
Decarbonising Electricity Grids with Investments in Long-Duration Energy Storage

2024

About this Report

This report specifically addresses professional investors and therefore aims to bring an investor viewpoint to the emerging long-duration energy storage sector.

The report was co-authored by Clean Horizon, a clean energy consultancy dedicated to the energy storage space. Learn more at www.cleanhorizon.com.

Readers are encouraged to review the important legal information provided at the end of this document on Page 46.



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Glossary

BESS	Battery Energy Storage System
CfD	Contract for Difference
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
OEM	Original Equipment Manufacturer
PPA	Power Purchase Agreement
RE	Renewable Energy
TSO	Transmission System Operator

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01

Introduction

01-1 What is LDES? | 01-2 Why deploy LDES? | 01-3 What are the challenges and how can they be overcome?

What is LDES?

This paper aims to assess the investment potential of deploying nascent long-duration energy storage (“LDES”) solutions with discharge durations of 8 hours and above to decarbonise electricity grids.

As the shift of energy supplies from dispatchable, fossil fuel-based generation to intermittent renewable energy sources progresses, energy storage solutions that can balance this ever-increasing intermittency have become a crucial pillar of a successful energy transition.

The balancing and flexibility needs have so far mainly accelerated the deployment of short-duration storage solutions (one to two hours) predominantly based on lithium-ion battery energy storage systems (“BESS”). However, market

needs are already shifting towards longer duration requirements that point towards the significant commercial potential of LDES solutions.

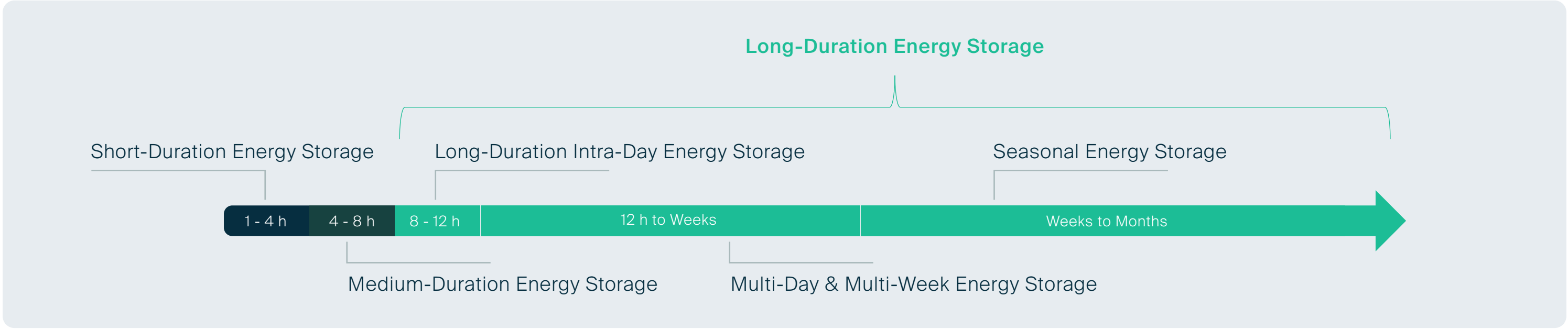
There is an increasing body of literature covering the detailed technical specificities of LDES and we will therefore not seek to cover those aspects in much detail. Our aim with this paper is to bring an investor viewpoint to the sector and to inform professional investors on our ongoing monitoring of this emerging sector.

Under the term LDES, we subsume energy storage solutions with discharge duration capacities of eight hours and above, as opposed to short-duration (<4h) and medium-duration energy storage (4 to 8h). Depending on the specific technology applied, LDES may provide intraday flexibility (up to 12h), multiday and multiweek flexibility (12h to weeks), and seasonal flexibility (months).

The vast majority of current LDES options with a credible path to commercial viability fall under the four categories electrochemical, chemical, mechanical, and thermal energy storage. The currently most relevant solutions that have been considered in the underlying analysis work of this paper are listed in Table 1 on pages 5-6.

Note that this paper aims to assess the investment potential of nascent LDES technologies and therefore does not focus on more mature and well documented technologies such as pumped hydro energy storage. While LDES solutions can also support the decarbonisation of heat, especially in industrial applications deployed directly with end users, this paper focuses on LDES applied to decarbonise electricity grids with utilities as the main source of revenues.

Figure 1: Delineation of Energy Storage Durations and Related Terminology



Source: SUSI Partners.



Table 1: Overview of Analysed LDES Technologies and Key Characteristics

Type	Technology	Typical Discharge Duration ¹	Response Time ²	Round-Trip Efficiency ²	Depth of Discharge ²	Construction Timeline (Yrs.) ²
 Electrochemical Storage	Sodium-Sulfur Batteries	6 hours and above	0.2-10 seconds	75-80%	100%	1
	Vanadium Flow Batteries	2 hours and above	<0.1 seconds	65-80%	100%	1-2
	Organic Flow Batteries	6 hours and above	0.2-10 seconds	65-75%	90%	1-2
 Chemical Storage	Hydrogen Energy Storage	Usually multi-hour storage (≥4 hours) due to overhead expenses	60 seconds	40-50%	100%	Variety of solutions; storage component usually takes <1 yr. to construct
 Mechanical Storage	Gravity Energy Storage	2 hours and above	1-30 seconds	75-90%	100%	1-3
	Liquid Air Energy Storage	3 hours and above	3-12 minutes	40-70%	100%	1-5
	Compressed Air Energy Storage	4 hours and above	3-12 minutes	30-80%	100%	1-5
 Thermal Storage	Molten Salt Energy Storage	6 hours and above	60 seconds	40-80%	80%	1-3
	Sand Energy Storage	15 hours and above	60 seconds	40-80%	80%	1-3

Sources: ¹ Clean Horizon, based on publicly announced projects and supplier claims. | ² BloombergNEF (2024), Long-Duration Energy Storage Cost Survey Tough Race (excl. Hydrogen data).

Response Time: Time it takes for a storage system to react to a signal or command from the TSO. Represents a key factor in a system’s ability to participate in ancillary markets (see page 34).

Round-Trip Efficiency: Tracks system losses and calculates the final energy output of the storage system as a percentage of initial energy provided to the system.

Depth of Discharge: Recommended maximum percentage of energy to be discharged compared to the total energy storage capacity of the system without reducing an asset’s estimated useful life.



Why Deploy LDES Solutions?

Although the term LDES may include a wide array of technological solutions, these technologies share some core features. Depending on the context in which they are deployed, they can have specific environmental, technological, and commercial advantages over other existing solutions in general, and lithium-ion batteries specifically, and can therefore fill specific gaps in the market.

General Advantages of LDES Solutions

1	Low-Carbon Solution	As opposed to natural gas power plants, they have close to zero operational emissions and therefore fit well into the envisioned net-zero energy systems of the future.
2	Widely and Quickly Deployable	As opposed to pumped hydro power plants and other larger-scale options, they are modular and hence have generally fewer geographical requirements and relatively short build timelines (although not as short as lithium-ion BESS).
3	Deferral of Grid Investments	Compared to upgrades and expansions of the transmission and distribution (“T&S”) grid, they can, in most cases, be deployed faster and very targeted in key locations that experience increased grid distress.
4	Enhancement of Energy Security	By diversifying energy storage options and reducing dependence on imported fuels, they contribute to greater energy security and resilience.
5	Support of Decentralised Energy Systems	They can support microgrids and decentralised energy systems, promoting local energy solutions and reducing transmission losses.

While lithium-ion batteries are highly effective for short-duration energy storage and applications requiring high power densities, LDES technologies offer distinct advantages in terms of cost, safety, scalability, environmental impact, and suitability

for long-duration and large-scale energy storage applications. These advantages make LDES solutions a valid component of a diversified and resilient energy storage strategy, especially for achieving long-term decarbonisation goals.

Advantages of LDES vs. Lithium-Ion Batteries

1	Lower Cost for Long Duration	LDES technologies often have lower costs per kWh for long-duration storage. With increasing discharge durations, LDES solutions benefit from a decreasing levelized cost of energy storage while lithium-ion batteries do not.
2	Longer Lifetimes & Reduced Degradation with Depth of Discharge	LDES technologies generally have longer technology lifetimes than lithium-ion batteries (10-15 years), stretching up to 60 years depending on the specific technology, and experience less degradation with deep discharges.
3	Bulk Energy Storage	Technologies like compressed air energy storage are ideal for large-scale energy storage services that lithium-ion batteries cannot economically provide.
4	Material Availability & Environmental Impact	LDES technologies often rely on more readily available raw materials, reducing concerns about supply chain constraints and environmental impacts associated with the critical materials used in lithium-ion batteries.
5	Temperature Tolerance	LDES technologies such as flow batteries and thermal storage can operate effectively across a wider range of temperatures compared to lithium-ion batteries, which can suffer from performance issues in extreme temperatures.
6	Reduced Risk of Fire and Thermal Runaway	LDES technologies often have a lower risk of fire and thermal runaway, which can be a safety concern with lithium-ion batteries, especially in large installations.

What Are the Challenges and How Can They Be Overcome?

As of mid-year 2024, investing in the deployment of LDES to decarbonise electricity grids is not yet a widely commercially viable option aside from specific off-grid applications. The two main challenges to overcome are:



Lack of Demand

Today, the share of intermittent renewables in electricity markets and consequently electricity price volatility and grid instability are still too low to justify an investment in LDES. However, many countries have set ambitious 2030 renewable energy targets, which should increase demand for storage solutions with extended discharge durations and simultaneously drive access to capacity markets.



High Technology Costs

Today, the levelized cost of storage ("LCOS") of LDES technologies is still too high to be competitive. However, although dependent on reliably increasing demand and initial support mechanisms, developments such as manufacturing ramp-ups, improved roundtrip efficiencies, and optimised supply chains could significantly bring down the overall system costs of LDES solutions.

For investors, an emerging LDES market could offer significant potential, with a well-timed market entry ahead of increased capital inflows into the sector being a crucial factor in maximising returns. This paper therefore provides an understanding of the relevant revenue streams and the required developments that can make LDES a viable investment opportunity in the coming years.

02

Technology Costs

02-1 Cost competitiveness of LDES | 02-2 LCOS analysis | 02-3 Technology cost projection (-2035) | 02-4 Requirements for cost competitiveness

Cost Competitiveness of LDES

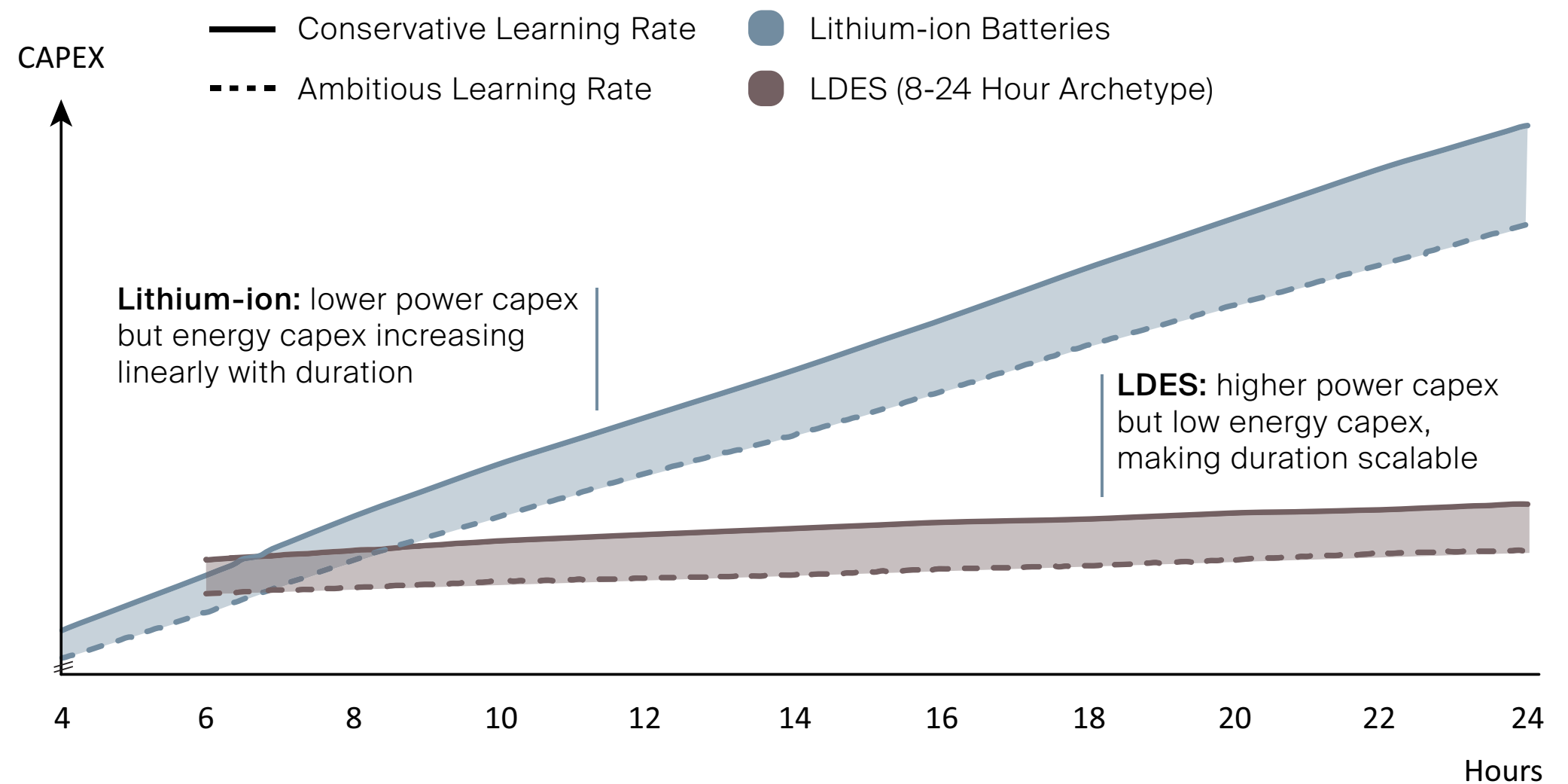
A key requirement for LDES to become commercially viable is their cost competitiveness, especially when compared to lithium-ion BESS, which today dominate the short-duration energy storage market and consequently benefit from significant economies of scale.

However, LDES solutions benefit from decreasing LCOS with increasing discharge duration, while lithium-ion BESS do not. As Figure 2 shows, the capital expenditures rise at a much steeper rate as the discharge duration increases for lithium-ion BESS than for LDES solutions, which benefit from low marginal costs for storing additional energy and are therefore highly scalable.

Levelized Cost of Energy Storage (LCOS)

Comparing the relative economics of different forms of LDES and lithium-ion BESS is best done by considering the levelized cost of energy storage ("LCOS") of each technology. The LCOS quantifies the discounted lifetime cost per unit of discharged electricity (e.g. EUR/MWh) for a specific storage technology and application. The metric therefore accounts for technical and economic parameters affecting the lifetime cost of discharging stored electricity. This measure allows to create a level playing field across technologies and takes into account their upfront capital costs, efficiency measures, and ongoing operational costs over the lifetime of the technology (see LCOS analysis on next page).

Figure 2: Energy Storage CAPEX by Duration for Lithium-Ion and LDES, 2030



Source: McKinsey & Company (2021), Net-Zero Power: Long Duration Energy Storage for a Renewable Grid.



LCOS Analysis

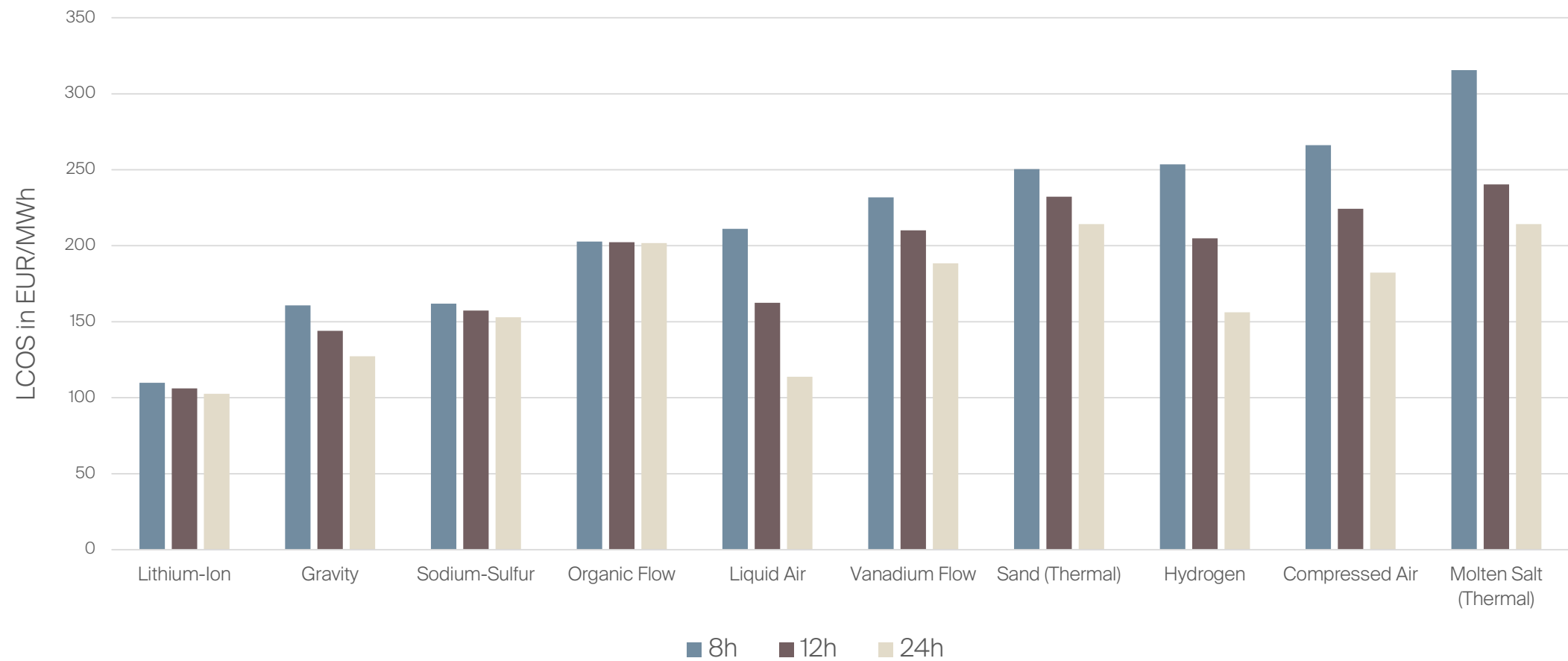
Based on 2023 data, we conducted an analysis of current LCOS of LDES and lithium-ion BESS for 8, 12, and 24-hour discharge durations that allows to compare different solutions on a level playing field.

While an LCOS calculation requires incorporating several assumptions that may still shift over time, it considers technology lifetimes as well as further factors and therefore creates a level playing field between technologies to facilitate a comparative cost analysis. Our LCOS computation was carried out over a 20-year period, taking into account the augmentation costs needed for technologies with shorter lifetimes.

It needs to be noted that our analysis provides a snapshot of prevailing LCOS without accounting for future cost reduction potential. Other available analyses, such as the one provided by BloombergNEF shown on the next page, can show the projected cost development of individual technologies, but not on an LCOS basis and therefore not allowing for a comprehensive comparison between technologies.

The results of the LCOS calculations for the different technologies under consideration are shown in Figure 3. While lithium-ion and organic-flow batteries only achieve minimal cost reductions with increasing discharge durations, other technologies are able to gain in competitiveness when longer discharge durations are assumed.

Figure 3: Solution Levelized Cost of Storage, 2023 Values for a System Connected to the High-Voltage Grid



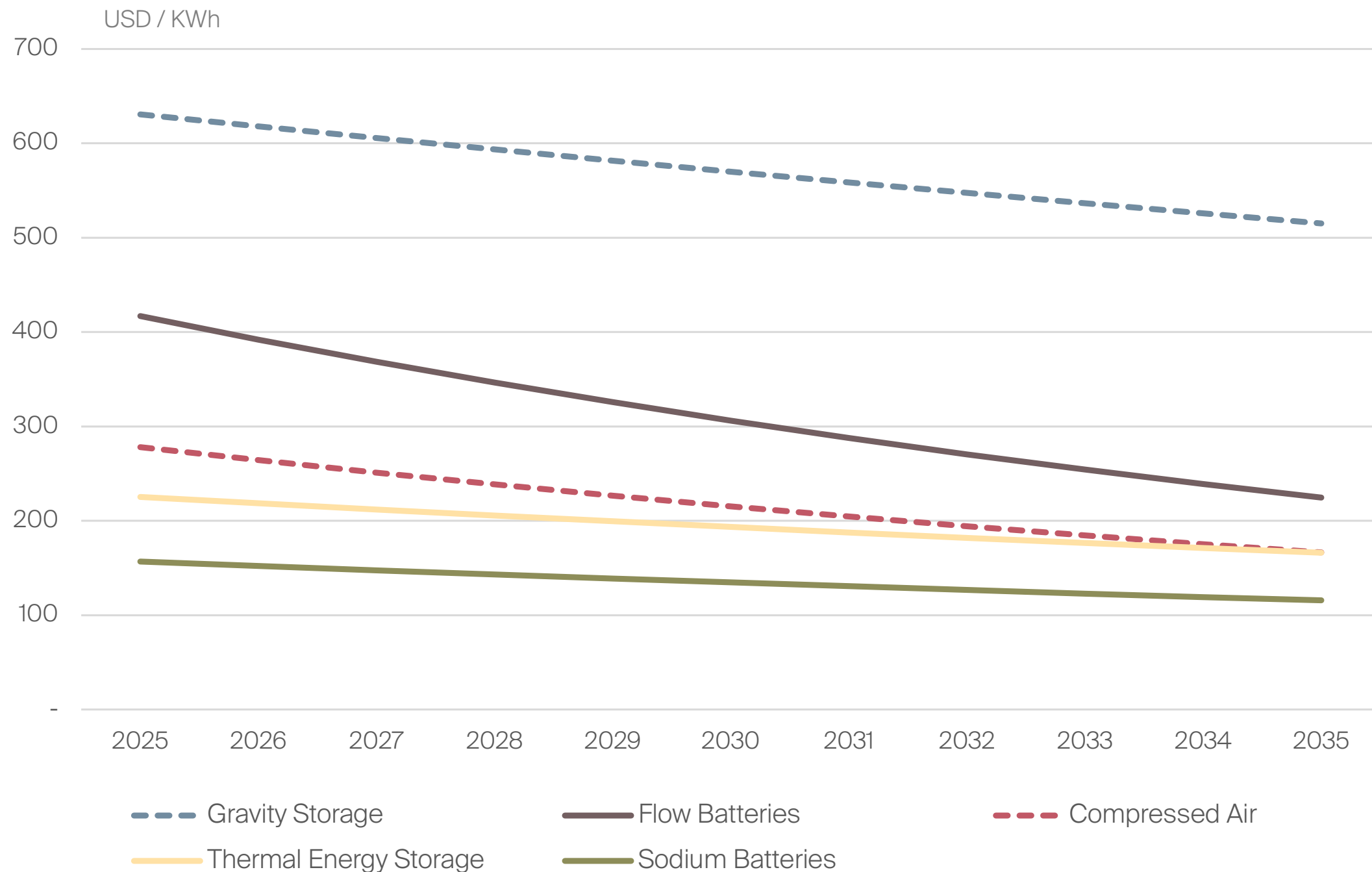
The following assumptions were retained for the LCOS calculation:

- All LDES systems are connected to the high-voltage grid. Their round-trip efficiencies take all necessary A/C-A/C power conversion, low-voltage/medium-voltage and medium-voltage/high-voltage transformers into account.
- The energy charged in the storage system is priced at 150 EUR/MWh, meaning that losses due to inefficiency are fixed at that price.

Source: Clean Horizon Analysis (2023).

Technology Cost Projection (-2035)

Figure 4: Global Average Costs of Selected LDES Solutions



Technology cost rankings are bound to evolve over time with technology costs decreasing as solutions gain in maturity and benefit from economies of scale.

Some LDES technologies are still in the development stage, meaning there is significant potential for cost reductions as the technologies mature. As research and development continue, we can expect significant improvements in the efficiency, reliability, and performance of LDES systems over the coming years.

Furthermore, as the supply chain for these technologies becomes more established and optimised, the costs associated with manufacturing, transportation, and installation will likely decrease.

A BloombergNEF projection of global average costs for selected LDES solutions until 2035 is shown in Figure 4. As noted previously, these cost developments do not allow for a comprehensive comparison of different technologies, which would require a calculation of LCOS projected into the future, which currently is not available for LDES.

Source: Bloomberg (2024), Long-Duration Energy Storage Cost Survey Tough Race.

Requirements for Cost Competitiveness

The cost competitiveness of LDES solutions is expected to improve significantly in the coming years through reductions in capital expenditures, enhanced technical efficiency, and the establishment of solution-specific ecosystems.



CAPEX Reduction

A reduction in the cost of both power and energy components of the LDES solutions will reduce the overall LCOS. Said evolution would be possible thanks to a) the ramp-up of manufacturing capacities that would help reach economies of scale and streamline production rates to keep up with demand, and b) optimised supply chain processes and reliance on abundant, non-expensive materials and equipment.



Improved Technical Properties

Technical properties such as round-trip efficiency, depth of discharge, and number of cycles play a major role when it comes to solution costs as it impacts charge/discharge costs by leading to higher energy losses if the solution has a low efficiency rate.



Established Ecosystem

As LDES technologies evolve and mature, solution providers will gain a comprehensive understanding of the technology attributes including operation and maintenance requirements, as well as product specificities in the context of their own market and geography, therefore reducing costs and improving efficiency.

03

Revenue Streams

03-1 Price arbitrage | 03-2 Capacity markets | 03-3 Ancillary services markets
| 03-4 Revenue stacking

Merchant Revenues from Price Arbitrage: Concept

Storage asset operators can purchase electricity at a relatively low price (when demand is low) and resell it at a higher price (when demand is high). This process, called arbitrage, helps absorb excess renewable penetration, which would otherwise go to waste and re-inject it at times of lower generation and higher demand.

Electricity is exchanged on the wholesale electricity market through national and international platforms with prices determined based on market mechanics, i.e. supply and demand. The wholesale market encompasses three critical markets:

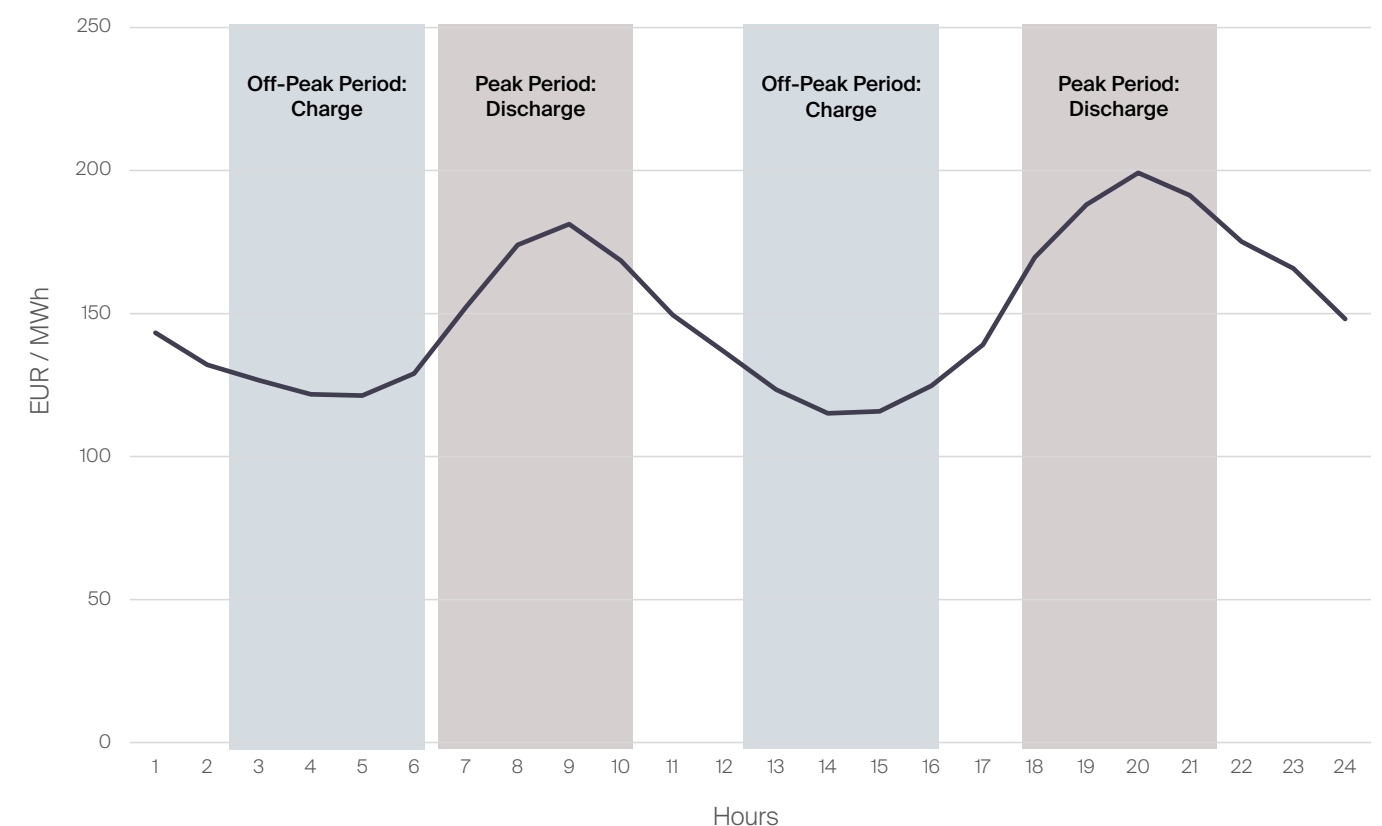
- 1. The Day-Ahead Market** where producers offer electricity for a given delivery period the next day.
- 2. The Intraday Market** where producers and consumers continuously exchange electricity throughout the day to cover for potential supply/demand mismatches.
- 3. Forward and Future Markets** for electricity are financial instruments that allow participants to buy and sell electricity at predetermined prices for delivery at a specified time in the future. The first involves customised, bilateral contracts while the second is for standardised contracts traded on centralised marketplaces.

During peak periods, demand compared to available load is high and producers can sell their electricity at a higher price whereas during off-peak periods, the demand compared to available load is low and consumers' willingness to pay drops.

The main advantage of storage systems lies in their ability to act both as electricity producers by injecting energy into the grid (discharge) and as consumers by drawing energy from the grid (charge).

As per Figure 5, day-ahead prices in the Netherlands over the 2021-2023 period already allow for short-term arbitrage opportunities on a daily basis. With increased renewables penetration, prolonged imbalances may occur that can be more economically covered by LDES than short-term solutions such as lithium-ion BESS.

Figure 5: Average Day-Ahead Power Prices 2021-2023, Netherlands



Source: ENTSO-E Transparency Platform.

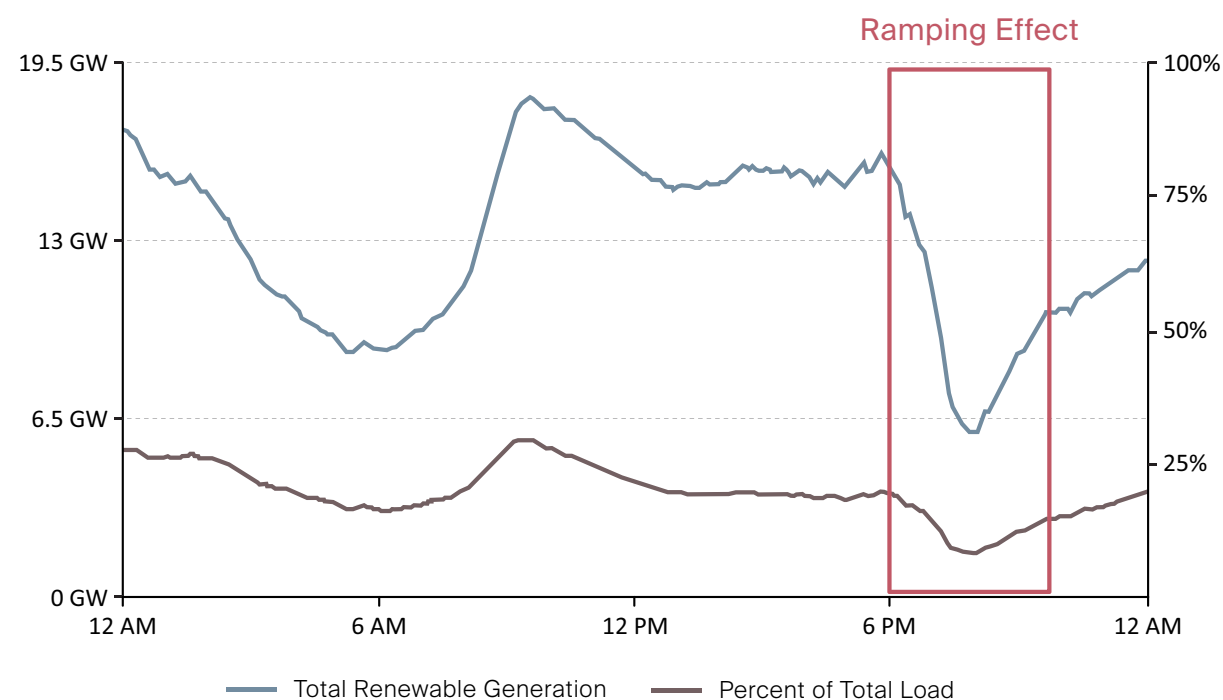
Arbitrage: Increased Volatility as a Captive Opportunity

The intermittent nature of solar and wind power adds uncertainty to production forecasts. Notwithstanding improvements in production forecasting, actual production can still deviate from estimates, resulting in increasingly volatile electricity prices, increasingly necessitating short-notice asset activations at very high prices in markets with challenged capacity reserves.

In Texas, for a 55-day period between mid-August and mid-October, the market cap of 5,000 USD/MWh was reached over 114 hours in total (8% of the time) due to discrepancies between the load forecasted by ERCOT (system operator) and the actual load.

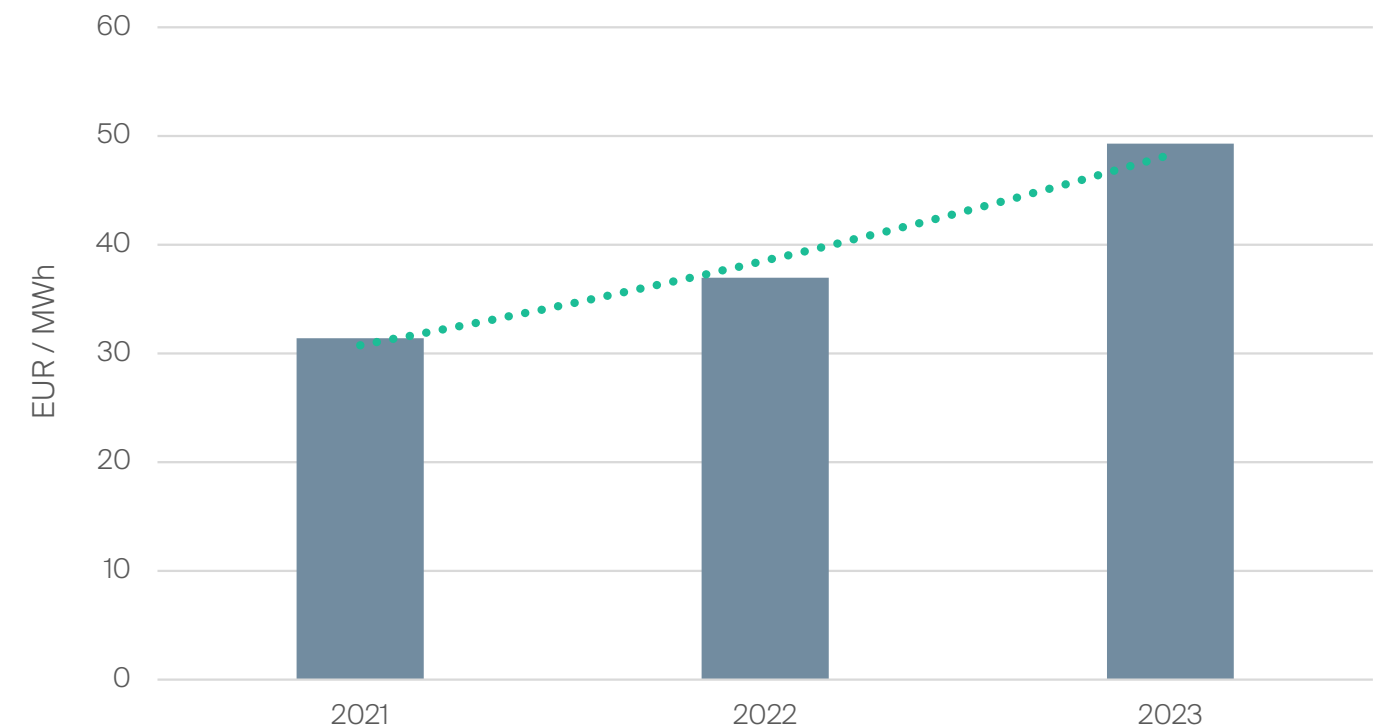
Stress events such as the ones in Texas often occur when solar production starts falling rapidly at sundown and alternative generation is not sufficient to compensate for this capacity drop. Yet it is precisely at this time of day that peak demand is greatest and many assets may need to

Figure 6: Ramping Effect (Texas ERCOT)



Source: GridStatus.io (2023).

Figure 7: Standard Deviation of Price Distribution on the Dutch Day-Ahead Market 2021-2023



Source: ENTSO-E Transparency Platform.

be activated at the last minute to ensure supply if available capacity margins are challenged – especially during system stress events. This effect is commonly referred to as the ramping effect and is characteristic of a high share of intermittent production. An illustrative example from the Texas ERCOT grid is shown in Figure 6.

Today, such price peak incidents remain limited in duration (1-4 hours) and generally are less frequently observed in other global markets with high interconnection levels and limited renewable energy shares. They are therefore largely captured by short-term energy storage assets such as lithium-ion BESS. However, LDES could benefit from their larger energy stock to benefit from

secondary (and potentially longer) price difference episodes to generate revenues through arbitrage once these low vs. high-price episodes gain in frequency and duration.

In addition to increased price volatility on intraday markets, increasing rates of day-ahead volatility, as illustrated by the growing standard deviation of prices e.g. on the Dutch market (see Figure 7), can further point towards tangible arbitrage opportunities for LDES. While not yet sufficient for LDES deployment, these tangible increases in volatility point towards a need for LDES if renewable energy penetration continues to increase.

Arbitrage: Zero and Negative Prices on Day-Ahead Markets

Several countries have been witnessing a rapid increase in the number of hours that cleared at negative or zero prices on the day-ahead electricity market, which would allow LDES to charge for free or even get paid to charge.

Extreme low-price events have two major causes:

1. **Lack of Flexibility of Conventional Generation Assets:** Since the process of shutting down and restarting conventional power plants is costly, operators often push such resources to run at minimum production levels even during low-demand hours when prices are very low.
2. **Increased Renewable Energy Adoption:** Renewable energy assets may continue to inject power into the grid even when supply exceeds demand if they operate under support mechanisms such as e.g. contracts for difference (“CFD”) that aim to provide long-term price visibility to foster investment. However, some governments (e.g. in the UK and anticipated in Spain) are reviewing said CFDs to stop payments when prices on the wholesale energy market reach zero or negative levels.

Zero or negative-price occurrences are especially beneficial for storage systems, which can charge for free – or even get paid to charge – during such events and then discharge during peak hours

when energy prices are the highest. The longer these episodes last, the more advantageous they will be for LDES projects that can fully charge at favourable rates.

Table 2 shows the number of negative and null-price occurrences in Spain and the Netherlands from 2021 to 2023. These occurrences have been increasing over the past three years as renewable energy uptake has accelerated.

Figure 8 shows the hourly distribution of negative and zero prices in Spain and Netherlands over the 2021-2023 period. As can be expected, these observations occur generally during low-demand periods, especially when solar production is at its highest over the noon and early afternoon periods.

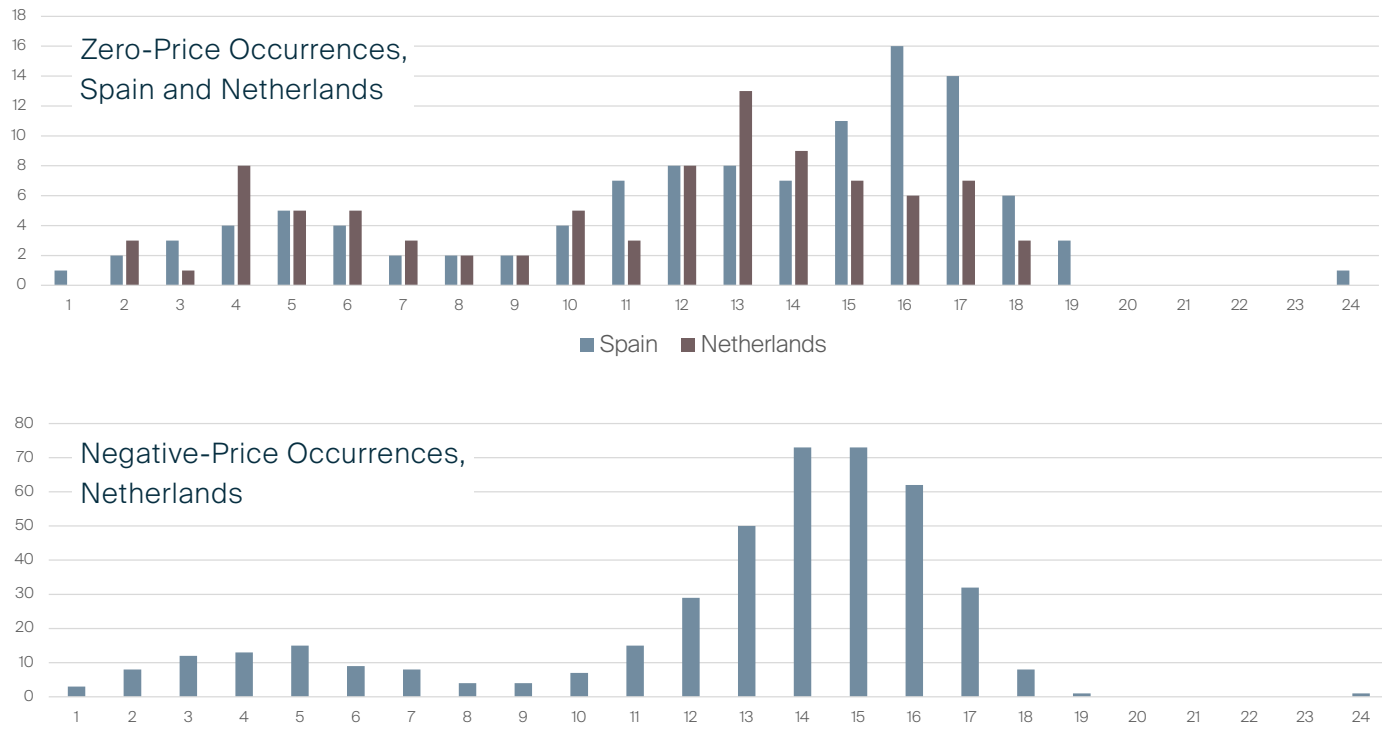
While it is still unclear whether the trend towards increasing zero and negative-price occurrences would propagate to other European and international markets, it is important to state that they represent a low-hanging revenue opportunity for energy storage but would not solely justify a long-term investment in LDES.

Table 2: Zero and Negative-Price Occurrences Netherlands & Spain, 2021-2023

	2021	2022	2023
0 EUR / MWh occurrences - Spain	0	3	107
0 EUR / MWh occurrences - Netherlands	16	25	49
Negative-price occurrences - Netherlands	70	85	272

Source: ENTSO-E Transparency Platform.

Figure 8: Hourly Distribution of Zero and Negative-Price Occurrences Netherlands & Spain, 2021-2023



Source: ENTSO-E Transparency Platform.



Capacity Markets

Capacity (or resource adequacy) mechanisms have been introduced to ensure security of supply at all times by providing project owners with revenue visibility and sufficient operational asset margin.

Open to both existing and new capacity, capacity market schemes were set up by system operators to provide project owners and investors with:

- An additional revenue stream to wholesale revenues via a capacity payment, without which conventional generators that struggle to cover their operating costs over the markets would be forced to shut down.
- Visibility through long-term contracts that could span from one up to 20 years depending on the market.

These mechanisms are managed in a variety of ways depending on the market, including through long-term procurements based on a tendering process, pay-as-bid auctions, and pay-as-clear auctions.

Under the pay-as-clear principle, system operators organise capacity auctions for contracts of one or more years, where asset operators bid a price in EUR/MW/year. The result of the auction then follows the merit order principle: bids are selected in order of increasing price until they cover the system operator’s needs in MW, and the clearing price is determined by the last (and most expensive) selected asset.

Among others, Ireland, France, Poland, the UK, and Italy have already set up capacity markets

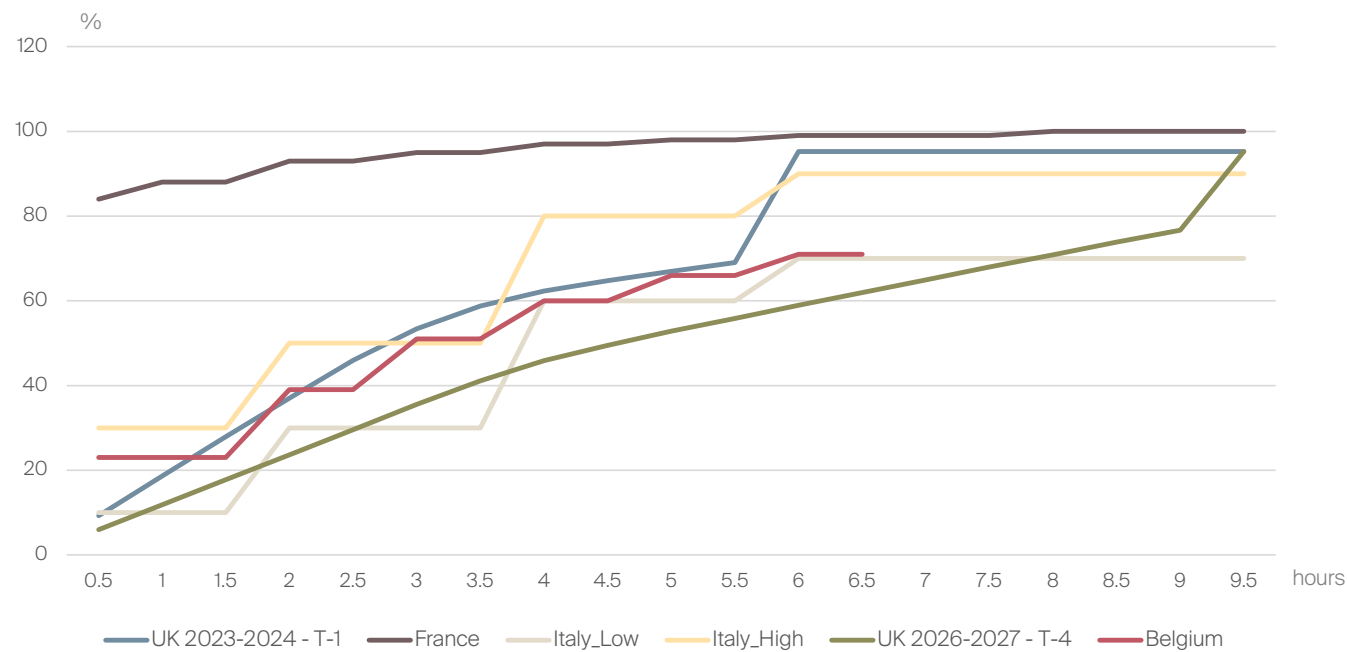
that allow for energy storage participation while Spain and Portugal are expected to take steps in that direction in the near future. As part of requirements set by the European Commission, French, Italian and Polish capacity markets have specific emission targets, thus making them particularly unfavourable to carbon-emitting technologies such as coal or gas power plants and encouraging the development of low-carbon, storage-based solutions such as LDES.

Table 3: Selected European Capacity Market Clearing Prices

	Clearing Price
UK 2023-2024	60,000 £/MW/yr.
UK 2026-2027	63,000 £/MW/yr.
France 2023-2024	28,670 €/MW/yr.
Belgium 2027-2028 ¹	36,372 €/MW/yr.

Source: as for Figure 9 (page 30)

Figure 9: Derating Factors as a Function of Discharge Duration in selected European Markets (in %)



Source: Clean Horizon based on public information from local TSOs (RTE in France, National Grid in the UK, Terna in Italy, Elia in Belgium)

As this mechanism mainly aims to ensure security of supply while thermal assets are being decommissioned as part of national decarbonisation strategies, some countries have started to favour longer-duration storage assets as they are able to sustain supply over longer episodes of system stress. This has led to the creation of “de-rating” factors whereby a ratio is applied to the nominal capacity (in MW) of an energy-limited resource such as storage in order to value its real capacity and compare its contribution to that of an infinite, stable capacity. Systems with a higher storage duration could therefore benefit from a higher de-rating factor.

For example, in the UK, a 4h-battery will receive only 45% of the capacity market revenues, whereas an 8h-battery will receive 60% of the total revenues. An overview of various derating factors in selected European markets is shown in Figure 9.

Although de-rating factors favour long-term storage systems, the revenues available from capacity trading may not be solely sufficient to justify an investment in an LDES system.

Ancillary Services Markets

In case of an imbalance between supply and demand on the electricity grid, LDES can be remunerated for helping grid operators in maintaining and re-establishing an equilibrium to prevent severe disruptions.

One of the main goals of transmission system operators ("TSO") is to ensure the security and quality of electricity supply in their operational zones by constantly keeping an equilibrium between supply and demand.



Battery Energy Storage

Balancing mechanisms are one of the tools that the system operator uses to balance electricity supply and demand. They allow the system operator to call upon additional generation/consumption or reduce generation/consumption on very short notice – minute by minute and second by second – to balance the system. In most markets, the TSO will organise auctions to procure the required amount of balancing energy based on historical needs.

Frequency Control

Beyond electricity balancing, the grid equilibrium is represented by a frequency (Hz) that may deviate from its nominal value (50 Hz in Europe, 60 Hz in the USA) if supply surpasses demand (over-frequency) and vice versa (under-frequency). To maintain the required frequency and ensure grid security, electricity producers and consumers can inject and withdraw electricity into and from the grid. This process is called frequency control and consists of several ancillary services regulated by reserve markets.

In Europe, three different reserves exist to ensure frequency control: the primary, secondary, and tertiary reserves, each being characterised by their respective activation time. Figure 10 illustrates the frequency regulation process, showing the sequential activation of primary (light green line), secondary (red line), and tertiary

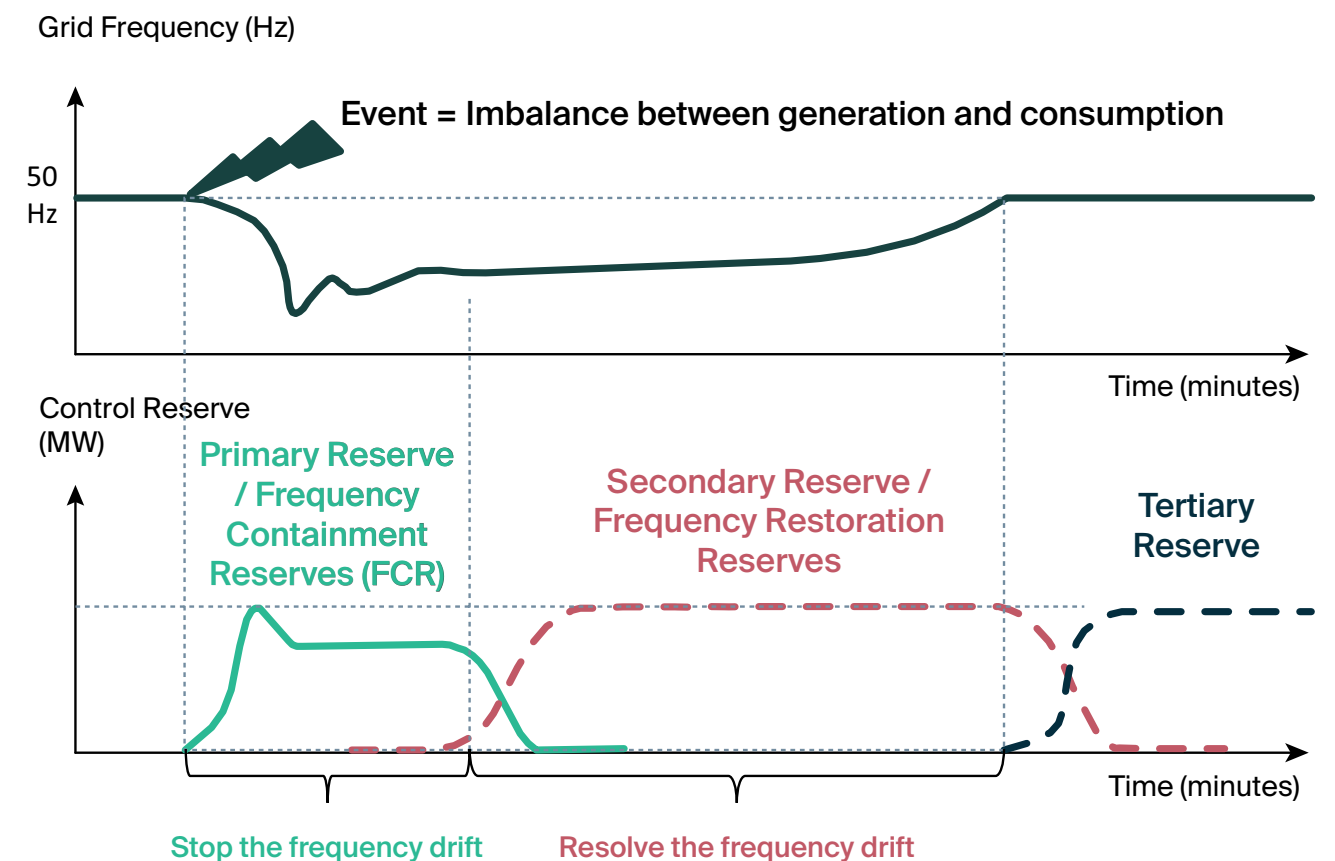
(dark blue line) reserves. These reserves work in sequence to resolve a grid frequency imbalance event (dark green line) and restore the frequency to its nominal value during an under-frequency incident.

Since storage systems can both inject and withdraw, they are well placed to capture associated revenues when activated on the ancillary services market. However, to fully participate in all three reserve categories, storage systems must meet specific technical

parameters. In this regard, LDES technologies are usually less competitive than lithium-Ion solutions due to the latter's short response times and the short activation duration required for primary and secondary reserves (from milliseconds to minutes).

Considering the limited capacity of this market, it is expected that current short-duration batteries will quickly saturate the market in most regions, making it only a secondary source of revenue for LDES technologies.

Figure 10: European Frequency Control Services



Source: Clean Horizon (2023)..



Revenue Stacking

The commercial viability of LDES solutions can be improved by accessing multiple revenue streams depending on the capabilities of the specific technology used.

Table 4 provides an overview of each analysed LDES technology's ability to access key revenue streams. While all analysed LDES technologies can generate revenues through arbitrage and participation in capacity markets (resource adequacy), their ability to participate in ancillary markets depends on their technical specificities. While technologies with short response times are better positioned to provide frequency response services with the fastest covering primary reserves, technologies with mechanical or spinning masses that tend to have longer response times can provide inertia to the grid (see also Table 1).

Depending on the innate properties of the specific technology used, investors may be able to generate cash flows from delivering additional services such as black-starting a microgrid or a grid pocket – depending on the exact extent of the local grid code's requirements – or support the decarbonisation of heat in industry. The actual type and number of services that can be provided by any given solution may also vary on a per-project basis depending on customer-requested customisations and hybrid storage configurations.

Table 4: Overview of Revenue Opportunities for Selected LDES Solutions

	Arbitrage (Energy Shifting)	Resource Adequacy	Primary Reserves	Ancillary Reserves (Secondary & Tertiary Reserves)	Inertia	Other Auxilliary Applications
Lithium-Ion Batteries	✓	✓	✓	✓	✗	Black-starting microgrids
Sodium-Sulfur Batteries	✓	✓	✓	✓	✗	Black-starting microgrids
Vanadium Flow Batteries	✓	✓	✗	✓	✗	Black-starting microgrids
Organic Flow Batteries	✓	✓	✗	✓	✗	Black-starting microgrids
Hydrogen Energy Storage	✓	✓	✗	✓	✗	Alt. uses in chemical industry, mobility etc.
Gravity Energy Storage	✓	✓	✗	✓	✓	Black-starting microgrids
Compressed Gas Storage	✓	✓	✗	✓	✓	Black-starting microgrids
Compressed Air Energy Storage	✓	✓	✗	✓	✓	Black-starting microgrids
Molten Salt Energy Storage	✓	✓	✗	✓	Partial	Heat; black-starting microgrids
Sand Energy Storage	✓	✓	✗	✓	Partial	Heat; black-starting microgrids

Source: Clean Horizon Analysis (2023) | BloombergNEF (2024). Long-Duration Energy Storage Cost Survey Tough Race.

04

Achieving Commercial Liftoff

04-1 Required renewable energy penetration rates | 04-2 Support mechanisms | 04-3 Timeline for commercial liftoff | 04-4 Conclusion

Required Renewable Energy Penetration Rates

As drivers of electricity price volatility, high shares of renewable energy in respective energy mixes will be the key factor in making LDES solutions an attractive investment opportunity.

As shown in section 3, LDES solutions in many cases compete with lithium-ion BESS for revenue opportunities. As long as price lows and price peaks do not regularly stretch over extended periods of time and involving larger volumes of electricity, lithium-ion BESS will be able to cover these imbalances more effectively than LDES solutions.

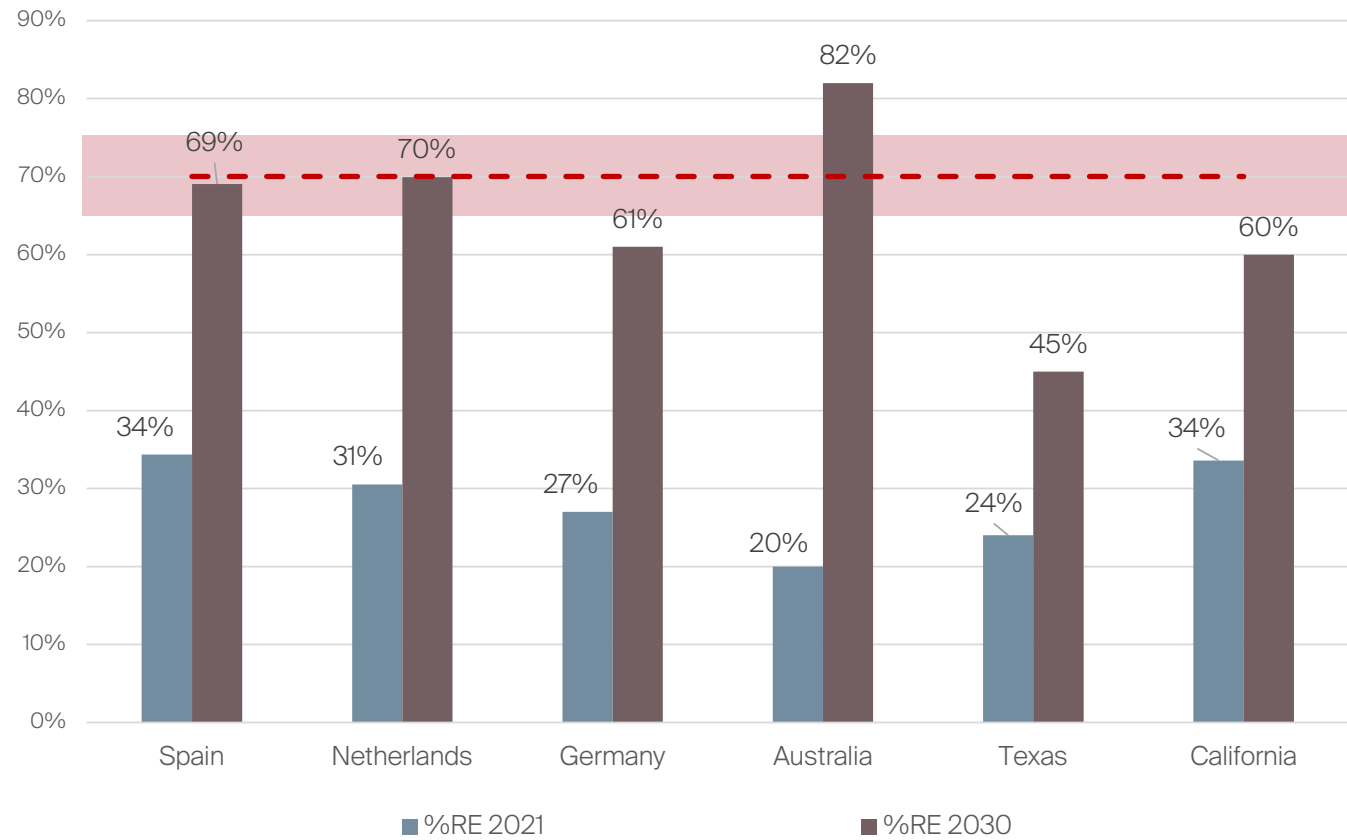
Based on the analysis of several power systems, we have observed that the use of LDES starts becoming a cost-effective way to stabilise a power system's LCOE when a break-even point of approximately 70% of covered load is reached. This is when price lows and price peaks reach extended durations with volumes that can no longer be more economically covered by lithium-ion BESS, capacity markets that allow for storage participation and favour longer-duration solutions become commonplace, and further avenues such as ancillary services increasingly offer additional revenue opportunities for LDES. However, this

break-even point can be reached at even earlier rates if LDES solutions can improve its cost-competitiveness with lithium-ion BESS.

In addition to the national renewable energy mix, neighbouring countries' renewable energy penetration rates and levels of interconnection with a considered market also play a major role in the validity of LDES solutions. Energy exchanges with neighbouring countries that have a higher renewable penetration rate will accelerate LDES development whereas ones with countries that have lower renewables shares will decelerate local LDES development.

National and state renewable energy targets can help identify promising markets for LDES adoption. Figure 11 shows that specific markets are aiming to cross the 70% renewable energy penetration mark by 2030, including Australia and the Netherlands with Spain following closely behind.

Figure 11: Projected Renewable Energy Penetration Rates by 2030 in Selected Countries



Source: Clean Horizon (2030 projections based on publicly available national or state RE targets)





Support Mechanisms

Support mechanisms provide the necessary financial stability, market signals, and technological backing needed to alleviate stakeholder uncertainty and drive investment during the scale-up phase of LDES.

With many LDES solutions still at a development or ramp-up stage, support mechanisms can play a critical role in accelerating the development and deployment of LDES solutions by bridging revenue gaps and improving investor confidence. By ensuring robust support structures, they can facilitate the technological advancements required to meet future energy storage needs and achieve broader energy transition goals.

A general awareness of the future importance of LDES has grown in recent years with countries drafting initiatives and conducting studies to create regulatory frameworks that will facilitate LDES access to electricity markets.

Support efforts for LDES to address stakeholder uncertainty on project returns and help accelerate technological advancement in the sector could come in many forms. Three main categories will play a meaningful role in this direction: deployment targets, revenue schemes, and technology support.

Leading the race in LDES support, the United States have already invested more than USD 1 billion in sector-oriented and solution-oriented funding. The UK comes in second with the GBP 69.5 million LDES Demonstration Fund. Australia is ranked third, as nascent project-oriented efforts from the Australian Renewable Energy Agency (ARENA) are emerging. While European efforts are yet to become concrete, first initiatives are emerging in Germany while other projects are being supported by the EU Innovation Fund (e.g. Sun2Store project in Spain).

1

Deployment Targets

Intermittent renewable energy targets point towards future volatility on electricity markets and thus help predict demand for LDES.

- Renewable energy targets
- Overall targets for installed storage volumes and LDES-specific targets

2

Revenue Schemes

Various revenue schemes can help cover the “missing money” gap and improve risk-adjusted returns for investors.

- Capacity markets
- Long-term contracts or 24/7 PPAs with public or private parties
- Contract-for-Difference programs
- Cap & Floor contracts

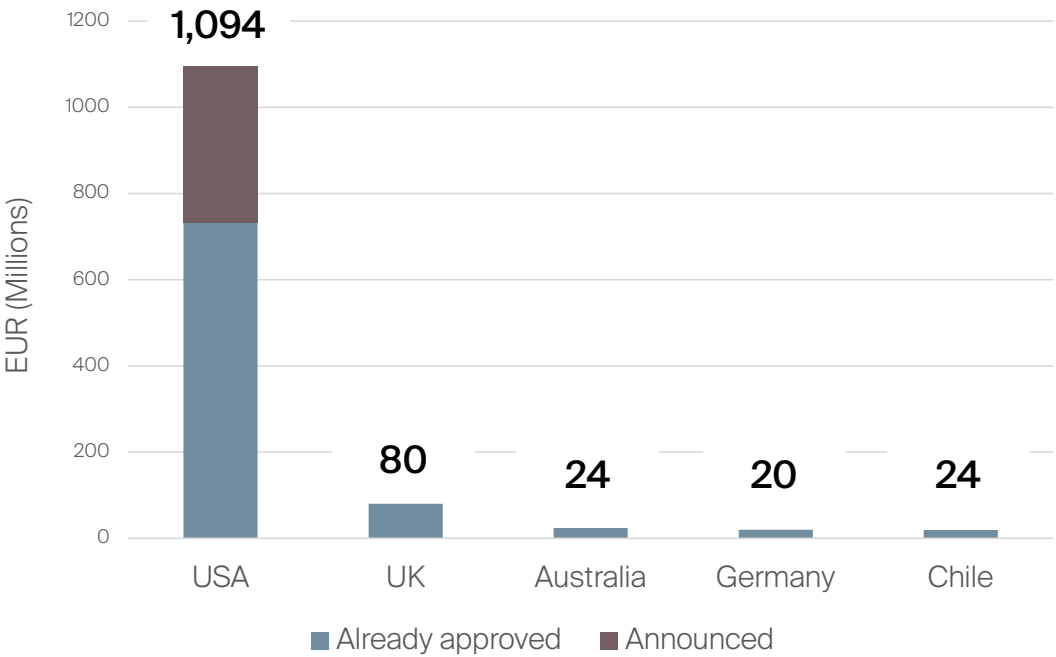
3

Technology Support

Technology-oriented support programs help accelerate the techno-economic optimisation of LDES technologies.

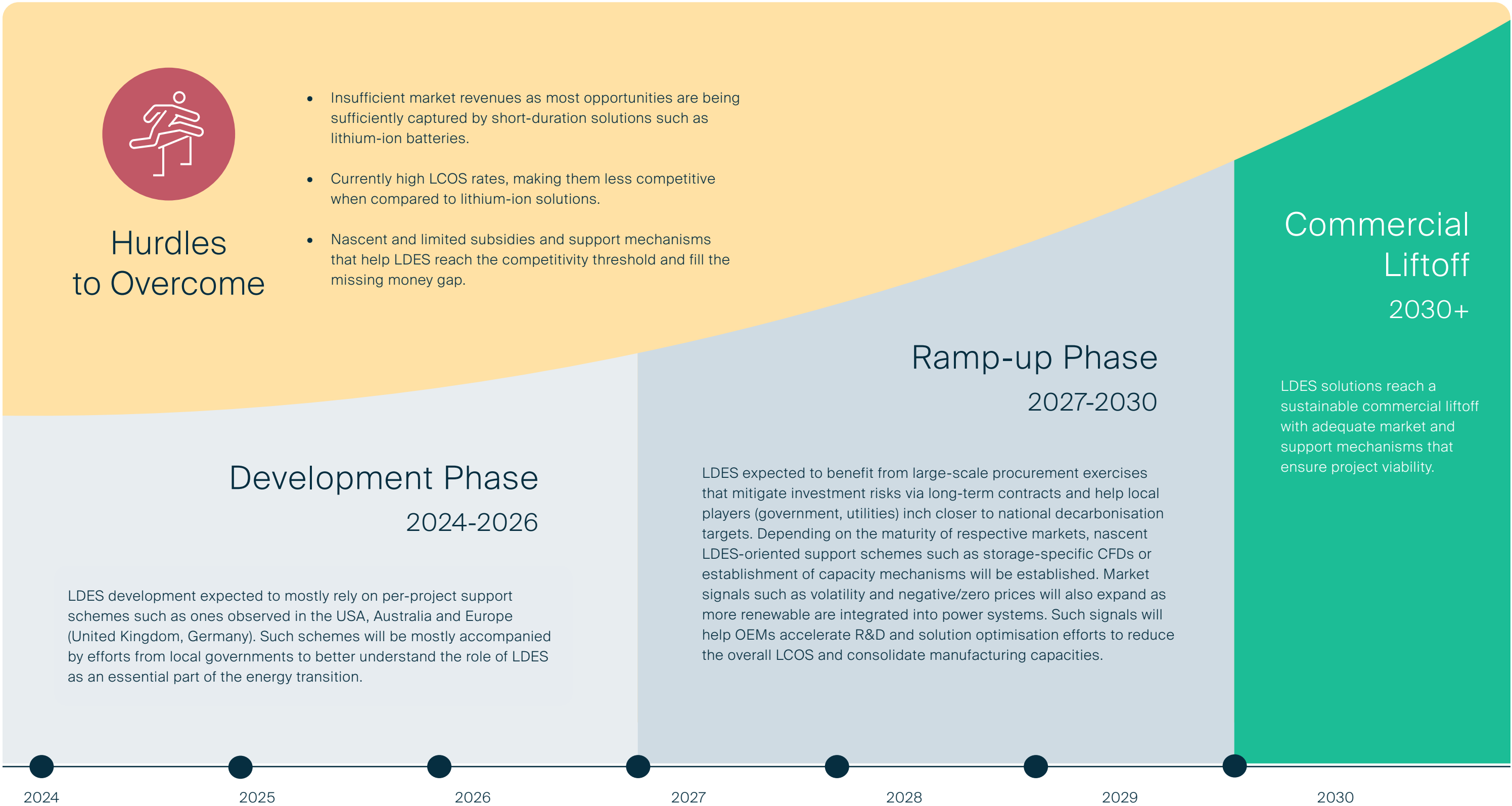
- Investment tax credits
- Loan guarantees
- Targeted tenders and direct funding of specific projects

Figure 12: Total LDES-Oriented Financing in Selected Countries



Source: Clean Horizon (2023).

Timeline for Commercial Liftoff



Conclusion

With renewable energy shares in the electricity mix increasing, LDES are expected to become a viable option to help further decarbonise electricity grids in specific markets, with a sustainable commercial liftoff anticipated around 2030.

Market signals, i.e. regular occurrences of extended periods of price volatility, will be the key factor in justifying long-term investments in LDES. These in turn are mainly driven by increasing shares of intermittent renewable energy in the electricity mix. Our analysis expects a 70% share of renewable energy to be the breaking point where investors can begin to expect sufficient and sustained demand for LDES solutions.

While renewables integration and price volatility very directly affect the merchant revenues from arbitrage, they also indirectly affect access to capacity markets and the need for ancillary services that can further support an investment case. In particular, access to capacity markets is expected to play a key role in reducing risks by providing cash flow visibility. Meanwhile, ancillary services are less likely to become a key component of LDES revenue stacks given most of the market is expected to be covered by short-duration solutions, i.e. lithium-ion batteries.

In the medium term – while widespread demand for LDES is still lacking – support mechanisms are expected to play a key role in pushing LDES solutions towards a sustainable commercial liftoff by allowing technologies to scale, bring down costs, improve their efficiencies and improve their overall competitiveness.

SUSI Partners' Perspective

The energy transition space continues to be very dynamic and investment decisions should not be based on an understanding of individual sectors alone. Analysing emerging sectors such as LDES is crucial to be able to capitalise on growth opportunities with a well-timed market entry and to recognise how the emergence of these technologies may create obsolescence risks elsewhere. We are therefore diligently monitoring the space, actively engaging with technology providers, developers, and other key stakeholders to identify and evaluate emerging opportunities despite the commercial liftoff of LDES technologies not being anticipated before 2030.

Our approach to LDES will likely be multifaceted with a primary focus on the equity side to gain substantial stakes in promising projects. Initial investments may include equity stakes in innovative developers, strategic partnerships with established technology providers, or joint ventures with developers that align with our long-term goals. These investments will be aimed at providing the necessary capital and resources to scale operations and build operational assets once technologies are deemed commercially viable.

Gravity Energy Storage



To ensure a comprehensive approach, we will also consider the debt side of investment, particularly for established companies with proven technologies and revenue streams. This could involve providing loans or other forms of financing to support expansion and deployment activities, ensuring that these companies have the financial stability to achieve their growth objectives.

Beyond deploying LDES solutions to decarbonise electricity grids, we recognise the potential of LDES technologies to decarbonise heat generation, a major source of global greenhouse gas emissions. This might include funding development projects focused on thermal storage innovations or investing in companies that are

pioneering the integration of LDES with heating systems. Opportunities in heat applications of LDES overall seem more tangible today than opportunities that derive revenues solely from grid-supporting functions.

In summary, our thorough analysis and strategic engagement in the LDES sector will position us to seize opportunities in a well-timed manner and provide us with a more comprehensive understanding of developments in the energy sector that may also affect investments in other sectors of the energy transition.



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