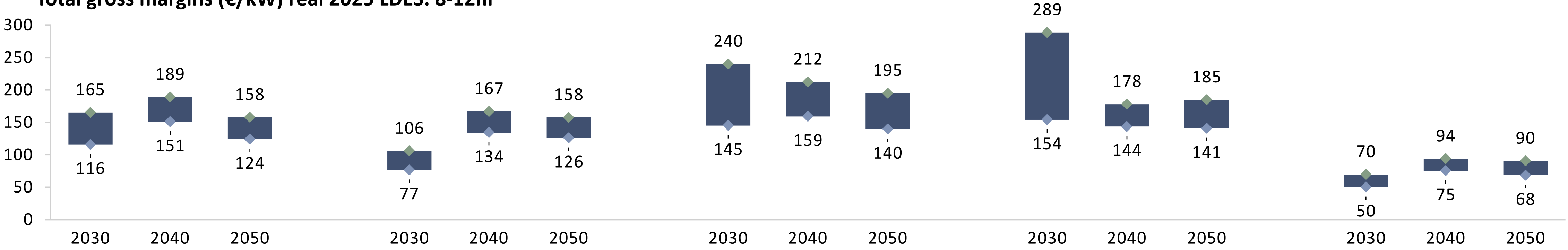
[1] This cost reduction estimate to the first GW of LDES installed. The 1GW of LDES reflects an 'LDES portfolio' consisting of the different LDES technologies we have assessed. The addition of LDES to the system results in gradual cannibalisation. This means the variable cost savings are not necessarily linear. We would expect an incremental reduction of the variable cost savings with each increase additional MW of LDES installed (all else being equal)

Some solutions are getting close to being ‘in the money’, most notably some >24h storage options in Germany and GB post 2040

Total gross margins* (€/kW) real 2025 LDES: 24-168hr



Total gross margins (€/kW) real 2025 LDES: 8-12hr



The upper and lower bounds of the range of gross margins reflect the most and least profitable technologies within each LDES duration category

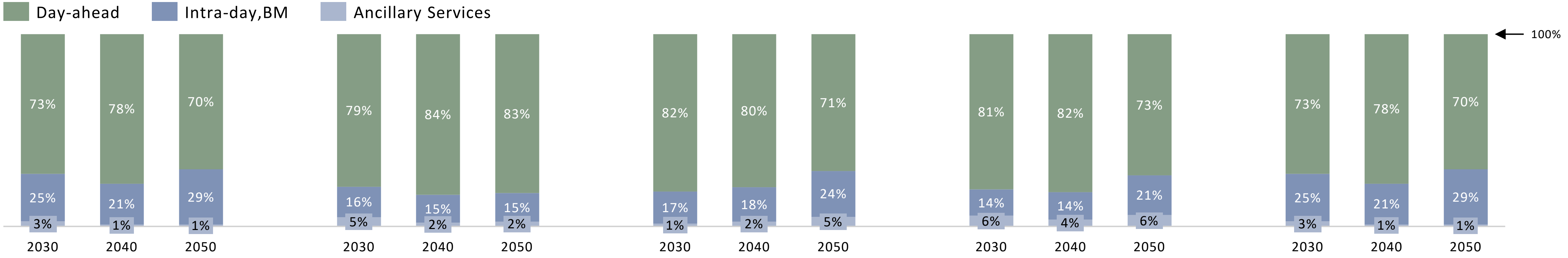
*Gross margins are calculated as the total revenues of selling energy – buying energy in the Day-ahead market, plus revenues of adjusting

**Note: for Finland, the revenues for ID and balancing were obtained from the same share as in Germany, due to the similarities in market configurations. For more information, refer to the Annex

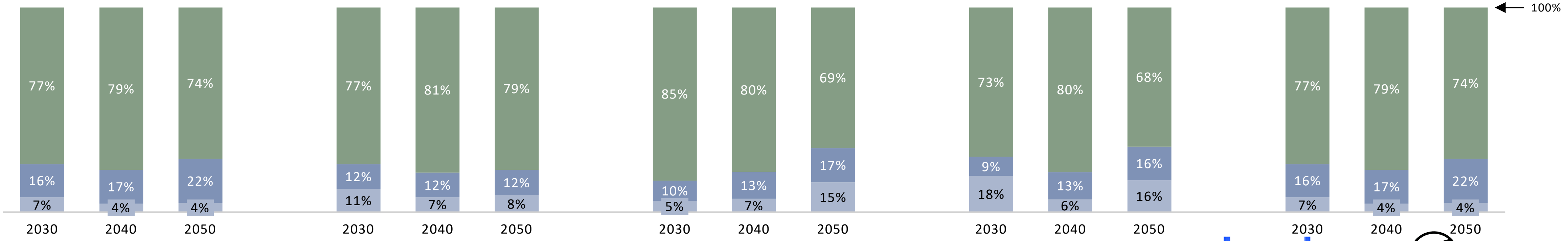
Most of the margins come from trading in the ex-ante traded markets

Germany **Great Britain** **Spain** **Portugal** **Finland***

% of gross margin per market LDES: 24-168hr

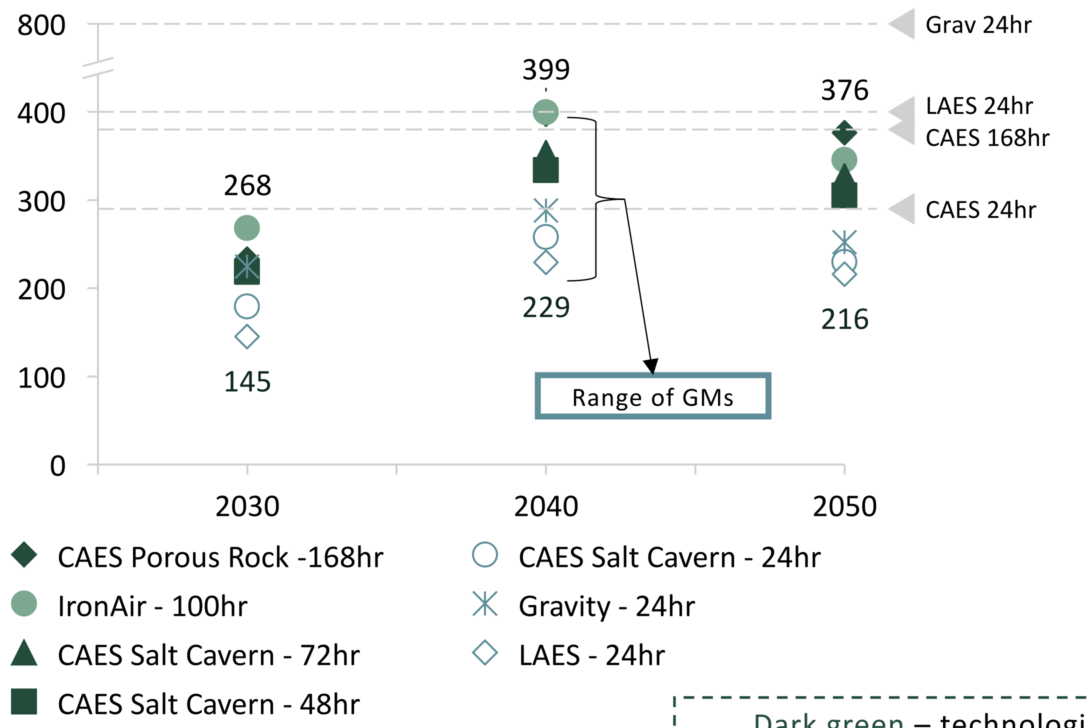


% of gross margin per market LDES: 8-12hr

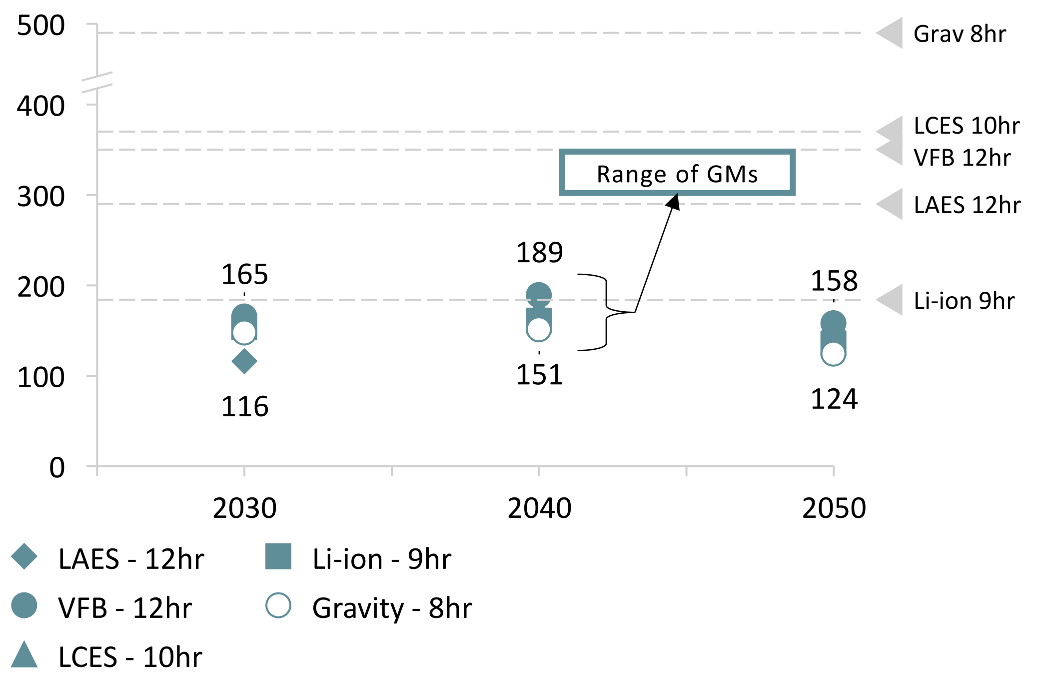


RESULTS – GROSS MARGINS

Margins for storage technologies with duration > 24h are relatively high in Germany and some are close to the current LCOS in 2040



Total gross margins* (€/kW) Germany, real 2025 LDES: 24-168hr



Total gross margins* (€/kW) Germany, real 2025 LDES: 8-12hr

Dark green – technologies meet the 2030 LCOS
Blue – technologies do not meet the 2030 LCOS

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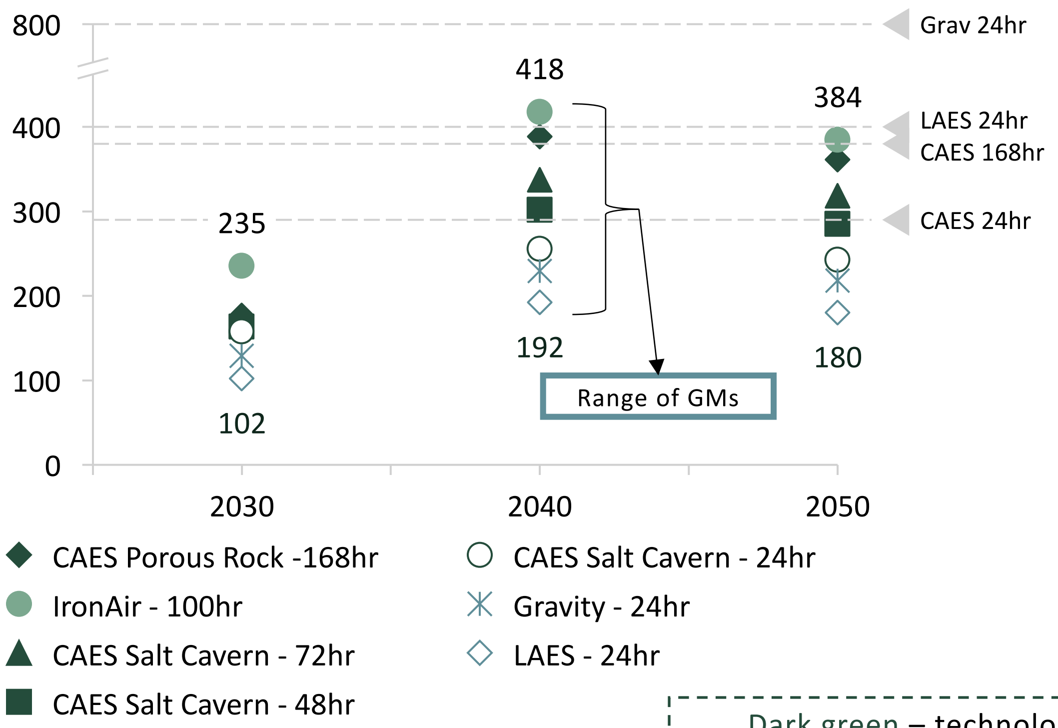
*Gross margins are calculated as the total revenues of selling energy – buying energy in the Day-ahead market, plus revenues of adjusting

** The projected LCOS presented is that as of 2030. We recognise that the LCOS is very likely to drop going forward in line with the learning curve.

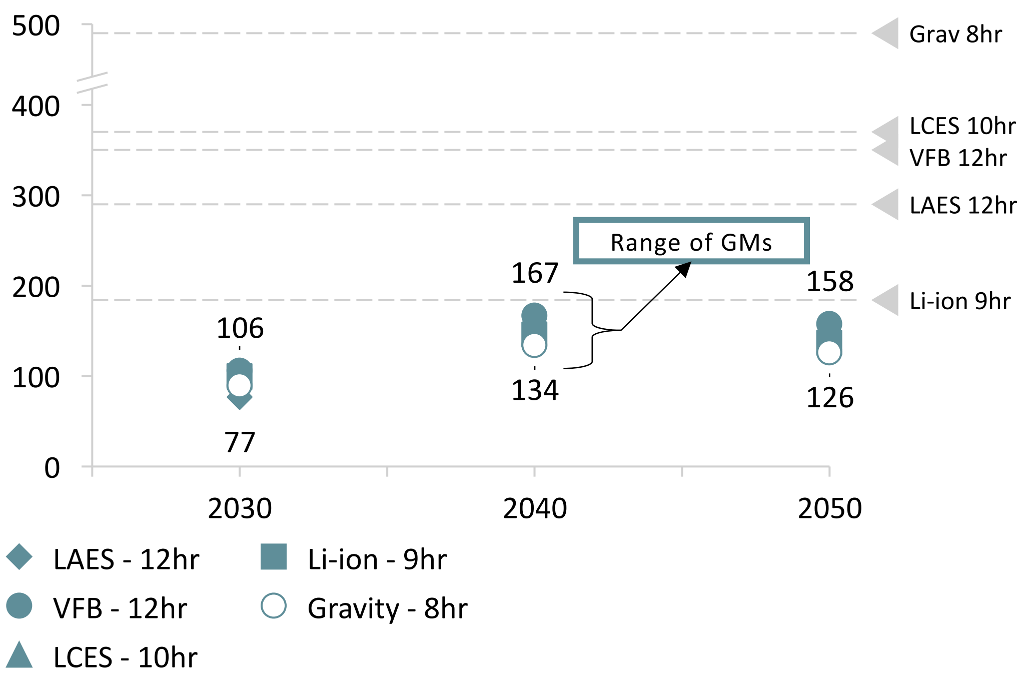
RESULTS – GROSS MARGINS

Margins for storage technologies with duration > 24h are relatively high in GB and some are close to the current LCOS in 2040

Total gross margins* (€/kW) GB, real 2025 LDES: 24-168hr



Total gross margins* (€/kW) GB, real 2025 LDES: 8-12hr



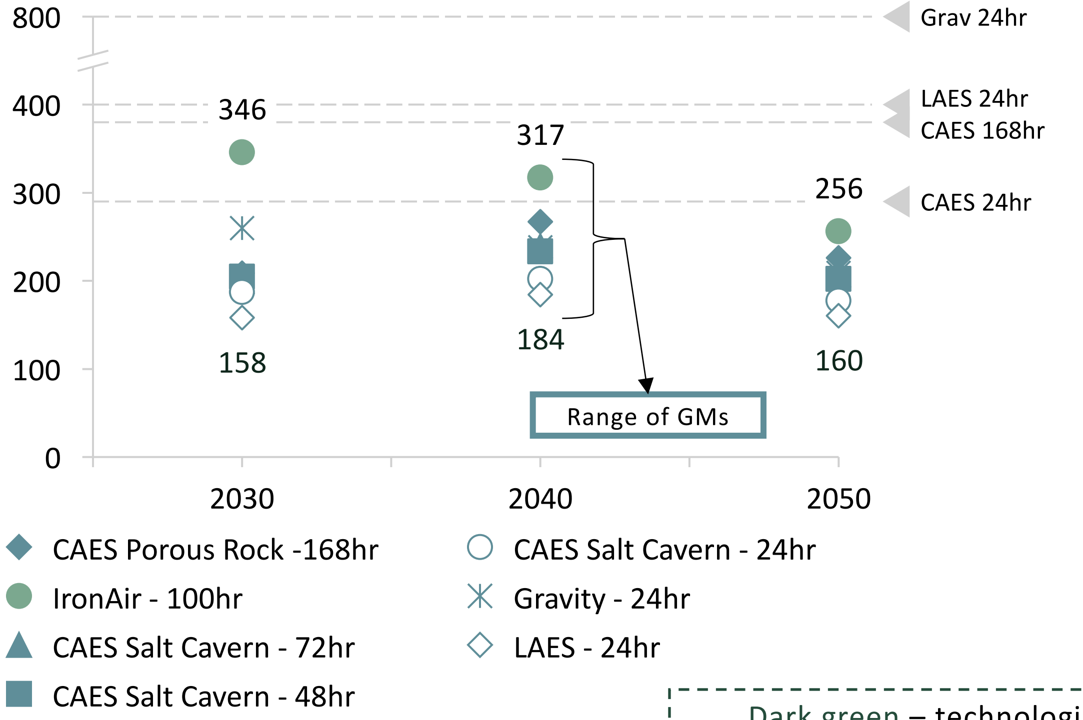
Dark green – technologies meet the 2030 LCOS
Blue – technologies do not meet the 2030 LCOS

*Gross margins are calculated as the total revenues of selling energy – buying energy in the Day-ahead market, plus revenues of adjusting

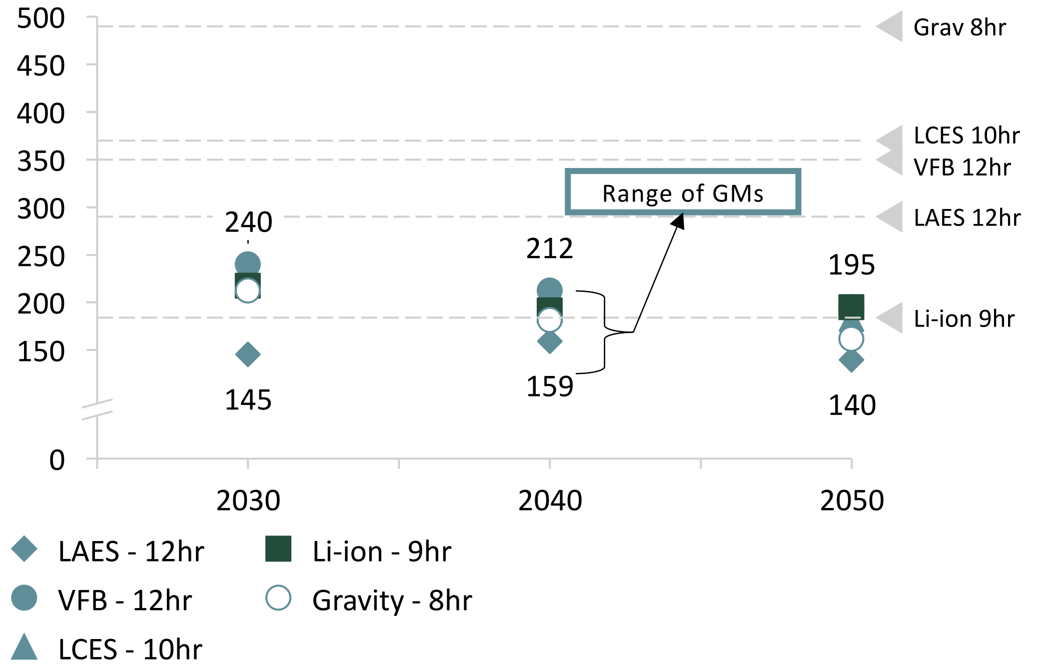
** The projected LCOS presented is that as of 2030. We recognise that the LCOS is very likely to drop going forward in line with the learning curve.

Our analysis suggests Spain and Portugal have the highest margins for storage technologies with duration between 8-12hr

Total gross margins* (€/kW) Spain, real 2025 LDES: 24-168hr



Total gross margins* (€/kW) Spain, real 2025 LDES: 8-12hr



Dark green – technologies meet the 2030 LCOS
Blue – technologies do not meet the 2030 LCOS

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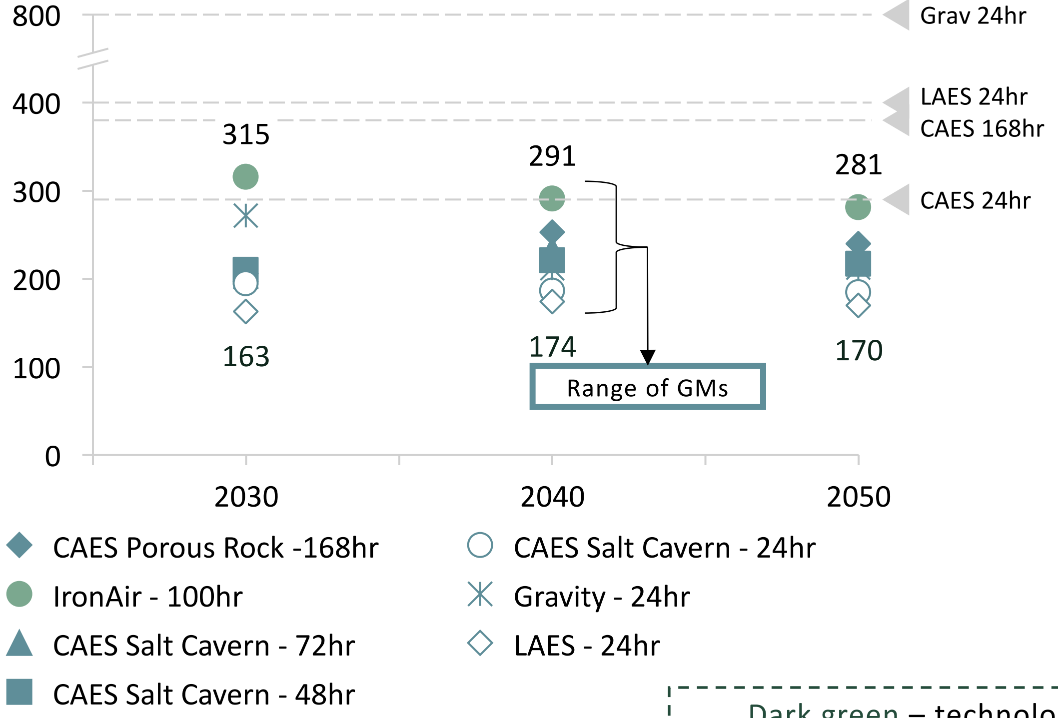
*Gross margins are calculated as the total revenues of selling energy – buying energy in the Day-ahead market, plus revenues of adjusting

** The projected LCOS presented is that as of 2030. We recognise that the LCOS is very likely to drop going forward in line with the learning curve.

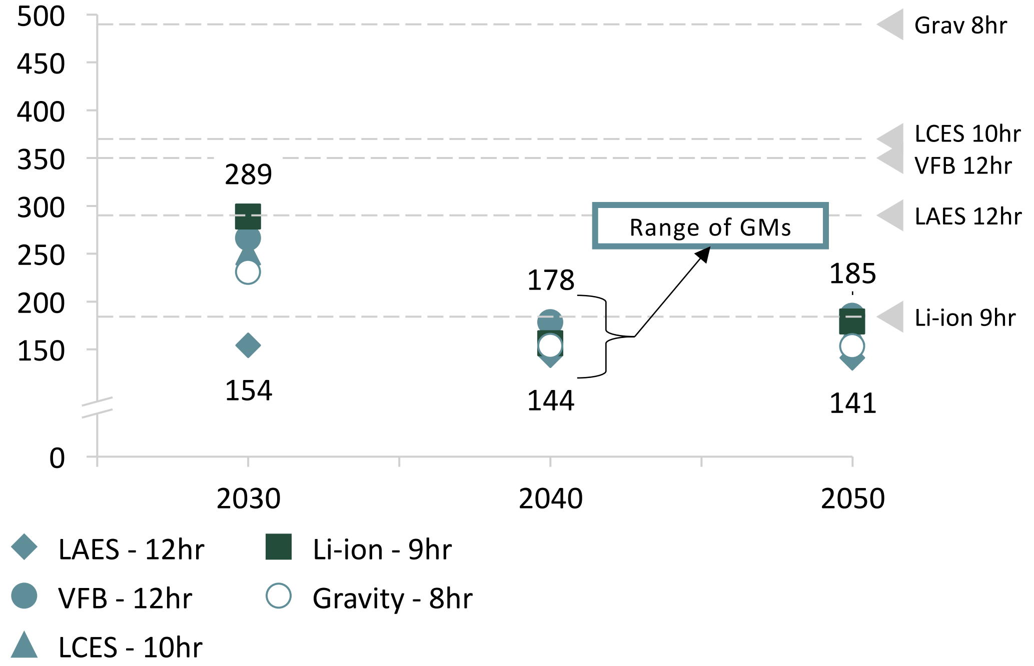
RESULTS – GROSS MARGINS

Our analysis suggests Spain and Portugal have the highest margins for storage technologies with duration between 8-12hr

Total gross margins* (€/kW) Portugal, real 2025 LDES: 24-168hr



Total gross margins* (€/kW) Portugal, real 2025 LDES: 8-12hr



Dark green – technologies meet the 2030 LCOS
Blue – technologies do not meet the 2030 LCOS

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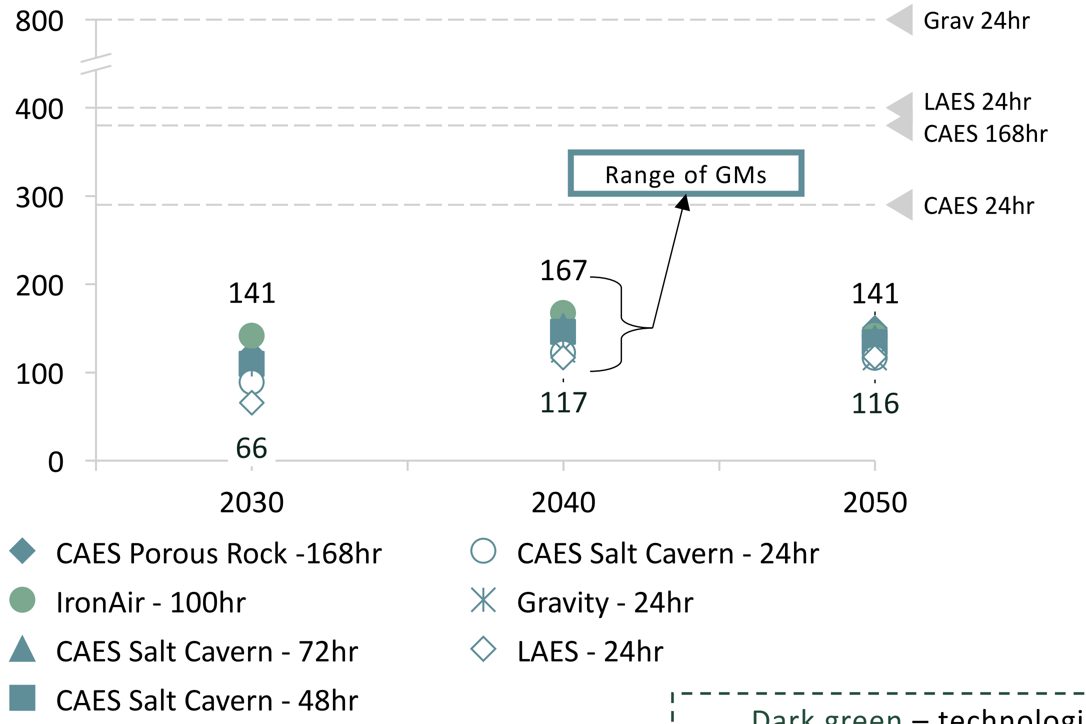
*Gross margins are calculated as the total revenues of selling energy – buying energy in the Day-ahead market, plus revenues of adjusting

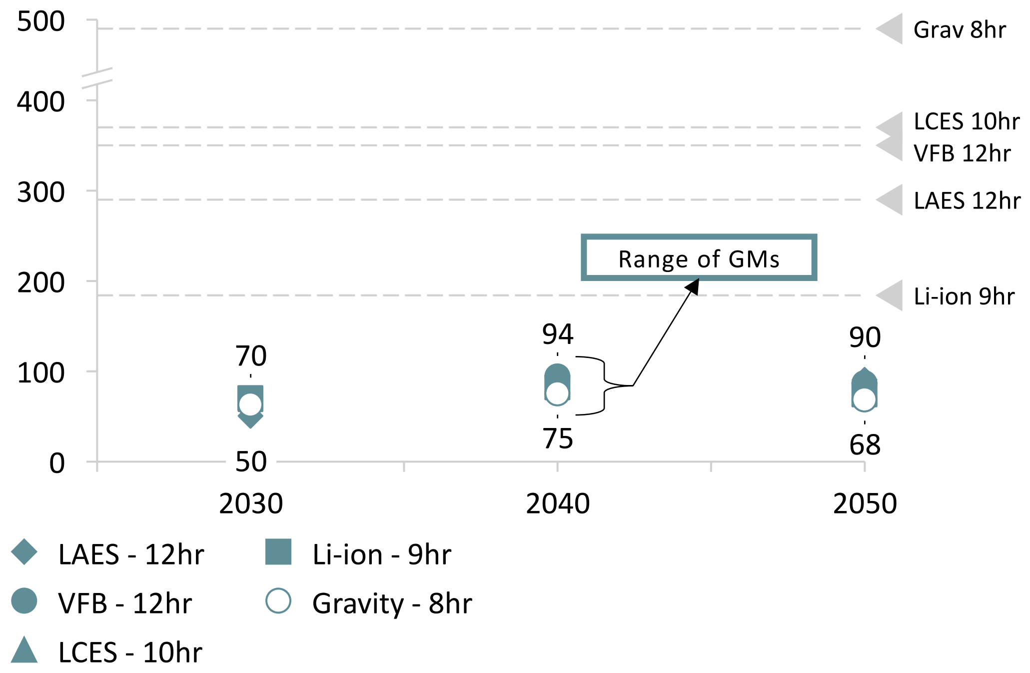
** The projected LCOS presented is that as of 2030. We recognise that the LCOS is very likely to drop going forward in line with the learning curve.

LDES margins achieved in our analysis for Finnish assets appear to be low – still, there may be opportunities for more strategic applications in ‘dry’ years

Total gross margins* (€/kW) Finland, real 2025 LDES: 24-168hr



Total gross margins* (€/kW) Finland, real 2025 LDES: 8-12hr



Dark green – technologies meet the 2030 LCOS
Blue – technologies do not meet the 2030 LCOS

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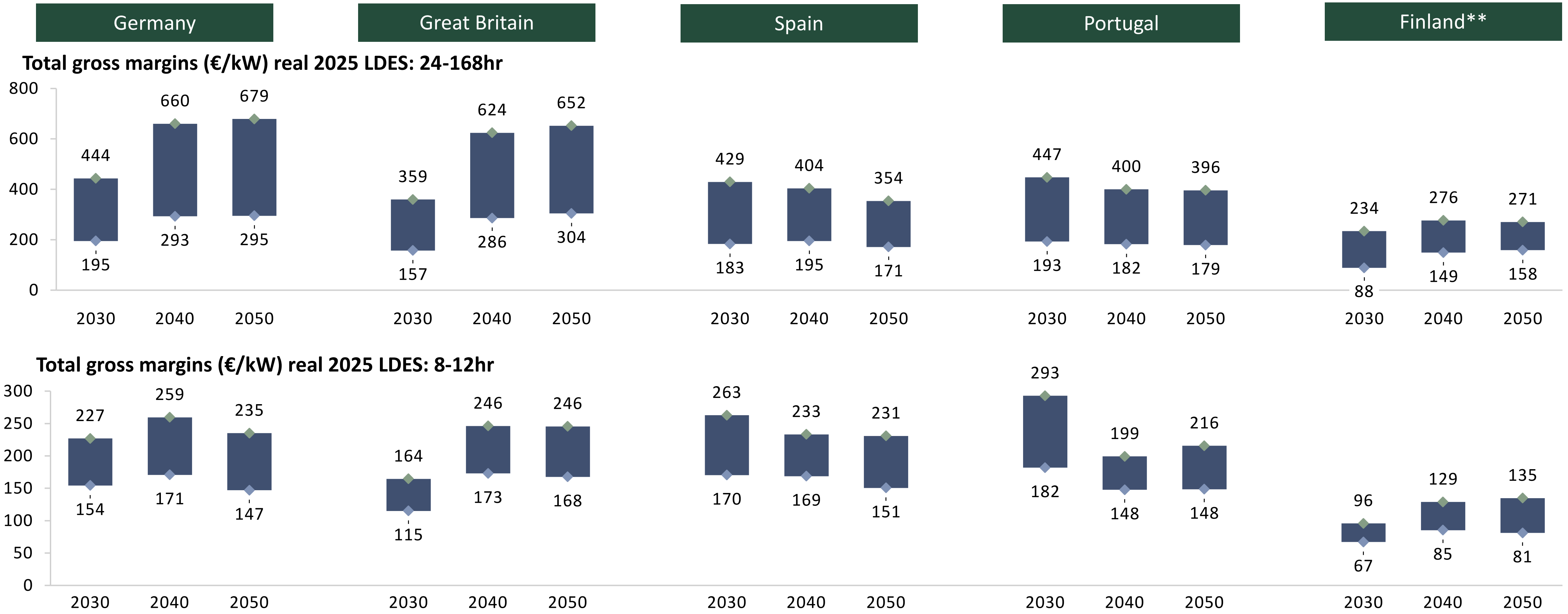
*Gross margins are calculated as the total revenues of selling energy – buying energy in the Day-ahead market, plus revenues of adjusting

** The projected LCOS presented is that as of 2030. We recognise that the LCOS is very likely to drop going forward in line with the learning curve.

An increase in the assumed ID and BM volatility[1] can increase overall margins



The upper and lower bounds of the range of gross margins reflect the most and least profitable technologies within each LDES duration category

1) Volatility was increase by 16% on average with respect to the initial run. This was achieved by increasing the bids and offer prices of all technologies to double the initial value

*Gross margins are calculated as the total revenues of selling energy – buying energy in the Day-ahead market, plus revenues of adjusting

**Note: for Finland, the revenues for ID and balancing were obtained from the same share as in Germany, due to the similarities in market configurations.

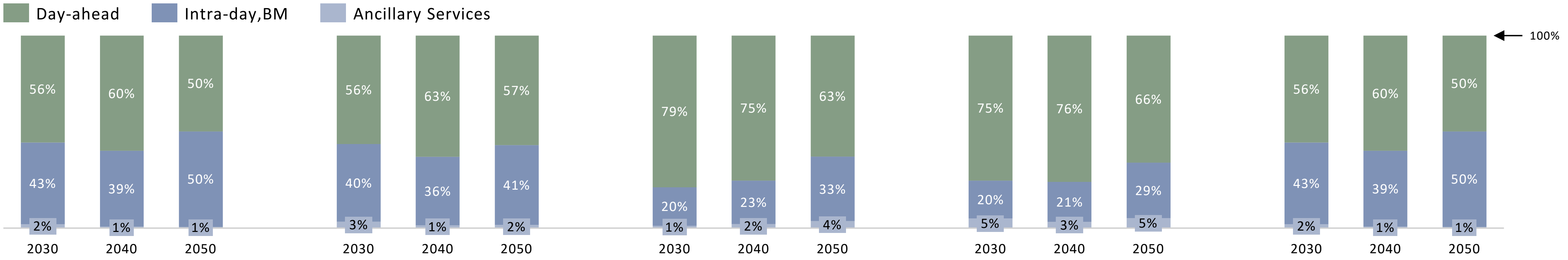
For more information, refer to the Annex

RESULTS – GROSS MARGINS

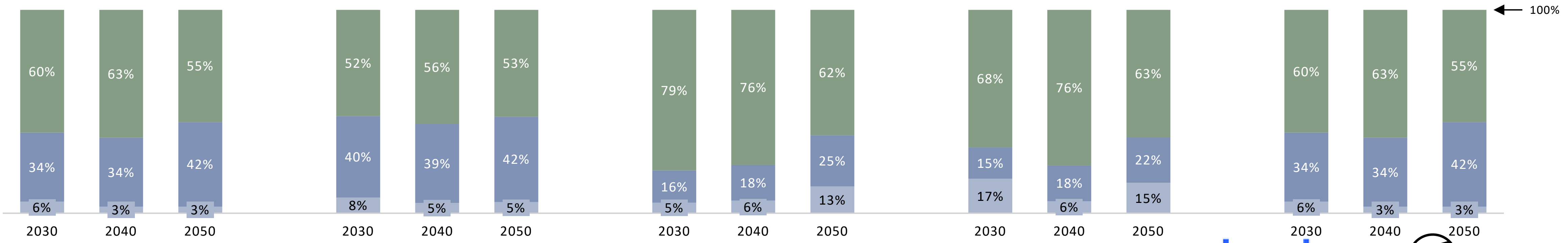
Obviously with more volatility the share of closer to real-time income increases

Germany | Great Britain | Spain | Portugal | Finland*

% of gross margin per market LDES: 24-168hr

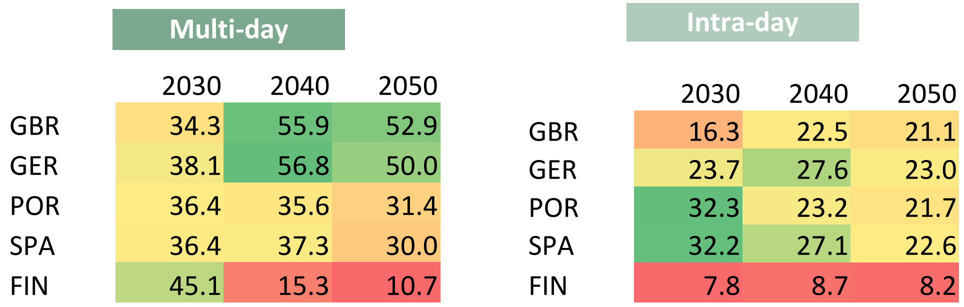


% of gross margin per market LDES: 8-12hr



LDES are well-positioned to build on greater multi-day and intra-day volatility from cycling across prolonged price cycles

WHOLESALE PRICE MEAN ABSOLUTE VOLATILITY, MULTI-DAY AVERAGES, €/MWH, REAL 2025*



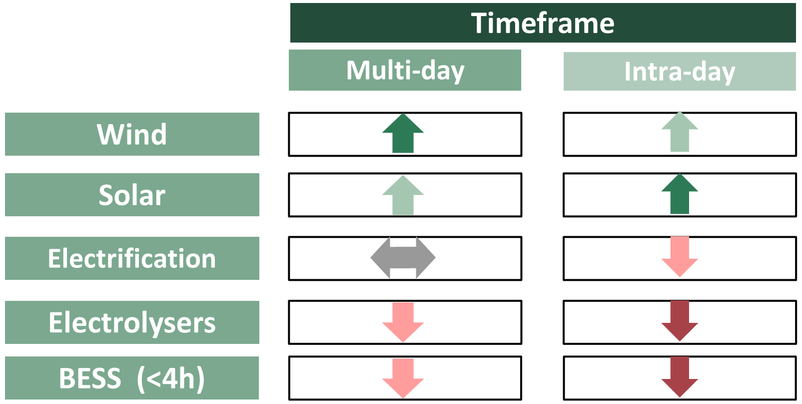
Multi-day

	2030	2040	2050
GBR	34.3	55.9	52.9
GER	38.1	56.8	50.0
POR	36.4	35.6	31.4
SPA	36.4	37.3	30.0
FIN	45.1	15.3	10.7

Intra-day

	2030	2040	2050
GBR	16.3	22.5	21.1
GER	23.7	27.6	23.0
POR	32.3	23.2	21.7
SPA	32.2	27.1	22.6
FIN	7.8	8.7	8.2

IMPACT ON PRICE VOLATILITY



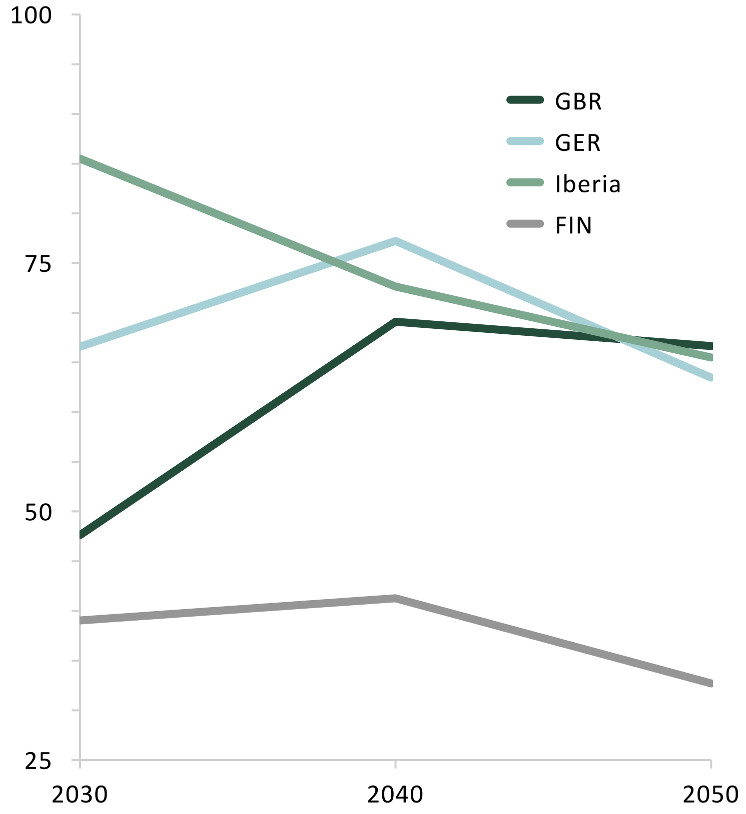
	Timeframe	
	Multi-day	Intra-day
Wind	↑	↑
Solar	↑	↑
Electrification	↔	↓
Electrolysers	↓	↓
BESS (<4h)	↓	↓

- Average intra-day and multi-day price volatility can help explain the relative flexibility requirements and need for storage with different characteristics.
- LDES can charge during prolonged low-price periods and discharge during high-priced periods. In NW Europe, LDES technologies appear to play a critical role in bridging multi-day wind ‘droughts’. In Southern Europe it is the within-day spreads that drive the LDES value.
- Multi-day volatility is primarily driven by wind generation, creating prolonged low-priced periods when there is persistent high wind output and extended high prices during low-wind periods. In NW European markets, like Germany and GB, it increases significantly by 2040 as wind capacity grows, before being gradually suppressed by electrolyser deployment and other forms of flexibility added on the system. Southern European markets, such as Spain and Portugal, show comparatively lower multi-day volatility, which decreases rapidly in the 2040s as large-scale electrolysers absorb surplus generation and dampen price swings.
- Intra-day volatility is predominantly shaped by solar generation, which creates strong daily price cycles, but is more directly moderated by electrolyser activity. Spain and Portugal exhibit higher intra-day volatility given their large solar fleets, though this declines markedly by 2040–2050 as electrolysers provide increasing intra-day demand response.

Note: Multi-day volatility is calculated as the average absolute difference between hourly prices and monthly average. Intra-day volatility is calculated as the average absolute difference between hourly prices and daily average.

The daily min-max spread is an important indicator for the need and value of storage

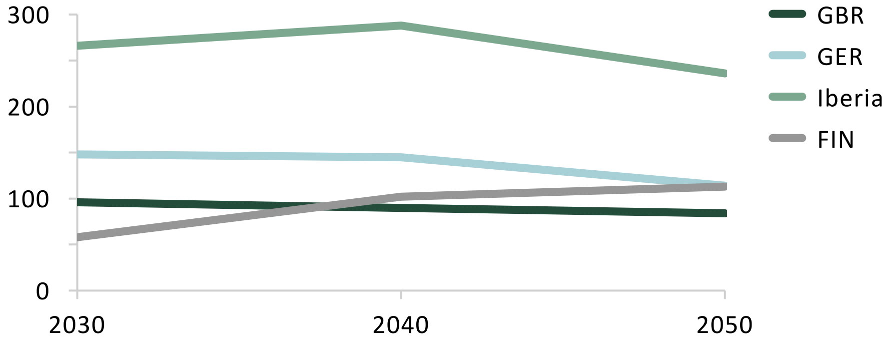
AVERAGE DAILY SPREAD (€/MWH)



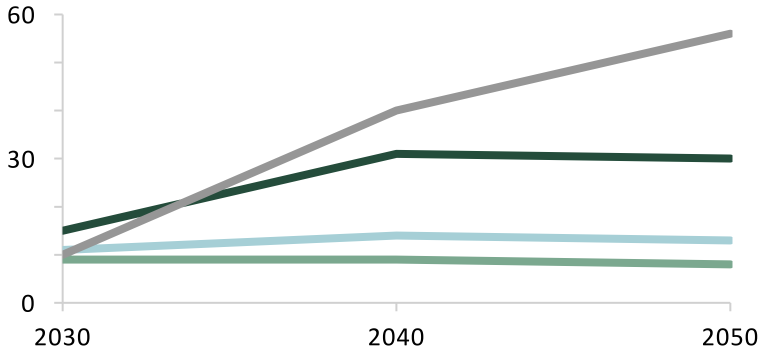
- A greater daily min-max spread is important for storage with shorter durations. Longer-duration storage can also benefit from this, but this means the additional storage capacity and duration would not be used efficiently.
- The average daily min-max spread in GB is low in 2030 given the relative storage and renewables capacity; however, as more wind and solar PV is added, the spread increases.
- In Germany, solar PV added in the 2030s increases the spread in 2040, but this trend reverses as more storage and electrolysers are deployed. These technologies increase demand at low-price hours and discharge over high-price hours, bringing prices closer with the daily min-max spread dropping.
- Abundant solar PV in Spain and Portugal means there are frequent zero-priced periods in 2030 and a high average daily spread. With additional flexibility provision added this spread drops in 2040 and 2050.

LDES assets with durations better aligned with market-specific low-price event patterns have the greatest ‘potential’ (1/2)

NUMBER OF LOW-PRICE EVENTS



AVERAGE DURATION PER LOW-PRICE EVENT (HOURS)

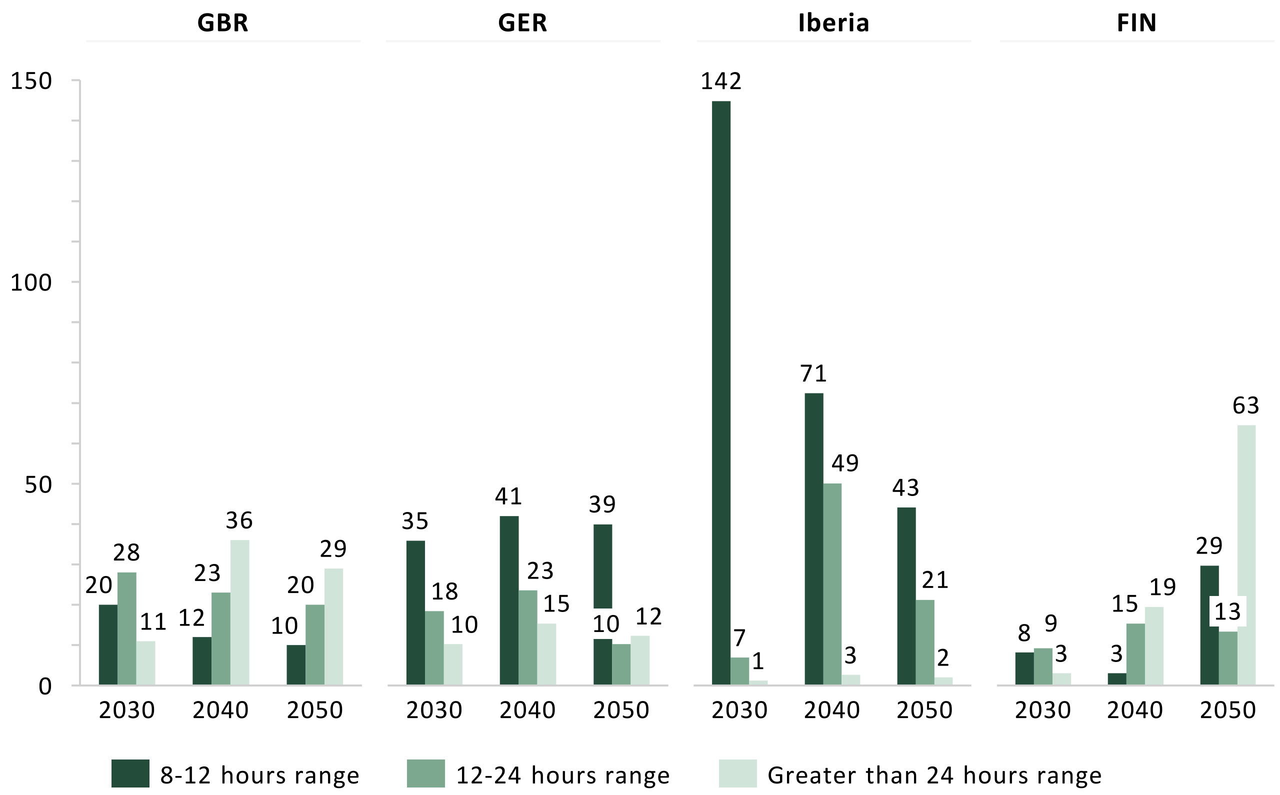


COMMENTARY

- In our analysis, we define a low-price event as an occurrence of consecutive hours with wholesale prices less than 1 €/MWh. We use two key metrics to assess low-price events:
  - the frequency of this happening (i.e. the number of such events in every year); and
  - the average duration of these events when they take place.
- Low-price events happen frequently in Iberia, but these do not last long. On the other hand, GB, with its high wind generation, has less frequent but more prolonged occurrences of such events, due to extended ‘windy’ periods.
- Germany lies somewhere between GB and Iberia – there are more low-priced events in Germany than GB, but significantly less than Iberia. The average duration is almost between Iberia and GB.
- Finland has a high relative wind generation share, and this is set to increase further going forward. This combined with the extensive hydro generation and the wider generation mix means both the frequency and duration of low-priced events is expected to increase going forward.

LDES assets with durations better aligned with market-specific low-price event patterns have the greatest ‘potential’ (2/2)

NUMBER OF EXTENDED LOW-PRICE EVENTS PER RANGE OF EVENT DURATION



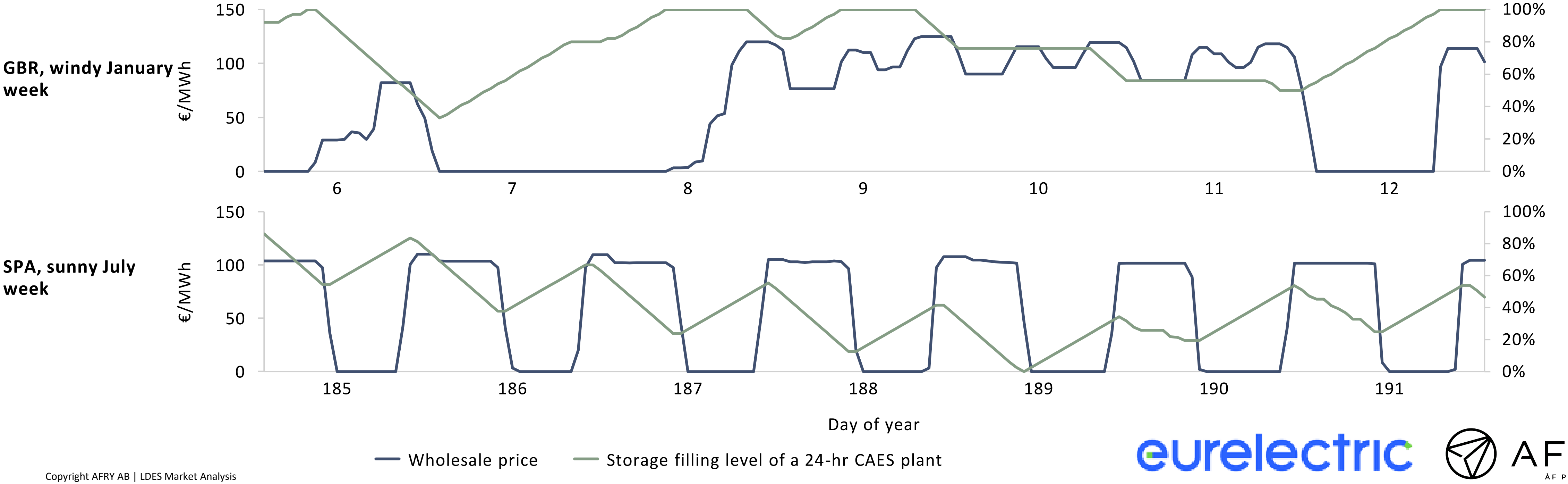
COMMENTARY

- In the chart on the left-hand side, we split the low-priced events into different event duration ranges.
- Regions like Iberia with higher solar PV generation have shorter low-priced events (i.e. in the range of 8-12 hours), which implies greater compatibility with LDES with relatively ‘shorter’ durations.
- However, places with relatively more wind generation (such as GB) favour longer-duration technologies as they have longer low-price events.
- Generally, such ‘extensive’ low-price events will not necessarily benefit short-duration batteries, and are a better fit for longer duration storage.

High daily price spreads and low-price events both support LDES margin creation

- The top snapshot shows that, in GB, long low-price events enable charging of an LDES asset at very low cost for an extended period of time. Given its storage capacity, the LDES asset can maintain a relatively high filling level even after multiple periods of discharging.
- Looking at the bottom snapshot, we can see that despite shorter low-price events in SPA, the high daily min-max spread suggests a completely different operating pattern. The LDES asset is cycling on daily basis.

HOURLY SNAPSHOTS OF WHOLESALE PRICE AND STORAGE FILLING LEVEL IN 2030

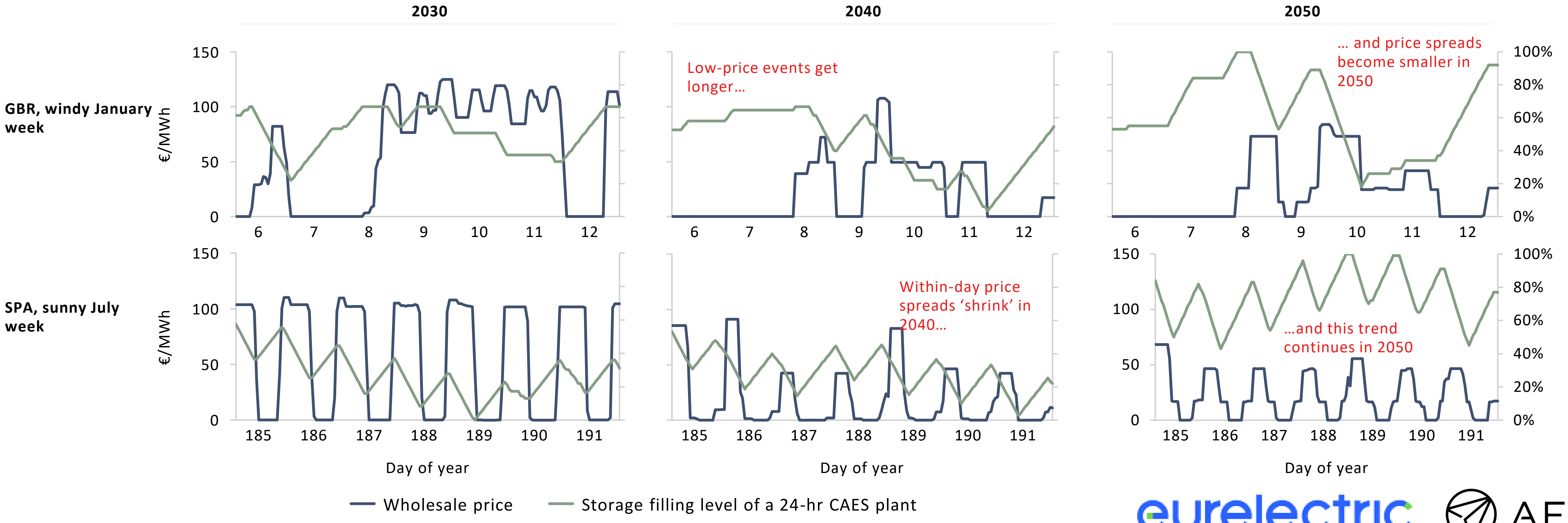


RESULTS – ANALYSIS OF KEY MARKET INDICATORS

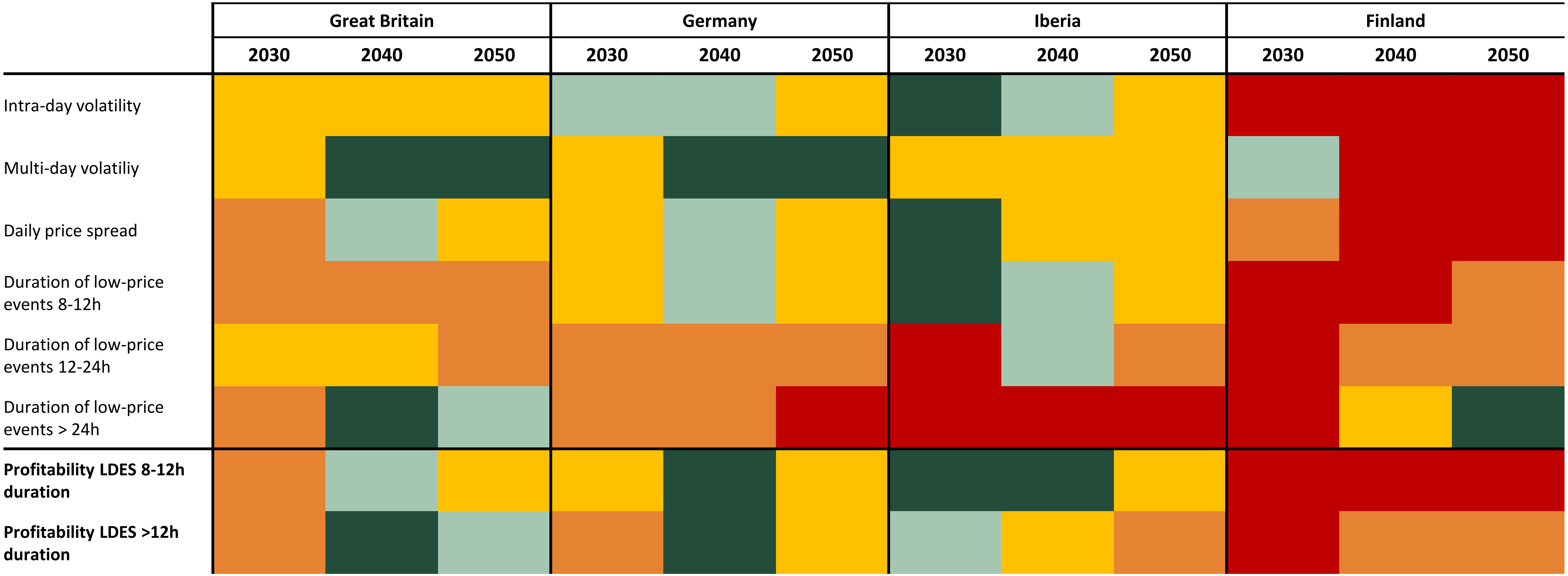
The underlying market price formation can help explain the LDES operation and captured margins

- In GB, longer low-price events in 2040 and 2050 enable more low-cost charging, which results in higher gross margins than 2030. Higher wind output in 2050 leads to ‘longer’ low-price events, but also smaller price spreads. This, in turn, results in lower margins in 2050 compared to 2040.
- In Spain, the within-day price spreads ‘shrink’ going forward . This, in turn, leads to a reduction in LDES gross margins out to 2050.

HOURLY SNAPSHOTS OF WHOLESALE PRICE AND STORAGE FILLING LEVEL IN 2030, 2040 AND 2050



Within-day price volatility coupled with more frequent extended low-priced events result in different opportunities for LDES

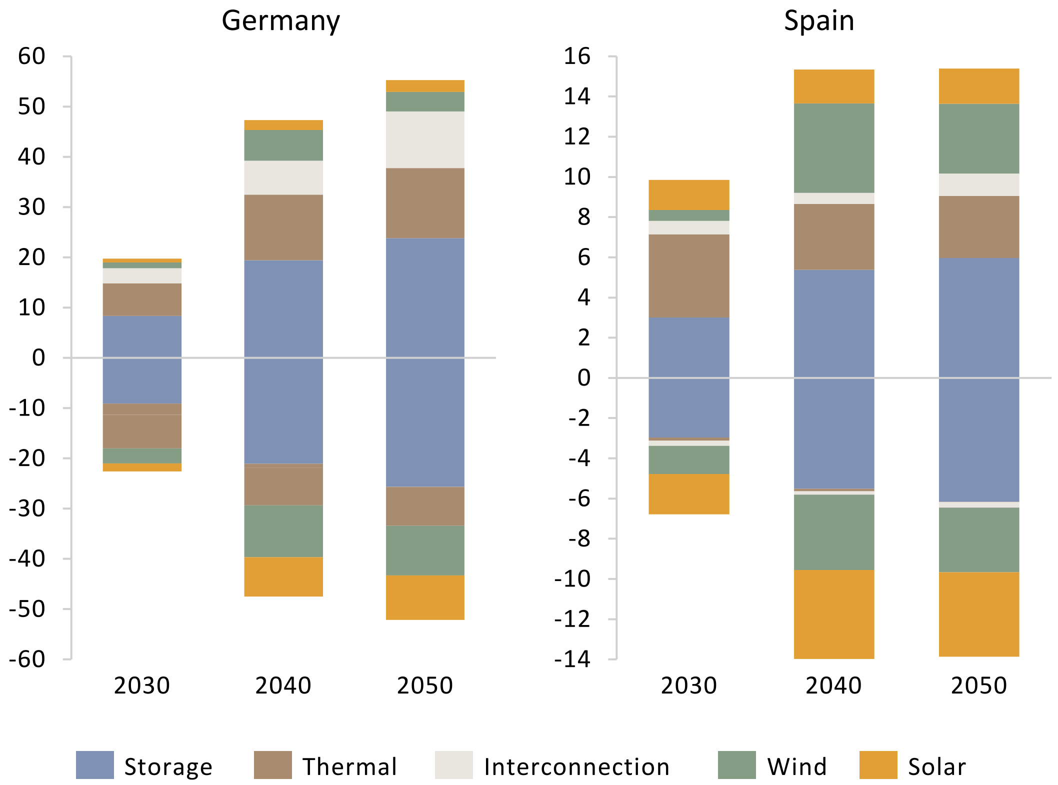


	Great Britain			Germany			Iberia			Finland		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Intra-day volatility	🟨	🟨	🟨	▨	▨	🟨	🟩	▨	🟨	🟥	🟥	🟥
Multi-day volatiliy	🟨	🟩	🟩	🟨	🟩	🟩	🟨	🟨	🟨	▨	🟥	🟥
Daily price spread	🟧	▨	🟨	🟨	▨	🟨	🟩	🟨	🟨	🟧	🟥	🟥
Duration of low-price events 8-12h	🟧	🟧	🟧	🟨	▨	🟨	🟩	▨	🟨	🟥	🟥	🟧
Duration of low-price events 12-24h	🟨	🟨	🟧	🟧	🟧	🟧	🟥	▨	🟧	🟥	🟧	🟧
Duration of low-price events > 24h	🟧	🟩	▨	🟧	🟧	🟥	🟥	🟥	🟥	🟥	🟨	🟩
Profitability LDES 8-12h duration	🟧	▨	🟨	🟨	🟩	🟨	🟩	🟩	🟨	🟥	🟥	🟥
Profitability LDES >12h duration	🟧	🟩	▨	🟧	🟩	🟨	▨	🟨	🟧	🟥	🟧	🟧

Keywords: matrices, table, tables

Energy storage technologies, including LDES, are expected to become one of the key ‘tools’ for managing flexibility needs

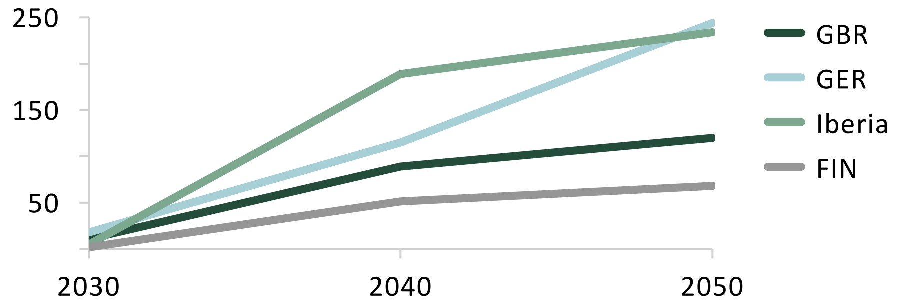
ACCEPTED BIDS AND OFFERS (TWH) FOR TWO CASES: NORTH-EUROPE COUNTRY AND SOUTH-EUROPE COUNTRY



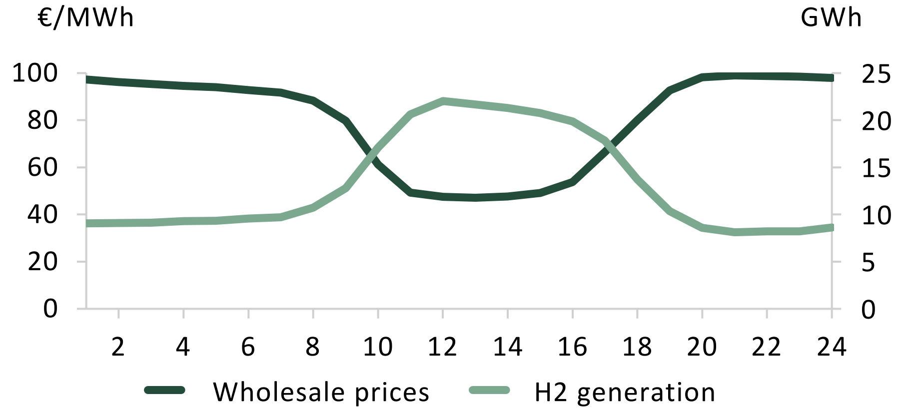
- A comparison of two representative countries from Northern and Southern Europe is presented on the left-hand side to highlight the role of storage in the balancing timeframe.
- Activated volumes increase going forward in both countries as more RES are added on the system, which leads to a larger greater need for Balancing Energy.
- In both markets, storage is the main Balancing Energy provider in both ‘up’ and ‘down’ directions

Electrolyser deployment can reduce intraday price spreads and dampen long-duration storage margin potential in the long-run

HYDROGEN GENERATION FROM ELECTROLYSIS (TWH)



AVERAGE DAILY SHAPE OF WHOLESALE PRICES (€/MWH) AND HYDROGEN GENERATION (GWH)

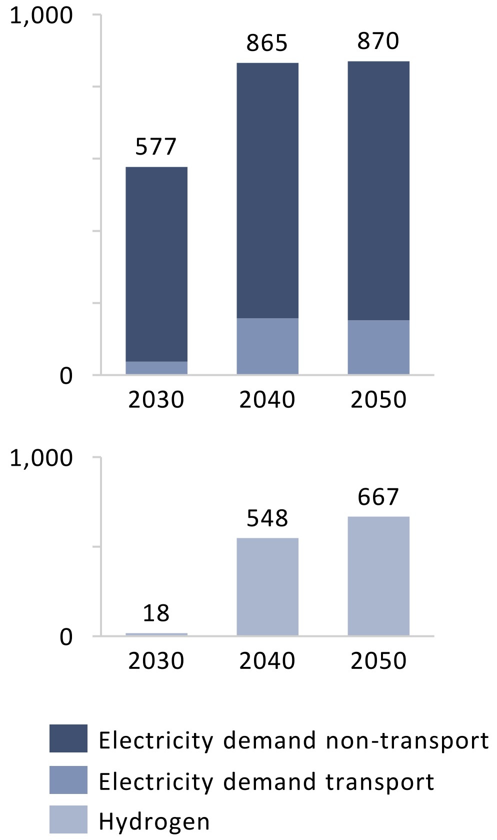


- Electrolysers are considered a source of flexibility, and as such, they generate over low-priced periods. This can be seen in the bottom chart on the left-hand side, where we compare hourly average production of H2 with hourly average power prices in Germany in 2040.
- The power demand from electrolysers pushes electricity prices up at times of high renewable generation. The result is:
  - reduced within-day price spreads, which directly impacts operation and margins for storage with a duration of 8-12 hours (but also longer durations); and
  - it somewhat limits the number of continuous periods of low or zero prices, resulting in more limited opportunities for charging at low prices for LDES with duration longer than 12 hours.
- In all countries in our analysis, an increase in hydrogen demand leads to a large-scale requirement for electrolysers. In 2050, the addition of electrolysers dampens the potential margins from the ex-ante energy markets for LDES.

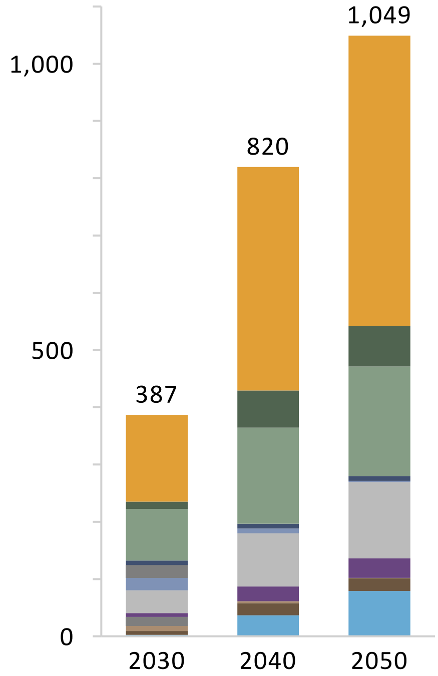
GERMANY

German wholesale prices remain at similar levels as power demand grows ta a fast pace

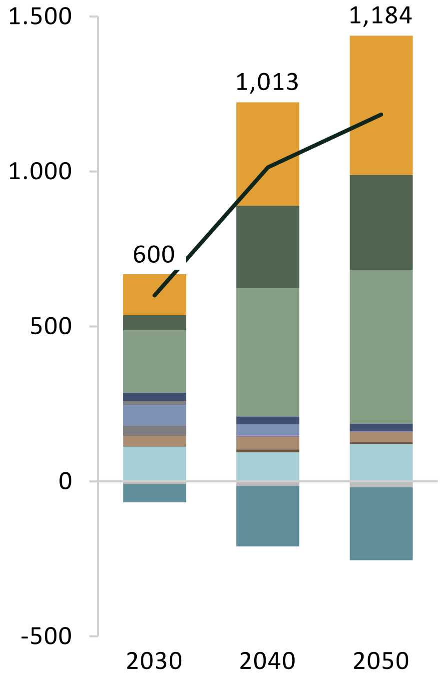
INPUT DEMAND (TWH)



CAPACITY (GW)

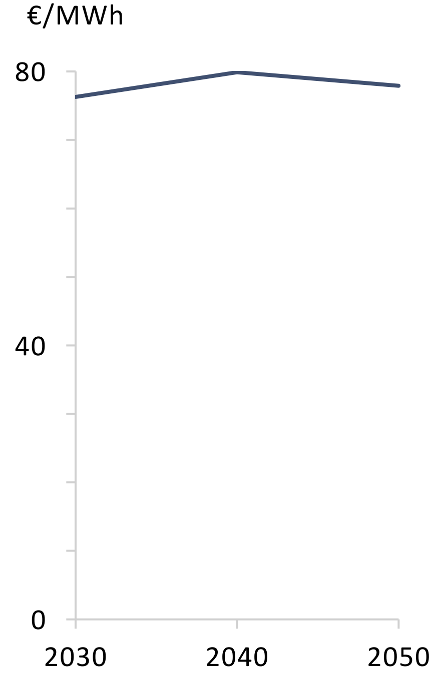


GENERATION (TWH)



Nuclear | Hydro | Hydrogen | Imports
Solar PV | Coal & Lignite | Other Thermal | Exports
Offshore Wind | Gas turbine | Other RES | Electrolyser
Onshore Wind | Storage | DSR | Total Demand*

WHOLESALE ELECTRICITY PRICES

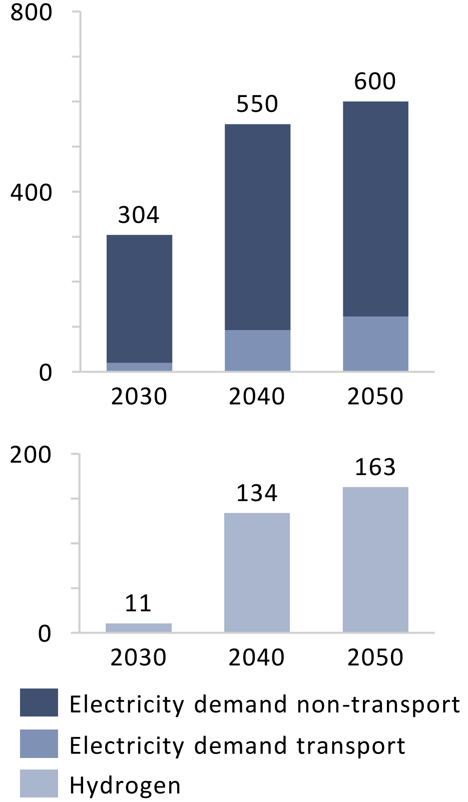


*Total demand is the model's output demand, calcualted as the input demand plus the electricity demand for electrolysis

GREAT BRITAIN

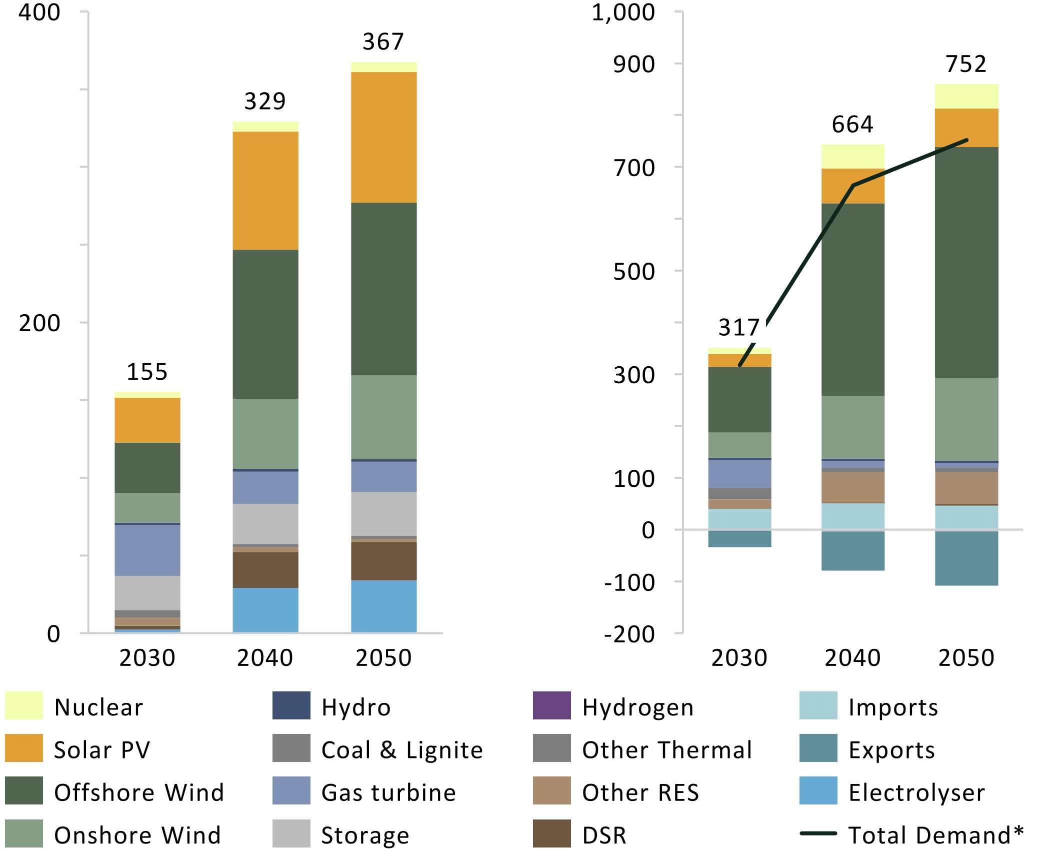
Renewables deployment outpaces demand and wholesale prices in GB follow a downard trend

INPUT DEMAND (TWH)

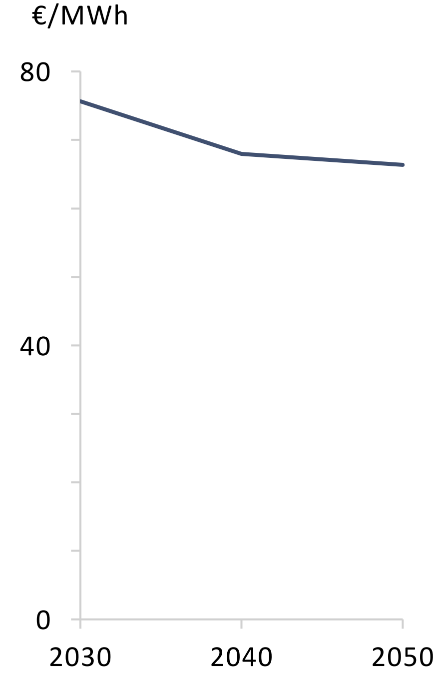


CAPACITY (GW)

GENERATION (TWH)



WHOLESALE ELECTRICITY PRICES

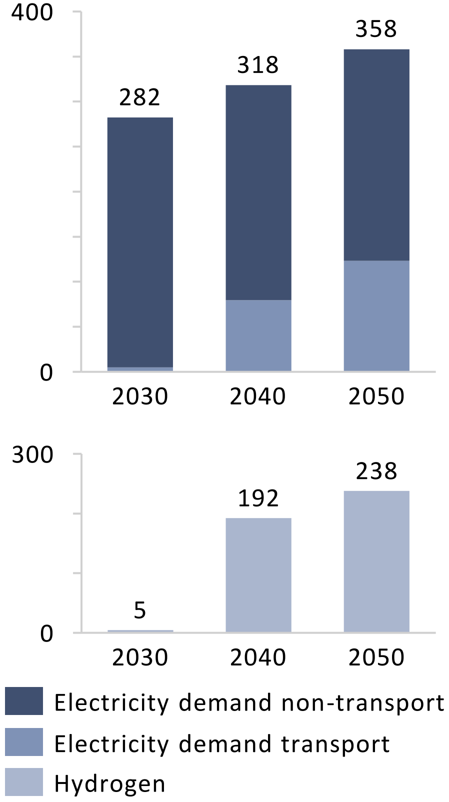


*Total demand is the model's output demand, calcualted as the input demand plus the electricity demand for electrolysis

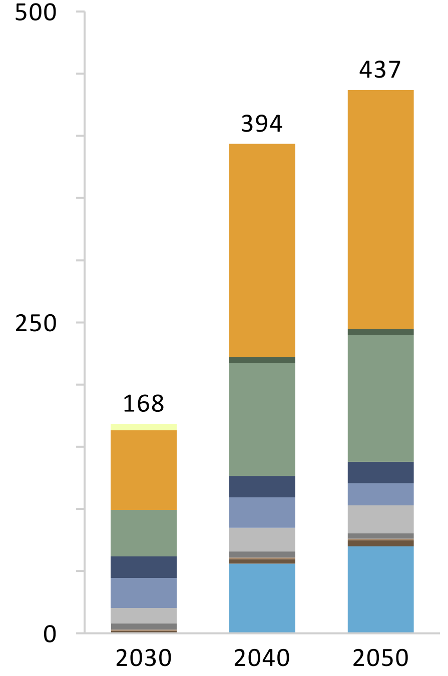
SPAIN

Spain has a surplus of renewables generation and given the limited demand growth, electricity prices remain at a low level

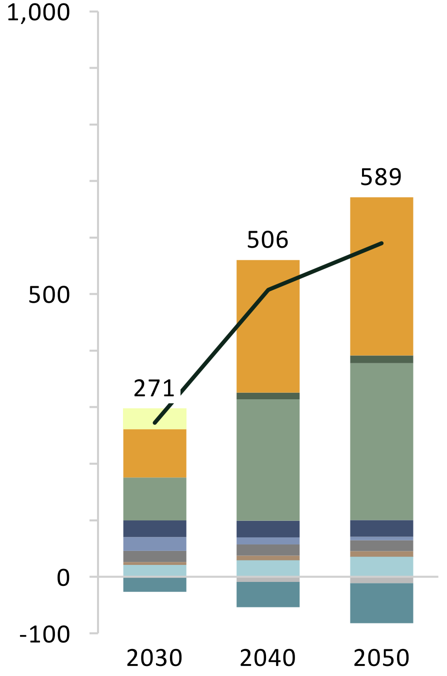
INPUT DEMAND (TWH)



CAPACITY (GW)

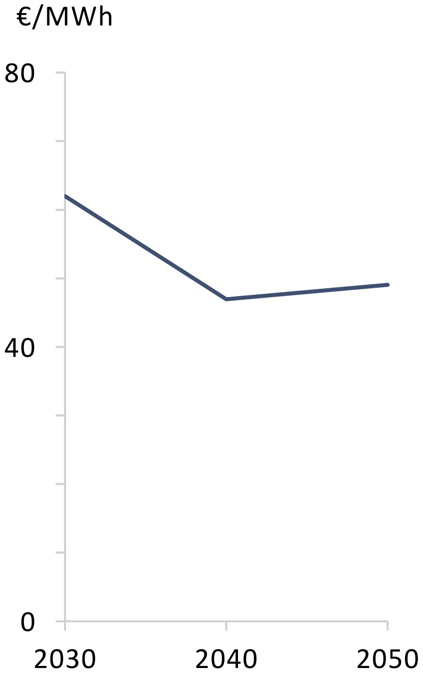


GENERATION (TWH)



Nuclear	Hydro	Hydrogen	Imports
Solar PV	Coal & Lignite	Other Thermal	Exports
Offshore Wind	Gas turbine	Other RES	Electrolyser
Onshore Wind	Storage	DSR	Total Demand*

WHOLESALE ELECTRICITY PRICES

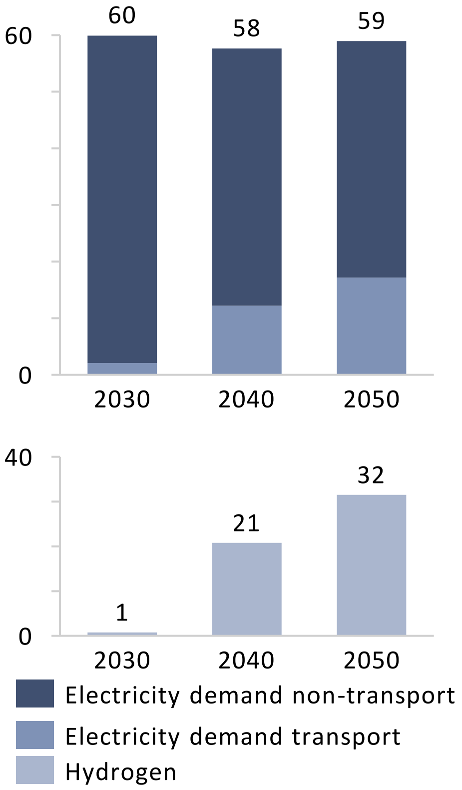


*Total demand is the model's output demand, calcualted as the input demand plus the electricity demand for electrolysis

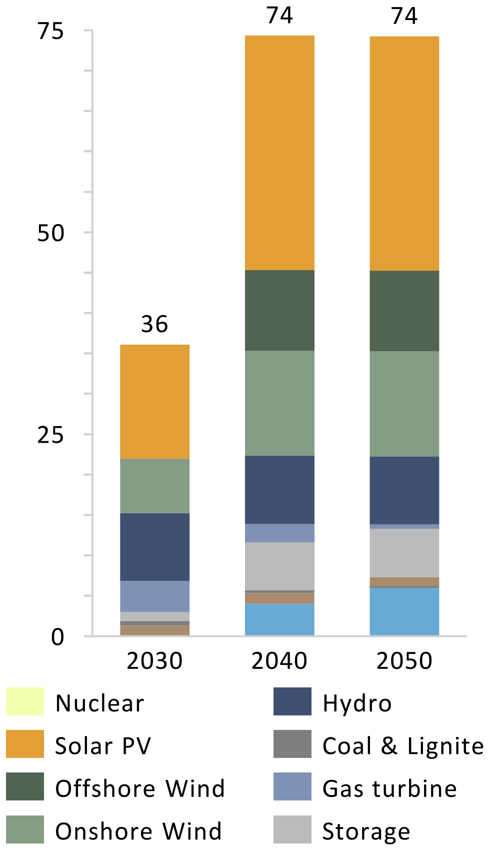
PORTUGAL

The Portuguese system also has significant renewable capacity coupled with moderate demand – power prices follow a similar trend as Spain

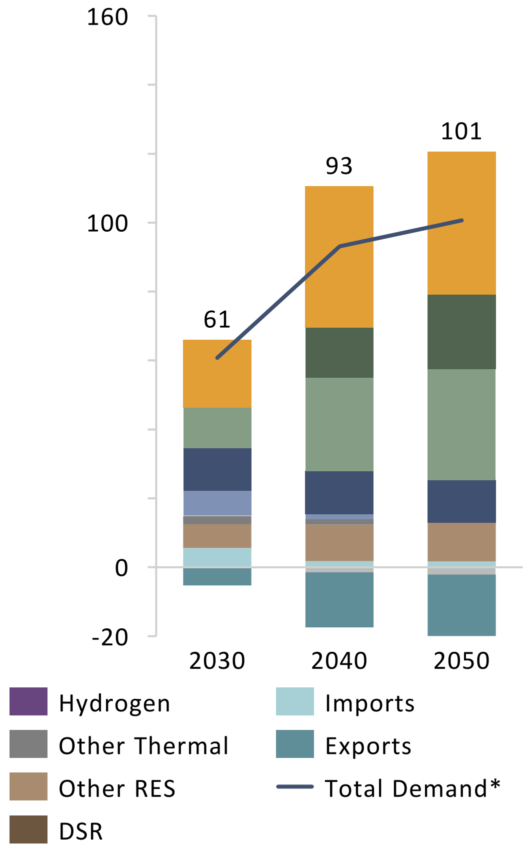
INPUT DEMAND (TWH)



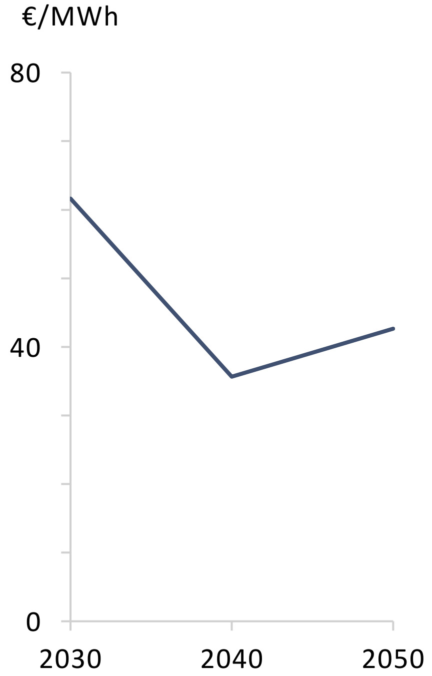
CAPACITY (GW)



GENERATION (TWH)



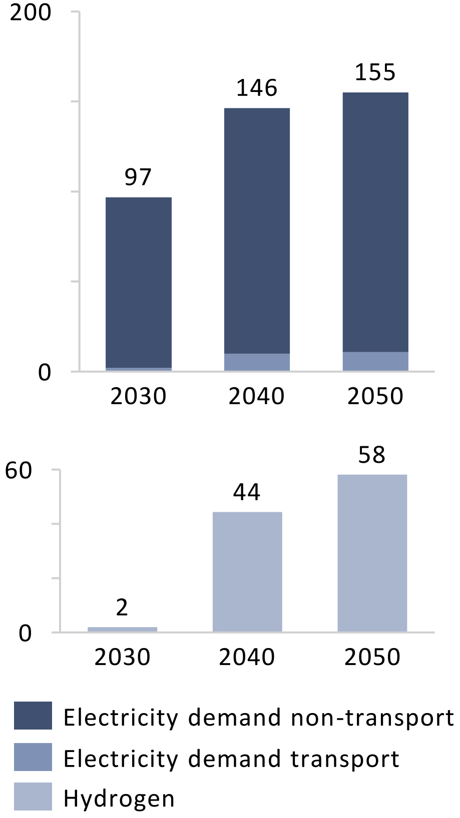
WHOLESALE ELECTRICITY PRICES



*Total demand is the model's output demand, calcualted as the input demand plus the electricity demand for electrolysis

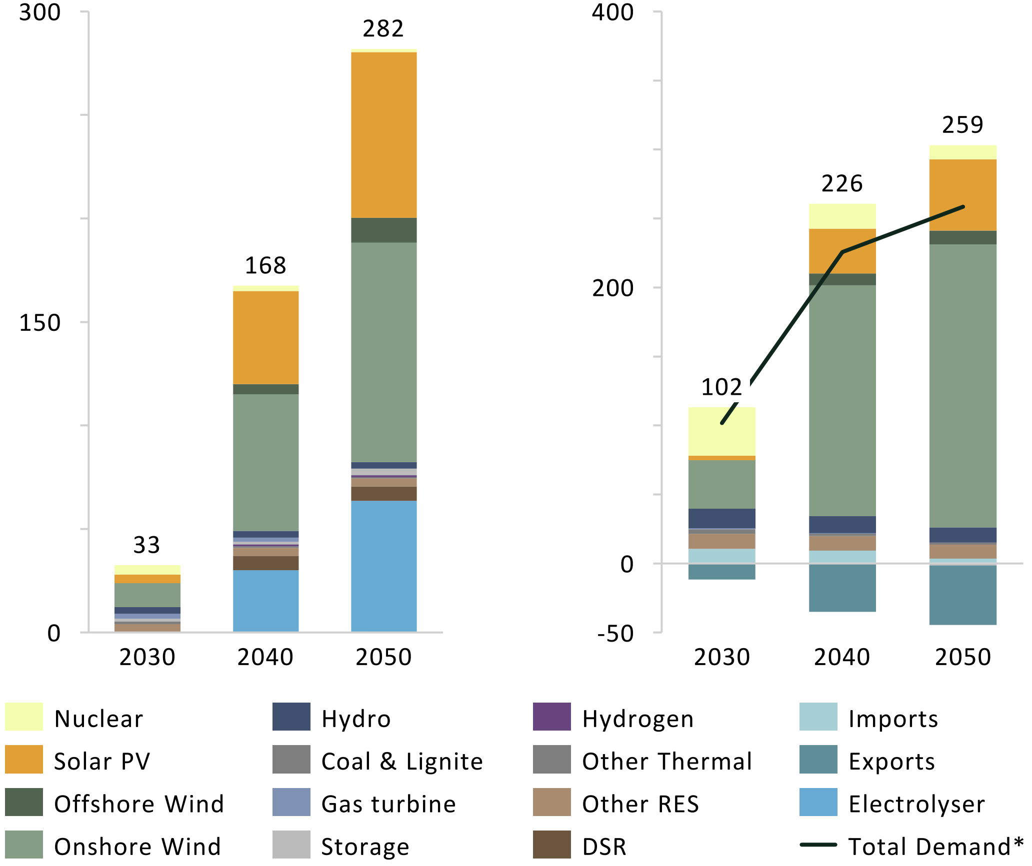
Finnish demand increases as data centers are added to the power system, but again the renewable capacity installed outpaces demand growth

DEMAND (TWH)

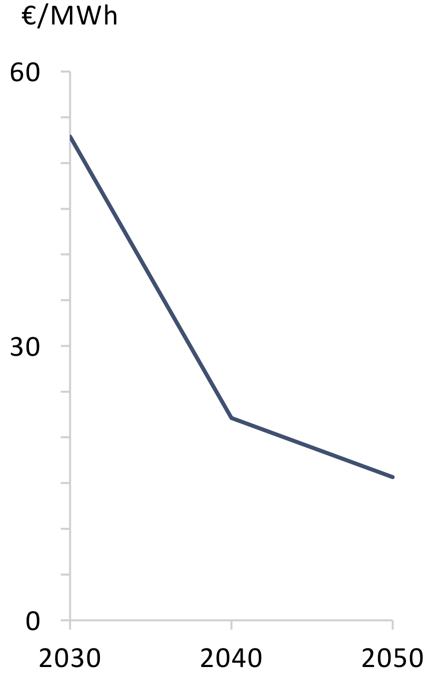


CAPACITY (GW)

GENERATION (TWH)



WHOLESALE ELECTRICITY PRICES



*Total demand is the model's output demand, calcualted as the input demand plus the electricity demand for electrolysis

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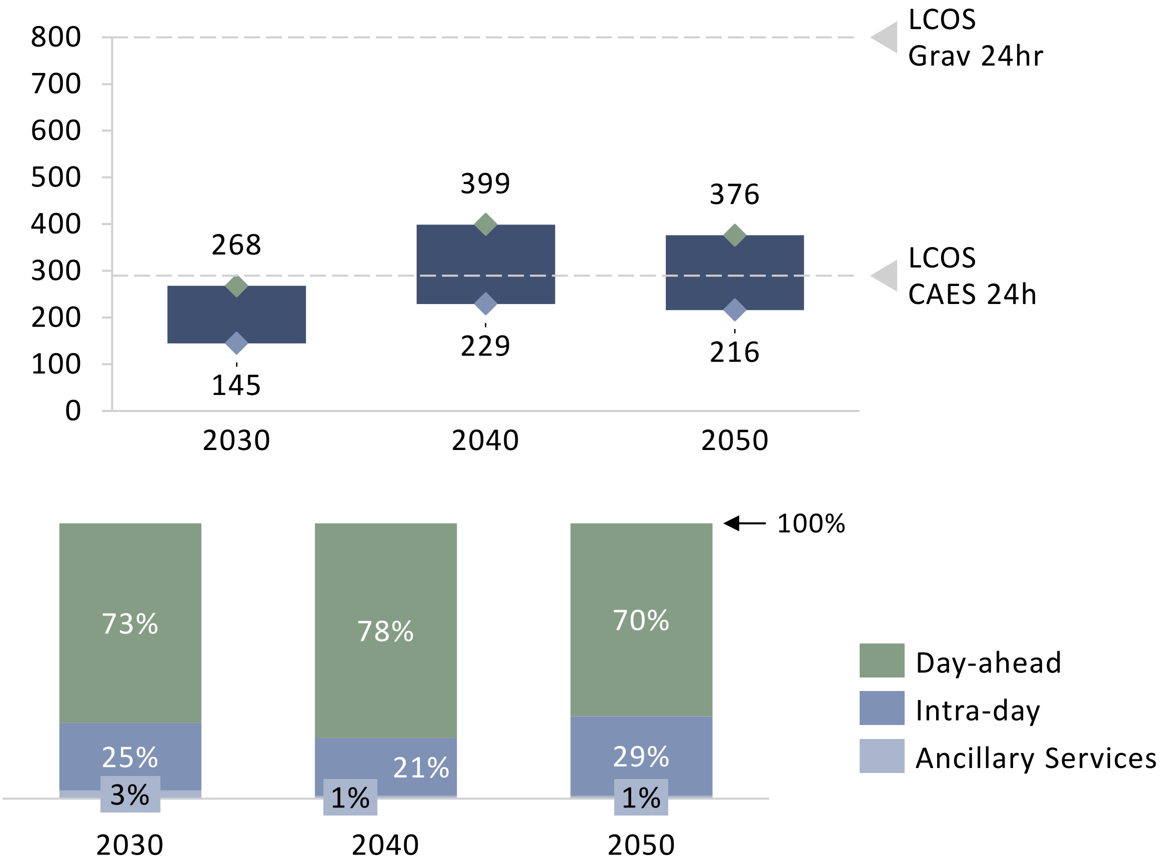
GERMANY

High wind penetration in Germany helps support LDES margins

GROSS MARGINS (EUR/KW) REAL 2025 LDES: 24-168HR

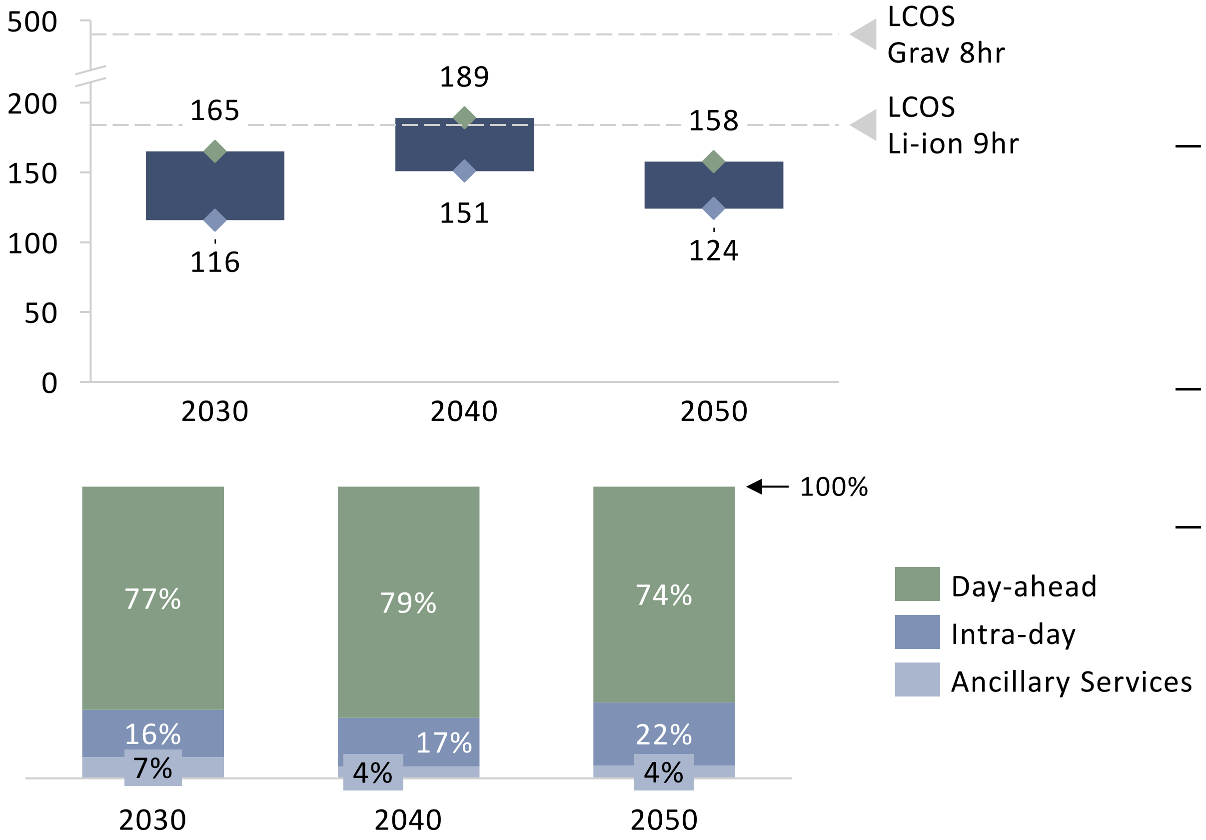


- The difference in gross margins across technologies is a result of the duration, efficiency and charging rate of these technologies, with Iron Air having the highest gross margins due to its long duration and symmetric charging/discharging rate.
- In 2030, most continuous periods of low or negative prices are within the range of 8-12 hours, which results in an underutilisation of these technologies. However, the large deployment of solar generation leads to daily price spreads of around 66EUR/MWh. This results in the plants profiting from charging during the periods of low prices and selling at high prices in the spot market.
- In 2040, the twofold result of an increase in price spreads up to ~77EUR/MWh due to large solar penetration, and an increase in continuous low-price periods (more than 12 hours) due to large wind generation, results in the largest gross margins for these technologies.
- In 2050, the large generation of hydrogen from electrolysers flattens the daily price spreads, leading to lower gross margins.
- It is important to point out, that some of these technologies' gross margins, like CAES 48h, reach their LCOS, while other technologies in the range, such as Gravity 24hr does not reach its LCOS and would require an additional support to reach their hurdle rate.

GERMANY

Germany has also significant solar PV capacity, and we expect 8-12h durations to also capture reasonably high margin

GROSS MARGINS (EUR/KW) REAL 2025 LDES: 8-12HR

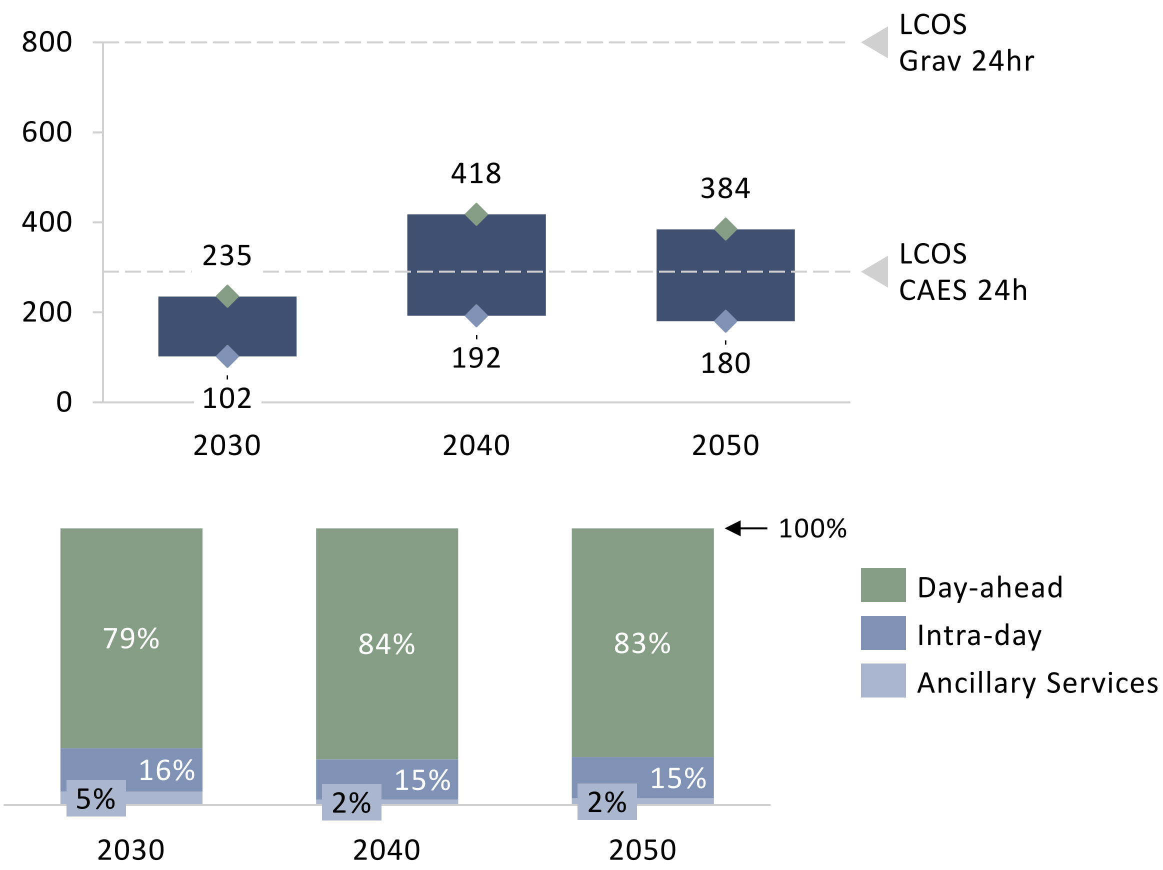


- In 2030, the large daily price spreads of ~66EUR/MWh, results in high gross margins from the day-ahead market. Additional revenues are obtained from ancillary services since the reserve markets are more lucrative and not cannibalised in these years.
- In 2040 the price spreads are larger than in other countries in NW Europe, ~77EUR/MWh, due to the large penetration of utility scale and distributed solar, and high demand at peak times. Additionally, the large amount of continuous low-price periods between 8-12 hours is the highest in this year. This leads to gross margins for these technologies being higher than in Southern European countries like Portugal.
- In a similar way as with longer duration storage, the large deployment of electrolysers, coupled with higher system flexibility by 2050 results in a decrease in gross margins for these technologies.
- In comparing the LCOS from the least expensive technology – an 8hr Li-ion battery- with the respective gross margins, it is seen that these technologies do not reach the expected LCOS.

GREAT BRITAIN

Great Britain presents the most lucrative country for longer duration storage, due to large penetration of offshore wind

GROSS MARGINS (EUR/KW) REAL 2025 LDES: 24-168HR



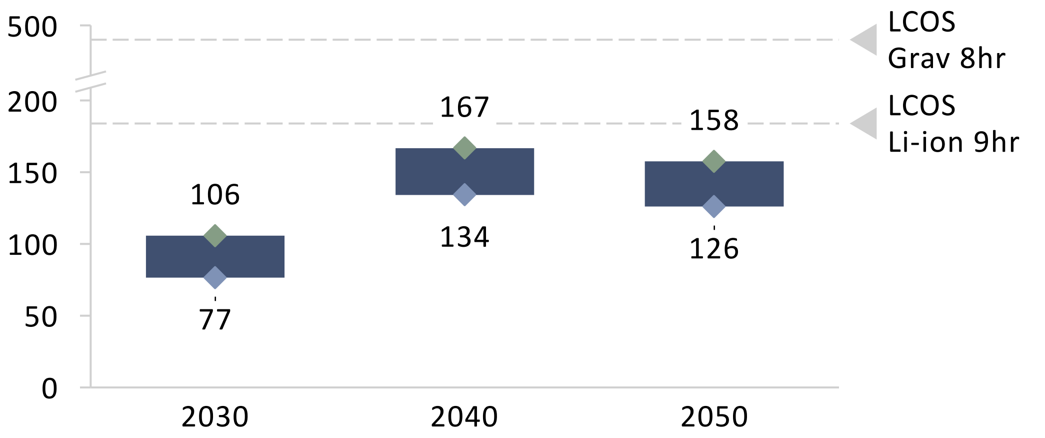
COMMENTARY

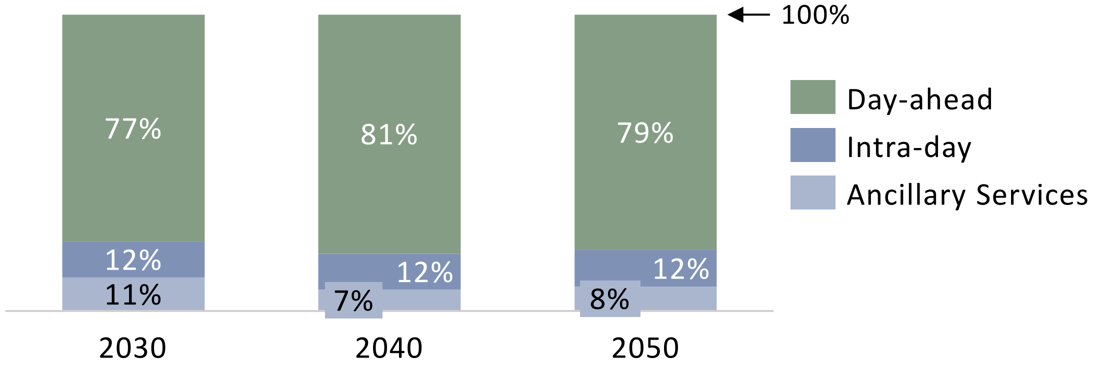
- In GB, the trends in gross margins for storage plants with duration higher than 24hr is similar in Germany, where the highest gross margins are obtained by Li-air due to its long duration and symmetric configuration.
- In 2030, the continuous periods of prices lower than 1EUR/MWh range between 8 and 24 hours. Additionally, the daily spread in prices is on average 47EUR/MWh. This leads to low opportunity for arbitrage for LDES.
- In 2040, the large penetration of offshore and onshore wind results in larger volatility in daily price spreads, as well as an increase in consequent periods of low prices for more than 24 hours, which is characteristic of the GB market. This results in an increase in gross margins from the day-ahead market.
- In 2050, the large electrification coupled with the large deployment of electrolysers results in a decrease in daily price spreads, and lower periods of low prices, leading to lower gross margins.
- Among these technologies, CAES from 24h and above reach their LCOS, while the other technologies would require an additional support to reach their hurdle rate.

GREAT BRITAIN

Medium duration storage presents lower gross margins in Grean Britain due to low price spreads and low solar PV penetration

GROSS MARGINS (EUR/KW) REAL 2025 LDES: 8-12HR





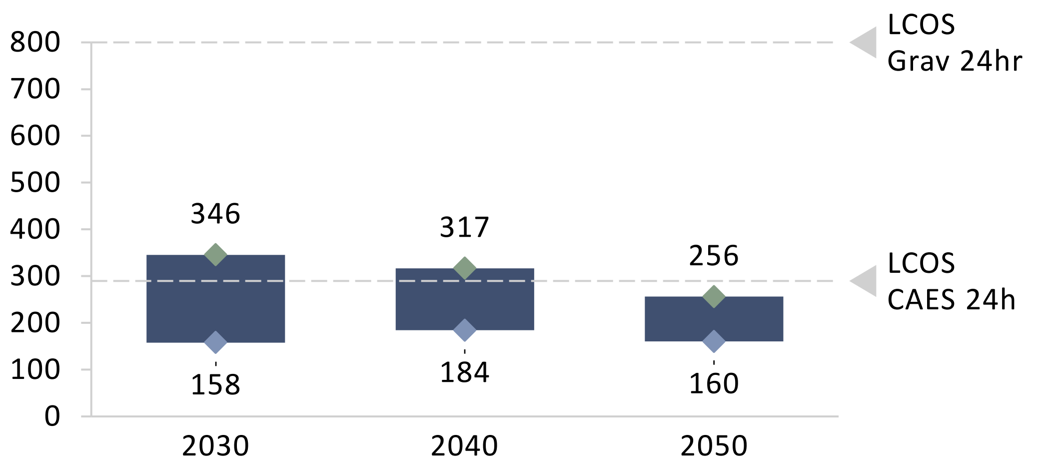
COMMENTARY

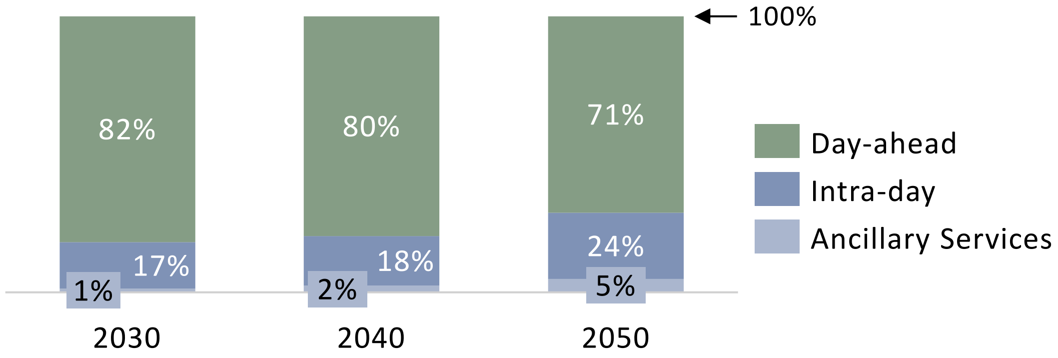
- The largest gross margins across technologies is from VFB due to the longer duration and the symmetric configuration, in comparison with LAES of the same duration.
- In a similar way as for longer duration storage, these plants see the highest revenues from arbitrage in the day-ahead market; however, they present higher revenues from ancillary services since they can respond at a faster rate than longer duration storage.
- These technologies follow the same trend in gross margins across the modelled period as the longer duration ones, where a peak in gross margins is reached in 2040 due to the increase in daily price spreads from 47EUR/MWh to 69EUR/MWh and the highest number of continuous periods of low prices between 8-12 hours.
- By 2050 the gross margins decrease slightly as a result of a reduction in daily price spread to around 66EUR/MWh.

SPAIN

The large price spreads due to solar penetration in Iberia in the early years, make the market lucrative for LDES, even if they are underutilised

GROSS MARGINS (EUR/KW) REAL 2025 LDES: 24-168HR





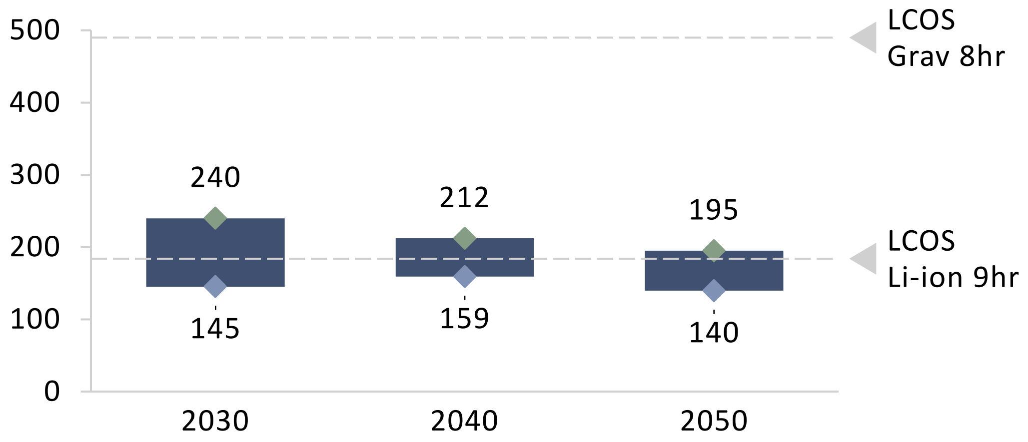
COMMENTARY

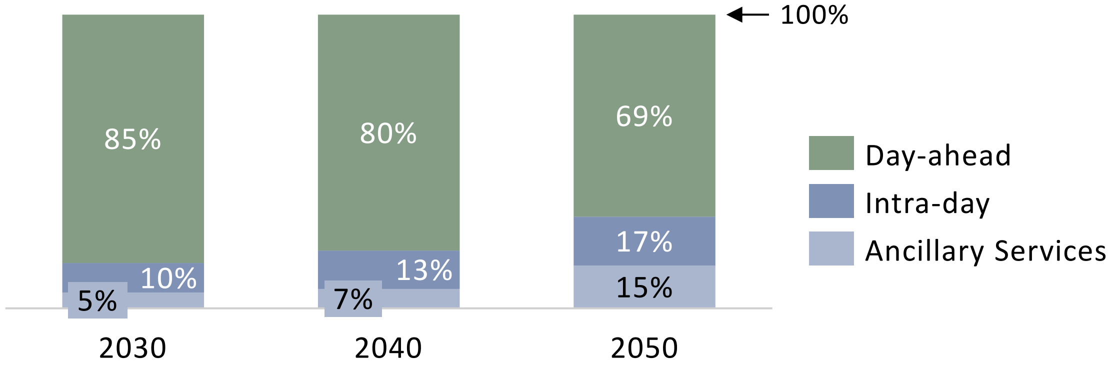
- Spain and Portugal present very similar results due to the interconnection between them and geographical location.
- In the early years, the already large deployment of solar PV in the Iberian peninsula, results in the largest daily price spreads in 2030 of ~85EUR/MWh. This results in the largest gross margins from most technologies, despite longer duration storage being underutilised in these years.
- In 2040, an increase in wind technologies results in longer periods of continuous low prices (more than 12hours), which is beneficial for these technologies. On the other hand, the larger penetration of electrolysers results in a decrease in daily price spreads to ~77EUR/MWh. Therefore, high gross margins are achieved in these years, although the most lucrative high prices in the spot market are rarer than in 2030.
- In 2050, the Iberian peninsula sees a flattening of the price spreads due to an increase in hydrogen generation through electrolysis. This reduces the long periods of continuous low prices by ~45%, resulting in lower gross margins.

SPAIN

The Iberian peninsula is the most lucrative market for storage with duration between 8-12 hours due to large price spreads and solar penetration

GROSS MARGINS (EUR/KW) REAL 2025 LDES: 8-12HR





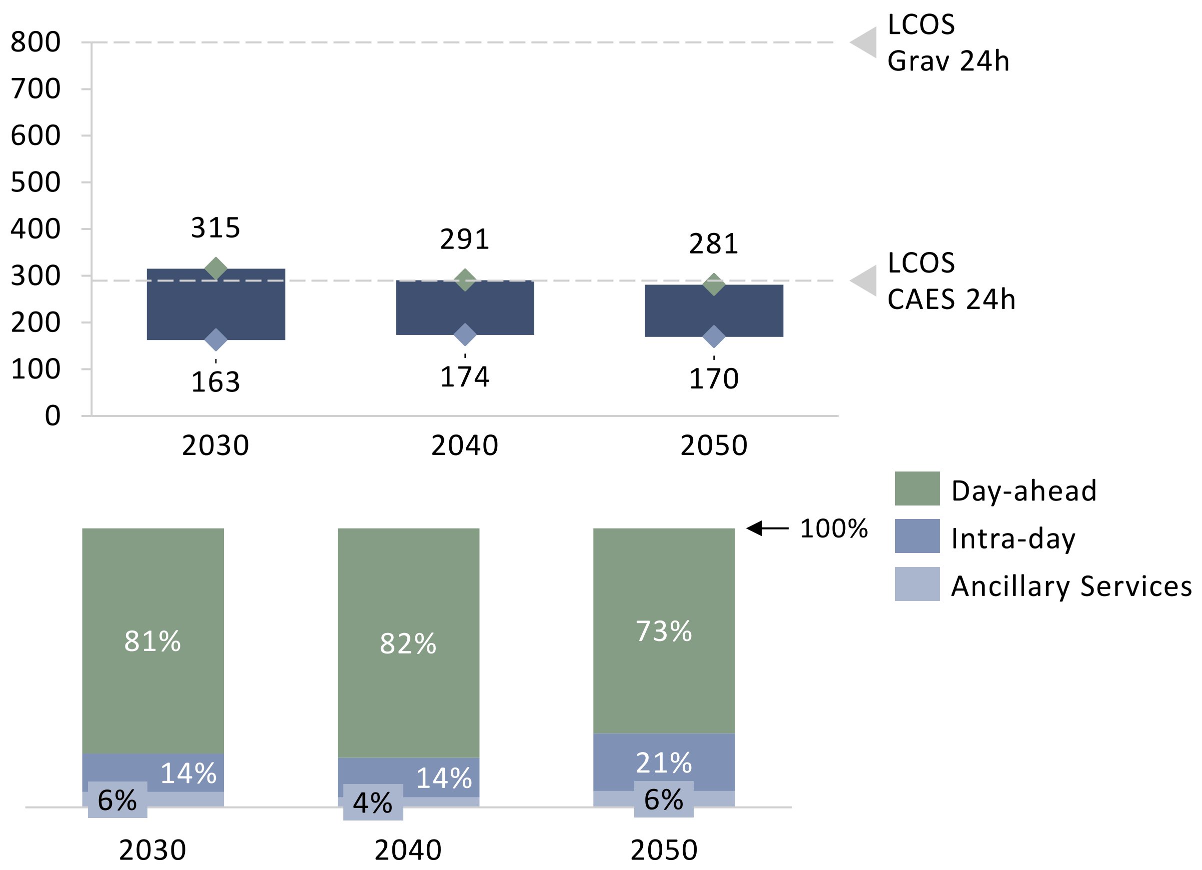
COMMENTARY

- The Iberian markets are the most attractive for LDES with durations between 8-12 hours. The highest gross margins are achieved by both 12hr VFBs as well as 10hr Compressed CO2. This is a result of the largest amount of periods of continuous low prices between 8 – 12 hours throughout the modelled period. Despite Iberia having the largest gross margins for 8-12hr storage, only Li-ion batteries reach their LCOS throughout the modelled period.
- In 2030, more than 170 periods of continuous low prices between 8-12 hours can be seen. This is a result of the large-scale penetration of solar PV. Additionally, the large price spreads in this year, make it the most lucrative for technologies with duration between 8-12 hours.
- In 2040, despite a decrease in periods of continuous low prices (75-110), and the decrease in price spreads (~77EUR/MWh), the gross margins are still significant since the market conditions are adequate for the utilisation of technologies between 8-12 hours.
- As is the case of longer duration storage, the market is cannibalised by the large penetration of electrolysers, which flattens the daily price spreads, and leads to lower gross margins for all technologies of medium duration.

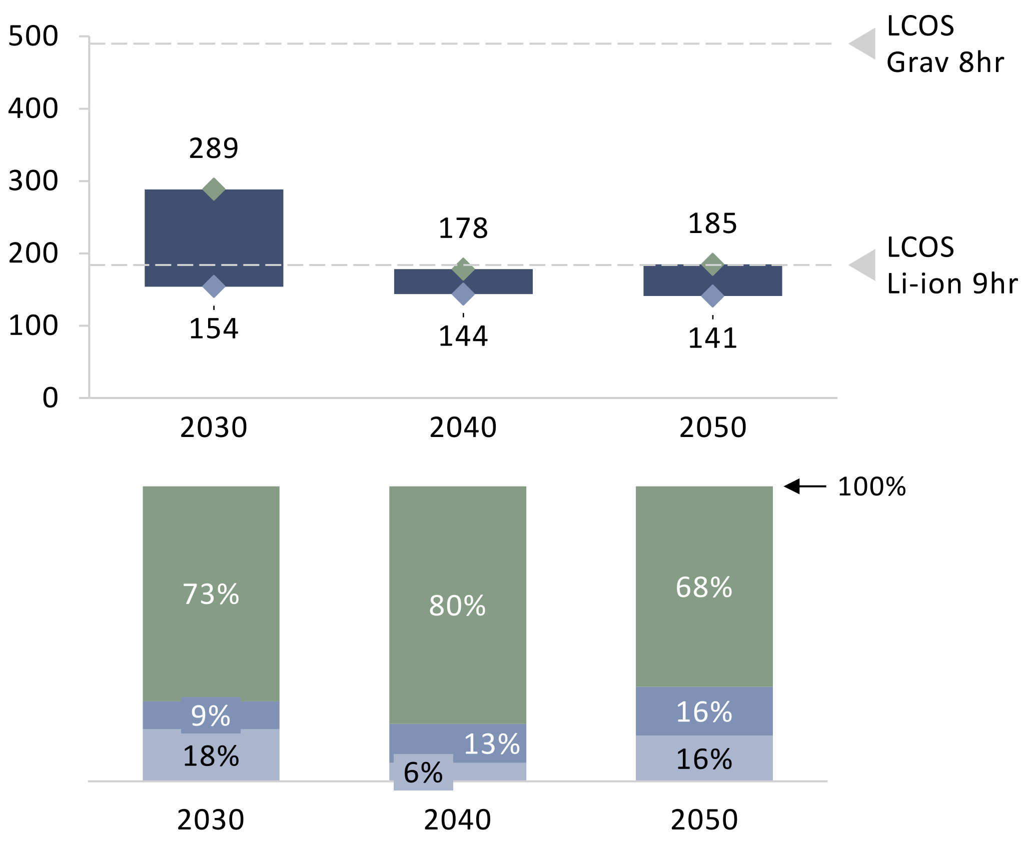
PORTUGAL

Portugal follows similar trends as Spain in terms of gross margins for all LDES technologies analysed

GROSS MARGINS (EUR/KW) REAL 2025 LDES: 24-168HR

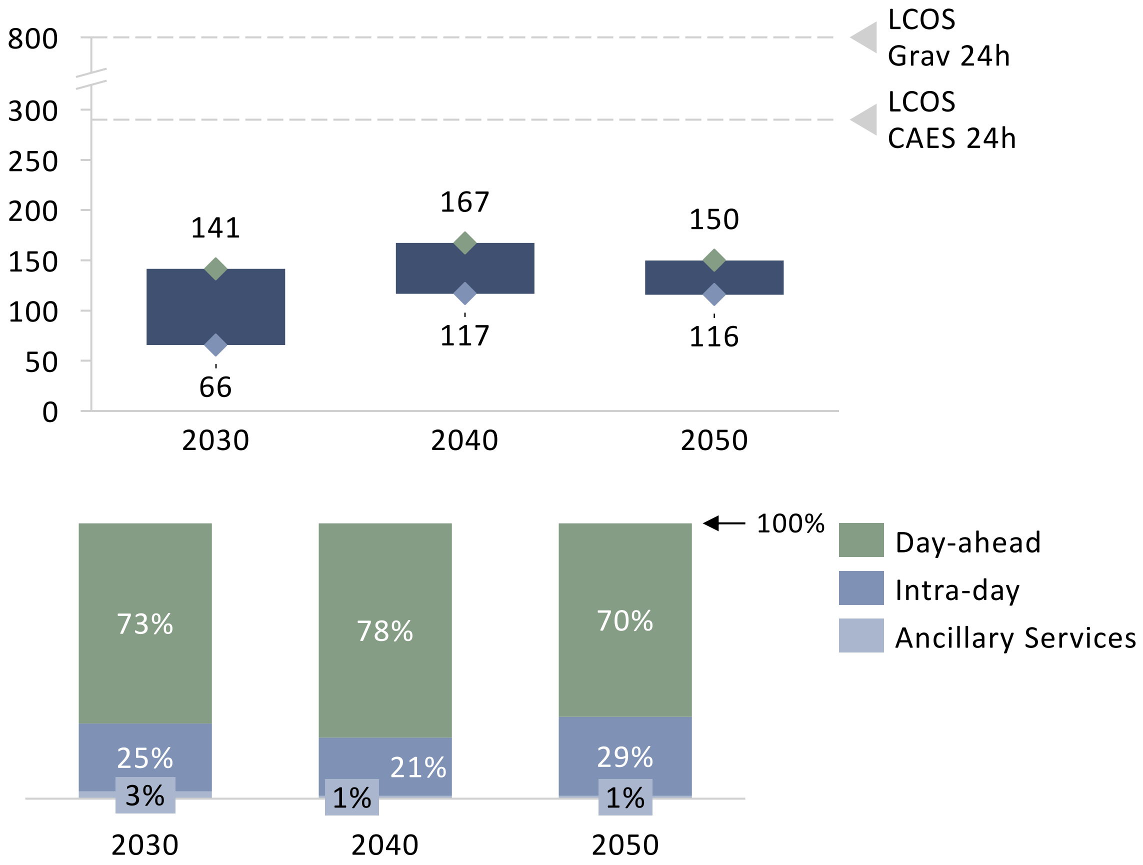


GROSS MARGINS (EUR/KW) REAL 2025 LDES: 8-12HR



Finland's low-volatility and flat prices makes LDES economically unviable without additional revenue support across all time horizons

GROSS MARGINS (EUR/KW) REAL 2025 LDES: 24-168HR



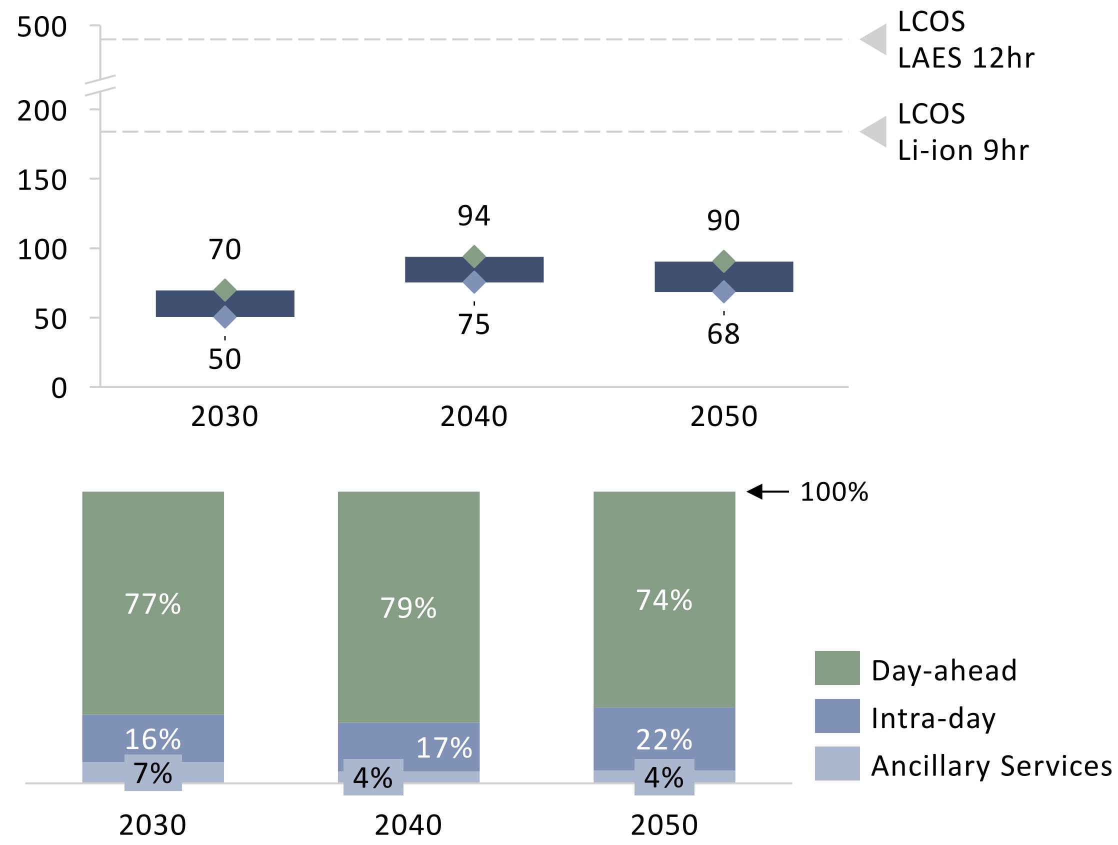
COMMENTARY

- Overall, the Finnish market presents a persistently unappealing case for LDES, as none of the technologies analysed reach their LCOS across any of the years modelled, pointing to a structural need for additional support.
- In 2030, the large multi-day volatility is outweighed by a low number of low-price periods, meaning that despite monthly price fluctuations, LDES assets are unable to charge at sufficiently low prices to generate viable returns.
- The case improves marginally in 2040, as deeper wind penetration drives longer low-price periods that offer more charging opportunities. However, the low multi-day volatility signals a broader flattening of prices throughout the month — consistent with annual average wholesale prices of around €22/MWh — such that while storage can charge over extended low-price windows, the prices at which it can sell are not high enough to turn a profit.
- By 2050, an annual average price of around €15/MWh and persistently low multi-day volatility indicate that prices remain depressed throughout the year. Despite a growing number of near-zero price periods that allow LDES to charge, the day-ahead prices available at discharge remain too low to support a viable business case.

FINLAND

Finland's hydro and electrolyser-dominated system makes a difficult case for 8–12 hour storage across all time horizons

GROSS MARGINS (EUR/KW) REAL 2025 LDES: 8-12HR



COMMENTARY

- Finland's hydro-dominated system naturally suppresses intra-day price volatility, limiting the arbitrage opportunity that 8–12 hour assets depend on. This effect is compounded over time by growing electrolyser deployment, which absorbs surplus renewable generation and further flattens within-day price differentials. As a result, none of the technologies with duration between 8-12 hours achieve their LCOS in any of the years modelled — making Finland one of the weakest markets for mid-duration LDES.

- Day-ahead trading is the dominant revenue source, but spread compression limits its upside.

- Ancillary services provide only marginal additional income, with reserve prices expected to fall below €5/MW/h as more storage enters the market.

- Balancing services are increasingly required in a renewables-heavy system, but contribute at most 22% of total gross margins — insufficient to meaningfully bridge the gap to LCOS.

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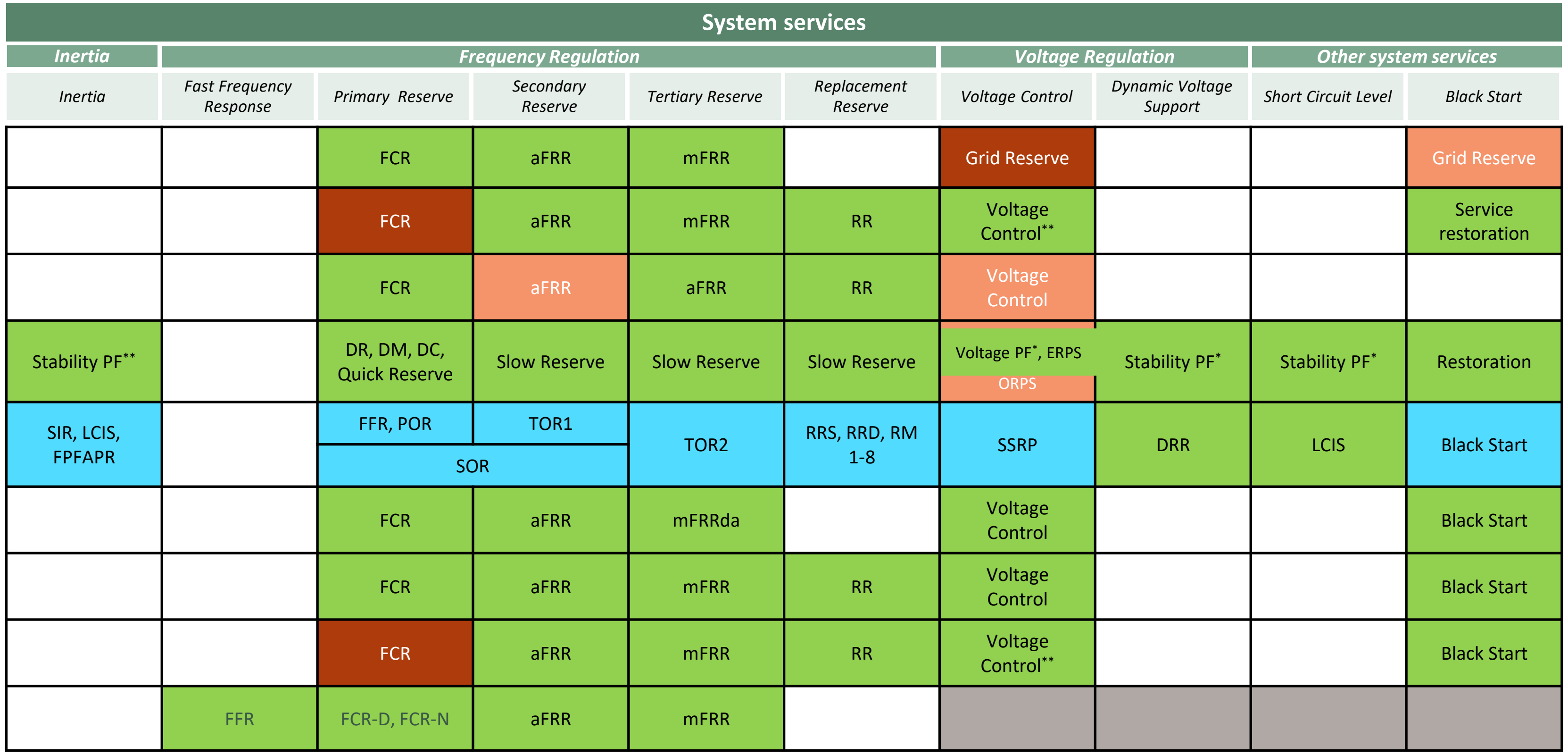
ANNEX – SYSTEM SERVICES

System services are becoming increasingly important for system operation



System services

	Inertia	Frequency Regulation				Voltage Regulation		Other system services	
	Inertia	*Fast Frequency Response*	*Primary Reserve*	*Secondary Reserve*	*Tertiary Reserve*	*Replacement Reserve*	*Voltage Control*	*Dynamic Voltage Support*	*Short Circuit Level*	*Black Start*
Germany			🟩 FCR	🟩 aFRR	🟩 mFRR		🟥 Grid Reserve			🟧 Grid Reserve
Spain			🟥 FCR	🟩 aFRR	🟩 mFRR	🟩 RR	🟩 Voltage Control**			🟩 Service restoration
France			🟩 FCR	🟧 aFRR	🟩 aFRR	🟩 RR	🟧 Voltage Control			
Great Britain	🟩 Stability PF**		🟩 DR, DM, DC, Quick Reserve	🟩 Slow Reserve	🟩 Slow Reserve	🟩 Slow Reserve	🟩 Voltage PF*, ERPS 🟧 ORPS	🟩 Stability PF*	🟩 Stability PF*	🟩 Restoration
Ireland	🟦 SIR, LCIS, FPFAPR		🟦 FFR, POR 🟦 SOR	🟦 TOR1	🟦 TOR2	🟦 RRS, RRD, RM 1-8	🟦 SSRP	🟩 DRR	🟩 LCIS	🟦 Black Start
Netherlands			🟩 FCR	🟩 aFRR	🟩 mFRRda		🟩 Voltage Control			🟩 Black Start
Poland			🟩 FCR	🟩 aFRR	🟩 mFRR	🟩 RR	🟩 Voltage Control			🟩 Black Start
Portugal			🟥 FCR	🟩 aFRR	🟩 mFRR	🟩 RR	🟩 Voltage Control**			🟩 Black Start
Finland		🟩 FFR	🟩 FCR-D, FCR-N	🟩 aFRR	🟩 mFRR		▨	▨	▨	▨

Legend

🟥	*Mandatory, no remuneration*
🟧	*Mandatory, remunerated*
🟦	*Voluntary – remuneration based on fixed/indexed price*
🟩	*Voluntary - market based remuneration*
▨	*No publicly available information found*
☐	*Product not available in this country*

*PF: Power Frequency; SIR: Synchronous Inertial Response; FFR: Fast Frequency Response; LCIS: Low Carbon Inertia Service; FCR: Frequency Containment Reserve; DR: Dynamic Regulation; DM: Dynamic Moderation; DC: Dynamic Containment; POR: Primary Operating Reserve; aFRR: automatic Frequency Restoration Reserve; mFRR: manual Frequency Restoration Reserve; SOR: Secondary Operating Reserve; TOR: Tertiary Operating Reserve; RR: Replacement Reserve; RRS: Replacement Reserve – Synchronised; RRD: Replacement Reserve – De-synchronised; RM: Ramping; ORPS: Obligatory Reactive Power Service; SSRP: Steady-State Reactive Power; ERPS: Enhanced Reactive Power Service; FPFAPR: Fast Post-Fault Active Power Recovery; DRR: Dynamic Reactive Response; ** In Iberia, plants are obliged to provide a minimum voltage control, but most needs are managed through the constraints management process

Storage can also benefit from ‘new’ revenues from the introduction of or remuneration for system services beyond Balancing Capacity/reserve

1. Inertia response

In traditional power systems, inertia is provided by the rotational mass of synchronous generators, absorbing and balancing sudden changes in the supply-demand balance. However, as more renewable energy sources are added, the amount of rotational mass decreases, challenging grid stability. Various solutions are being developed to address this, including advanced control strategies and innovative provision of inertia from low-carbon solutions. Storage can provide ‘synthetic’ inertia , and this could be an additional income stream also for LDES (for example through short-term markets, long-term contracts or regulated payments).

2. Fast response

Fast response refers to the ability of a power system to accurately respond to changes in system conditions. Fast response (<5s) is critical for maintaining grid stability and ensuring the reliable operation of the power system, complementing inertia response. Fast response can be achieved through various means, including energy storage technologies. Energy storage systems such as batteries or flywheels can provide fast response by injecting or absorbing power to balance sudden changes in demand or supply. Similarly, power electronics devices such as FACTS (Flexible AC Transmission Systems) and HVDC (High Voltage Direct Current) provide control over the flow of power in the grid to help maintain system stability.

3. Dynamic reactive power

Dynamic reactive power relates to reactive power that can be rapidly adjusted to maintain voltage stability. Unlike steady-state reactive power, which is supplied by fixed devices such as capacitors and reactors, dynamic reactive power is provided by power electronics devices such as STATCOMs (Static Synchronous Compensators) and SVCs (Static VAR Compensators). These devices can quickly inject or absorb reactive power to help regulate voltage levels. Dynamic reactive power is particularly important in modern power systems, where there is an increasing amount of intermittent renewable energy.

4. Ramping

Denoted as the gradual increase or decrease in the output of a power plant or renewable energy resource to maintain the supply-demand balance. It typically has a duration longer (up to several hours) than those addressed by Frequency Containment or Frequency Restoration Reserves. Ramping is an important concept in power system operations, as it can affect the stability and reliability of the grid.

Source: AFRY analysis

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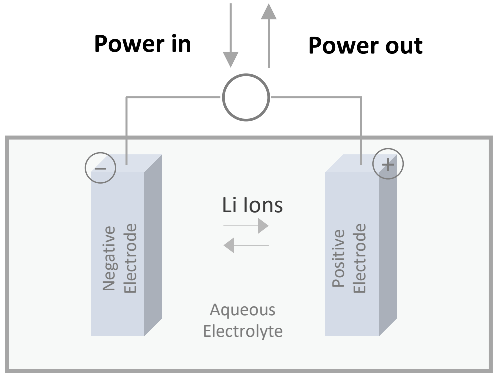
LiB are currently the most cost-effective solution for within-day energy shifting

DESCRIPTION OF LITHIUM-ION BATTERIES (LIB)



CHARGE MODE

Electricity is used to move the lithium ions from the positive electrode to the negative electrode where they are stored

DISCHARGE MODE

In the discharge mode the reverse flow occurs: the lithium ions flow from the negative to the positive electrode generating a flow of electrons

Source: ENTEC, DOE, EASE, MIT, Scientific Literature review

KEY PERFORMANCE DATA AND PROS - CONS

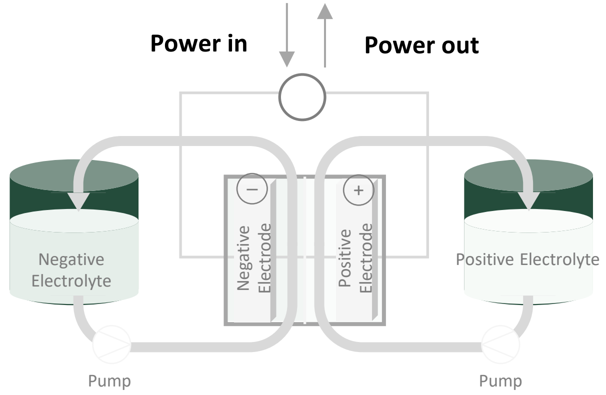
POWER RANGE	0.1 MW – 400 MW
ENERGY RANGE	Up to 1 GWh
DISCHARGE TIME	Up to 12h
LIFETIME	~ 20 years
REACTION TIME	milliseconds
EFFICIENCY	~ 85 %
ONLINE CAPACITY	~ 20 GW/30 GWh in Europe

👍 Most cost-effective solution for intra-day electricity shifting, which represents the largest segment of the storage market

👎
- Value chain concerns due to rare materials
- Limited lifetime
- Battery degradation over time

VFB has the advantage of independently scaling power output and energy stored; however, cost is still above that of LiB

DESCRIPTION OF FLOW BATTERIES (VFB)



CHARGE MODE

Electricity flows from the positive to negative electrode, leading to the electrochemical reaction of ions which move to the negative and positive electrolyte where they are stored

DISCHARGE MODE

In the discharge mode, the reverse electrochemical reaction occurs causing the ions to release the stored electric energy

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	Up to 100 MW
ENERGY RANGE	Up to 400 MWh
DISCHARGE TIME	4h – 24h
LIFETIME	~ 23 years
REACTION TIME	milliseconds
EFFICIENCY	~ 70 %
ONLINE CAPACITY	~ 500 MW /1500 MWh worldwide

Power output and energy stored can be scaled independently

Little degradation and longer lifetime than Li-Ion

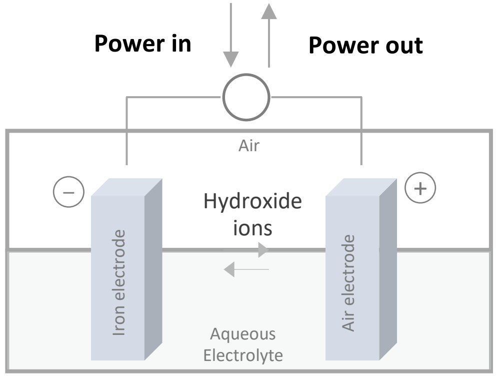
Lower efficiency compared to other technologies

Higher investment cost

Source: ENTEC, DOE, EASE, VANITEC, Scientific Literature review

Iron-air batteries use readily available materials; however, efficiency is low and they have a large footprint

DESCRIPTION OF IRON-AIR BATTERIES (IAB)



CHARGE MODE

Electrons from the charging current react with the rusted iron, turning it into iron and releasing hydroxide ions; these react with the air electrode, forming water, electrons and oxygen.

DISCHARGE MODE

Oxygen enters the battery through the air electrode, reacting with water to form hydroxide ions that rust the iron electrode, release electrons that form the discharge current.

Source: Form Energy, Scientific Literature review

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	Up to 500 MW
ENERGY RANGE	Up to 50,000 MWh
DISCHARGE TIME	100h
LIFETIME	~ 30 years
REACTION TIME	milliseconds
EFFICIENCY	~ 50 %
ONLINE CAPACITY	~ 15 MW /1500 MWh worldwide

Capacity to significantly scale up storage using widely available resources

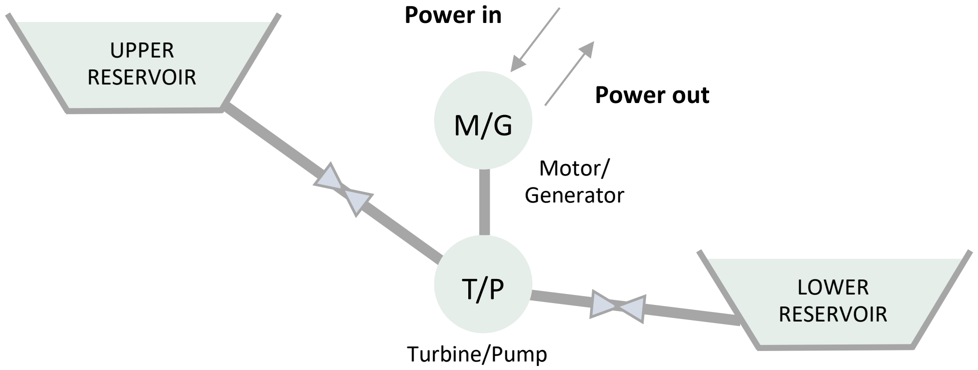
Potential lifetime of 30 years

Large physical footprint due to low energy density

Low round trip efficiency

PHES is the most mature storage technology, but cost-effective deployment is restricted to specific locations

DESCRIPTION OF PUMPED HYDRO ENERGY STORAGE (PHS)



CHARGE MODE

Electricity is used to pump water from a lower reservoir to a higher one, thus storing its potential energy

DISCHARGE MODE

The water from the upper reservoir is released converting the potential energy into power using a turbine and a generator

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	5 MW – 3 GW
ENERGY RANGE	Up to 40 GWh
DISCHARGE TIME	Some h – some days
LIFETIME	~ 50 years
REACTION TIME	Seconds
EFFICIENCY	~ 70-85%
ONLINE CAPACITY	~ 50 GW/350 GWh in Europe[1]

Enables large scale energy storage with long durations

Most mature technology

Requires specific geographical features, limiting suitable locations

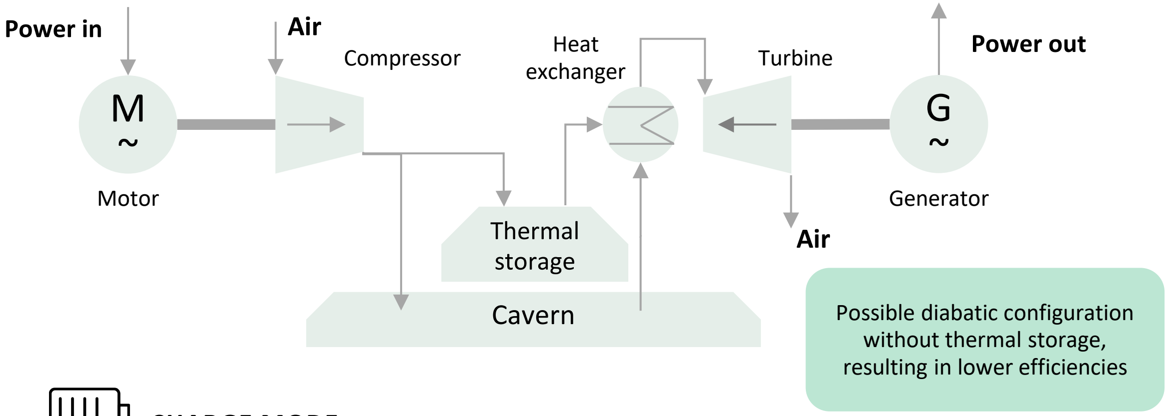
Long approval processes

Source: ENTEC, DOE, EASE, MIT, Scientific Literature review

Note 1) Energy capacity estimated based on a 7-hour average duration, as referenced by Terna for Italy

CAES is one of the most promising longer duration storage technologies expected to be deployed over the coming years

DESCRIPTION OF COMPRESSED AIR ENERGY SYSTEMS (CAES)



Possible diabatic configuration without thermal storage, resulting in lower efficiencies

CHARGE MODE

Surplus power compresses air to 70 bars, with temperatures over 600°C. Hot air transfers heat to a thermal storage before being injected in caverns under pressure (around 50 °C).

DISCHARGE MODE

Air is reheated via thermal storage and expanded in a turbine to generate power without fuel.

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	10 – 300 MW
ENERGY RANGE	100 MWh - 10 GWh
DISCHARGE TIME	Some h – some days
LIFETIME	>30 years
REACTION TIME	Minutes
EFFICIENCY	~ 65%-70%
ONLINE CAPACITY	~ 1 GW/7 GWh worldwide

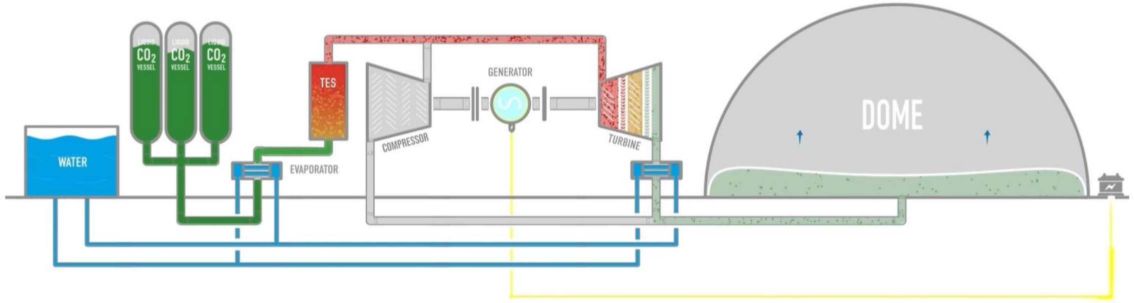
- Large power and energy range envelopes
- Mature and reliable component technologies

- Highly location-specific, dependent on caverns
- High capital costs and large footprint
- Limited E/P ratio due to the thermal storage

Source: ENTEC, DOE, EASE, Scientific Literature review

LCES is an emerging storage solution with much higher density than CAES; no critical material requirements or degradation compared to Li-ion BESS

DESCRIPTION OF LIQUID CO2 ENERGY STORAGE (LCES)



CHARGE MODE

CO2 is compressed to around 70 bar, which raises its temperature to approximately 400°C. The compressed CO2 is then cooled down using a Thermal Energy Storage (TES) system and stored in its liquid phase at ambient temperature.

DISCHARGE MODE

The liquid CO2 is reheated through the TES and expanded in a turbine to generate power. The exhaust CO2 is collected in a dome, ready to be recompressed and stored for the next cycle.

Source: EnergyDome, Scientific Literature review

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	2 – 25 MW
ENERGY RANGE	Up to 200 MWh
DISCHARGE TIME	From hours to days
LIFETIME	>30 years
REACTION TIME	Seconds
EFFICIENCY	~ 75%-80%
ONLINE CAPACITY	~ 110 MW/220 MWh[1] worldwide

Liquid carbon dioxide can be stored at ambient temp

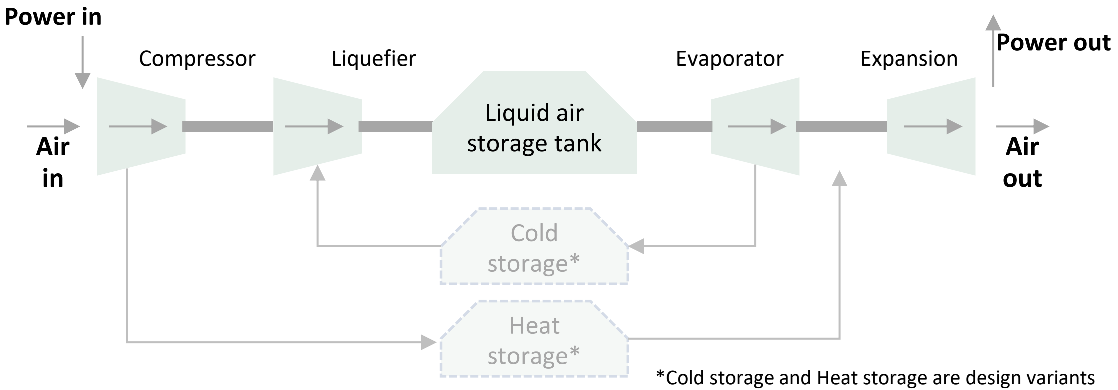
Liquid CO2 has a ten times much higher energy density than CAES systems

Early-stage technology with complex design

Limited power range, further constrained by the large land area required for the dome

LAES is an emerging technology; upfront investment cost is currently relatively high

DESCRIPTION OF LIQUID AIR ENERGY STORAGE (LAES)



*Cold storage and Heat storage are design variants to increase process efficiency

CHARGE MODE

Electricity is used to liquefy air to -196 °C which is then stored in cryogenic tanks at low-pressure

DISCHARGE MODE

In the discharge mode, the liquid air is compressed and evaporated. The high-pressure and superheated gaseous air is expanded through a steam turbine to generate electricity.

Source: ENTEC, DOE, EASE, Highview Power, Scientific Literature review

KEY PERFORMANCE DATA AND PROS - CONS

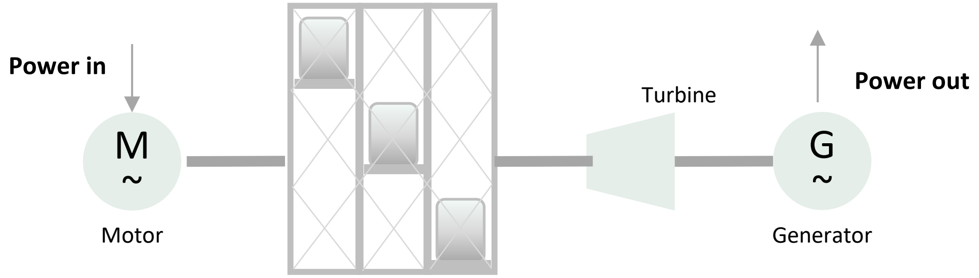
POWER RANGE	Up to 100 MW
ENERGY RANGE	Up to 2.5 GWh
DISCHARGE TIME	Some h – some days
LIFETIME	~ 30 years
REACTION TIME	Minutes
EFFICIENCY	~ 60 %
ONLINE CAPACITY	~ 5 MW /15 MWh worldwide

Scalable technology with no size or geographic constraint
Designed based on established processes in the turbomachinery and industrial gas sector

High investment cost for the plant construction.
Lower efficiency compared to other technologies. The liquefaction of air is a particularly electricity intensive process

GES is in the early development stage; costs are still uncertain, but do not appear to be cost-competitive currently

DESCRIPTION OF GRAVITATIONAL ENERGY STORAGE (GES)



CHARGE MODE

Electricity is used by a motor to lift a mass thus storing its gravitational potential energy

DISCHARGE MODE

The lifted mass is dropped converting the gravitational energy into power using a turbine and a generator

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	Up to 25 MW
ENERGY RANGE	Up to 100 MWh
DISCHARGE TIME	Some h – some days
LIFETIME	~ 50 years
REACTION TIME	Seconds
EFFICIENCY	~ 80%
ONLINE CAPACITY	~ 42 MW/168 MWh worldwide

Modular technology allowing flexibility in size

Limited storage degradation

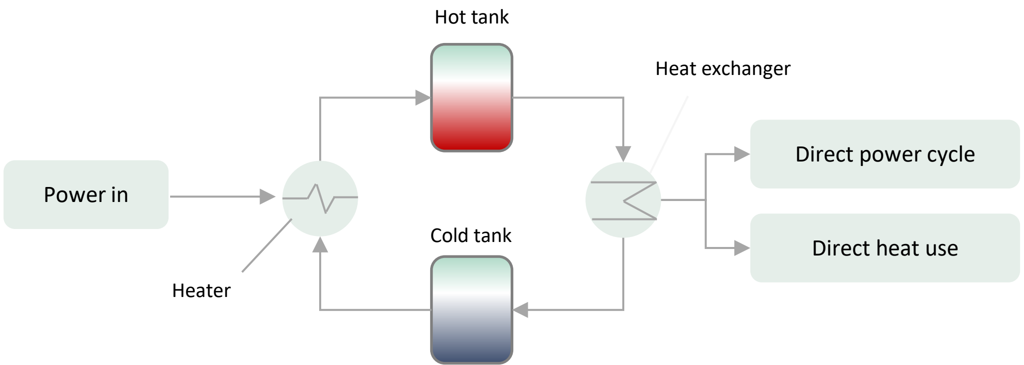
No rare materials involved

Higher unitary capital costs compared to other storage technologies

Source: ENTEC, DOE, EASE, MIT, Scientific Literature review

TES is based largely on ‘off-the’ shelf components and can be used as stand-alone or add-on and is thus a promising solution for both power and heat use

DESCRIPTION OF MOLTEN SALT THERMAL ENERGY STORAGE (TES)



CHARGE MODE

Electricity from the grid is used to heat the thermal storage fluid to temperatures as high as 400-700°C (with potential advancements reaching 1500°C in the near future).

DISCHARGE MODE

The stored heat is transferred to a secondary working fluid, which can either be used for direct electricity production through a power cycle or for direct heat applications

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	Up to 100 MW
ENERGY RANGE	Up to 1 GWh
DISCHARGE TIME	Some h – some days
LIFETIME	>30 years
REACTION TIME	Minutes
EFFICIENCY	~ 50-55%
ONLINE CAPACITY	~ 1 GW/8.5 GWh in Europe[1]

Tech based on mostly standardized components

Can be deployed as stand-alone baseload and as add-on facilities at operating power plants

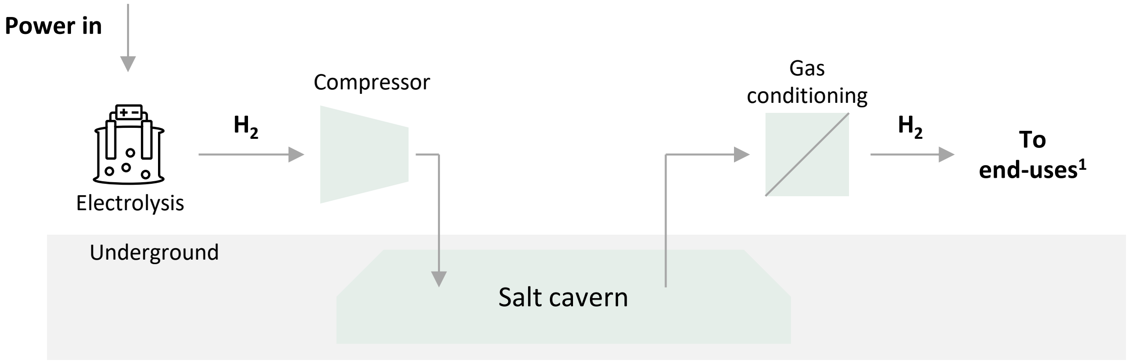
Higher capital costs compared to batteries, coupled with relatively lower round-trip efficiency

Limited E/P ratio due to thermal storage constraints

Notes: 1) This refers to Molten Salt technologies, frequently use in concentrating solar power plants. There are no commercial power-to-Heat-to Power storage projects in Europe Source: ENTEC, DOE, EASE, SYSTEMIQ, Scientific Literature review

Hydrogen can be stored underground into salt caverns, which can be cycled at weekly or monthly timescales

DESCRIPTION OF HYDROGEN SALT CAVERN STORAGE



CHARGE MODE

Hydrogen is injected into the salt cavern, which is a sealed underground chamber formed by dissolving salt layers. The impermeable walls ensure the containment of hydrogen at high pressure

DISCHARGE MODE

Hydrogen is withdrawn from the cavern as pressure is reduced, allowing the gas to flow back to the surface through pipelines and into a gas conditioning system.

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	10 MW – 1 GW
ENERGY RANGE	10 GWh – 400 GWh
DISCHARGE TIME	Above 168h
LIFETIME	~ 30 years
REACTION TIME	hours
EFFICIENCY[2]	~ 95 %
ONLINE CAPACITY	160 GWh in Europe by 2030

Allow for weekly to monthly duration storage

Large storage capacity and power range

Highly location specific, dependent on geological soil composition

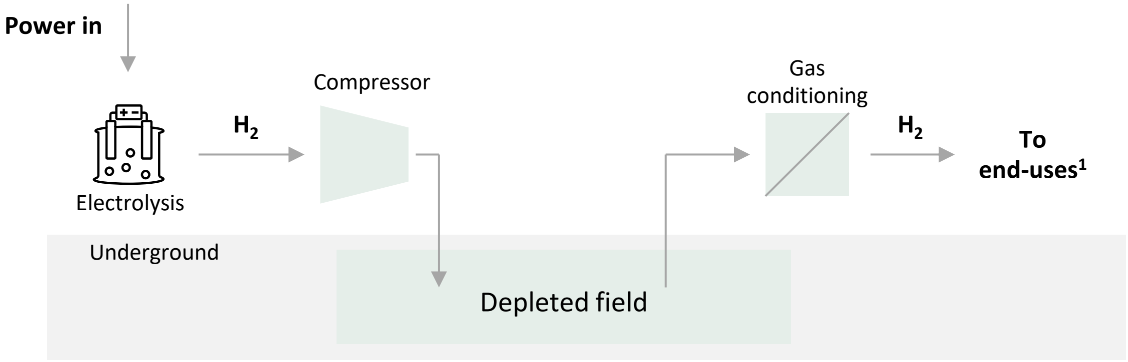
High capital expenses for mining and infrastructure

Source: H2 Infrastructure map

Note 1) Either direct use or reconversion to power. 2) Considering only storage efficiency, i.e. compression, leakages, and conditioning. Full round-trip efficiency of the power-H2-power would drop to <50% due to electrolysis and electricity reconversion efficiencies.

Hydrogen can also be stored in depleted oil & gas fields, which typically allow for slower injection and withdrawal rates

DESCRIPTION OF HYDROGEN DEPLETED FIELDS STORAGE



CHARGE MODE

Similarly to salt cavern storage, hydrogen is injected into porous rock formations previously used to store hydrocarbons, with the gas filling the empty pore spaces under controlled pressure

DISCHARGE MODE

Hydrogen is extracted from the depleted field and the conditioned before pipeline injection. Due to presence of hydrocarbons which may contaminate the hydrogen, conditioning process may be more thorough than for a salt cavern injection

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	1 MW – 1 GW
ENERGY RANGE	10 GWh – 500 GWh
DISCHARGE TIME	Above 720h
LIFETIME	~ 30 years
REACTION TIME	hours
EFFICIENCY[2]	~ 95 %
ONLINE CAPACITY	15 GWh in Europe by 2030

Large storage capacity and power range

Potential re-use of existing infrastructure installed in the hydrocarbon fields

Highly location specific, dependent on geological soil composition

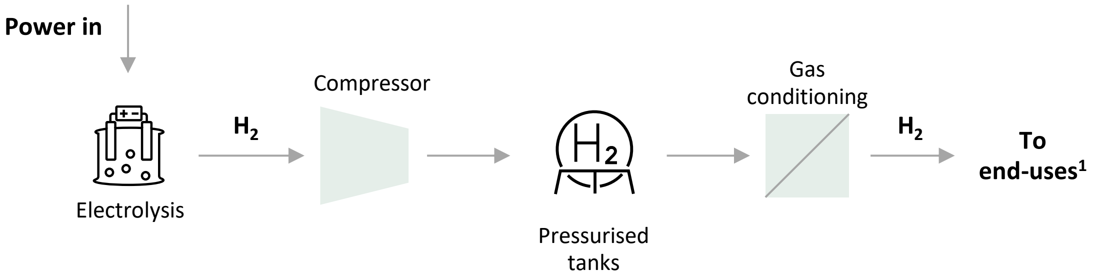
Slow discharge rates allowing only monthly cycles

Source: H2 Infrastructure map

Note 1) Either direct use or reconversion to power. 2) Considering only storage efficiency, i.e. compression, leakages, and conditioning. Full round-trip efficiency of the power-H2-power would drop to <50% due to electrolysis and electricity reconversion efficiencies.

Hydrogen can be stored in pressurised tanks, which allows for scalable, yet more costly, storage

DESCRIPTION OF HYDROGEN PRESSURISED TANKS



Power in

Electrolysis

H_2

Compressor

Pressurised tanks

Gas conditioning

H_2

To end-uses[1]

CHARGE MODE

Hydrogen gas is compressed and injected into pressurised tanks up to 350/500 bar and then safely stored

DISCHARGE MODE

Hydrogen is then withdrawn through a controlled outflow from the tank

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	1 MW – 30 MW
ENERGY RANGE	10 MWh – 300 MWh
DISCHARGE TIME	Some h – some days
LIFETIME	~ 30 years
REACTION TIME	hours
EFFICIENCY[1]	~ 95 %
ONLINE CAPACITY	n/a

Scalable and flexible storage systems, which can be installed modularly in the desired locations

Allow for short-term hydrogen balancing

Limited storage capacity, with costs being a key barrier for scalability above 300MWh

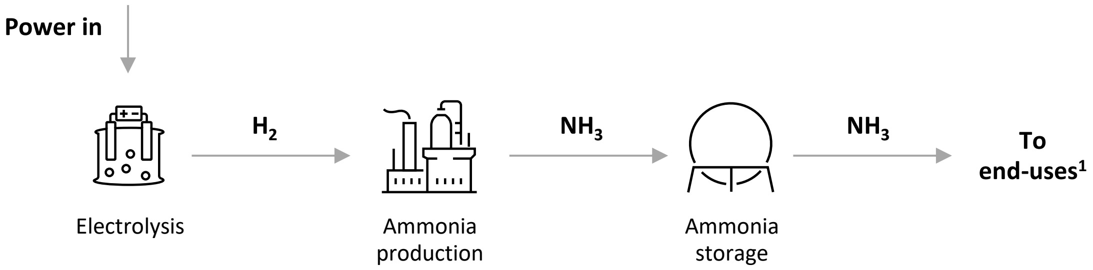
High energy and cost requirements for compression

Source: H2 Infrastructure map

Note 1) Either direct use or reconversion to power. 2) Considering only storage efficiency, i.e. compression, leakages, and conditioning. Full round-trip efficiency of the power-H2-power would drop to <50% due to electrolysis and electricity reconversion efficiencies.

Additionally, hydrogen can be converted into carriers, such as ammonia, which can be easily stored despite a more complex value chain

DESCRIPTION OF AMMONIA POWER-TO-X VALUE CHAIN



Power in

H_2 → NH_3 → NH_3 →

Electrolysis

Ammonia production

Ammonia storage

To end-uses[1]

CHARGE MODE

Hydrogen is converted into ammonia, typically via the Haber-Bosch process, which is then stored in refrigerated above ground tanks

DISCHARGE MODE

Ammonia is then withdrawn from the tank and can then be readily used or can be converted into power via dedicated ammonia solid oxide fuel cells

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	1 MW – 100 MW
ENERGY RANGE	Up to 5-10 GWh
DISCHARGE TIME	Some hours - months
LIFETIME	~ 20 years
REACTION TIME	hours
EFFICIENCY[2]	~ 98 %
ONLINE CAPACITY	n/a

Easier transport and storage compared to hydrogen, given its higher liquefaction temperature

Versatile uses, as a fuel or chemical feedstock

Toxicity and handling risks

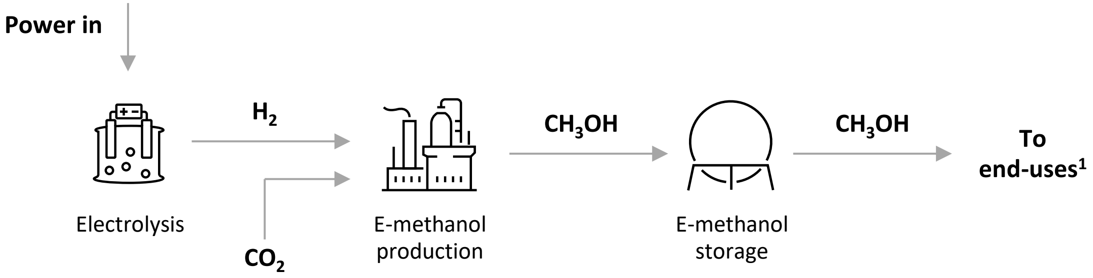
Lower round-trip efficiency, especially due to an energy-intensive production process

Source: H2 Infrastructure map

Note 1) Either direct use or reconversion to power. 2) Considering only storage efficiency, i.e. compression, leakages, and conditioning. Full round-trip efficiency of the power-H2-power would drop to <50% due to electrolysis and electricity reconversion efficiencies.

Similarly, hydrogen can be combined with CO2 to produce e-methanol, then stored in liquid form at ambient temperature

DESCRIPTION OF E-METHANOL POWER-TO-X VALUE CHAIN



Power in

Electrolysis

H_2

CO_2

E-methanol production

CH_3OH

E-methanol storage

CH_3OH

To end-uses[1]

CHARGE MODE

Hydrogen and CO2 are used to synthesise methanol, which is then stored at ambient temperature in above ground tanks

DISCHARGE MODE

Methanol is extracted from the tank and can be readily used or converted back into power via dedicated methanol solid oxide fuel cells

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	1 MW – 100 MW
ENERGY RANGE	Up to 5-10 GWh
DISCHARGE TIME	Some hours - months
LIFETIME	~ 20 years
REACTION TIME	hours
EFFICIENCY[2]	~ 98 %
ONLINE CAPACITY	n/a

Easier transport and storage compared to hydrogen, since methanol is liquid at ambient temperature

Versatile uses, as a fuel or chemical feedstock

Needs for a CO2 source for the production process

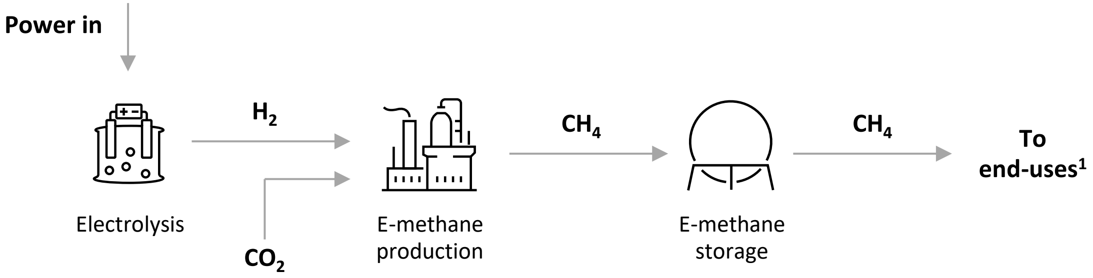
Lower round-trip efficiency, due to its production process

Source: H2 Infrastructure map

Note 1) Either direct use or reconversion to power. 2) Considering only storage efficiency, i.e. compression, leakages, and conditioning. Full round-trip efficiency of the power-H2-power would drop to <50% due to electrolysis and electricity reconversion efficiencies.

E-methane can leverage the existing natural gas infrastructure, though it can be synthesised from H2 via a complex production process

DESCRIPTION OF E-METHANE POWER-TO-X VALUE CHAIN



CHARGE MODE

E-methane synthesised from hydrogen and CO2 is injected into natural gas storage facilities, such as underground caverns, depleted fields, or above-ground pressurised tanks, likely taking advantage of the existing infrastructure

DISCHARGE MODE

In discharge, e-methane is withdrawn from the storage facility and can be readily used across all different natural gas applications

KEY PERFORMANCE DATA AND PROS - CONS

POWER RANGE	100 MW – 1 GW
ENERGY RANGE	Up to 10 TWh
DISCHARGE TIME	Some hours - months
LIFETIME	~ 30 years
REACTION TIME	Minutes
EFFICIENCY[2]	~ 98 %
ONLINE CAPACITY	n/a

- Reuse of existing infrastructure for storage and conversion to power
- Flexible end-uses, as it can replace natural gas

- Needs for a CO2 source for the production process
- Lower round-trip efficiency, due to its highly energy-intensive production process

Source: H2 Infrastructure map

Note 1) Either direct use or reconversion to power. 2) Considering only storage efficiency, i.e. compression, leakages, and conditioning. Full round-trip efficiency of the power-H2-power would drop to <50% due to electrolysis and electricity reconversion efficiencies.

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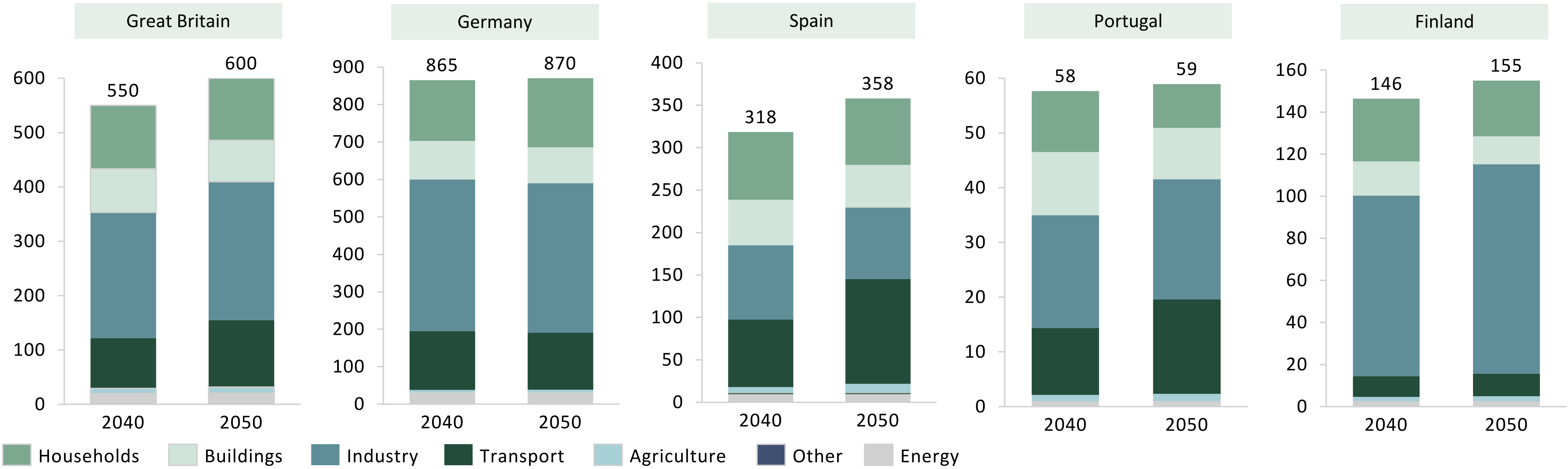
The power demand we have used in our analysis is based on the TYNDP 2024 study

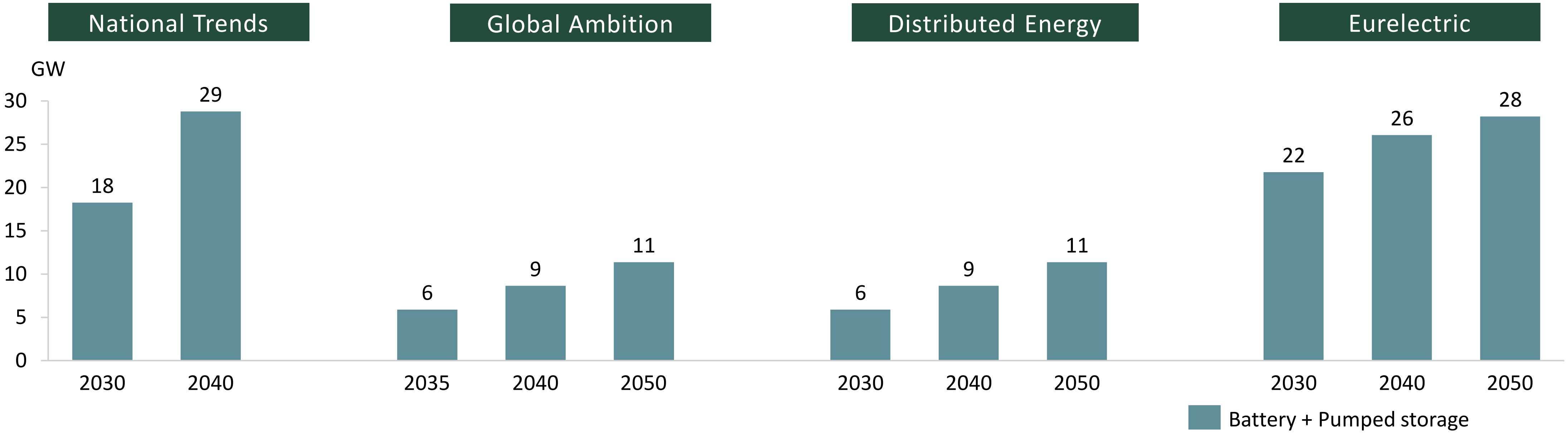
- The total input demand from TYNDP 2024 scenarios for EU countries is obtained from data available online – Demand Scenarios TYNDP 2024 After Public Consultation and split into the categories below.
- For GB, the total input demand considered is the "Native Demand" from the TYNDP Distributed Energy scenario, and split based on the split share of the total EU demand.



For the purposes of the Eurelectric scenario we have slightly adjusted the 2040 and 2050 storage capacities from the TYNDP National Trends values

- Storage capacity in the Global Ambition and Distributed Energy scenarios from TYNDP is smaller that the expected capacity in 2030 in the National Trends scenario. A scenario with 9-11 GW of total storage in GB assumes no increase in storage capacity from the current installed capacity (~10GW), which is not realistic.

- An increase of battery capacity from the 2030 assumptions were determined as an adjustment of the National Trends scenario based on the economic viability of energy storage.



Source: https://app.powerbi.com/view?r=eyJrIjoiZDcyMmIwYmYtYWRiOC00NDI4LWIyOWYtYTFiNTA1ZGViMzE2IiwidCI6IjdmZmJlY2NmLTBjMWItNDk2Yy04OTc4LTg5MjA5YzJkMzc1ZCIsImMiOjh9

ANNEX – FINLAND ID AND AS MARKETS

For this analysis, we have used a simplified approach for estimated income from the intraday and balancing markets in Finland

Intraday and ancillary services revenues can be considered “residual value pools” 1.	For LDES, ~80% of the total revenues are captured from the day-ahead market arbitrage, therefore, ID and AS revenues are marginal and reflect residual system needs. ID revenues would come mainly from forecast errors and short-term system imbalances, while AS would come from residual reserve needs.
Shared structural characteristics between GER and FIN markets 2.	Despite differences in size, Germany and Finland share key structural characteristics: high and increasing onshore wind penetration, declining thermal inertia and reserve provision, similarity in type of ancillary service market requirements. For LDES assets, these conditions create comparable monetization opportunities per MW, even if total volumes differ.
DA dominance “masks” country-specific differences 3.	Given that day-ahead arbitrage constitutes ~80% of the revenues, a larger discrepancy in AS and ID revenues would lead to a small impact in total revenues. In Finland in particular, the role of hydro is expected to suppress ID volatility and cover a large amount of the AS requirement. Therefore, the assumption that the shares of revenues in these markets are equivalent to those in Germany represent a more optimistic scenario for LDES.

AFRY