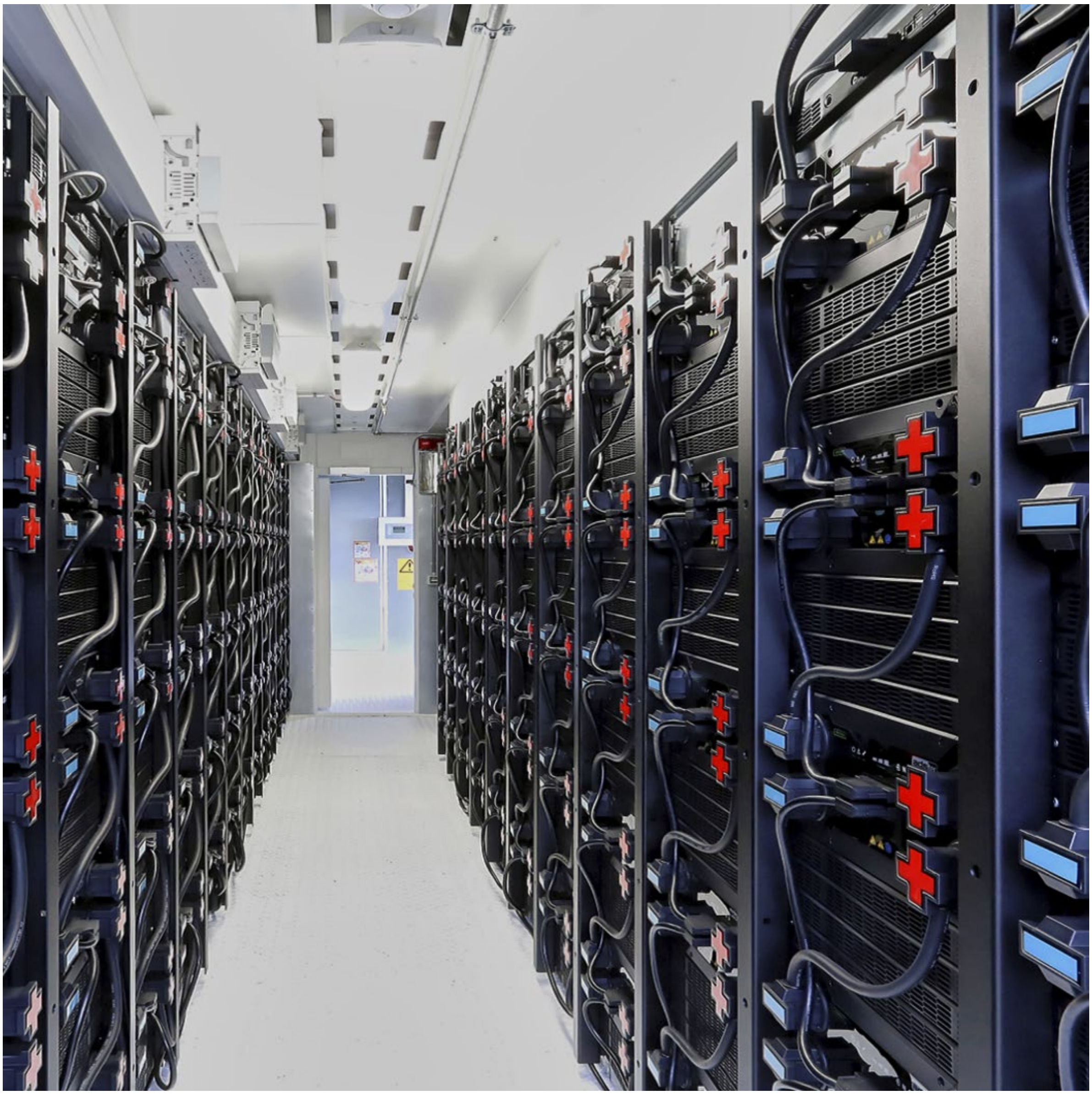
A CAR WITHOUT BRAKES

OPPORTUNITIES IN ELECTRICITY STORAGE

INDUSTRY BACKGROUND FROM LONGSPUR RESEARCH



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ELECTRICITY STORAGE

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OPPORTUNITIES IN ELECTRICITY STORAGE

Electricity storage and especially long duration storage is essential to deliver decarbonisation with a total addressable market of a similar order of magnitude to that for hydrogen, biofuels or carbon capture. It has the potential to become a major sub sector of the energy market.

A car without brakes

The requirement for energy storage in a market dominated by intermittent renewables is essential. We would go so far as to say that designing a renewable energy system without storage is like designing a car without brakes, it is that essential. Simply looking at the chemical energy storage in a pre-decarbonisation electricity system shows over 50 days of storage. Most of this will be removed if we are to meet the 1.50C target of the Paris Agreement and electrify the energy system.

Demand underestimated in any net zero outcome

Academic meta studies on storage show consistently high demand to balance networks. Our analysis of these suggests a total storage demand of between 355TWh and 38TWh depending on renewable penetration with the low number assuming net zero targets for 2050 are missed. A central figure of 127TWh could deliver a net zero outcome. These big numbers are not especially helpful when addressing market demand for individual companies. We have segmented and sized the storage market across five segments with different technologies best placed to address each segment.

This is not a format war

Different storage segments have different needs and will be best served by different technologies. Costs vary by duration and cycle lives, response times and locational constraints all vary but there are markets for all. Lithium-ion works very well at short durations with two hours now dominating and is possibly competitive at up to four hours where high cycling can be avoided. Flow batteries avoid cycling issues and could dominate the economics beyond four hours. At long durations of more than 10 hours, thermal, compressed air and pumped hydro offer the large capacities required for multi day and seasonal storage. Finally, gravity, flywheels and supercapacitors can meet the rapid response, but short duration needs required to balance power systems.

Listed opportunities

Listed opportunities include fund-based lithium-ion developers **Gresham House** (GRID LN), **Gore Street** (GSF LN) and **Harmony Energy** (HEIT LN). **Invinity Energy Systems** (IES LN) and **Corre Energy** (CORRE ID) are leaders in flow batteries and compressed air storage respectively and **Drax Group** (DRX LN) and **SSE** (SSE LN) run pumped storage in the UK and **Genex** (GNX AU) in Australia. **CAP-XX** (CPX LN) offers exposure to supercapacitors, **AMTE Power** (AMTE LN) to lithium ion and sodium ion and **Gelion** (GELN LN) to lithium sulphur, lithium silicon and zinc bromide technologies. **Talga Group** (TLG AU) is progressing silicon anode technology and eVTOL developer **Lilium** (LILM US) deploying it.

Industry background from Longspur Research

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STORAGE IS KEY TO DECARBONISATION

Decarbonisation towards a net zero outcome requires significant electrification of our energy systems using intermittent renewable power. This is required to replace not only current fossil fuel-based electricity generation but also to provide new power for electric vehicle charging, electrification of heat and the generation of hydrogen and other "efuels". Most of this electricity supply must meet demand needs instantaneously otherwise system frequency moves away from its design level. This has the potential to cause blackouts to large areas or risk damaging connected equipment. This was always true, but the intermittent nature of low carbon generation coupled with more volatile demand makes instantaneous balancing go the system much harder.

Storage has always been a key component of any energy system

Before renewable energy started to be deployed at scale, we had lots of energy storage in the form of chemical energy with an estimated 353TWh in the UK and 5,446TWh in the US. This was comprised of coal stocks, oil in tank farms, gas in linepack and petrol and diesel in vehicle tanks. If we decarbonise, this is going to disappear. The US figure represents 70 days of total energy consumption, and the UK figure represents 56 days. We do not necessarily need that much in an all-electric system, but this still gives a feel as to the order of magnitude required.

Filing in the gaps

We do need storage to cover gaps in electricity generation created by renewables intermittency and also to take advantage of surplus generation when it is curtailed from networks by lack of demand or grid constraints. Periods of low generation can last for days in instances of combined low wind and dense cloud cover. These are the so called dunkelflaute (dark doldrums) periods. Research shows that dunkelflaute events lasting more than 24 hours can lead to total lost generation of 50 to 100 hours every month during winter in Northern Europe. Even solar is unavailable during the hours of darkness in any day. Storage is also needed for shorter timeframes including very the very short needs of frequency management, filling during unexpected losses of generation before other technologies can fill the supply gap.

This is not a format war

Different needs for storage and integrated system-wide solutions mean there are many use cases with energy think tank the Rocky Mountain Institute cataloguing 13 separate uses. While most storage applications will serve a number of these, creating a revenue stack, none can cover all needs and the system as a whole will require several storage and other flexible generation technologies. As a result, there is no format war between competing storage technologies but rather a range of solutions which can be selected from for each application.

Market sizing

There are several ways of looking at how much storage will be required. We can take the storage lost from fossil fuel storage figure which globally we estimate at 20,000TWh. However, this storage was cheap, and we don't think durations of over a month are required at scale. If we instead look at the amount of wind and PV forecast and assumed storage to remove the potential generation "gaps" we can derive a figure of between 241TWh and 311TWh. Looking at much more detailed research in the academic literature allows us to map storage requirements against renewable energy penetration (cite references). This would support a market range of 38TWh to 355TWh depending on the level of renewable energy penetration. The high number is based on the IPCC's WG3 report example of an energy mix that will achieve net zero by 2050 and the low numbers is from the same source for a mix that fails to hit this target. A central figure based on the IEA's World Energy Outlook 2022 Net Zero Scenario shows a figure of 127TWh.

Segmenting the market

We see five main markets for storage:

- Frequency response and arbitrage trading < 4 hours
- Volume trading, short sundown solar 4 hours to 10 hours
- Longer sundown solar and short wind gaps 10 hours to 36 hours
- Weekly, wind balancing 36 hours to 108 hours
- Very long-duration >108 hours

Key solutions

The dominant form of energy storage currently is pumped hydro (PHS). It is capital intensive and time-consuming to build but the levelised cost of energy storage can be low given long-durations and service for many decades. Compressed air (CAES) technologies have the potential to store large volumes of energy provided a suitable location can be found. Both PHS and CAES require suitable locations limiting their deployability. Gravity is also reliant on finding appropriate sites. Flow batteries are very deployable and can be cycled many times. Thermal storage can offer the benefits of PHS or CAES without specific location requirements. Supercapacitors and flywheels can be fast acting although are more limited to duration. Lithium while making a strong play in the sector becomes expensive at longer durations and has a number of physical limitations.

Hydrogen can also be used as a form of storage but given weak round trip efficiency we see it as a one-way solution to renewables curtailment with curtailed power converted by electrolysing water into hydrogen and oxygen with the hydrogen used directly or further processed into “efuels” such as ammonia or methanol.

Electricity storage technologies

Technology type	Lithium ion	Flow battery	Pumped hydro	CAES	Thermal	Gravity	Super-capacitor	Flywheel
Response time	ms	ms	s	3-10 min	s	ms	μs	ms
Inertia	No	No	Yes	Yes	Yes	Yes	No	No
Cycle life	7,000	>20,000	30,000	12,000	30,000	30,000	30,000	30,000
Energy density (kWh/m3)	150-500	10	0.5-2	0.5-12	80-500	0.2-3.1	30-90	20-80
Roundtrip efficiency	90%-95%	65%-85%	60%-85%	55%-75%	60%-65%	75%-80%	85%-98%	85%-95%

Source: Longspur Research

Market sizing for each segment

Based on research on the UK market an assumption of constant or near constant power at each duration means that the segment sizes largely reflect the relative duration of energy stored. It is likely that longer duration storage will also be higher power storage, so this assumption is necessarily conservative for long-duration storage. In fact, it becomes more conservative the longer the duration. We think that for market sizing this makes a simple duration weighted segmentation a sensible tool as it builds in this conservative assumption. Based on this we think the total addressable markets for each segment are as follows.

Segment market share estimates

Source	**Longspur**	**Longspur**	**IEA**
Scenario	IPCC WG3 1	IPCC WG3 2	WEO 22
Total electricity generated (TWh)	108,444	111,111	73,231
Renewable generation (TWh)	106,667	73,889	64,506
% Renewable	98%	67%	88%
Storage as a % of generation	0.327%	0.034%	0.173%
Storage required (GWh)	354,962	38,197	127,002
Duration split (TWh)			
0-4	1,753	189	627
4-12	4,136	445	1,480
12-36	13,786	1,483	4,932
36-108	41,357	4,450	14,797
>108	293,931	31,629	105,166
Total	354,962	38,197	127,002
Market share (TWh)			
Li Ion	1,753	189	627
Flow	7,582	816	2,713
Thermal	115,209	12,397	41,221
CAES	115,209	12,397	41,221
PHS	115,209	12,397	41,221
Total	354,962	38,197	127,002
Capactiy (GW)			
Li Ion	438	47	157
Flow	528	57	189
Thermal	631	68	226
CAES	631	68	226
PHS	631	68	226
Total	2,859	308	1,023

Source: Longspur Research

In April 2022 we undertook an analysis of the Intergovernmental Panel on Climate Change's (IPCC) Working Group 3 (WG3) report – *IPCC Report is a Major Warning, Longspur Research, 13 April 2022*. We estimated a range for green hydrogen electrolysis capacity of 4,506GW to 4,957GW. We estimated a range of bioenergy and carbon capture and storage (BECCS) capacity of 807GW to 1,585GW. And we estimated biofuel production at between 14,722TWh and 19,903TWh. With our new estimate range of electricity storage capacity of between 308GW and 2,859GW or 38,197TWh to 354,962TWh it can be seen that electricity storage represents a segment of the clean energy industry of a similar magnitude to these segments. As with those sectors it has the potential to represent a major opportunity in the energy transition.

Investment opportunities

Listed company exposure to the opportunities in storage is mixed but a number stand out. In short duration lithium ion systems, fund based developers such as **Gresham House Energy Storage Fund** (GRID LN), **Gore Street Energy Storage Fund** (GSF LN) and **Harmony Energy Income Trust** (HEIT LN) offer exposure to the UK storage market and beyond. One of the leading global vanadium flow battery developers is **Invinity Energy Systems** (IES LN). **Corre Energy** (CORRE ID) is a leader in compressed air energy storage. Pumped storage is usually developed or owned by larger utilities or IPPs with **Drax Group** (DRX LN) looking to expand its Cruachan pumped storage site in Scotland and **SSE** (SSE LN) planning a new project at Coire Glas. Australian **Genex Power** (GNX AU) has developed pumped storage using existing mining infrastructure. Other technologies are largely represented by private companies with **Malta Inc** being a leader in thermal storage and **Energy Vault** and **Gravitricity** developing gravity storage systems. At the very short duration end of the market **CAP-XX** (CPX LN) develops supercapacitors, **AMTE Power** (AMTE LN) is active in lithium ion and sodium ion technologies, **Gelion** (GELN LN) in lithium sulphur, lithium silicon and zinc bromide, and private **Qnetic** is developing flywheel systems. **Talga Group** (TLG AU) is also progressing silicon anode technology and eVTOL developer **Lilium** (LILM US) offers exposure to silicon anodes at the application end.

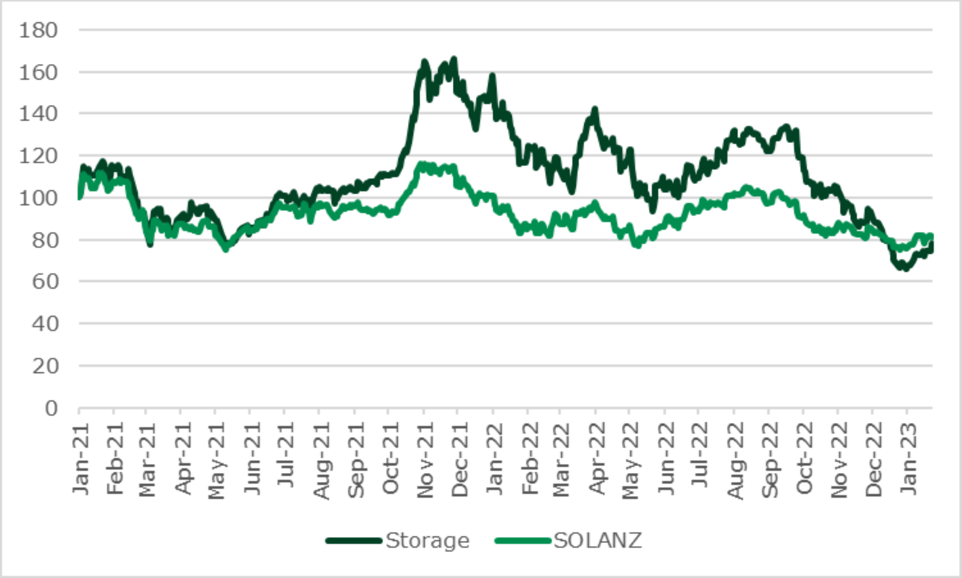
Listed storage companies

Company	Market Cap (£m)	EV (£m)	Ticker	Description
Corre Energy	182	162	CORRE ID	Compressed air
Drax Group	2,607	3,865	DRX LN	Pumped storage
Invinity Energy Systems	49	41	IES LN	Vanadium flow batteries
AMTE Power	19	19	AMTE LN	Sodium ion batteries
Azelio	23	25	AZELIO SS	Thermal storage
Brenmiller Energy	24	20	BNRG IT	Thermal storage
Cap-XX	23	41	CPX LN	Supercapacitors
EOS Energy Enterprises	112	219	EOSE US	Zinc halide batteries
ESS Tech	323	191	GWH US	Iron flow batteries
Fluence Energy	3,154	2,931	FLNC US	ESS system provider
Gelion	55	39	GELN LN	Zinc bromide batteries
Genex Power	118	303	GNX AU	Pumped storage
Gore Street Energy Storage	533	533	GSF LN	Li-ion
Gresham House Enrg Strg	893	893	GRID LN	Li-ion
Harmony Energy Income	279	279	HEIT LN	Li-ion
Lilium	447	447	LILM US	Silicon anode
Redflow	48	43	RFX AU	Zinc bromide flow batteries
Saltx Technology	57	52	SALTB SS	Thermal storage
SSE	18,541	18,541	SSE LN	Pumped storage
Talga Group	316	316	TLG AU	Silicon anode
Zinc8 Energy Solutions	23	21	ZAIR CN	Zinc air batteries

Source: Bloomberg, Longspur Research, *Longspur Research client

Using data from the Active Net Zero Global Clean Energy Universe from Longspur Radnor Indices, we can plot the performance of the key storage companies in the market. These companies took longer than other clean energy sectors to benefit from the rotation into positive ESG stocks that began in 2020 but performed well in late 2021 and held value throughout most of 2022. However, a broad decline across the clean energy space from September hit storage names heavily.

Active Net Zero Global Clean Energy Universe - Storage

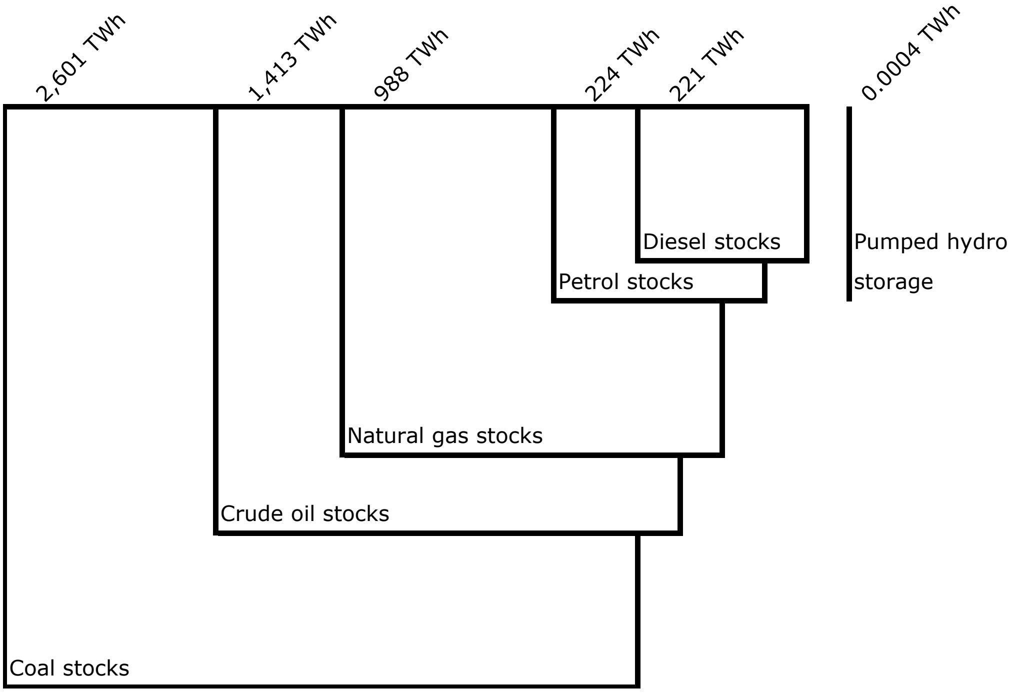


Source: Longspur Radnor Indices

WHY STORAGE

In the past, chemical energy storage was always a major part of the energy mix. Traditionally most energy has been stored chemically in oil tanks, coal stocks, gasometers and linepack. However, coal is being phased out and it is likely that a significant amount of oil and gas will follow if we are to hit net zero emissions targets. If we look at the total energy market, a move to net zero will entail the loss of 5,500 TWh of mainly chemical energy storage in the US market alone. This is equivalent to 70 days of average energy consumption. In the UK the comparative figures are 352TWh representing 56 days of storage.

Energy Storage in the USA



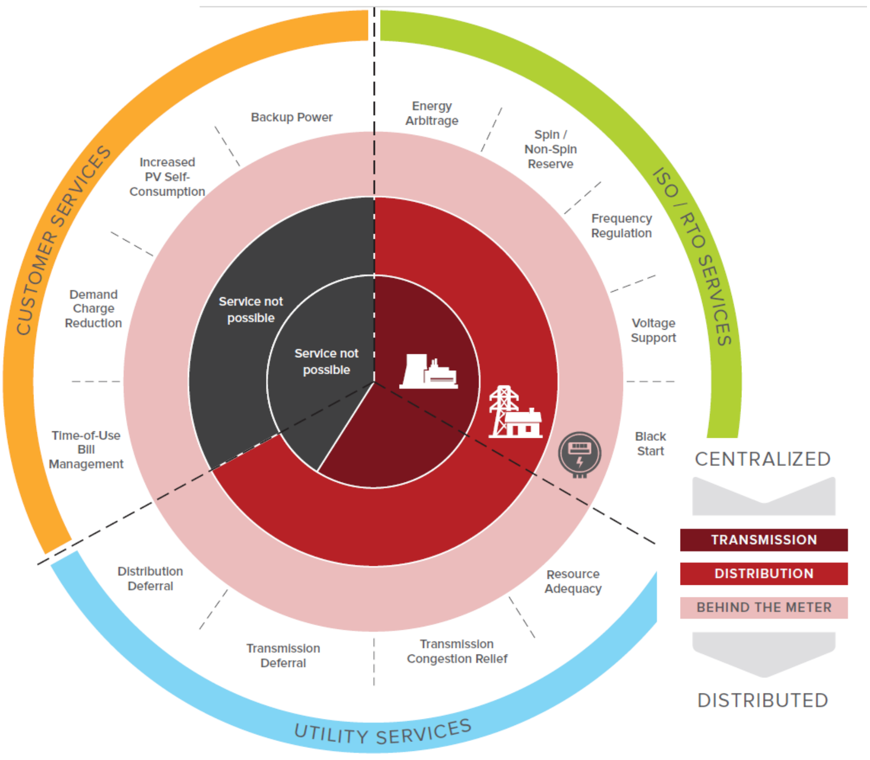
Source: Longspur Research, EIA, based on Simon Gill, University of Strathclyde, 2015

Extrapolating globally suggests up to 20,000 TWh of storage will be lost as we move from a fossil fuel-based energy system to one driven principally by renewable electricity. This is equal to approximately 80% of total energy demand.

STORAGE IS COMPLEX

The Rocky Mountain Institute identifies 13 use cases for stationary electricity storage applications.

Power Storage Use Cases

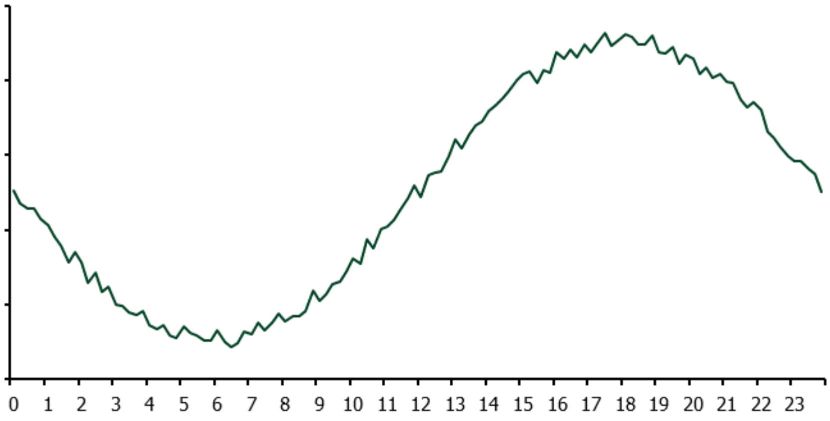


Source: Rocky Mountain Institute

The main areas of value in the market today are arbitrage (technically trading electricity rather than arbitrage as it is not risk-free) and frequency response.

We can assess these needs by considering main groups of demand based on storage duration across a typical day. A simplified picture of power demand across a 24-hour period is shown below, illustrating the need to convert a typical grid's daily power supply profile to a baseload demand need. The profile supplied varies across the day with small variations from second to second and larger variations across the day.

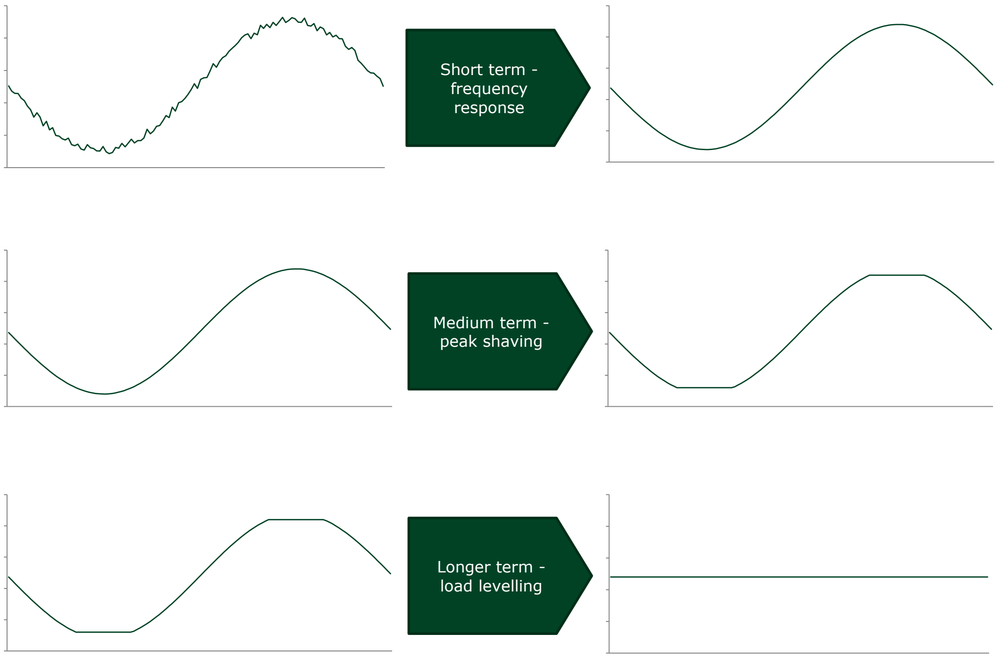
Idealised daily electricity demand



Source: Longspur Research

Storage can flatten this demand profile entirely but to do so there are three principal applications for daily or diurnal storage.

How storage can flatten demand

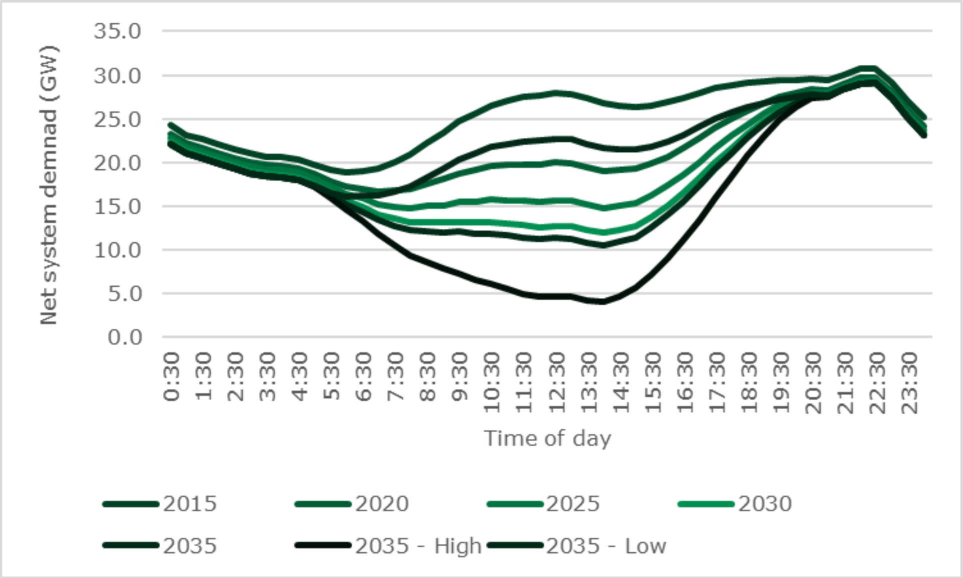


Source: Longspur Research

The short-term market needs storage solutions of up to 30 minutes, with more responsive solutions providing superior performance. Peak shaving requires storage from one to six hours and load levelling needs six hours of storage or more.

As more solar energy is added to any system the net demand in the middle of the day when the sun is shining starts to drop. This can be seen in the so-called duck curve below which subtracts solar generation from daily demand. This creates a “belly” of low demand followed by a very rapid increase in demand to the evening peak. Storage can flatten this demand making grid management easier and more efficient. From the graph below it can be seen that the amount of storage capacity required to flatten this demand can be significant, and that the duration of this is between 8 and 12 hours.

Duck curve showing how net demand is reduced with solar generation



Source: National Grid

Beyond daily storage there is an additional need for inter day and seasonal storage which requires higher volumes to be stored for longer periods. Simply to balance out the gaps in wind generation requires storage of above 10 hours. A recent study shows that the average gap in wind output for an offshore wind farm is 13 hours and to cover all gaps requires over three days of storage.

Storage required to meet lost wind output at an offshore wind farm

	Lost hours	Missing power	Missing power (MWh)*	Storage (MWh)*
Largest gap	82	100%	1,005	1,124
Average gap	13	69.40%	145	162
Smallest gap	1	7.70%	16	18

Source: Project Neos Public Report, * assumes peak demand at 16.4MW

Long periods of low wind when combined with cloudy weather reducing solar output are known as dunkelflaute or dark doldrums. On average there are 50 to 100 hours of such periods occurring in Northern Europe in each of the months of November, December and January when such events are defined as those lasting 24 hours or longer.

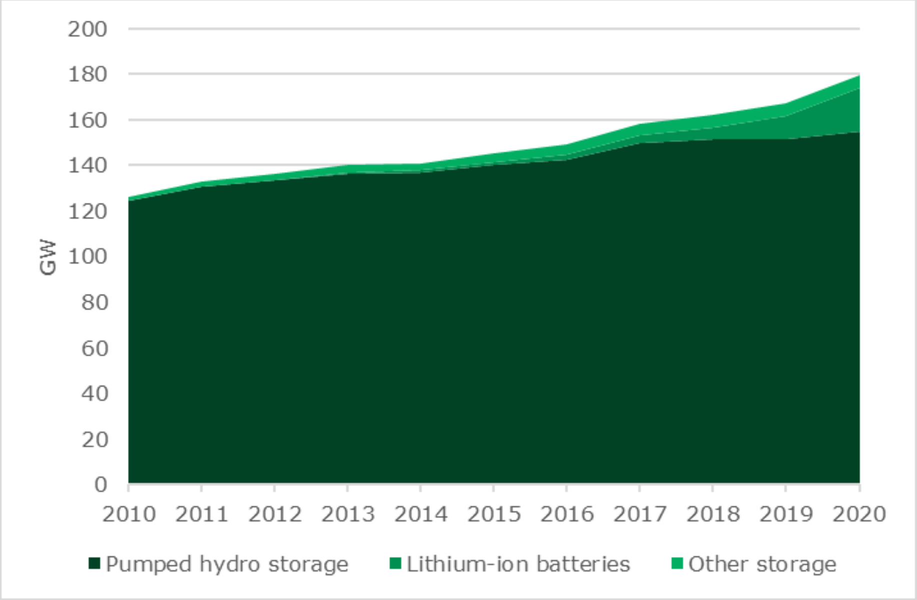
While solar will be stronger in summer and wind stronger in winter, creating some useful balancing, in most geographies, this balancing is not perfect requiring some inter seasonal storage with very long durations.

Following from the above we see five main markets for storage:

- Frequency response and arbitrage trading < 4 hours
- Volume trading, short sundown solar 4 hours to 10 hours
- Longer sundown solar and short wind gaps 10 hours to 36 hours
- Weekly, wind balancing 36 hours to 108 hours
- Very long-duration >108 hours

To date most electricity storage has been very long-duration pumped hydro. However, over the past five years lithium-ion has become a major contributor at short durations.

Global grid connected storage capacity

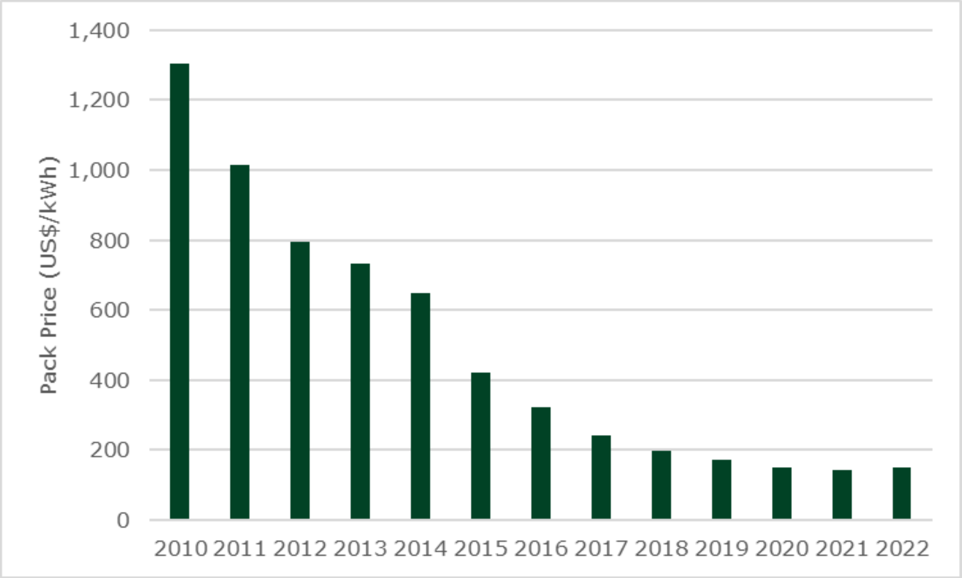


Source: BNEF

THE LITHIUM-ION REVOLUTION

As a result of an extremely well-developed manufacturing base and global supply chain owing to their widespread use in consumer electronics, lithium-ion batteries currently dominate the short end of the stationary battery market in terms of deployments.

Lithium-Ion Energy Storage Costs



Source: Bloomberg New Energy Finance

Lithium-ion is now cheaper than pumped storage at shorter durations. It has emerged as an economic solution at shorter durations and, if anything, is displacing open cycle gas turbines and gas or diesel reciprocating engines.

Why lithium-ion is not a universal solution

Batteries are now being seen by some as the ideal solution to solving the intermittency issues of renewable energy. While current lithium-ion batteries certainly have potential in these areas, there are certain issues which mean that they are not necessarily a cure-all:

- Operating life
- Thermal runaway
- Cost development and raw material scarcity
- Inability to provide synchronous generation and replace inertia loss
- Limited scale cost reduction with duration

Life

The life of a battery is usually expressed in the number of full charging cycles that a battery can deliver before there is a noticeable loss of power delivered. Because a lithium-ion battery is damaged if it is fully discharged, its cycle life is often based on the assumption of limiting depth of discharge to 80%. Even with this limitation, lithium-ion batteries can only deliver around 5,000 cycles, with storage capacity decreasing with every cycle to as low as 50% of the initial rating at end of life. Exposure to temperature extremes, rapid charging (a full charge in less than one hour), repeated cycles within a short time period or operating within high or low states of charge for extended periods also reduce the cycle life of a lithium-ion battery.

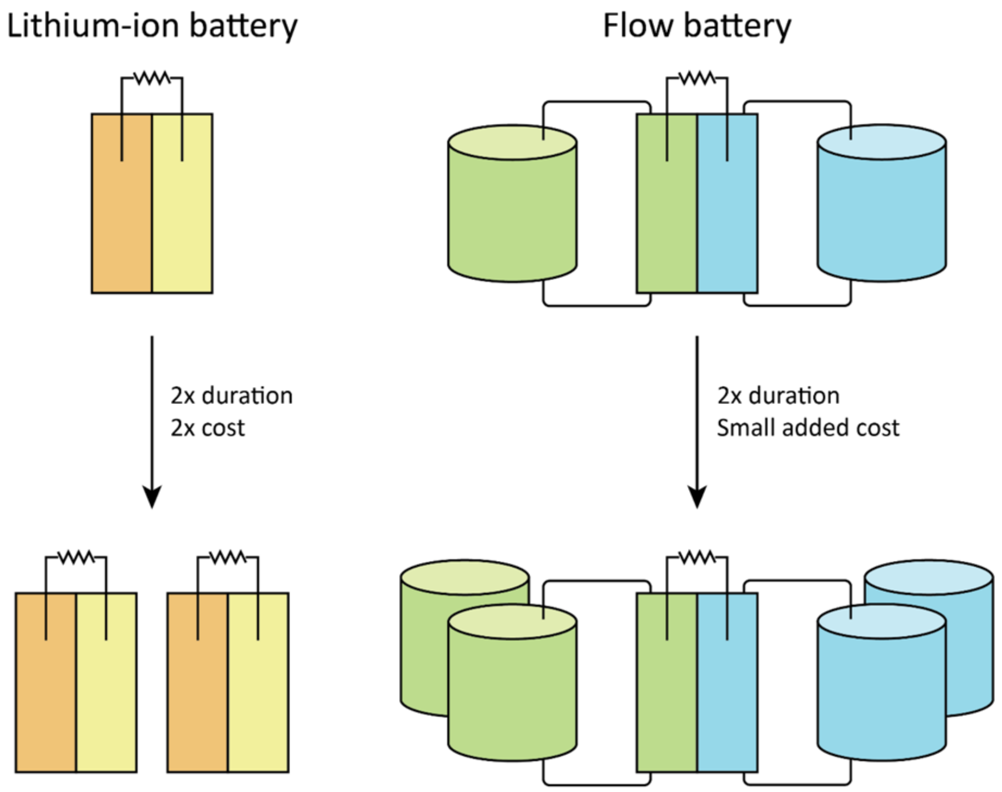
Thermal runaway

Lithium-ion batteries have also had some well-publicised issues with thermal runaway which can in certain circumstances lead to fire. There have been a number of well-publicised incidents involving lithium-ion batteries catching fire including the Boeing 787 Dreamliner and the Tesla Model S. In the stationary storage space fires at Moss Landing in California, Carnegie Road in the UK and more than 30 fires in South Korea suggest that this is a major issue.

Scalability with duration

Lithium-ion batteries are composed of many cells which are grouped into packs and modules. However, if you want to double the duration you need to double the number of cells. There is some scaling advantage in a complete system as the balance of plant has some benefits of scale, but broadly speaking, lithium-ion battery cost is correlated with duration. Longer duration technologies: CAES; flow batteries; thermal; and pumped storage; decouple the storage capacity from the electricity generating "engine". This engine does not change size with duration, and as duration increases, the average cost falls.

Scaling of batteries compared



Source: Information Technology and Innovation Foundation

Cost development

There is a broad assumption that lithium-ion costs will continue to fall based on a learning curve assumption similar to Moore's Law. This is not actually a law but merely an observation and there is no defined causality which is a feature typical of learning curves. Abernathy and Wayne's classic paper on learning curves (The Limits of the Learning Curve, Harvard Business Review, September 1974), which studied the learning curve of the model T Ford, emphasised that the cost reductions achieved had to be worked for and had to come from a deliberate focus on cost above all else, often at the expense of flexibility. Cost increases reported by lithium-ion manufacturers in 2021 and 2022 further imply that cost reductions in lithium technologies may be limited by the cost of input materials.

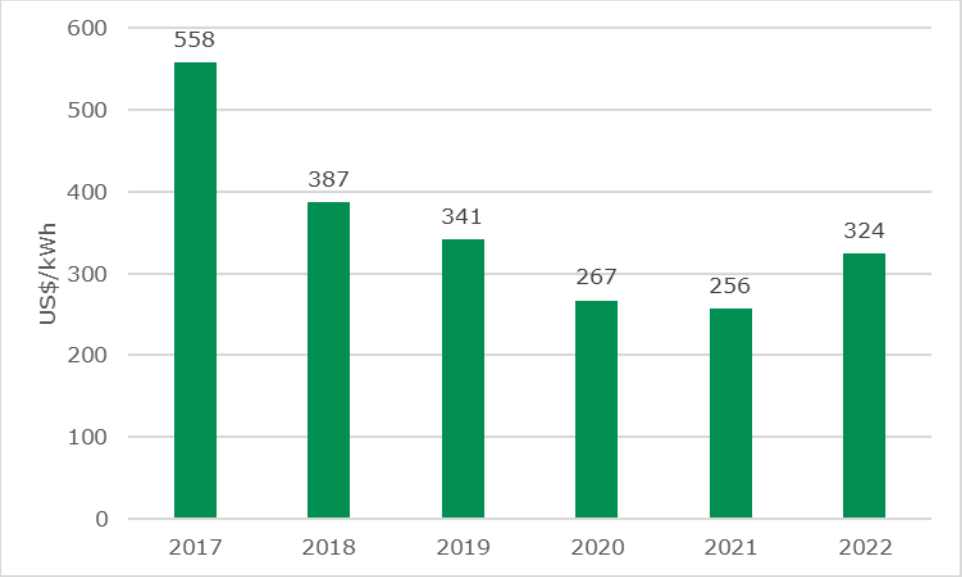
Looking at the facts we see a number of issues that might result in slower than expected cost progression for lithium-ion batteries.

- Material constraints – supply chain restrictions in key materials
- Low margins – limited scope for competition to drive reductions
- Electro chemistry – gains cannot be considered linear

Electro chemistry does not usually lend itself to simple solutions. For example, lithium-ion technology has been struggling with a problem known as voltage fade for a number of years now. This has limited gains in energy density and hence duration.

2022 has actually seen an increase in system costs largely due to the cost of lithium carbonate which has risen 3.8 times since 2021.

Turnkey energy storage system costs (4 hour duration)



Source: Bloomberg New Energy Finance

Lithium production is set to increase in 2023 with announced capacity breaking through the 1mtpa barrier. Even factoring in raw material constraints there should be sufficient capacity for demand. As a result we expect a downward learning curve to re-emerge but for all the reasons above we see this as not necessarily at the rate of the most aggressive assumptions.

OTHER SOLUTIONS

The dominant form of energy storage currently deployed is pumped hydro (PHS). It is capital intensive and time-consuming to build but the levelised cost of energy storage can be low given the ability to store long-durations and remain in service for many decades. Compressed air (CAES) technologies have the potential to store large volumes of energy provided a suitable location can be found. Both PHS and CAES require suitable locations limiting their deployability. Gravity is also reliant on finding appropriate sites. Flow batteries are very deployable and can be cycled many times. Thermal storage can offer the benefits of PHS or CAES without specific location requirements. Supercapacitors and flywheels can be fast acting although are more limited to duration.

Hydrogen storage is a contender but suffers from low round-trip efficiency; in addition, rising gas prices mean the increased value of hydrogen either as a fuel for direct use or for conversion into products such as methanol or ammonia make pure storage using hydrogen less competitive. We see hydrogen as an efficient conversion technology to deal with curtailment rather than a storage technology per se.

Electricity storage technologies

Technology type	Lithium ion	Flow battery	Pumped hydro	CAES	Thermal	Gravity	Super-capacitor	Flywheel
Response time	ms	ms	s	3-10 min	s	ms	µs	ms
Inertia	No	No	Yes	Yes	Yes	Yes	No	No
Cycle life	7,000	>20,000	30,000	12,000	30,000	30,000	30,000	30,000
Energy density (kWh/m3)	150-500	10	0.5-2	0.5-12	80-500	0.2-3.1	30-90	20-80
Roundtrip efficiency	90%-95%	65%-85%	60%-85%	55%-75%	60%-65%	75%-80%	85%-98%	85%-95%

Source: Longspur Research

FLOW BATTERIES

The first flow battery was used to power an airship in 1884 using a zinc-chlorine technology. In the 1970s NASA further developed the technology using iron and chromium and later zinc bromide. In 1984 the University of New South Wales built the first prototype vanadium redox flow battery. In contrast to lithium-ion batteries which store electrochemical energy in relatively small battery cells, flow batteries use a liquid electrolyte stored in large tanks instead. In VFBs, this electrolyte is composed of vanadium dissolved in a stable, non-flammable, water-based solution.

A BETTER STORAGE SYSTEM

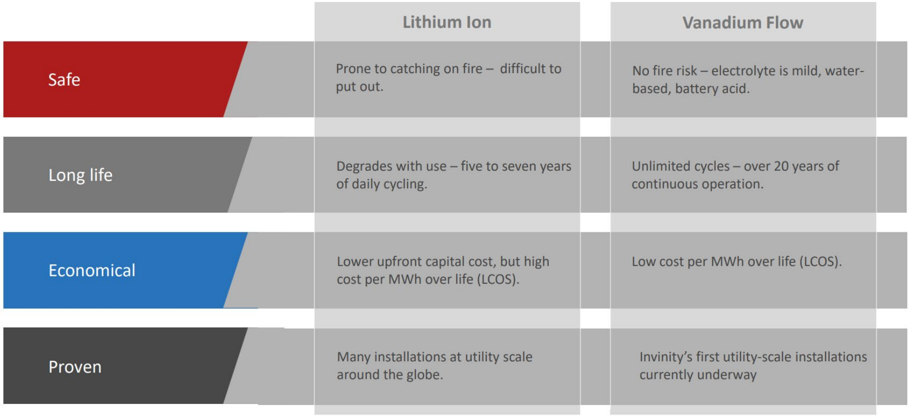
Vanadium flow batteries have been developed over a long period and has several key characteristics that provide an advantage in the market, notably a safe and stable chemistry, long performance lifecycle, no marginal cycling costs, and proven versatility across all storage applications.

1) A safe, stable and non-flammable vanadium electrolyte chemistry with a far lower risk profile than other battery storage technologies.

2) Flow batteries can perform in the field for 25+ years, matching most renewable assets, with unlimited cycling and no capacity degradation. Lithium-ion batteries can require replacement after around 5,000 cycles due to degradation, whereas a VFB can continue to operate for 20,000 cycles or more without the need to replace the whole system.

3) Massive throughput and no marginal cycling costs allow flow batteries to deliver energy at the lowest price per MWh stored & discharged over the lifetime of the product. VFBs can generate more attractive returns than lithium-ion batteries in certain applications, specifically those requiring multiple, daily, charge/discharge cycles such as solar 'firming' and peak-shaving for industrial sites, a key market segment for Invinity and its VFB products.

Lithium-ion vs Vanadium Flow Energy Storage Characteristics

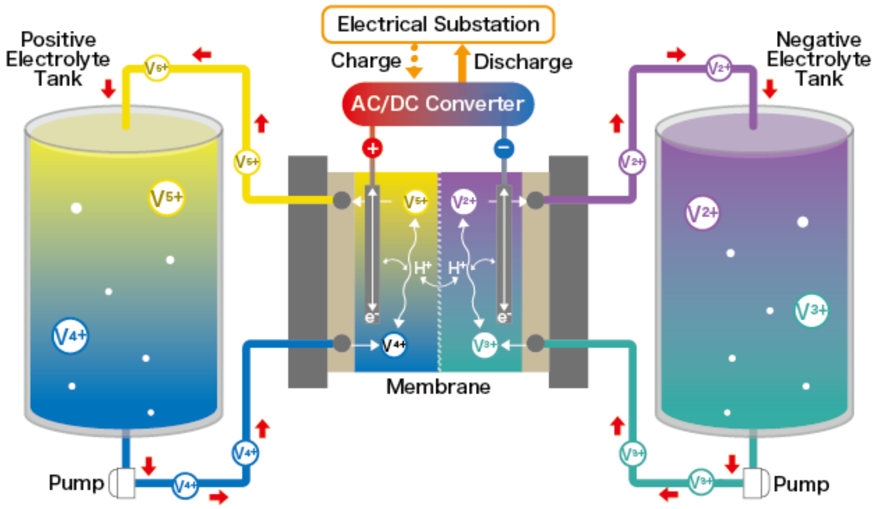


	Lithium Ion	Vanadium Flow
Safe	Prone to catching on fire – difficult to put out.	No fire risk – electrolyte is mild, water-based, battery acid.
Long life	Degrades with use – five to seven years of daily cycling.	Unlimited cycles – over 20 years of continuous operation.
Economical	Lower upfront capital cost, but high cost per MWh over life (LCOS).	Low cost per MWh over life (LCOS).
Proven	Many installations at utility scale around the globe.	Invinity's first utility-scale installations currently underway

Source: Invinity

The battery is designed around a "cell stack" of multiple electrochemical cells which combine together in series to deliver the power output from a single flow battery module. Positively and negatively charged vanadium electrolyte is stored in two tanks which can be sized for the required battery duration.

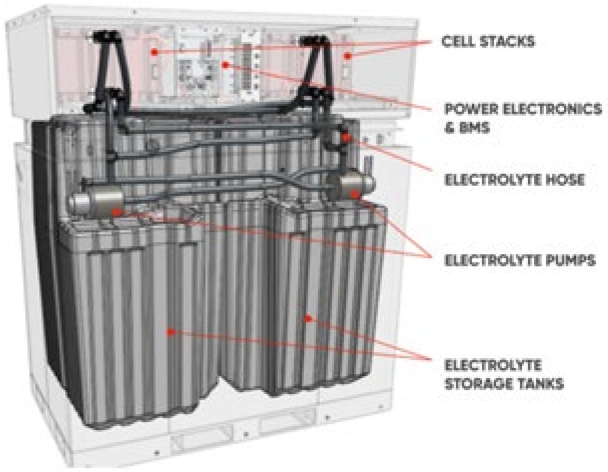
Structure of Vanadium flow battery



Source: LE System Co

Flow battery can be straightforward to manufacture and install. The configuration minimises land use and the layout can be designed to be containerised in ISO units.

Inside a Vanadium Flow Battery



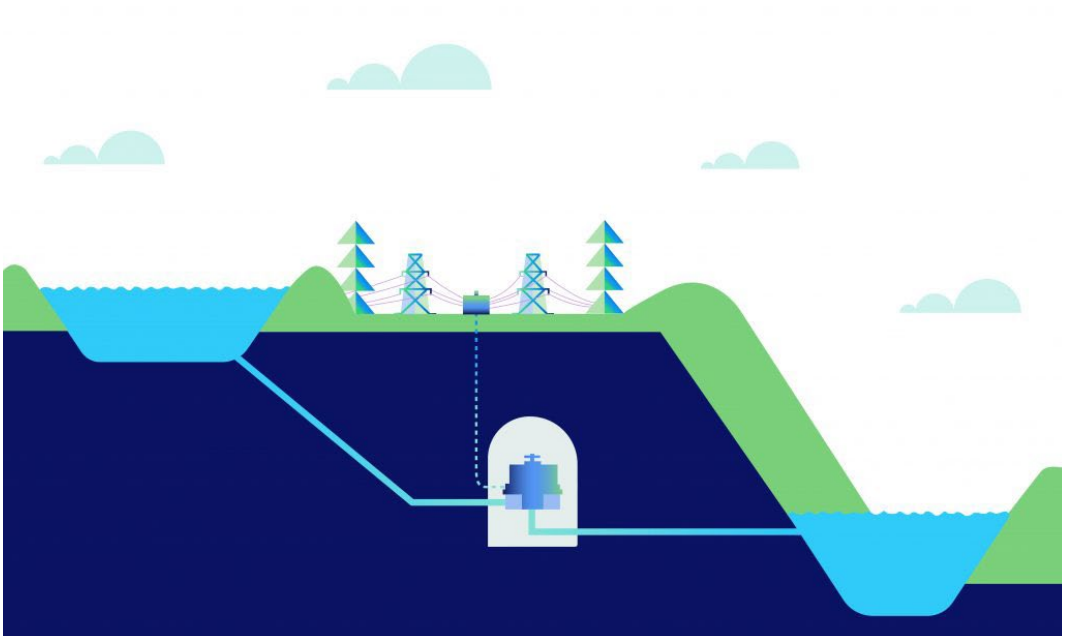
Source: Invinity

PUMPED HYDRO STORAGE

Pumped hydro is a very well proven storage technology that accounts for the vast majority of energy storage currently deployed. It makes use of gravity with a high level reservoir letting water flow though turbines to a lower reservoir or other water body to generate electricity. In this regard it is identical to an impoundment hydro-electric generation plant. However, the turbines can be reversed to act as pumps or secondary pumps are installed so that water can be pumped up to the top reservoir to recharge the system which, unlike hydro, is not reliant on rainfall to replenish the source of energy.

The main requirement for a pumped hydro project is suitable geography where there is the potential to place a reservoir at a suitable height above a lower body of water. This tends to limit suitable locations to hilly or mountainous terrain. Often this can be in areas of natural beauty so permitting can sometimes be challenging. The projects also usually involve tunnelling which can add to the construction risks with tunnel collapse a potential problem especially in newer geologies. Costs can be high, but the technology remains one of the few ways to deliver very long duration storage at scale.

Inside a Vanadium Flow Battery



Source: Drax Group

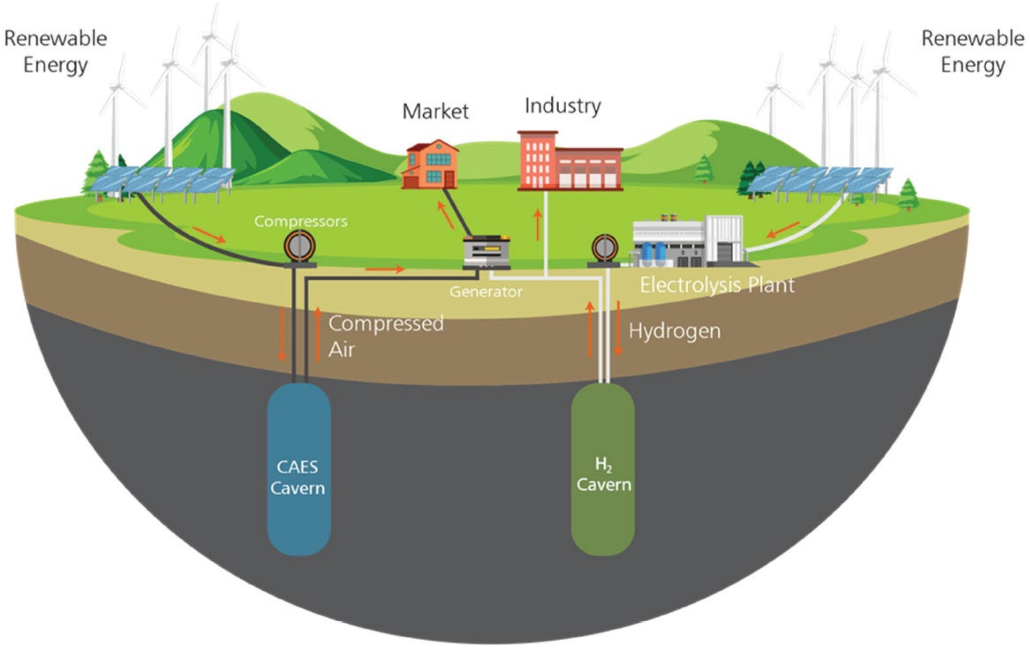
COMPRESSED AIR ENERGY STORAGE (CAES)

Underground energy storage in the form of compressed air provides a low-cost storage solution for a minimum of 10-12 hours, and subject to cavern sizes, a duration of 80-100 hours can be achieved for 300 MW+ of energy storage. A combination of relatively unlimited storage cycles and significantly lower capital costs provides for much lower annualised costs for CAES versus lithium-ion battery at these longer durations. The process uses electrical energy to compress air and store it under high pressure in underground geological storage facilities. This compressed air can be released on demand to produce electrical energy through a turbine to power a generator and in turn produce electricity.

Compressing air or hydrogen in salt caverns is an economically viable, scalable storage technology that will be able to reach true grid scale in excess of 100MW and offer both short and long-term duration storage. CAES has been operating reliably and safely since 1978 in Germany and 1991 in the U.S. The technology uses specifically designed underground storage caverns created in geological salt deposits by a process known as solution mining or leaching.

During operation of the CAES facility, in the storage phase, electricity is used to compress air into the storage cavern. In the generation phase, the compressed air is released and pre-heated using a fuel to drive turbines, producing electricity when required. Two CAES caverns of 0.5 million cubic metres can generate 320MW of power over a 3-4 day duration. CAES can also be combined with green hydrogen stored in co-located caverns to fuel the generation of electricity.

Typical CAES project with co-located hydrogen electrolysis



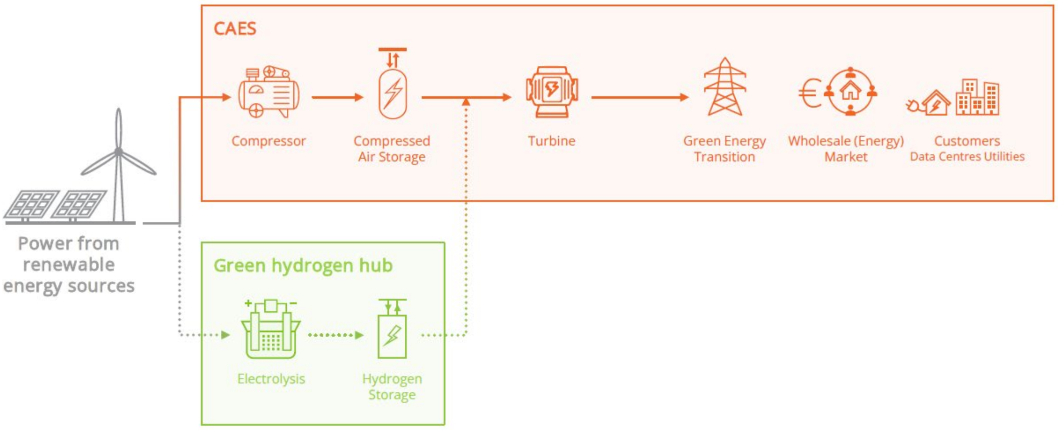
Source: Corre Energy

The construction of a CAES project can be divided into the above ground installation and the below ground salt caverns. The salt caverns are large solid cavities in the salt layers made by dissolving salt. For a typical above ground installation, 220MW of compression capacity could be divided over four compressors at 55 MW each. Compressors compress outside air into compressed air and use (excess) electricity for this purpose.

The compressed air needs to be cooled before it enters the cavern using hybrid cooling towers, resulting in the application of both air and water cooling. This results in an air temperature of 50 degrees Celsius, an ideal temperature to guarantee the safety and stability of the cavern.

Full operation of the CAES facility involves the use of electricity to force air into the storage cavern during the storage phase before the compressed air is released and heated to drive turbines and in turn produce electricity when needed during the generation phase. When the electricity is supplied back to the electricity network, two Turbine Expanders with a total capacity of 320 MW are used. This air expansion process will once again cause the air to cool and further heating will be required before electricity can be used. Corre Energy has a solution able to use hydrogen for this process on a large scale and heat the compressed air which drives a modified turbine to produce electricity.

Combined CAES and Green hydrogen hub



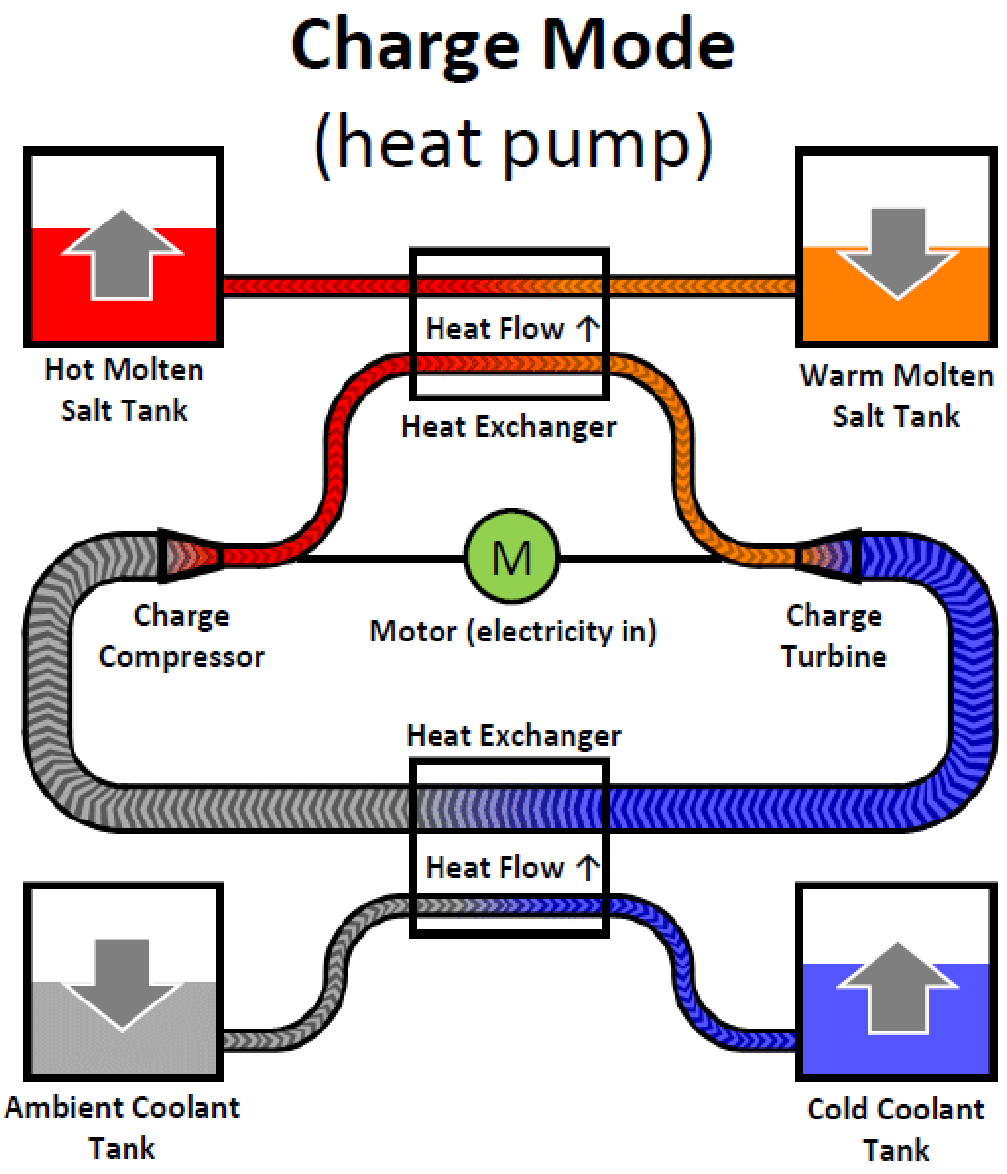
Source: Corre Energy

THERMAL STORAGE

Modern electro-thermal energy storage systems have improved on a technology once limited by poor round trip efficiency. Malta Inc has developed a technology using molten salt and designs utilising a closed loop air Brayton thermodynamic cycle. The proprietary system converts electricity to heat in molten salt and also cools a refrigerant. The use of cold as well as heat makes the Malta system more efficient than other technologies. As a result, the roundtrip efficiency is higher than earlier thermal storage solutions.

When charging, the system operates as a heat pump. Electricity is used to power a motor which drives the charge compressor and the charge turbine. Heat flows into a hot molten salt tank and out of a cold coolant tank.

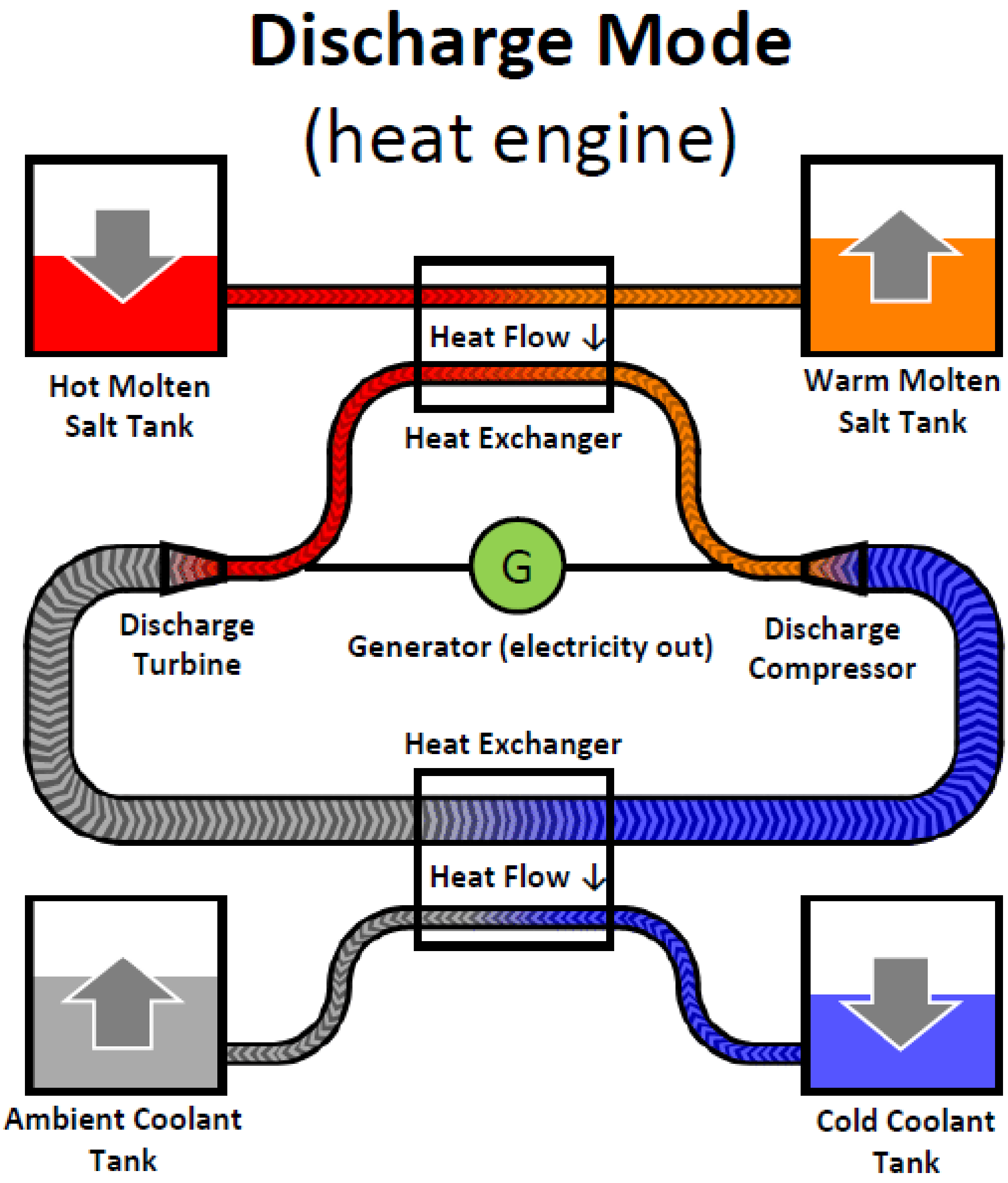
Thermal storage in charge mode



Source: Malta Inc

On discharge, the system reverses with heat flowing out of the hot molten salt tank and into the cold coolant tank with the difference driving a discharge compressor and a discharge turbine which together drive a generator.

Thermal storage in discharge mode



Source: Malta Inc

OTHER STORAGE TECHNOLOGIES

Overall, we see supercapacitor, gravity and flywheel technologies as key to very short duration applications for needs such as frequency management but less relevant for the high volume energy market segments we are analysing. These are potentially interesting specific niche opportunities, and they may take market share from lithium ion in time.

Supercapacitors

While a supercapacitor is more technically known as an electric double layered capacitor ("EDLC"), the term is appropriate as the supercapacitor will store 10 to 100 times more energy than a traditional electrolytic capacitor of the same volume. A capacitor stores energy in an electric field created between two conductors separated by a dielectric medium. While a capacitor can be charged and discharged much more rapidly than a battery, the amount of energy that can be stored is comparatively limited. Capacitors have many other uses in electronics especially as filters.

The supercapacitor brings the high power characteristics of capacitors to energy storage with attributes that are more useful than battery technologies in several key respects:

- Long life – significantly more (thousands) charges than a battery before showing any signs of degradation
- Very rapid (mS) charging and discharging
- High range of operating temperature (-40oC to +85oC)
- Higher power density
- But lower energy density – while this is improving it restricts duration to the sub hour space, mainly down to seconds

More importantly the limitations of both supercapacitors and batteries can be overcome by combining the two in hybrid systems.

Capacitors have been seen as the solution to high power requirements, but ordinary capacitors have extremely low energy densities and this limits their use. Supercapacitors get round this by offering better energy densities combined with high power density. This opens up a considerable range of applications for short duration energy storage.

Gravity storage

Gravity storage works on the same principal as a grandfather clock and can therefore be described as having reasonably proven underlying technology. Several models are being developed including the crane based Energy Vault and the drilled shaft of Gravitricity. This latter can be sited in existing mineshafts or drilled shafts in city centres creating specific niche opportunities. The overall duration is limited but these solutions can be fast reacting.

Flywheels

Flywheels are also limited as to duration but do offer fast response. However, newer technologies such as Qnetic offer durations of up to 12 hours making a more viable solution. This is early stage though and development risk remains.

New technologies

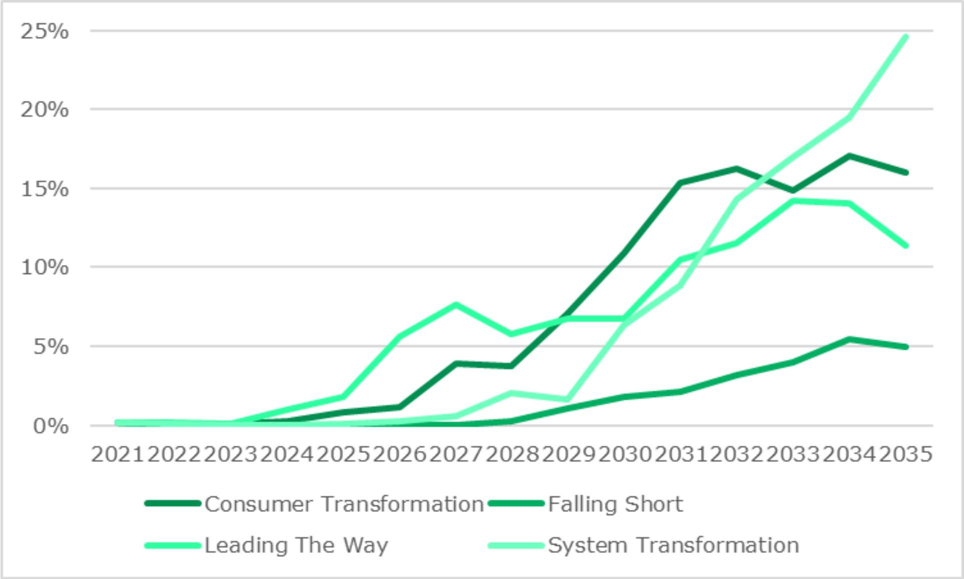
A number of new technologies are targeting the stationery storage opportunity. These include liquid air storage, and new battery chemistries notably based on zinc or sodium ion and new flow battery chemistries.

ONE WAY FLEXIBILITY SOLUTIONS

We see storage as a subcategory of flexibility which can either take power out of the system or put it back in. There are also flexible generators which can put power in and there are things such as loadbanks which can deal with excess power on the system although usually this is lost. However, the ability to create useful energy fuels using electricity creates a more valuable flexibility solution and key to this are solutions using electrolysis of water to create hydrogen and other hydrogen based fuels. The need for solutions to absorb excess power is growing along with storage as grid capacity cannot always cope with the large increases in production delivered by intermittent renewables. Currently such loads are curtailed with curtailment now accounting for up to 20% of potential output in high penetration renewable geographies such as Australia.

In the UK, curtailment is forecast to grow, peaking at up to 25% of renewable output by 2035 in a high renewables scenario.

UK curtailment forecasts under four scenarios



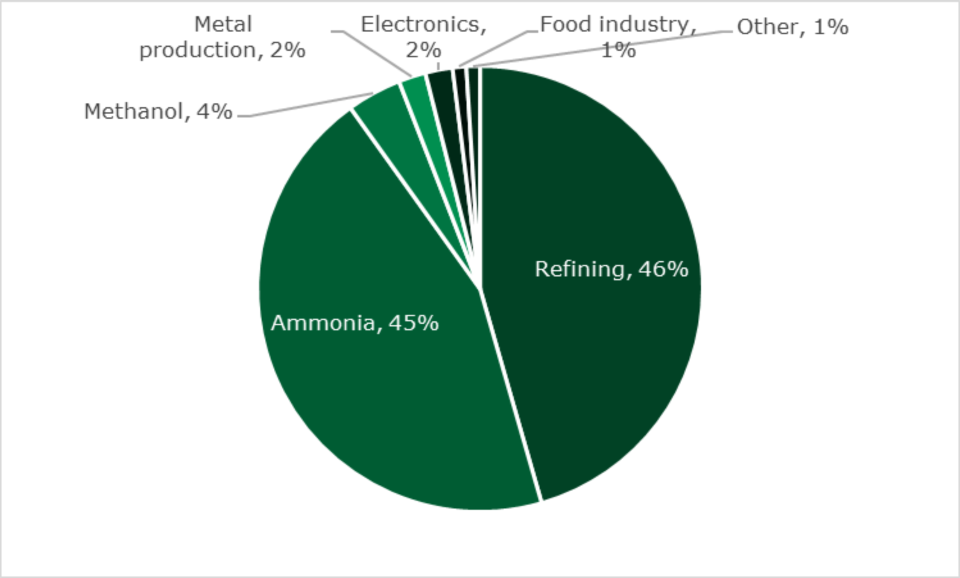
Source: National Grid ESO FES 2022

Hydrogen has been proposed as a storage solution with hydrogen being produced from the electrolysis of water and then being used to generate electricity through a fuel cell. However, the round trip efficiency here is very low. But hydrogen has other uses and as a direct fuel or processed further into ammonia or methanol can create low carbon liquid fuel solutions for difficult to decarbonise applications.

HYDROGEN PRODUCTION

The world currently produces around 50Mt of hydrogen annually. This is primarily used in the refining industry to reduce the sulphur content of diesel fuel and for the production of ammonia for fertilizer. While refining has seen margin expansion with recent rises in the price of oil and gas, traditional ammonia production is under pressure as a result of the higher cost of gas and is a potential area for distruption from low carbon “green” ammonia production.

Current uses of hydrogen



Source: US Department of Energy

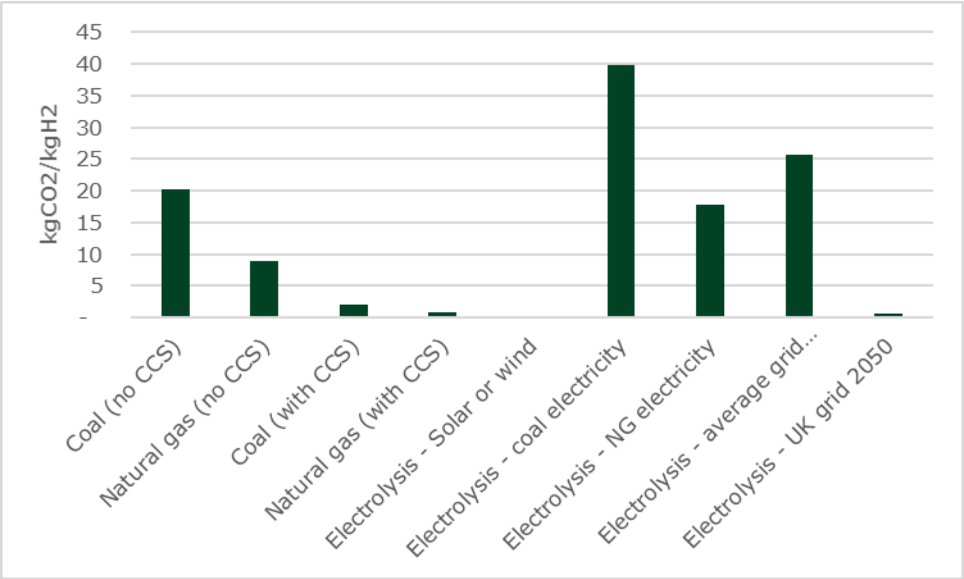
Currently, hydrogen is mainly produced by steam reformation of natural gas. This “grey” hydrogen production using steam methane reformation (SMR) is energy intense and a major emitter of CO_2.

As a result, the key pathways for low carbon hydrogen production are either the electrolysis of water or SMR combined with carbon capture and storage (CCS) to minimise the emissions problem, creating “blue” hydrogen. Adding the likely cost of CCS increases the cost of SMR. Also, CCS does not remove fugitive methane (CH_4) emissions from the SMR process or upstream of it. There is currently some debate about the extent of these and in reality it varies case by case.

Recent work from authors at Cornell and Stanford universities has suggested that blue hydrogen could be a significant emitter thanks to these fugitive emissions. They have used a top-down approach to these emissions, and we have seen criticism of this suggesting they are overestimated. Either way, it is clear that blue hydrogen is not emission free to the extent that green hydrogen can be. Where emissions are subject to a carbon tax, this potentially puts blue hydrogen at a cost disadvantage.

Truly low carbon, or “green”, hydrogen can be created from the electrolysis of water with renewable energy providing the electricity. “Blue” hydrogen can also be considered low carbon as can “purple”, “red”, “pink” (from nuclear energy) and “turquoise” (from methane pyrolysis).

CO2 emissions from hydrogen production



Source: BNEF

Types of green hydrogen electrolyser

There are several types of electrolyser with proton exchange membrane (PEMEC) and alkaline (AEC) electrolysers dominating the market at present. Solid oxide electrolysers (SOEC) are newer but starting to gain traction. Anion exchange membrane electrolysers (AEMEC) and membrane-free electrolysers (MFEC) are developing technologies. PEMECs are a fast reacting technology but are higher cost thanks to the use of expensive catalysts. Alkaline electrolysers are cheaper but less responsive, taking longer to start up when needed. Electrolyser manufacturer NEL (NEL NO) manufactures both PEM and alkaline types and expects the capital cost of these to converge by 2030. Solid oxide electrolysers offer greater efficiency and membraneless electrolysers have long lives reducing overall lifetime costs.

Alkaline electrolyser technology is well proven with large scale alkaline units being operated since the 1920's. Driven by demand for hydrogen for ammonia production, many projects were completed with output in the 2-3 ton per hour (50 –70tpd) range. However these were rendered uneconomic by steam methane reforming as plentiful natural gas became available. Recent rises in the price of natural gas are beginning to reverse this differential.

Several factors come into play when choosing between electrolysers. Flexibility can be important with PEM electrolysers offering millisecond response times and flexible operation. This makes them a better choice for pairing with intermittent renewable energy where operators are targeting electricity response markets for some of their income. For the alternative fuels market and Power-to-X, cost and efficiency are more important considerations and solid oxide may be the best option here. Additionally, the ability to use waste heat and run in continuous operations can made solid oxide particularly attractive.

Electrolyser technologies compared

	AEC	**PEMEC**	**SOEC**	**MFEC**
Voltage efficiency (%HHV)	62-82	67-82	<110	73-78
Operating Temp. (C)	60-80	50-80	650-1,000	20-80
Operating Pressure (bar)	<30	<200	<25	35
Gas purity (%)	>99.5	99.99	99.9	99.999
System Response	Seconds	Milliseconds	Seconds	Seconds
Cold-start time (min.)	<60	<20	<60	<20
Stack Lifetime (h)	60,000-90,000	20,000-60,000	<10,000	219,000
Maturity	Mature	Commercial	Demonstration	Demonstration
Capital Cost (€/kWe)	1,000-1,200	1,860-2,320	>2,000	1,860-2,320

Source: Imperial College, CPH2, Longspur Research

LEVELISED COST OF STORAGE

The levelised cost of storage (LCoS) calculates the level of average pricing for energy delivered from an energy storage system that must be achieved to deliver a positive return to investors in the technology. If the LCoS can be brought below the expected average revenue, then the technology will get deployed.

LCoS amortises the capital costs of storage over the lifetime output of the system and takes these together with the unit operating costs to give a cost per unit of output. The figure is given by the following formula:

$$LCoS = \frac{capital\ cost\ x\ capital\ recovery\ factor + fixed\ O\&M}{annual\ expected\ generation\ hours} + variable\ O\&M + charging\ cost$$

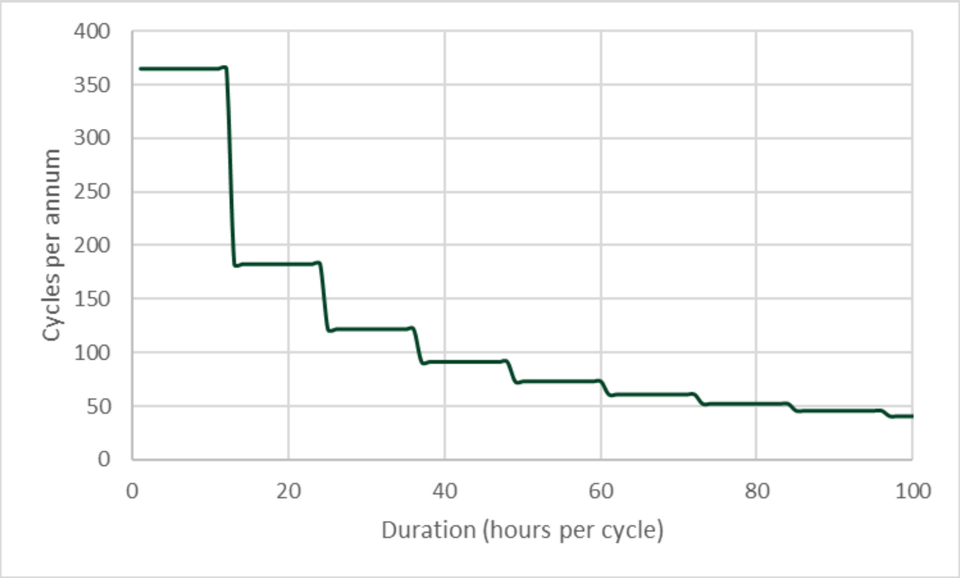
It is important to note that there is a distinction between capital costs which are related to the power output of the technology and those which are related to the energy output. A battery cell can only add more energy by adding another cell, doubling the energy but also doubling the cost related to the battery cells. Of course, there are other costs including the balance of plant which do not double, but overall, the levelised cost is comparatively static across durations before the impact of multi day storage is taken into account.

Duration

Duration is the amount of time energy can be discharged following a single full charge. If we multiply the power capacity of the storage technology by duration, we get the total energy stored in a single charge. When considering duration in the LCoS calculation, we need to consider that for every period of discharge there must be a period of charging. This assumes that charging and discharging periods are equal. This is a reasonable assumption for most storage technologies.

As duration increases, the maximum number of cycles in any year becomes limited. A duration of six months can only have a single cycle in any year. A duration of 12 hours, with a single charge and discharge every day will have a maximum of 365 cycles in a year. We have assumed that for durations over 12 hours, annual cycles are reduced by the rounded up fraction of 12.

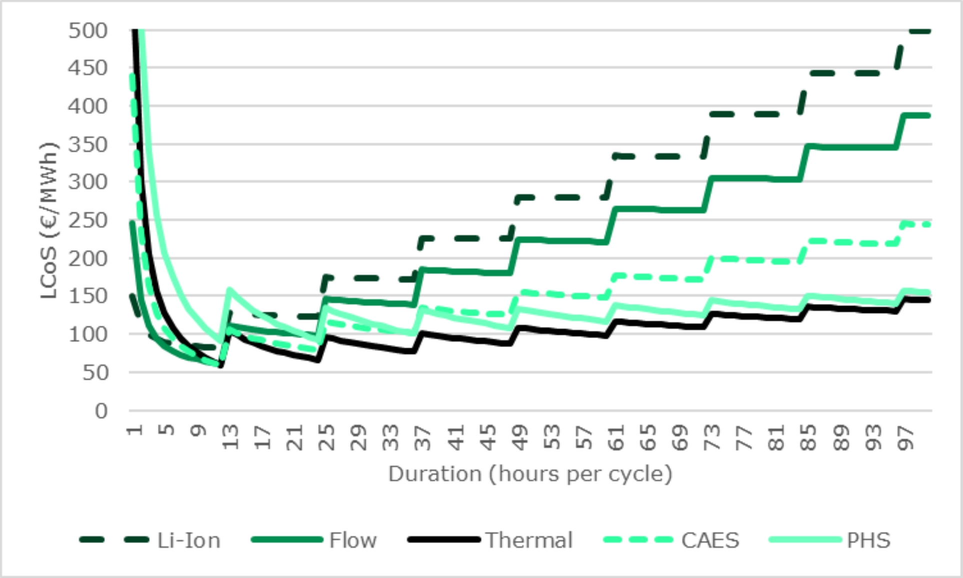
Duration and maximum cycles per annum



Source: Longspur Research

Using these assumptions, we can plot LCoS against duration.

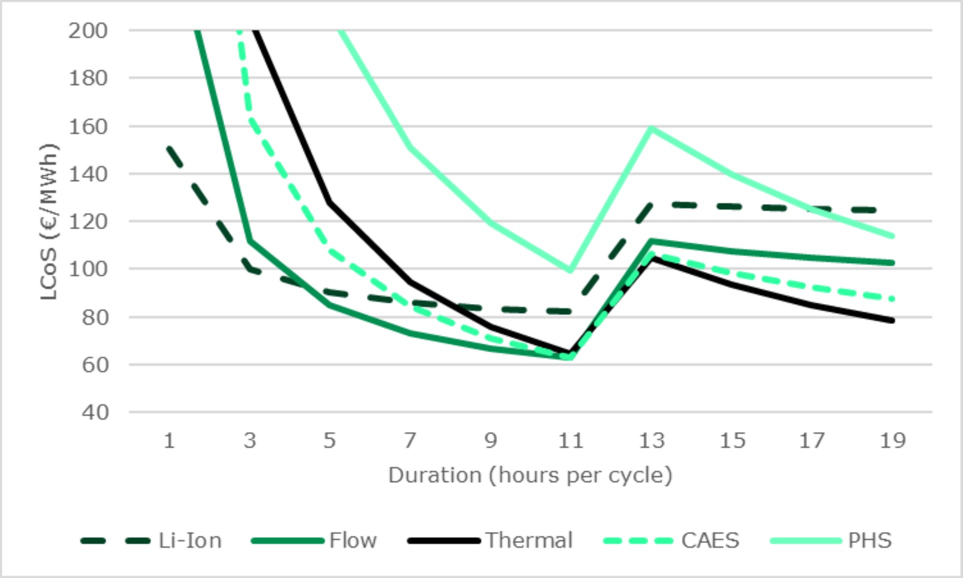
Levelised cost of storage against duration



Source: Longspur Research

This shows that lithium-ion is dominant at durations of up to four hours. This is reasonably consistent with the type of deployments we are seeing in the market today. Beyond four hours, flow batteries are more economic out until about 10 hours when thermal and CAES weigh in. Eventually at multi day durations pumped hydro covers its capital costs to become more cost efficient.

Levelised cost of storage against duration detail

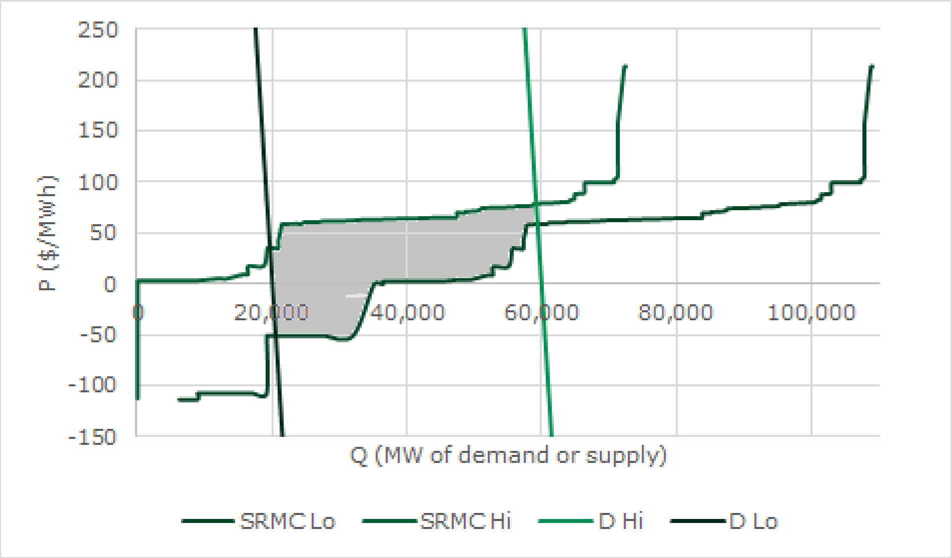


Source: Longspur Research

STORAGE ECONOMICS

We can examine the economics of electricity storage using a traditional supply and demand graph. Because of the instantaneous nature of the market with demand changing every 20 ms (in a 50Hz system), we really need to show two demand curves, one with the peak demand in the year (D Hi) and one with the minimum demand (D Lo). Also, because intermittent renewable supply varies, we think it helpful to show the limit points in two supply curves (based on short run marginal cost), one with all renewable capacity available (SMRC Lo) and one with no renewable capacity available (SRMC Hi). Prices across the year should all fall in the shaded area between the curves.

Electricity market supply and demand in a 60GW peak market



Source: Longspur Research, BNEF, National Grid FES

The average price for the year will be roughly in the middle of this area. It can be estimated using assumptions of average demand and supply. Full forecasts are available using Monte Carlo simulation techniques to capture the variation in demand and weather-related supply to pinpoint the exact point in the middle of this area. However, processing this data is calculation heavy with one consultant reporting a ten-hour run time to prepare a forecast.

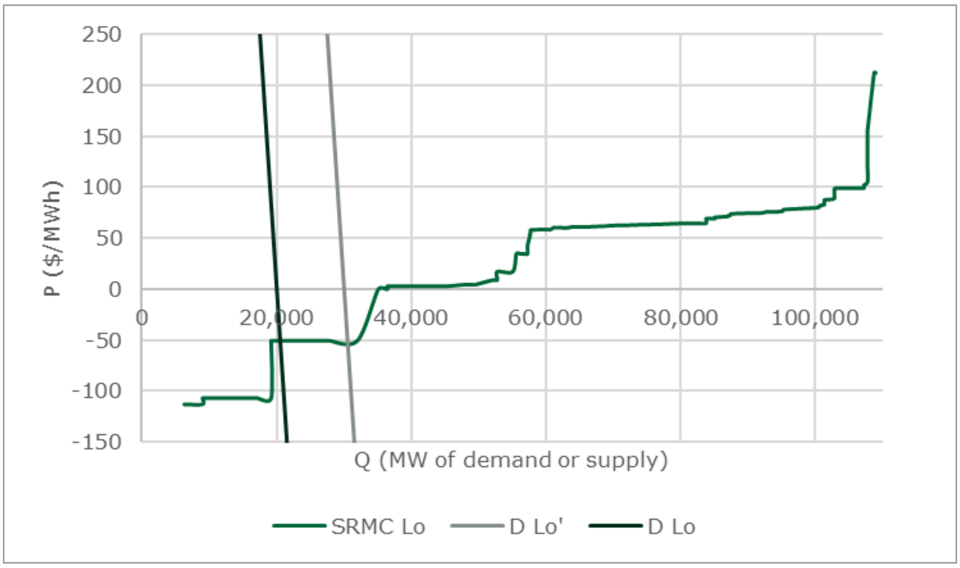
The low supply curve includes renewables with negative short run marginal costs resulting from subsidy programmes. The subsidy is only paid when the generator runs, so there is the potential that they are prepared to bid negatively, down to the level of subsidy. This may be rare but does happen and is increasing as more renewables are added to the system.

Adding storage

Storage is both a source of demand and supply. Storage charges as demand and discharges as supply. Charging will ideally take place when supply is at a maximum and demand at a minimum. With negative pricing, energy storage could be paid to charge, although in practice we think the actual low charging point will be zero.

Discharging will try to take place when demand is at a maximum and supply at a minimum. While storage will also sell services to the ancillary markets and the capacity market, it can make money from trading the difference between the high demand/low supply periods and the low demand/high supply periods. If we add storage capacity two things happen. The capacity moves the low period demand curve to the right to represent the additional demand caused by charging.

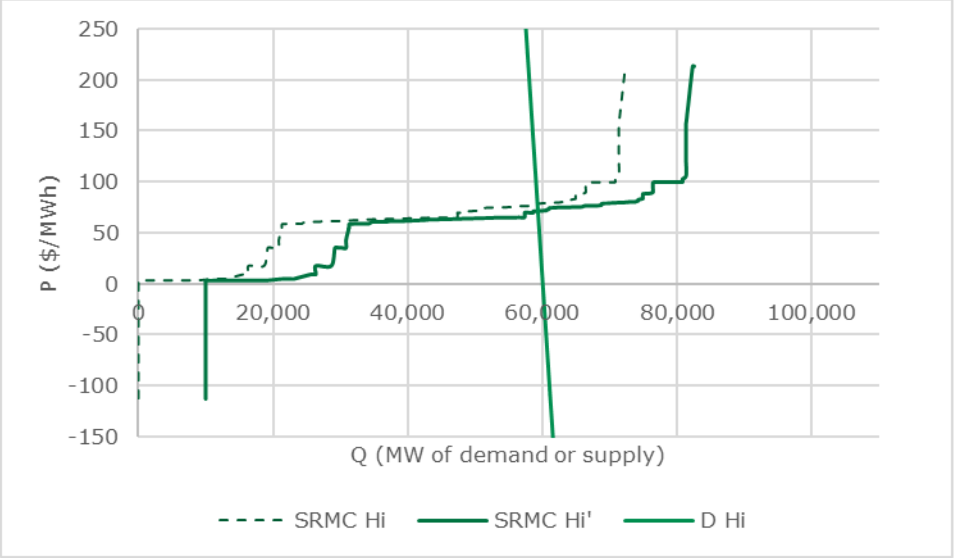
Impact of 10GW of storage charging



Source: Longsur Research

Then the high period supply curve is moved to the right (new supply is added), representing discharging.

Impact of 10GW of storage discharging



Source: Longspur Reseach

Looking at these graphs we can see that we can add over 30GW of new storage before the charging cost rises materially above zero and before the discharge price falls below £50/MWh. We would caution that this is the extreme range available, but it does give a useful illustration of the fact that trading spreads can remain attractive even with a lot of new storage capacity in the market.

30GW represents c.50% of the peak demand in our market example. This is a significant opportunity and if this opportunity presents itself in other similar markets, we are underestimating the opportunity for stationary energy storage systems.

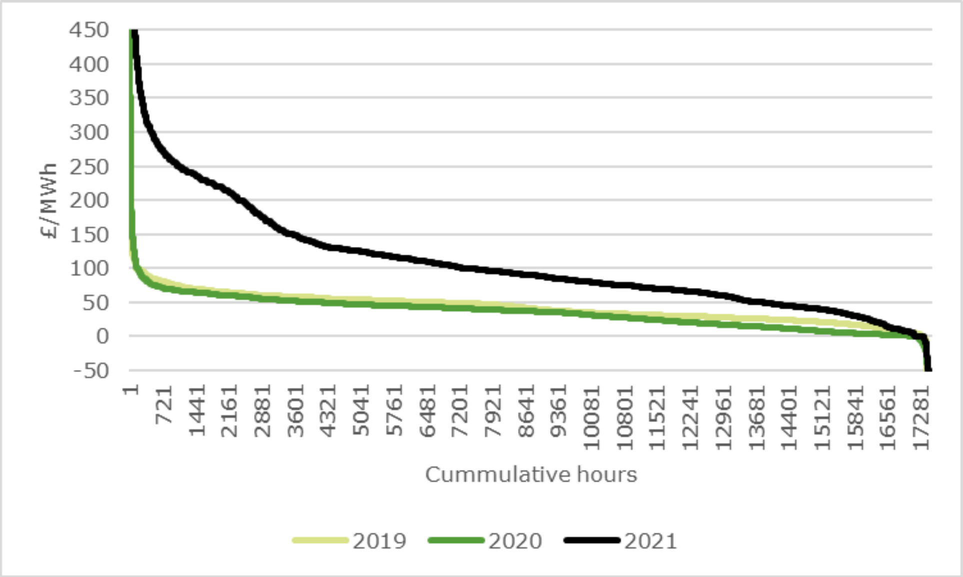
STORAGE PRICING

This analysis is based on an examination of the two extreme cases in the market, that of maximum renewable availability and that of minimum renewable availability. We need to look at market behaviour between these two points. We have used the UK market as a good source of data in a deregulated power market with high renewables penetration and where we have data for the short-term balancing mechanism, which is close to being a spot market, run on a half hourly basis.

Recent pricing

Prices for every half hour in each of the years 2019, 2020 and 2021 are plotted in descending order of price to give a price duration curve for each year.

Balancing mechanism price duration curves

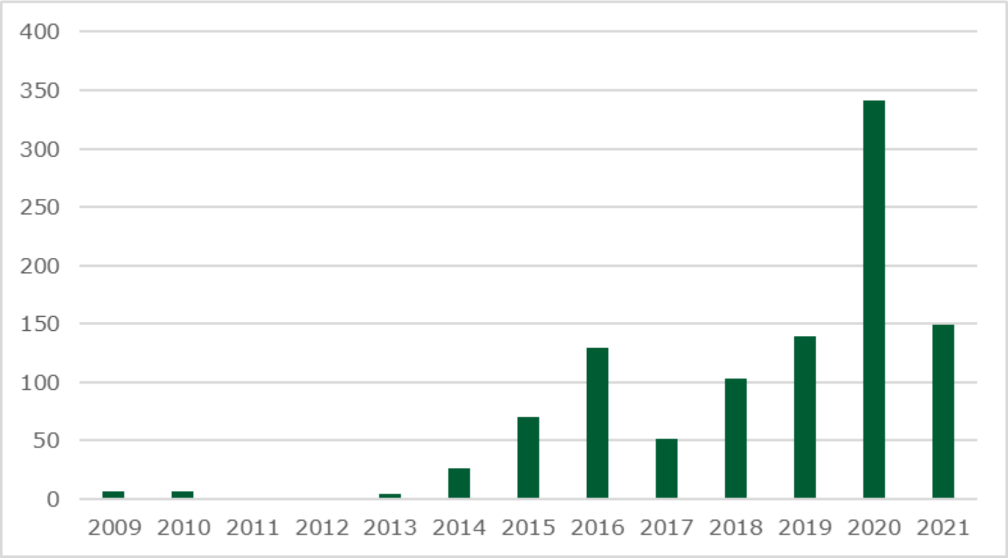


Source: Elexon, Longspur Research

Storage seeking arbitrage revenue will buy power at the right-hand end and sell it at the left-hand end of the curve. The flatter the curve, the less money can be made from arbitrage and the steeper the curve, the more money can be made.

2021 is an interesting year with low wind output and high gas and carbon prices. The price duration curve has increased along its length with a notable filling out towards the peak (left-hand end). Less obvious is the fact that 2020 saw a decline in baseload pricing, modest but indicative of future pricing as more renewables are added to the system. Negative pricing events more than doubled in 2020.

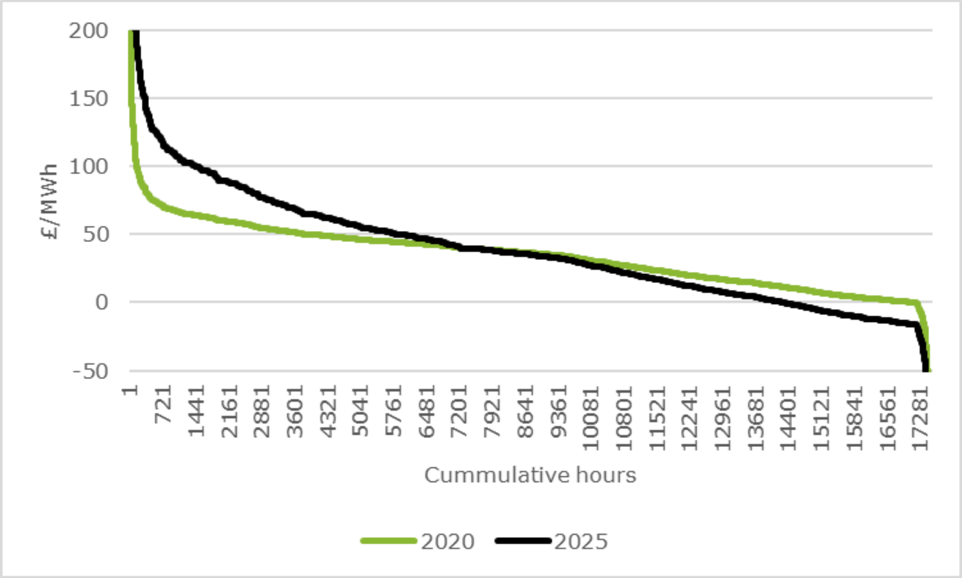
Negative pricing events



Source: Elexon, Longspur Research

Looking forward we expect a pivoting of the curve around the middle as carbon prices rise and eventually with the entry of hydrogen gas turbines. This will increase the value of arbitrage for storage assets.

Expected price duration curve evolution



Source: Elexon, Longspur Research

In addition to this growing revenue opportunity in energy arbitrage, ancillary service revenue from providing a number of support services to help balance grids will be available to Malta. Also, ownership and management of a storage assets gives the operating company a trading advantage through control of a real option in the market.

STORAGE POLICY

For the 193 nation states who have aligned themselves with the Paris Agreement, pursuing to a 1.5ºC outcome is a policy commitment. The key guide to getting to this outcome are the pathways summarised in the IPCC's recent WG3 report.

This report highlights the problems of low carbon generation being either intermittent, in the case of renewables, or insufficiently flexible, in the case of nuclear, and these impact power systems in a number of ways, creating problems such as loss of inertia and voltage stability issues. All these issues have solutions with storage a key component and likely to see growing demand over the coming years. The WG3 report gives full recognition to this.

"Flexibility technologies - including energy storage, demand-side response, flexible/dispatchable generation, grid forming converters, and transmission interconnection - as well as advanced control systems, can facilitate cost-effective and secure low-carbon energy systems (high confidence)."

"To achieve very low carbon systems, significant volumes of storage will be required."

In addition to lithium-ion batteries, the benefits of longer duration technologies including flow batteries are considered, with the report emphasising that a portfolio of complementary technologies is likely to be optimum.

"No single, sufficiently mature energy storage technology can provide all the required grid services - a portfolio of complementary technologies working together can provide the optimum solution (high confidence)."

With this in mind we expect to see supportive government policies emerging in countries which are Paris signatories.

USA

The US is supporting long-duration storage through the through the DOE's Long Duration Energy Storage Shot initiative, part of the Energy Earthshots program. This makes available US$1.16bn of funding to reduce the cost of storage in one decade by 90% from a 2020 lithium-ion baseline in storage systems that deliver over 10 hours of storage such as Malta.

More broadly, US policy on energy storage has become significantly more supportive with the issue of Order 841 from the Federal Energy Regulatory Commission (FERC). This removes barriers to distributed and behind the meter energy storage and orders regional transmission operators (RTOs) and independent system operators (ISOs) to configure wholesale markets to all storage assets to provide capacity, energy and ancillary services. This allows full revenue stacking at all storage scales and as it is federal regulation, it applies across the US.

The recently enacted Inflation Reduction Act of 2022 provides $30bn ten-year corporate tax credits for clean energy and energy storage including stand-alone storage. This offers a tax credit of up to 50% for projects including long-duration energy storage. Apart from the clear direct support for storage, this will also grow renewable energy penetration increasing market demand for storage. Previously tax credits were only available for storage when combined with solar generation, but these are now open to stand alone storage projects and those coupled with wind generation.

The EU

The European Commission acknowledges that energy storage has a key role to play in the transition towards a carbon-neutral economy, and it addresses several of the central principles in the Clean Energy for all Europeans package.

The Commission also provides substantial co-financing for projects via direct grant funding and financial instruments, principally via the Connecting Europe Facility ("CEF") and the EU Innovation Fund.

Regulation (EU) 347/2013 of the European Parliament and of the Council provides for the designation of Projects of Common Interest (PCIs). PCI designation also allows projects to benefit from CEF financial instruments administered by the European Investment Bank. PCIs can also benefit from accelerated permit granting through coordination of procedures by a single national authority in each EU Member State.

At an institutional level the European Network of Transmission System Operators for Gas and Electricity ("ENTSOG" and "ENTSO-E"), use Ten-Year Network Development Plans ("TYNDP") as a tool to map and plan the future of the energy and gas networks. It is a prerequisite for obtaining PCI status, which can in turn unlock EU grant funding opportunities.

Plans for a EU response to the US Inflation Reduction Act are likely to result in further support for storage under the proposed Green Industrial Plan.

UK

Despite the possibility of attractive merchant pricing for long duration energy storage, the UK government is also consulting on support for new storage. It sees large-scale and long-duration electricity storage as providing an important role in decarbonising our energy system, for example by storing renewable power and discharging it over periods of low wind. However, it sees evidence that this type of storage faces market challenges that mean it may struggle to deploy at scale.

The key issues seen are as follows:

- High upfront capital costs and long lead times – true for pumped storage. While some other technologies can be deployed more rapidly, they tend to lack the scale required to store large amounts of energy for long periods.
- Lack of track record – not really an issue for pumped storage which was first used in 1907.
- Revenue uncertainty – and although not specifically mentioned in the BEIS call for evidence document this should really include uncertainty over the cost of charging. Revenue and cashflow uncertainty is perhaps the biggest issue, while we think attractive merchant pricing is possible, this cannot be said with the certainty that a debt funder would require.
- Market signals – specifically the weakness of inter-day and inter-week price signals compared with intraday signals.

The consultation responses have not yet been published but the background paper suggests four mechanisms for support.

- Regulated asset base
- Cap and floor
- Contract for difference
- Reformed Capacity Market

Pumped hydro operator Drax Group (DRX LN) has commissioned a report by KPMG into the options. It concludes that a cap and floor solution would be the best option against a range of criteria. The Cap and Floor mechanism stands out as clearly providing certainty of cash flow and, if structured correctly, can show that this is sufficient to cover the cost of debt and hence unlock asset financing to allow new projects.

The UK has also provided funding towards long duration storage feasibility studies and Invinity is already benefiting from £700,000 of funding towards the feasibility study for a 40MWh project co-located with solar PV generation. The funding is part of the £1bn Net Zero Innovation Portfolio of which £100m is committed to address "energy storage and flexibility innovation challenges".

DEMAND FOR STORAGE

BALANCING INTERMITTENT RENEWABLES

To hit net zero, electrification with low carbon sources is key. Most of these will be intermittent wind and solar photovoltaic generation. A number of forecasts are available for the amount of low carbon generation required. We have undertaken our own assessments of the Intergovernmental Panel on Climate Chante's (IPCC) two example cases in their Working Group 3 (WG3) report. These give a Paris aligned high point and a non-compliant low point. We have also shown forecasts the International Energy Agency's World Energy Outlook which is also Paris aligned and gives a sensible central case.

Renewable energy capacity for net zero outcomes (GW)

GW	WG3 - 1	WG3 - 2	IEA
Wind	6,263	6,342	7,795
Solar PV	19,132	11,098	15,468
Other	1,025	968	4,041
Total	26,419	18,408	27,304

Source: IPCC, BNEF, IEA, Longspur Research

If we assume that wind requires 24hours of storage to remove most of the risk of low wind events and PV requires 8 hours to cover darkness, then we can estimate the storage required to deliver a reliable energy stream.

Storage requirements to balance wind and solar PV (TWh)

	Duration	WG3 - 1	WG3 - 2	IEA
Wind	24	150	152	187
Solar PV	8	153	89	124
Other	0	0	0	0
Total		303	241	311

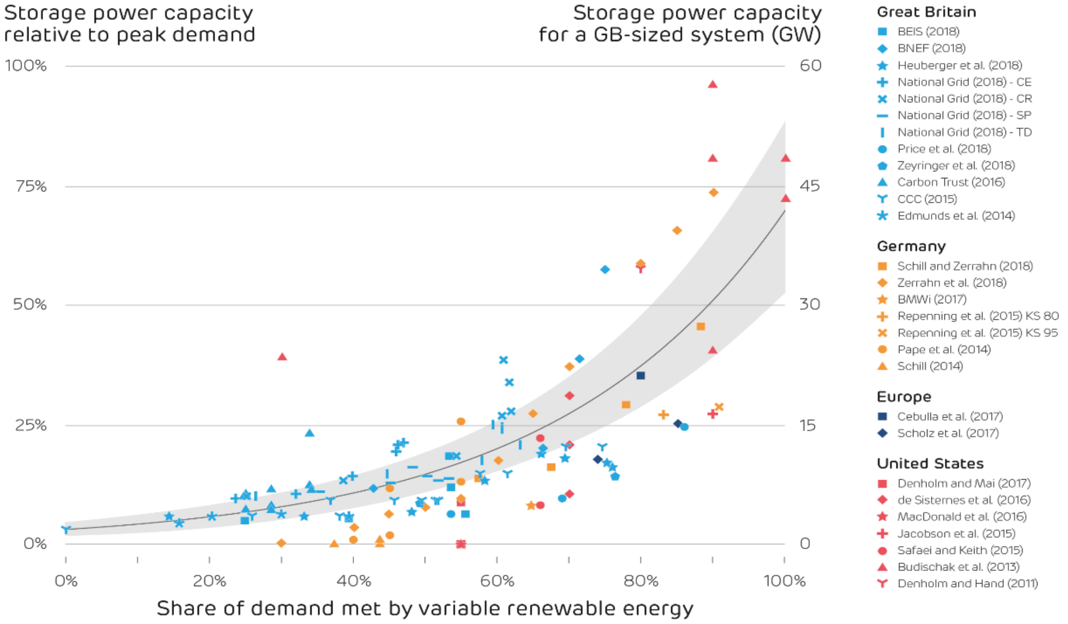
Source: IPCC, BNEF, IEA, Longspur Research

However, there are instances where a portfolio effect reduces the impact of intermittency with low wind offset by high wind elsewhere. This is generally more limited than some expectations and restricted geographically but it does suggest that our basic estimates could be on the high side.

A MORE DETAILED ANALYSIS BASED ON ACADEMIC WORK

As we add more intermittent renewable energy, the demand for storage and long-duration storage in particular increases. The following meta study of research by Imperial College London shows this fairly clearly.

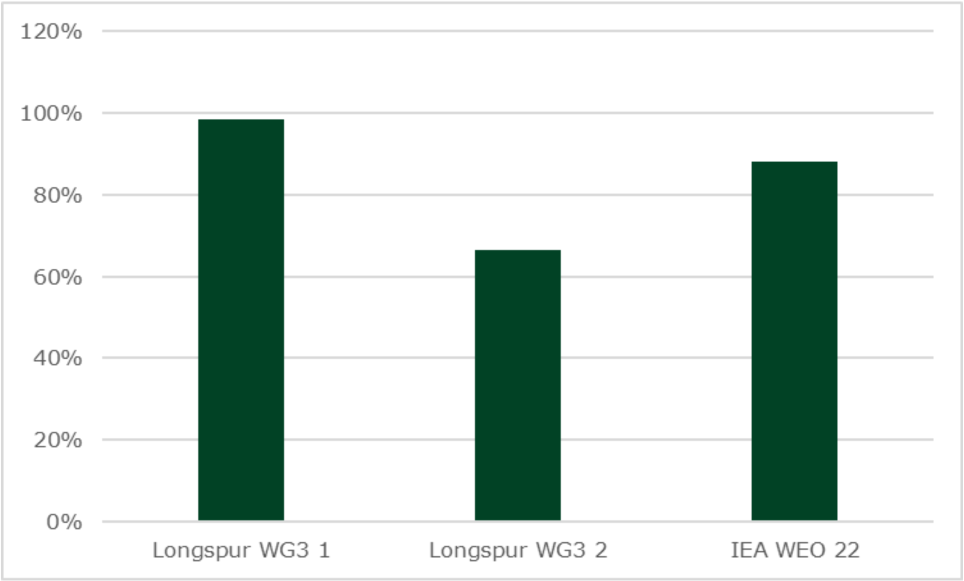
Storage capacity relative to renewable penetration



Source: Imperial College based on Zerrahn et al., 2018.

The key driver is the penetration of variable renewable energy as a percentage of total electricity demand. Again using our sample forecasts, we can see a range of penetration from 67% to 98%.

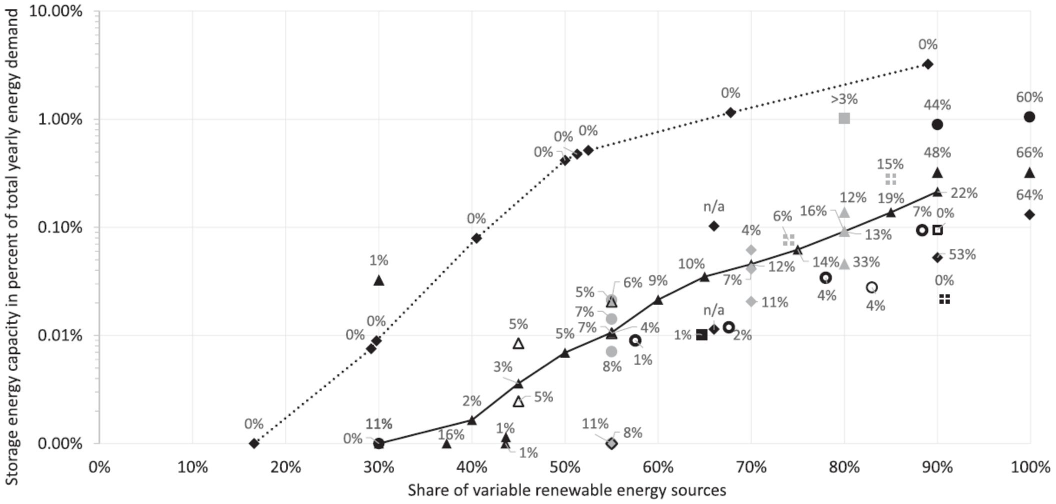
Renewable energy penetration forecasts for 2050



Source: Longspur Research, IPCC, IEA,

The Imperial work shows storage expressed as storage power capacity as a percent of peak demand. However, to really work out storage demand we need to know how much storage energy capacity is needed rather than power. The Imperial study draws heavily on another meta study; Zerrahn, A, Schill, W, Kemfert, C, *On the economics of electrical storage for variable renewable energy sources*, European Economic Review 108 (2018) 259–279. This shows the storage energy capacity as a percentage of total annual energy demand.

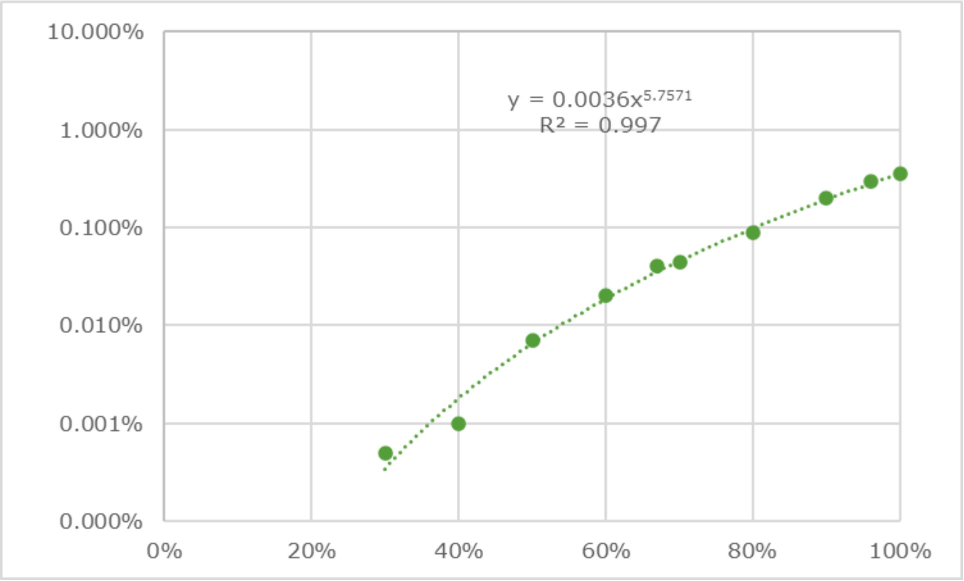
Storage energy requirements in recent research literature



Source: Zerrahn et al., 2018. Percentages show curtailment. Upper line assumes no curtailment.

We have plotted a trendline to this data to derive a relationship between variable renewable energy penetration and the required storage energy capacity demanded to minimise curtailment. Note that this does not eliminate curtailment but represents the least cost outcome. Even with significant energy storage, curtailment varies from 2% at 40% renewable penetration to 22% at 90% with 66% if there is 100% variable renewable energy supply. Our trendline has the equation $S = 0.036P^{5.7571}$ where S = storage as a percent of annual energy demand and P = variable renewable energy penetration.

Best fit line to Zerrhan et al.



Source: Zerrahn et al., 2018.Longspur Research

We can use this with the penetration forecasts to estimate demand for storage. This suggests that the Paris compliant scenario with 98% renewable penetration would mean storage of 0.3% of yearly electricity demand and the non-compliant scenario with 67% penetration would mean 0.03% of yearly demand.

Global total addressable market for energy storage

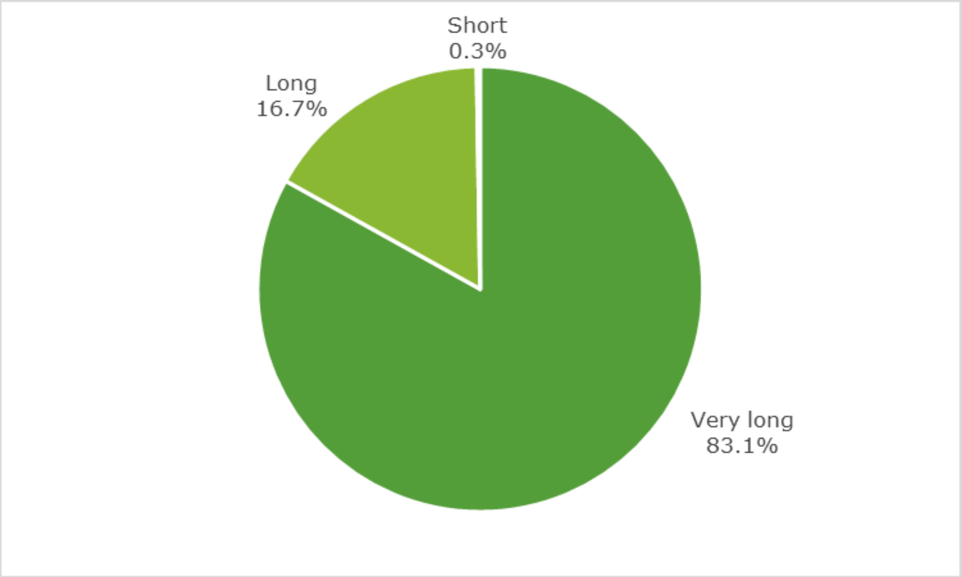
Source	**Longspur**	**Longspur**	**IEA**
Scenario	IPCC WG3 1	IPCC WG3 2	WEO 22
Total electricity generated (TWh)	108,444	111,111	73,231
Renewable generation (TWh)	106,667	73,889	64,506
% Renewable	98%	67%	88%
Storage as a % of generation	0.327%	0.034%	0.173%
Storage required (GWh)	354,962	38,197	127,002

Source: IPCC, Longspur Research, BNEF, IEA

HOW MUCH LDES IN THE TOTAL?

Recent research has distinguished between short, long and very long-duration storage with long defined as durations of 4 to 200 hours and representing 16.7% of the total storage volume. Very long is over 200 hours and represents 83.1% of the total.

Storage segment energy capacity split



Source: Cárdenas, B, Swinfen-Styles, L, Rouse, J, Garvey, S.D; Short-, Medium and Long-Duration Energy Storage in a 100% Renewable Electricity Grid: A UK Case Study. Energies 2021, 14

Reviewing this segregation suggests that the authors have assumed a constant or near constant level of power at each duration so that the segmentation proportions largely reflect the relative duration of energy stored. It is likely that longer duration storage will also be higher power storage, so this assumption is necessarily conservative for long-duration storage. In fact, it becomes more conservative the longer the duration. We think that for market sizing this makes a simple duration weighted segmentation a sensible tool as it builds in this conservative assumption. The split in timings for key duration-based segments is shown below.

Segment capacity weightings

Use case	Duration (hours)	Weighting
Frequency and trading	<4	0.5%
Volume trading	4-10	1.2%
Sundown solar	10-30	3.9%
Weekly, wind balancing	30-90	11.7%
Seasonal	>90	82.8%

Source: Longspur Research

MARKET SHARE FOR STORAGE TECHNOLOGIES

Our levelized cost analysis suggests that for durations over roughly 30 hours PHS, CAES and thermal can outcompete other technologies. Of course, different sites will have different economics and PHS and CAES are restricted to locations where the geography, in the case of PHS, and the geology, in the case of CAES, are required for these technologies to be used. Flow batteries can join these technologies down to 4 hours and below where lithium ion dominates and at even shorter durations where it can gain benefit from its ability to cycle indefinitely.

But because durations are longer further out, the long duration storage technologies have potentially very large markets indeed. Using our assumptions above together with our high and low range of total storage market estimates we can suggest total addressable markets for the key storage segments.

Segment market share estimates

Source	**Longspur**	**Longspur**	**IEA**
Scenario	IPCC WG3 1	IPCC WG3 2	WEO 22
Total electricity generated (TWh)	108,444	111,111	73,231
Renewable generation (TWh)	106,667	73,889	64,506
% Renewable	98%	67%	88%
Storage as a % of generation	0.327%	0.034%	0.173%
Storage required (GWh)	354,962	38,197	127,002
Duration split (TWh)			
0-4	1,753	189	627
4-12	4,136	445	1,480
12-36	13,786	1,483	4,932
36-108	41,357	4,450	14,797
>108	293,931	31,629	105,166
Total	354,962	38,197	127,002
Market share (TWh)			
Li Ion	1,753	189	627
Flow	7,582	816	2,713
Thermal	115,209	12,397	41,221
CAES	115,209	12,397	41,221
PHS	115,209	12,397	41,221
Total	354,962	38,197	127,002
Capactiy (GW)			
Li Ion	438	47	157
Flow	528	57	189
Thermal	631	68	226
CAES	631	68	226
PHS	631	68	226
Total	2,859	308	1,023

Source: Longspur Research

Even at the short end these are big markets. Using the average duration figures we can estimate the market sizes in both energy (TWh) and power (GW) for the main storage technologies assuming equal shares of the segments where each is competitive.

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