Deep Dive
Long Duration Energy Storage

Contents

1. Introduction

As the world seeks to limit global temperature rise by cutting greenhouse gas emissions, it's clear that the power generation sector is key since it's responsible for one third of emissions. Luckily, **the global power industry is rapidly reducing emissions by switching from fossil-fired generation to wind and solar power**.

Yet, the increasing presence of renewable energy solutions in the power mix makes **new challenges** emerge: **Traditional power infrastructure, designed for consistent energy generation from i.e. fossil fuels, struggles to handle the fluctuations inherent in wind and solar power.** This creates a situation of inconsistent generation, where the flow of electricity becomes uneven, leading to potential strain on the grid. **Once grids reach a tipping point of around 60% penetration of wind and solar energy, the capability to handle fluctuations in demand and supply by storing surplus energy and releasing it when necessary, is crucial for cost-effective decarbonization of the economy** and becomes critical.[1] To achieve this capacity, **different technologies for energy storage and release have been developed: Lithium (Li-ion) battery, hydrogen turbines, pumped storage hydropower (PSH) and long-duration energy storage (LDES).**

LDES refers to any technology that competes in storing energy for extended durations, enabling sustainable electricity discharge over several hours, days, or even weeks at a competitive cost and scale. This includes approaches like **mechanical, thermal, electrochemical, or chemical storage**. It holds the potential to make a substantial contribution to decarbonizing the economy while being economically scalable.

The beauty of LDES lies in its flexibility. **Unlike traditional storage, it can integrate multiple energy forms – electricity, heat and hydrogen**. This versatility makes LDES a key enabler for decarbonization across industries. That’s why it’s also attracting rising interest interest from governments, utilities, and transmission operators, and investment.

Many LDES technologies currently exist, but they are at different levels of maturity. Some have been deployed commercially, some are still at the pilot phase. Projections guess that the **TW power of LDES solutions need to scale by approx. 400x in the next 20 years to build a cost-optimal net-zero energy system**. Like this, 10% of all electricity generated would be stored in LDES at some point. To be cost-optimal, costs of LDES solutions have to be decreased by 60%.[2]

This deep-dive provides an overview the **different sub-categories** and **application fields** of LDES and covers some of the current **deployment** in the market, the **funding environment** and **what still needs to happen** to make LDES technologies fly in the long-run.

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[1] https://www.ctvc.co/ldes-long-duration-energy-storage-tech/

[2] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey

2. Decarbonization of Energy Systems

To achieve net-zero economies and keep global warming below 1.5°C, a rapid decarbonization of energy systems, particularly the power sector, is essential by 2040. Since the power sector is among the largest emitters of greenhouse gases, its decarbonization is key to unlocking a net-zero future.

While **high renewable energy use can have an impact on stability and reliability of the power system**, overcoming these **three challenges** is crucial for a fully decarbonized energy sector:

- **Power supply and demand imbalances:** A stable power grid **relies on a constant match between electricity produced (supply) and what consumers use (demand)**. Imbalances occur when these don't align. These imbalances can cause voltage fluctuations or even blackouts if not addressed quickly.
- **Change in transmission flow patterns:** Traditionally, power flowed from large, centralized power plants to consumers. Now, with the rise of renewable energy like wind and solar farms, electricity generation is becoming more distributed. This shift is **changing how power flows across the grid, with some lines becoming overloaded while others are underutilized**. This requires grid upgrades and smarter management to ensure efficient and reliable electricity delivery.
- **Decrease of system inertia:** The power grid **relies on inertia from spinning generators, like flywheels, to maintain a stable frequency.** With more wind and solar replacing traditional power plants, this inertia is decreasing.

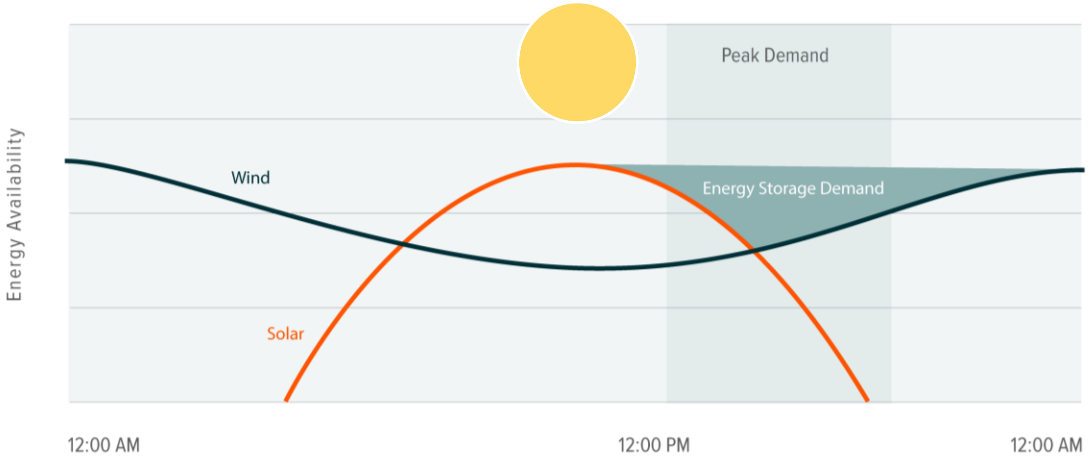

Illustration 1 Peak generation vs. peak demand during the day (Source: Global X ETFS)

These three challenges are solvable by **introducing flexibility into the power sector across different time spans**:

- **Intraday (<24 hours)**: Here energy storage services are required for peak-shifting and grid-stability services (within a single day). Here batteries are great for everyday grid balancing and handling peak demand spikes**. Lithium-ion currently are likely to dominate the market here, due to cost advantages**, but faster long-duration options with a relatively fast dispatch time can still compete by exploiting price fluctuations.
- **Multi-day/week (24-100 hours):** This tackles **overnight power needs and periods when renewables like solar struggle** (i.e. cloudy days or storms). Traditionally, backup plants filled this gap, but LDES can offer a cleaner solution.
- **Seasonal (>100 hours):** This addresses natural variations in solar and wind **across seasons, and even extreme weather events. LDES can help reduce reliance on expensive gas "peaker" plants** which might operate for just a few hundred hours a year and use up to 50% more natural gas than baseload combined cycle gas generators.

Achieving clean energy is an important goal, but keeping the lights on 24/7 with renewables is tricky. **Current solutions have drawbacks**: **Gas plants** pollute the air, **pumped hydro** is limited by geography and expensive to build large-scale and **Lithium-ion batteries** work well for short-term, but not cost-effective for all future needs of the power system.

That's where **Long Duration Energy Storage (LDES) comes in**. It's the **missing piece for a cost-effective clean energy future.**[3] [4] [5]

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[3] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey

[4] https://www.ctvc.co/ldes-long-duration-energy-storage-tech/

[5] Evaluating emerging long-duration energy storage technologies; Shan et al.

3. Long Duration Energy Storage (LDES)

3.1 LDES in a Nutshell

Long Duration Energy Storage is the technology that enables renewable energy to power our grids and accelerate carbon neutrality. Through long duration energy storage, the transition towards renewable energy is affordable, reliable and sustainable**. Wind, solar and other renewables are becoming the lowest cost forms of generation but need storage to match supply with demand**.[6]

There are multiple use cases for LDES technologies in balancing the power system and making it more efficient. **These include support for system stability, firming corporate power purchase agreements (PPAs) and optimization of energy for industries with remote or unreliable grids**. Similarly, there is a lot of potential in using LDES in off-grid systems, which have a lower level of flexibility and currently rely mainly on fossil fuels. But by far the largest proportion of deployment is expected to be related to the central tasks of energy shifting, capacity provision and T&D optimization in bulk power systems. **It is likely that a diversified suite of solutions needs to be deployed to achieve a cost-effective decarbonization of the power system in the long run**. The upside of deploying LDES at scale, is great though. It is estimated that by 2040, thanks to LDES 1.5 to 2.3 gigatons of carbon dioxide equivalent (Gt CO2eq) could be avoided per year – meaning around 10 to 15 percent of today's power sector emissions.

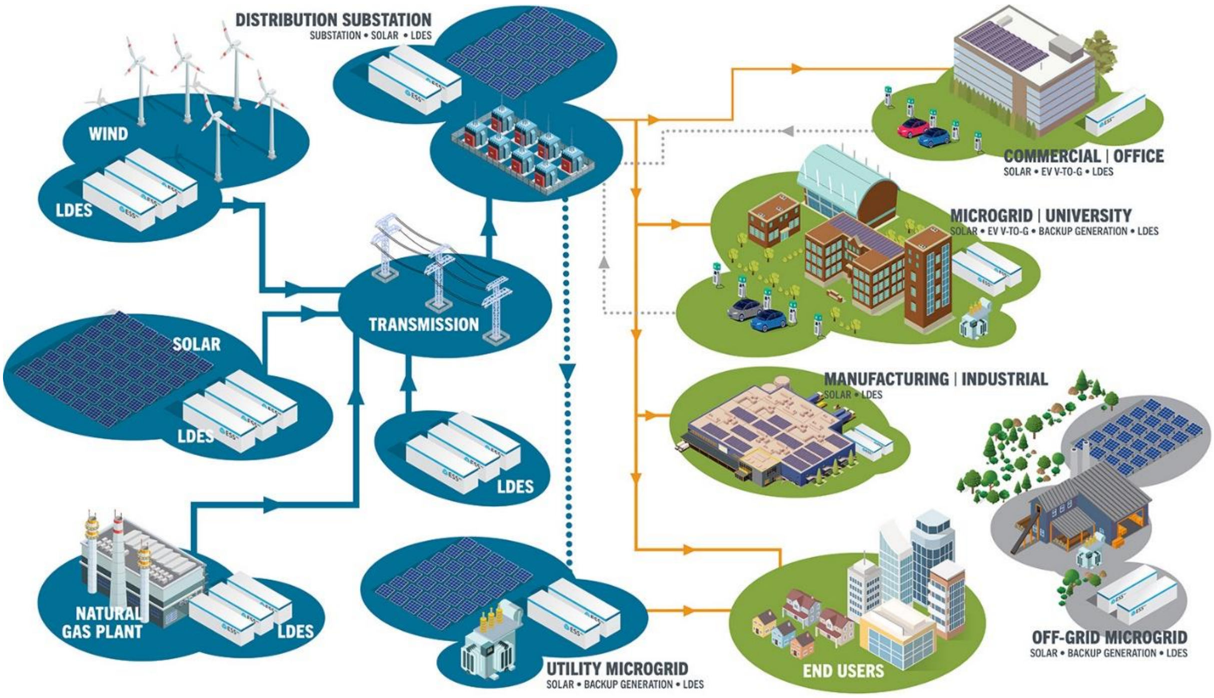

Illustration 2 How Long duration energy storage (LDES) fits into our energy system (source: Solar Power World Online)

LDES Today: LDES technologies have pretty low marginal costs for storing electricity: they enable decoupling of the quantity of electricity stored and the speed with which it is taken in or released. Furthermore they are widely deployable and scalable and they have relatively low lead times compared to upgrading of transmission and distribution (T&D) grids**. As a consequence, there is an increasing interest in investment, with more than 5 gigawatts (GW) and 65 gigawatt-hours (GWh) of LDES announced or already operational.**

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[6] https://www.ldescouncil.com/

LDES Tomorrow: There are studies stating that LDES has the potential to deploy 1.5 to 2.5 terawatts (TW) power capacity—or 8 to 15 times the total storage capacity deployed today—globally by 2040. On another note, it could deploy 85 to 140 terawatt-hours (TWh) of energy capacity by 2040 and store up to 10 percent of all electricity consumed. **This might result in a total investment amount between 1.5-3 Trillion USD and a potential value creation of USD 1.3 trillion by 2040.**

Preconditions for successful deployment of LDES:

- **Cost reduction:** Making LDES a reality requires bringing down the costs. Luckily, the **learning curve suggests it's achievable, just like other nascent energy technologies** in the recent past, including photovoltaic and wind power. More research (R&D), larger projects, and efficient manufacturing will all play a part. Ultimately, how fast we ramp up LDES depends on two things: the rate of decarbonization of the power sector and the deployment of variable renewable energy (RE) generation.
- **Government action:** LDES is promising, but getting there needs a government push. Lowering costs, attracting investment, and creating a clear path to profit for companies are all crucial. An enabling governmental ecosystem would include the implementation of **(i) long-term system planning**, (ii) **early compensation mechanisms that reduce uncertainty** for investors in a still young market, and (iii) **supportive policies, regulations, and market designs**.[7]

3.2 Types of Novel LDES Technologies

The value of long-duration energy storage is widely discussed among scientists, and there seems to be agreement about the value-add of LDES in general but it is challenging for one technology to outperform others in all metrics and to dominate all the markets. Studies show that anyways a mix of all the different LDES technologies is needed to achieve the decarbonization of the energy system. Nevertheless, many of those technologies are under early-stage development and could significantly improve their performance in the next few years. For example, energy and power CAPEX could decline by 60 percent in the next 15 years, while round-trip-efficiency (RTE, see description below) could grow by 10 to 15 percent as the commercialization of systems accelerates.

In this chapter the different types and subtypes of novel LDES technologies are described and following metrics are compared:

Market Readiness: This refers to how **commercially available and mature a LDES technology is**, which impacts its near-term deployment potential and ability to be integrated into the grid. Market readiness is important as it determines how quickly a technology can be scaled up to meet growing energy storage needs.

Energy Capacity Costs (USD/kWh): Those costs refer to the **capital expenditures associated with the storage medium itself, such as the battery cells, tanks, or other storage components** that determine the total energy storage capacity and are a key performance parameter for LDES technologies. These costs are typically expressed in $/kWh and can vary significantly between different LDES technologies like pumped hydro, flow batteries, and hydrogen storage. Some researcher state, that for LDES to attain a wide adoption energy capacity costs should be somewhere around 20 USD/kWh.[8]

Max Deployment Size (MW): This is the maximum scale at which a LDES technology can be deployed, in terms of power capacity (MW) or energy capacity (MWh). **Larger max deployment sizes allow LDES technologies to provide greater grid-scale storage and flexibility**, making them more valuable for integrating high levels of renewable energy.

Max. Nominal Duration (Hours): This is the maximum duration for which a LDES technology can continuously discharge at its rated power output. **Longer nominal durations enable LDES to**

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[7] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey

[8] Long duration energy storage; Deloitte

provide firm capacity and reliability during extended periods of low renewable generation, making them critical for decarbonizing the power system.

Average Round Trip Efficiency (%): This is the ratio of the energy output from a LDES system to its energy input, expressed as a percentage. **Higher round trip efficiencies mean less energy is lost during the storage and discharge cycles**, improving the overall cost-effectiveness and **environmental benefits** of the LDES technology.[9]

There are **other metrics** which would be useful to compare the different categories like **modularity, long-term energy storage capability, operational lifetime and flexibility, environmental impact, siting requirements, power capacity costs (kW), levelized cost of storage and value stacking potential**. To our knowledge, there is a lack of robust studies including those metrics on this topic, making comparisons challenging.

Regarding environmental impact resp. carbon reduction potential **all LDES technologies have the potential for significant carbon reductions** by enabling higher renewable energy integration and reducing reliance on fossil fuels. The specific carbon impact and costs will depend on the technology type and application. **Mechanical and thermal LDES tend to have lower operational environmental impacts** in general **and higher round-trip efficiencies** (and therefore fewer energy loss during storage and discharge cycles), while electrochemical systems have higher impacts from materials production. Nevertheless, a detailed LCA is needed to fully evaluate the trade-offs for each specific technology and application.[10]

Besides large-scale aboveground PSH projects, which represent more than 95 percent of all LDES capacity installed, **as of today over 250 novel LDES projects have been announced** at different commercial stages. Around 75% of the capacity is already contracted, under construction or operational. However, most of the capacity is associated with traditional molten salts and CAES technologies, which have some deployment limitations compared to novel LDES (such as their large footprint and limited modularity). In the illustration below, you can find an overview of different LDES projects running or in planning worldwide.[11]

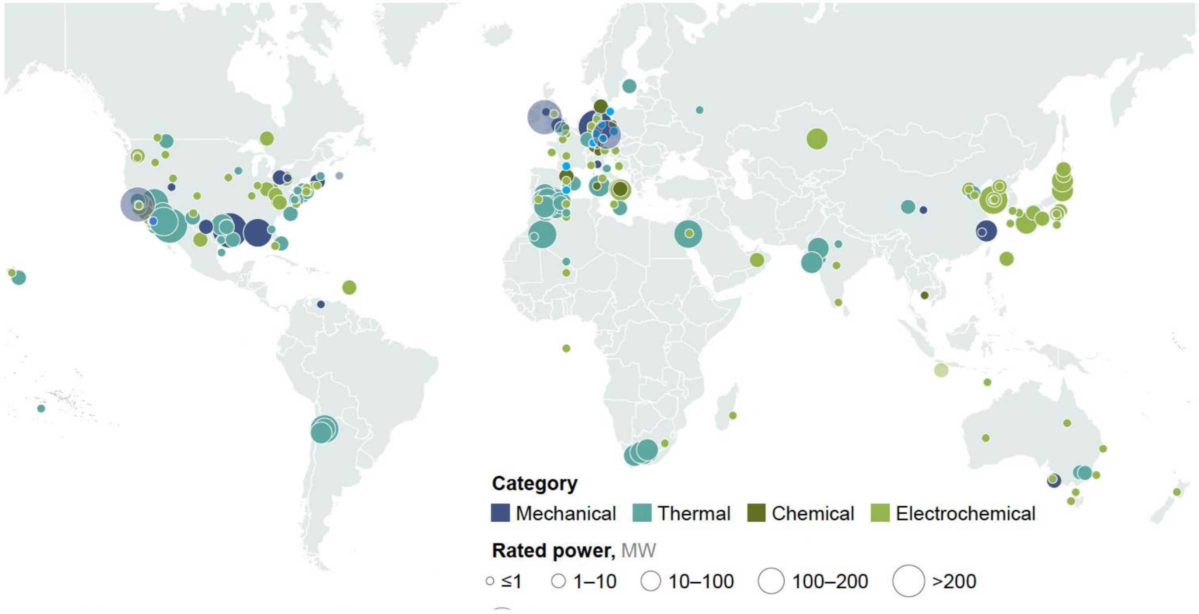

Illustration 3 LDES project pipeline by type (excl. large-ground PSH) (source: Net-zero power – long duration energy storage for a renewable grid)

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[9] Pathways to Commercial Liftoff: Long Duration Energy Storage; US Departement of Energy; Long Duration Storage: What You Need To Know | EnergySage;

[10] Advanced Grid-scale Energy Storage Technologies; Dep. of Hydro and Ren. Energy, Indian Institute of Technology Roorkee

[11] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey

3.2.1 Mechanical Storage

The most widespread and mature storage technology is **pumped hydro (PSH) accounting for 95 percent of the total energy storage capacity worldwide**. It's a traditional form of mechanical storage. Nevertheless, there are **new versions, for example geomechanical pumped hydro**, which uses the same principles as aboveground PSH but with underground water reservoirs. Like this, the dependence on geographical conditions (i.e. land usage) can be reduced. (Company example: RheEnergise)

Another emerging mechanical energy storage solutions is **compressed air energy storage (CAES)** which stores energy as compressed air in pressure-regulated structures (either underground or above surface). In its insulated form, CAES also uses thermal storage to store the heat that is generated during compression and which is then released during the discharge cycle. (Company example: Hydrostor)

Furthermore **gravity-based energy storage** is another promising form of mechanical storage. Energy is stored by lifting a heavy object or just mass and being let down whenever energy is needed. This technology is still in an earlier stage of commercial development. (Company example: Energy Vault)

One more subcategory is the so-called **liquid air energy storage (LAES)**. This technology uses liquid CO2, which can be stored at high pressure and room temperature and then released in a turbine in a closed loop without emissions. It works similarly to CAES by compressing air but uses electricity to cool and liquify the medium and store it in cryogenic storage tanks at low pressure. That's why LAES is classified in the intersection of mechanical and thermal storage. (Company example: Energy Dome)[12]

Illustration 4 Hydrostor's advanced compressed air energy storage pilot plant in Ontario, Canada (Source: Hydrostor)

Advantages: Mature technologies with proven track records (e.g. pumped hydro, compressed air); Typically high round-trip efficiencies (60-80%); Long operational lifetimes (20-60 years); Low operating costs

Disadvantages: Geographically constrained by siting requirements; High upfront capital costs; Some technologies have limited energy density[13]

3.2.1.1 Compressed Air (CAES)

It works by using electricity to compress air into a large underground cavern (i.e. salt) or other pressure-regulated structure (recharge). When electricity is needed, the compressed air is released, heated, and expanded through a turbine to generate electricity (discharge).

Market Readiness: Commercial (TRL 4-7)
Energy Capacity Cost in 2021 (USD/kWh): 16-295
Max Deployment Size (MW): 200-500
Max. Nominal Duration (Hours): 6-24 (typically 4-8)
Average Round Trip Efficiency (%): 40-70
VC-Investment in 2021-22 (MUSD): 112
Start-up Examples: Hydrostor, Green-Y, Cheesecake Energy, Apex CAES

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[12] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey

[13] Scenario deployment analysis for Long-Duration Electricity Storage; Department for Energy Security & Net Zero; https://www.ctvc.co/ldes-long-duration-energy-storage-tech/

Advantages: Relatively low energy capacity costs; Mature technology with some commercial deployment
Disadvantages/Challenges: Lower round-trip efficiency; Some CAES systems requiring burning fossil fuels; Requires specific geological formations for air storage (limiting siting options)

3.2.1.2 Liquid Air (LAES)

This technology stores electricity by liquefying air into insulated tanks (recharge). During times of high electricity demand, the liquefied air is evaporated, expanded, and heated to produce power through a turbine (discharge).

Market Readiness: Pilot (commercial announced)
Energy Capacity Cost in 2021 (USD/kWh): 400-500
Max Deployment Size (MW): 50-100
Max. Nominal Duration (Hours): 10-25 (typically 4-12)
Average Round Trip Efficiency (%): 40-70
VC-Investment in 2021-22 (MUSD): 24
Start-up Examples: Innovatium, Highview Power
Advantages: Air as storage medium is widely available; Potential for high round-trip efficiency if waste heat is utilized
Disadvantages/Challenges: Complex design; High CAPEX; Still in demonstration phase

3.2.1.3 Liquid CO2

It uses basically the same technology as liquid air but instead energy is used to compress CO2 to a liquid state (recharge). To discharge the liquid is evaporated, expanded and heated to spin a turbine.

Market Readiness: Pilot
Energy Capacity Cost in 2021 (USD/kWh): approx. 200
Max Deployment Size (MW): 10-500
Max. Nominal Duration (Hours): 4-24
Average Round Trip Efficiency (%): 40-70
VC-Investment in 2021-22 (MUSD): 40
Start-up Examples: Energy Dome
Advantages: Potential for lower energy capacity costs than LAES; Can utilize waste heat or cold to improve efficiency
Disadvantages/Challenges: Unproven; Safety-risk; Technical challenges around compression, liquefaction, and storage of CO2

3.2.1.4 Gravity-Based (GES)

Those systems store energy by using excess electricity to lift heavy weights or blocks to a high position (charge). When energy is needed, the weights are released and allowed to fall, driving generators to produce electricity (discharge).

Market Readiness: Pilot
Energy Capacity Cost in 2021 (USD/kWh): 190-731
Max Deployment Size (MW): 20-1’000
Max. Nominal Duration (Hours): 0-15 (typically 4-12)
Average Round Trip Efficiency (%): 70-90
VC-Investment in 2021-22 (MUSD): 224
Start-up Examples: Energy Vault, Renewell, Gravitricity, Ares, EnergyBank, Gravity Power
Advantages: Uses established mechanical principles, potentially lowering costs; Flexible siting options

Disadvantages/Challenges: Still early development; Limited data on performance, costs, and scalability; Potential land use and environmental impacts depending on the technology

3.2.1.5 (Novel) Pumped Hydropower (PHS)

Traditional pumped hydropower has two water reservoirs at different elevations, that can generate power as water moves down from one to another (discharge), passing through a turbine. Power is used by the system to bring the water back up to the upper reservoir (recharge). Novel pumped hydropower systems aim to address the limitations of conventional pumped storage hydropower (PSH) by introducing innovative designs and configurations.

This includes for example the **pumped hydro-compressed air energy storage (PHCA) system**, which combines pumped hydro with compressed air storage to better accommodate the intermittent nature of renewable energy sources and uses a constant-pressure design to improve efficiency compared to traditional PSH.

Another novel PSH concept is the **"shell pumped storage"** system developed by Obermeyer Hydro. This design reduces the need for large, complex underground digging-work by using a vertical shaft to position the pump-turbine/motor-generator, significantly lowering capital costs and construction risks.

Furthermore the **geomechanical pumped storage (GPS) technology**, as explored by Quidnet Energy, leverages existing oil and gas drilling techniques to create high-pressure "storage lenses" in underground rock formations. This modular, low-cost approach to PSH can potentially enable broader deployment of pumped storage projects.

Another example is Swiss company RheEnergise, which replaces water with a high-density fluid, meaning that projects can be installed on hills 2.5x lower than with conventional hydro, projects are 2.5x smaller by volume and can be entirely hidden underground.

Market Readiness: Commercial
Energy Capacity Cost in 2021 (USD/kWh): 220-511
Max Deployment Size (MW): 10-100
Max. Nominal Duration (Hours): 0-15
Average Round Trip Efficiency (%): 50-80
VC-Investment in 2021-22 (MUSD): 13
Start-up Examples: Quidnet, MineStorage, RheEnergise, Obermeyer Hydro
Advantages: Mature, widely deployed technology with high TRL; Potentially relatively low energy capacity costs; High round-trip efficiency and long operational lifetimes
Disadvantages/Challenges: Geographical constrains by topography; Long development timelines and high upfront capital costs

[14] [15] [16] [17]

3.2.2 Thermal Storage

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[14] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey;
[15] https://www.ctvc.co/ldes-long-duration-energy-storage-tech/
[16] LDES - Net Zero Industry Report; LDES; Council & Roland Berger
[17] Long duration energy storage; Deloitte

Illustration 5 Storenergy's pilot project is a 3 MWh TES system deployed in Spain. (Source: Storenergy)

Thermal energy storage (TES) technologies store energy in the form of thermal energy, which can be later converted back into electricity or used directly for heating and cooling applications. **The general operating principle involves a charging cycle where electricity or heat is used to store thermal energy, and a discharging cycle where the stored thermal energy is extracted and brought back into the system.**

Depending on the underlying principle used to store the thermal energy, TES technologies can be classified into three main categories:

Sensible heat storage, where thermal energy is stored by increasing the temperature of a solid or liquid medium.

Latent heat storage, where thermal energy is stored through the phase change of a material, such as the melting and solidification of phase change materials.

Thermochemical storage, where thermal energy is stored by driving endothermic and exothermic chemical reactions, which can be reversed to release the stored energy.

These technologies use different mediums to store the heat such as molten salts, concrete, aluminum alloy, or rock material in insulated containers. Furthermore, the charging equipment options include, among others, resistance heaters, heat engines, or high temperature heat pumps among others.

Molten salt-based thermal energy storage is the most widespread long-duration energy storage (LDES) technology used in conjunction with concentrated solar power (CSP) plants accounting for 77% of all thermal energy stored. In this application, the molten salt is heated by the concentrated solar radiation and stored for later use to generate steam and drive a turbine to produce electricity. However, this molten salt-CSP combination presents some unique characteristics that differentiate it from other novel LDES technologies. Firstly, the CSP plant itself has a **large physical footprint and can only be effectively deployed in regions with high solar radiation**, limiting its widespread adoption. Additionally, the **system is not modular**, making it less flexible than other LDES options.

What is special about the thermal LDES technology is that it can **discharge both electricity and heat**. By leveraging thermal LDES, the heat sector can be decarbonized through the provision of sustainable, high-temperature heat, complementing the role of thermal LDES in electricity storage and grid integration. **This dual-purpose capability makes thermal LDES a versatile and valuable technology in the transition to a low-carbon energy system**. Currently, only about 10% of total heat consumption is supplied by renewable energy sources. Thermal LDES technologies can help address this gap by providing zero-emissions, high-grade heat to energy-intensive industries that rely on fossil fuels and have limited decarbonization alternatives. [18] [19]

Advantages: High energy densities possible; Can provide very long discharge durations; Low operating costs; Simpler and fewer moving parts than mechanical systems, modular options available

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[18] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey

[19] Evaluating emerging long-duration energy storage technologies; Shan et al.

Disadvantages: Lower round-trip efficiencies (50-60%) than mechanical, Many designs still at early commercial stage, Some systems require advanced materials/engineering[20]

3.2.2.1 Latent Heat

Energy is used for phase transition of a storage medium and then reverting it to release heat.

Latent Heat storage, frequently called Phase Change Materials (PCM), utilizes a phase transition of its storage medium, reverting it to release heat, and can be further manipulated by imposing pressure conditions.[21]

Market Readiness: Commercial
Energy Capacity Cost in 2021 (USD/kWh): n/a
Max Deployment Size (MW): 10-100
Max. Nominal Duration (Hours): 25-100
Average Round Trip Efficiency (%): 20-50
VC-Investment in 2021-22 (MUSD): 186 (Total of both: latent and sensible heat)
Start-up Examples: StorWorks, Azelio
Advantages: Higher energy storage density compared to sensible heat storage; Wide range of phase change materials (PCMs) available
Disadvantages/Challenges:

3.2.2.2 Sensible Heat

Sensible heat stores energy in the temperature of a material (recharge), later drawing it out through an exchanger to generate power via steam production or the expansion of another working gas/fluid (discharge)[22]

Market Readiness: R&D/Pilot
Energy Capacity Cost in 2021 (USD/kWh): 130-600
Max Deployment Size (MW): 10-500
Max. Nominal Duration (Hours): 200
Average Round Trip Efficiency (%): 55-90
VC-Investment in 2021-22 (MUSD): 186 (Total of both: latent and sensible heat)
Start-up Examples: KraftBlock, Kyoto Group, Hyme, EnergyNest, 1414 Degrees, SaltX, Malta
Advantages: Generally lower cost and more widely available storage materials; Simpler technology compared to latent heat storage;
Disadvantages/Challenges: Poor electric efficiency

[23] [24] [25]

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[20] Scenario deployment analysis for Long-Duration Electricity Storage; Department for Energy Security & Net Zero; https://www.ctvc.co/ldes-long-duration-energy-storage-tech/

[21] Evaluating emerging long-duration energy storage technologies; Shan et al.

[22] Evaluating emerging long-duration energy storage technologies; Shan et al.

[23] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey;

[24] https://www.ctvc.co/ldes-long-duration-energy-storage-tech/

[25] Long duration energy storage; Deloitte

3.2.3 Electrochemical Storage

Illustration 6 Visualization of Form Energy's commercial-scale pilot in Minnesota, USA (Source: Form Energy)

There is a new development of different battery types emerging to provide long duration flexibility. **They typically consist of varying chemistries and materials**.

Flow batteries have the potential to provide flexible long-duration storage as they **can be configured in different arrangements based on power and energy needs**. Flow batteries have been under development for decades, yet renewed interest due to technological breakthroughs and cost reductions in solar and wind have renewed interest in a separation of power and energy components that cannot be achieved with lithium-based batteries. The ability to substitute different electrolytic, membrane, and electrode materials make flow batteries an innovative technology for commercialization and deployment by experimenting with different chemistries and materials.

Flow batteries, despite their diverse subtypes, have advantages in the minimum deliverable size, energy footprint and cost, making them suitable for the residential and commercial sectors, but their high idle loss constrains their charge-discharge cycle to several weeks.

Electrochemical and hybrid flow batteries store electricity in two chemical solutions that are stored in external tanks and pushed through a stack of electrochemical cells, where charge and discharge processes take place thanks to a selective membrane. Ther are also experiment with liquid electrolytes and a metal anode, combining properties of conventional flow and metal air batteries. These batteries are suited for long-duration applications where low chemical and equipment costs are possible.

Metal-air batteries store energy by using a metal (such as zinc, iron, magnesium, or aluminum) as the anode and air as the cathode. An electrolyte is used to facilitate the electrochemical reactions. They rely on low-cost, abundant earth metals, water, and air. This results in potentially high scalability and low installed system costs. Additionally, many of these solutions do not suffer from thermal runaway, making them safe to install and operate. [26]

Advantages: Highly scalable with flexible siting, fast response times, mature supply chains for some chemistries

Disadvantages: Lower energy densities than other LDES categories, relatively short operational lifetimes (5-20 years), many battery types face materials/cost challenges[27]

3.2.3.1 Metal-Air

In these systems, the anode is made of pure metal (e.g. iron) and a reaction occurs with ambient air when the metal anode is oxidized (discharge). An electrical current is then used to convert the rust back to iron (recharge).

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[26] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey

[27] Scenario deployment analysis for Long-Duration Electricity Storage; Department for Energy Security & Net Zero; https://www.ctvc.co/ldes-long-duration-energy-storage-tech/

Market Readiness: Prototype/Commercial
Energy Capacity Cost in 2021 (USD/kWh): approx. 20 (Iron-air)
Max Deployment Size (MW): 10-100
Max. Nominal Duration (Hours): 8-100
Average Round Trip Efficiency (%): 40-75 (typically below 50%, but can be higher depending on sub-category: aqueous metal-air: approx. 60%; non-aqueous lithium-air: approx.75%)
VC-Investment in 2021-22 (MUSD): 675
Start-up Examples: Form Energy, EnZinc, Zinc8
Advantages: High energy density potential; Use abundant and low-cost metal anodes
Disadvantages/Challenges: Large size; Unproven; Limited cycle life and rechargeability; Technical challenges around reversible metal-air reactions

3.2.3.2 Flow Batteries

A flow battery is an electrochemical cell in which two chemical components are dissolved in liquids and pumped through the system on either side of a membrane. Usually there are two terms used which are interchangeable in most cases: Redox flow batteries (RFBs) or flow batteries (FBs).[28]

Several studies highlight the **rapid progress being made in flow battery technologies, with new chemistries, architectures, and performance improvements** being actively researched and developed to expand the applications of this promising energy storage solution.

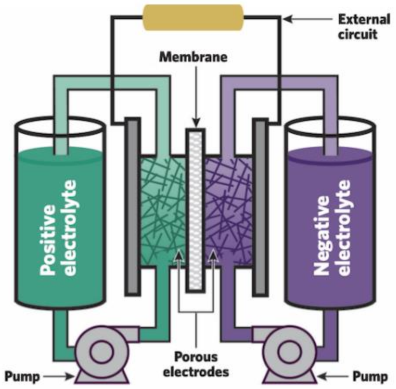

Illustration 7 Traditional flow battery (Source: MIT News)

There are numerous sub-categories which mainly differ in the architecture (traditional/fluid-fluid vs. hybrid vs. redox-targeting) and the chemistries (aqueous vs. non-aqueous and organic vs. inorganic). A more detailed description of the subcategories is not provided in this section, but the most important developments are highlighted.[29]

Vanadium Redox Flow Batteries (VRFBs) are considered the most mature and predominant flow battery chemistry, with some large scale projects already in place. The search results indicate VRFBs are an attractive investment as they use vanadium, a widely available material that can be recovered from waste products. They are **also considered a more sustainable solution compared to lithium-ion batteries as they do not utilize conflict materials like cobalt**.

Aqueous Sulfur Flow Batteries use aqueous sulfur-based electrolytes, **taking advantage of the low cost of sulfur**. These flow batteries use low-cost, abundant sulfur-based electrolytes, making them an appealing investment case. Proof-of-concept has been demonstrated, achieving promising cycle life and round-trip efficiency.

Metal-CO2 Batteries combine the oxidation of a metal (e.g. zinc) with the reduction of CO2 at the cathode. They aim to provide an **eco-friendly solution for CO2 utilization while generating electricity**.

Semi-Solid Flow Batteries use semi-solid slurries as the active materials, which are pumped through the cell during charge/discharge. This approach **aims to increase the energy density** compared to conventional flow batteries.

Nanoelectrofuel batteries is a new variation on flow batteries that uses nanoparticles to significantly **boost the energy density, up to 15-25 times higher than conventional flow batteries**. The

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[28] Technology Strategy Assessment - Flow Batteries; Sprenkle et al.
[29] Technology Strategy Assessment - Flow Batteries; Sprenkle et al.

goal is to develop a flow battery system small and energy-dense enough for use in electric vehicles. [30] [31] [32] [33] [34]

Market Readiness: Early Commercial
Energy Capacity Cost in 2021 (USD/kWh): 356-835
Max Deployment Size (MW): 10-100 for traditional flow, >100 for hybrid flow
Max. Nominal Duration (Hours): 8-100 (Aqueous electrolyte flow batteries from 25-100)
Average Round Trip Efficiency (%): 50-96 (Vanadium redox flow batteries: 65%-96%; Zinc-cerium flow batteries: 62%)[35]
VC-Investment in 2021-22 (MUSD): 122
Start-up Examples: ESS, VRB Energy, Invinity, CellCube, Primus Power, H2 Inc., Redflow
Advantages: Long cycle life and calendar life; Flexible siting options
Disadvantages/Challenges: High footprint; High CAPEX; Limited energy density

3.2.3.3 Novel Chemistries

Here alternative materials in place of lithium are used, but the cell structure is conventional by having a anode-cathode structure.

Start-up Examples: Eos, Ambri, EnerVenue, e-Zinc, Enerpoly

[36] [37] [38]

3.2.4 Chemical Storage

With this technology **energy is converted into high energy density chemical fuels**. Hydrogen, syngas and other energy-carrying chemicals can be produced from a variety of energy sources, including renewable energy, nuclear power, and fossil fuels. There are two popular emerging technologies which are based on **power-to-gas concepts: power-to-hydrogen-to-power, and power-to-syngas (synthetic gas)-to-power.**

The stored hydrogen or other chemicals can then be used to generate electricity when needed, by feeding the stored energy back into the grid. Alternatively, the chemicals can be sold and utilized in industrial applications.

Chemical LDES technologies offer flexibility, as the stored energy can be used either to generate electricity or as a chemical feedstock. This makes them well-suited for seasonal energy storage and balancing supply-demand mismatches.

While hydrogen is the most advanced chemical LDES technology, there are **challenges around the current reliance on fossil fuels for hydrogen production**. **Developing green hydrogen production is a key priority to fully realize the decarbonization potential of chemical LDES.** [39] [40]

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[30] The evolution of energy storage; Nafion
[31] Can Flow Batteries Finally Beat Lithium; IEEE Spectrum
[32] 4 alternatives to lithium-ion batteries currently exciting investors; Tamarindo
[33] Federal Policy to Accelerate Innovation in Long-Duration Energy Storage: The Case for Flow Batteries; ITIF
[34] To flow or not to flow. A perspective on large-scale stationary electrochemical energy storage; Pokhrial et al.
[35] Life cycle assessment (LCA) for flow batteries: A review of methodological decisions; Dieterle et al.
[36] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey
[37] https://www.ctvc.co/ldes-long-duration-energy-storage-tech/
[38] Long duration energy storage; Deloitte
[39] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey
[40] Long duration energy storage for the power system: A diverse field of technologies eager for deployment; LDES Council

Advantages: Can store large amounts of energy for seasonal timescales; Leverages existing gas infrastructure; Zero emissions when using renewable energy sources

Disadvantages: Currently low round-trip efficiencies; High capital costs for hydrogen production, Emerging technologies with limited deployment[41]

3.2.4.1 Power-to-Gas-to-Power (incl. Hydrogen and Syngas)

Power-to-gas has emerged as a potential way to convert electricity into gas, such as hydrogen, for heat or transportation. The major advantages are the opportunities for large-scale and long-duration storage that gas provides – and the potential for sector coupling across electricity, gas, transportation, and heat networks.

Hydrogen-based power-to-gas-to-power systems work by using surplus renewable electricity to produce green hydrogen via electrolysis. The hydrogen can be stored in tanks, caverns, or pipelines for later use.

Alternatively, the hydrogen can be combined with captured CO2 to produce synthetic natural gas (methane, also known as syngas), which has similar properties to natural gas and can be stored and later burned in conventional power plants. [42] [43]

Market Readiness: Pilot (commercial announced)
Energy Capacity Cost (USD/kWh in 2021): n/a
Max Deployment Size (MW): 10-100
Max. Nominal Duration (Hours): 500-1’000
Average Round Trip Efficiency (%): 40-70
VC-Investment in 2021-22 (MUSD): n/a
Advantages: Ability to store energy for very long durations; Potential for large-scale, seasonal storage; Versatile end-use applications for hydrogen/syngas
Disadvantages/Challenges: High capital costs, especially for green hydrogen production; Energy losses in conversion steps; Immature technology with limited commercial deployments

[44] [45] [46]

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[41] Scenario deployment analysis for Long-Duration Electricity Storage; Department for Energy Security & Net Zero; https://www.ctvc.co/ldes-long-duration-energy-storage-tech/

[42] Evaluating emerging long-duration energy storage technologies; Shan et al.

[43] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey

[44] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey;

[45] https://www.ctvc.co/ldes-long-duration-energy-storage-tech/

[46] Long duration energy storage; Deloitte

4. Market for LDES Technologies

Modeling and projections indicate that the total addressable market (TAM) for long-duration energy storage (LDES) technologies has significant growth potential in a net-zero emissions scenario**. Estimates suggest that the LDES TAM could reach a scale of 1.5 to 2.5 TW by the year 2040.**

If the projected cost reductions for LDES technologies materialize, they could account for a substantial share of the future energy capacity mix. Analyses show that **LDES could potentially store around 10 to 15 percent of the total energy consumed globally by 2040**. This would displace some of the capacity that would otherwise be met by lithium-ion batteries and hydrogen turbines.

The estimated value of this market **could reach around USD 1.3 trillion by 2040**.

4.1 Deployment

LDES technologies paired with renewables are a viable, cost-efficient and readily appliable option for industrial decarbonization, as observers consider these technologies offer a pretty simple solution for industrial emissions.

Short-term energy storage (under 24 hours) will dominate initial needs due to the current lower share of renewables. This allows for managing daily variations in renewable energy supply. However, **long-term storage (24+ hours) will also see early adoption in regions with unreliable grids or for businesses requiring consistent renewable power** (e.g., high-availability corporate PPAs). Both short-term and long-term storage solutions are expected to see commercial demand in the coming years. In summary, it is expected that a balanced mix of flexibility durations will be necessary in the long run.

According to studies there are five particular value-creation fields:

Energy shifting, capacity provision, and T&D (transmission and distribution) optimization: The mismatch between peak generation from renewable sources and peak electricity demand is a hurdle in grid integration. LDES technologies offer a solution by storing excess renewable energy and releasing it during high-demand periods. It is expected to result in the largest share of deployment in 2040 – 80 to 90% resp. **1’300-2’300 GW** installed power capacity (of total 1’500-2’500 GW).

Optimization of energy for industries with remote or unreliable grids: LDES empowers remote or grid-unreliable industrial facilities to secure reliable power. This applies to areas with weak grid infrastructure or those completely isolated from the grid, such as heavy industries in remote locations. It is projected that by 2040 the installed power capacity amounts to approx. **110 GW** (4-7%).

Supporting island grids: Isolated power grids, like those on small islands, can leverage LDES for reliable electricity. This eliminates dependence on traditional, potentially unreliable, power sources. It is projected that by 2040 the installed power capacity amounts to approx. **90-100 GW** (4-7%).

Firming for PPAs: LDES can bridge the gap for renewable energy buyers. This allows businesses with renewable power-purchase agreements (PPAs) to access clean energy even when renewable generation is low, ensuring they can achieve 100% renewable electricity use. It is projected that by 2040 the installed power capacity amounts to approx. **40 GW** (2-3%).

Providing stability services: LDES acts as a grid stabilizer. This technology helps maintain grid stability by responding to fluctuations and outages. For example, LDES can inject stored energy during transmission disruptions, mitigating the impact and ensuring reliable power delivery. It is projected that by 2040 the installed power capacity amounts to approx. **0 GW** (0%).

For instance, leading industrial firms are already taking proactive steps to pilot and deploy long-duration energy storage (LDES) technologies as a means to decarbonize their operations. Impatient to reduce their carbon footprint, these blue chip companies are leveraging LDES solutions to achieve their sustainability goals (e.g. Tata Steel, ArcelorMittal, BHP, Rio Tinto, Yara, Avery Dennison, Eni and Microsoft are among the industrial firms embarking on projects to demonstrate the ability of LDES technologies to decarbonize their operations). The commercially available LDES technologies, both for electricity and heat generation, have the technical capability to reduce industrial emissions by as much as 65% and an emission reduction opportunity of approx. 8 GT CO2.[47] [48]

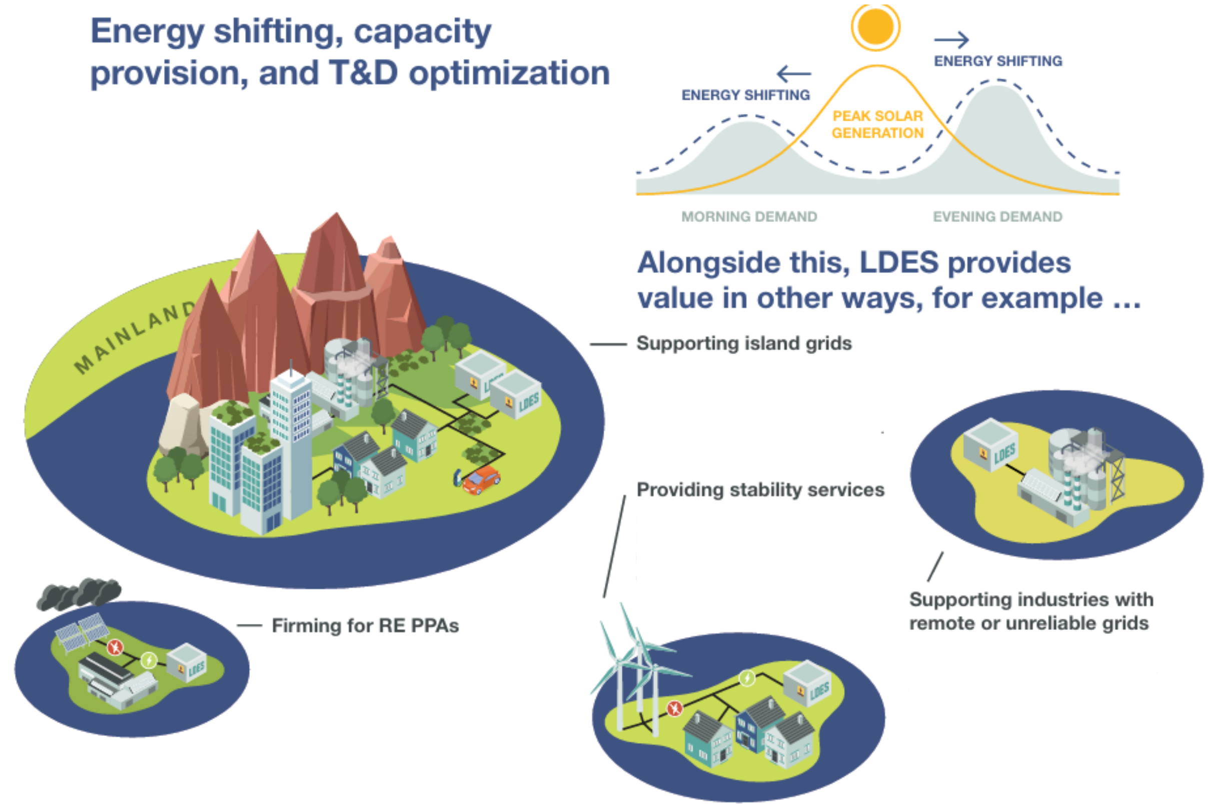

Illustration 8 Overview of LDES applications (Source: LDES Council & McKinsey)

4.2 Funding Environment

As stated earlier and as of today, no clear winner has emerged among the different long-duration categories. Among all the categories there have been quite a fluctuation and a steady rhythm of bankruptcies and new investments. Many technologies technically work but there are still critical points which have to be proven: Do those technologies work at an acceptable price point and development cycle, and can the businesses in that field stay afloat long enough to actually prove those hypotheses?

That last step has been hard for companies to fulfill, as **in previous years there were almost no commercial customers** around paying for those technologies. This is now **starting to change mainly for two reasons**: 1) **wind and solar are now competing very effectively for capacity additions** in the U.S. and other developed countries and 2) Many **utility companies, states and nations are upping their targets for clean energy**.[49]

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[47] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey
[48] LDES - Net Zero Industry Report; LDES Council & Roland Berger
[49] https://www.greentechmedia.com/articles/read/most-promising-long-duration-storage-technologies-left-standing

In the US, the federal administration supports the development of LDES by i.e. targeting 100% clean energy by 2035, providing an investment tax credit for standalone energy storage and announcing a 350 MUSD funding for LDES demonstration projects. This opportunity was recognized by investors, which is seen in the growth of overall funding from 218 MUSD in 2019 to 1’200 MUSD in 2022.[50]

The share of investments among the different subcategories of LDES technologies can be seen in the illustration below. **Start-ups focused on metal-air batteries received most funding in the last two years. This was mainly driven by one investment of 650 MUSD into a start-up developing a relatively inexpensive iron-air technology**. The company Form Energy claims to provide bulk energy storage with a duration of more than 100 hours at a cost of 20 USD/kWh.[51]

With similar governmental support and incentive schemes in other parts of the world the investment opportunity will likely lead to further funding growth. However, long duration energy storage technologies like flow batteries, compressed air or gravity-based solutions look set to enter the market at scale in the second half of the 2030s. [52]

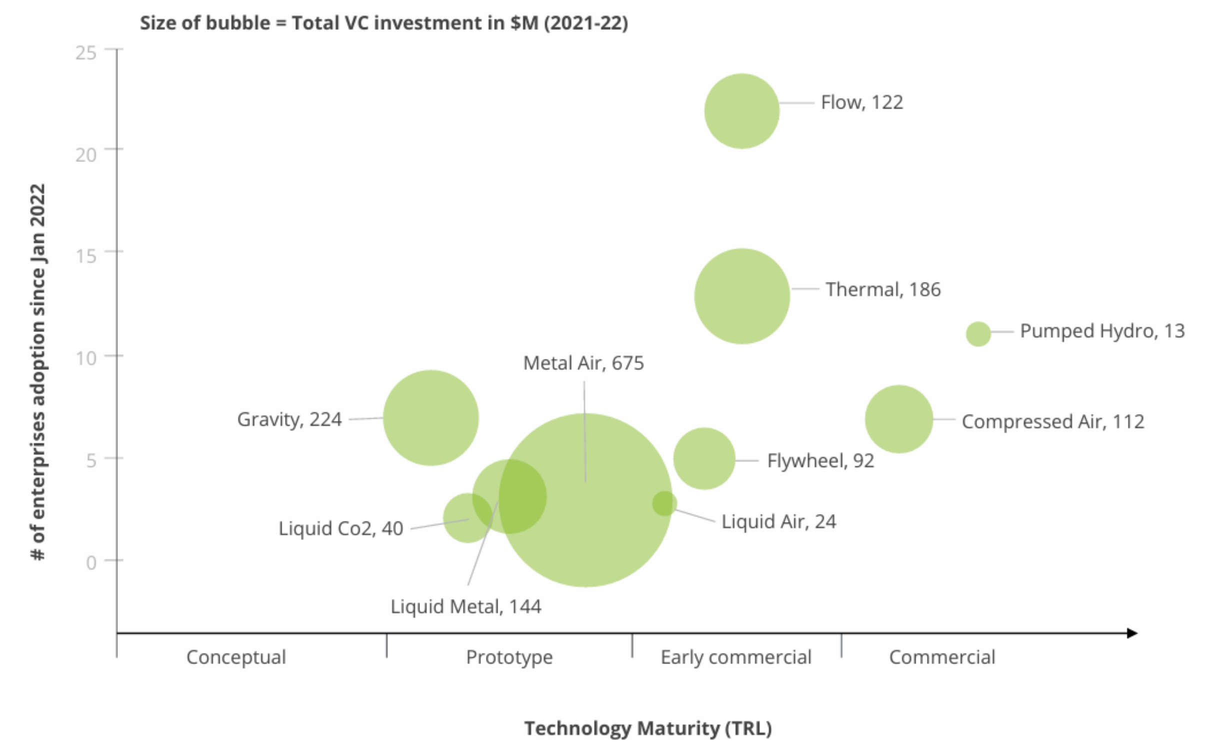

Illustration 9 LDES funding and adoption by technology (source: Long duration energy storage; Deloitte)

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[50] Long duration energy storage; Deloitte
[51] Long duration energy storage; Deloitte
[52] Long duration energy storage to scale in second half of 2030s; Energy storage news

5. The Road Ahead: What Needs to Happen to Make LDES Fly

5.1 Cost Development

Novel LDES are technologies at the beginning of the development cycle. **As of today, there is a cost gap compared to more mature li-ion (low durations) and hydrogen turbine (long duration) technologies**. The LDES cost-reduction rate compared to li-ion and hydrogen turbines will determine the level of uptake of the novel LDES technologies. **Only the most competitive LDES technologies are expected to receive the capital to scale up over the next decade and therefore constitute the dominant portion of the mix by 2030.**

As the technologies are scaled they will reduce in cost**: LDES is expected to follow similar cost reduction trends as other breakthrough energy technologies like offshore wind and batteries**. Projections suggest CAPEX learning rates of 12-18%, driven by advancements in technology and the benefits of achieving larger operational scale.

Furthermore, energy storage capacity costs are expected to **to decline by 60 percent and** the round-trip efficiency (RTE) of these technologies is also projected **to improve by 10 to 15 percent**, which drives the competitiveness of LDES in the long run.

A study suggests that by 2030:

- LDES can be **cost competitive against Li-ion for durations above 6 hours**, with a distinctive advantage above 9 hours
- LDES can be **cost competitive against hydrogen turbines with the same operational profiles for durations below 150 hours.**

To unlock the potential of LDES, creating the right investment ecosystem is essential. This ecosystem will accelerate investments and address the current cost gap and technological uncertainties of this new market.[53]

5.2 Market Enablers

To further advance LDES technologies and driving their economic and technical maturity **they should be aligned with the deployment of renewable energy at large-scale**. A lack of supportive market mechanisms could significantly delay the deployment of LDES technologies. Someone could argue that there is an analogy to the development of renewables: Their growth was accelerated by public policy support.

According to studies several potential areas of support have been identified, which help attracting appropriate levels of private investments, lower the entry barriers and ensure financial returns:

Long-term system planning: This includes nation-wide upfront energy planning (i.e. capacity mix, grid infrastructure, etc.), target-setting regarding renewable energy, and international coordination.

Support for deployments and scaling-up capabilities: This includes support programs to reach cost cutting potentials, test new market mechanisms, reduce CAPEX and create incentives for customers to pick up technology.

Market creation: Market designs must be created, which ensure that financial returns are positive during the lifetime of the investment. Additionally, regulation should be facilitated for LDES advancement (e.g. safety standards and other market rules).

In general, off-grid applications are already cost effective and require the least support relative to other applications. On-grid heat applications that can be electrified today and hard-to-electrify sectors require policies that incentivize industrial customers to electrify their fossil-fueled heat

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[53] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey

processes (i.e. elimination of government support for fossil fuels) and ensure that electric grids can support larger electricity loads (i.e. grid planning to support large, newly-electrified loads).[54] [55]

Furthermore, there are other aspects essential for LDES to be an interesting investment opportunity:

1) Renewable energy penetration (especially wind and solar) will reach over 60%, resulting in additional long duration energy storage needs.
2) Limited timely grid improvements and lithium-ion battery capacity leave room for LDES to fill the long-duration storage gap.
3) Persistent energy price fluctuations across day and season offer arbitrage opportunities for LDES. [56]

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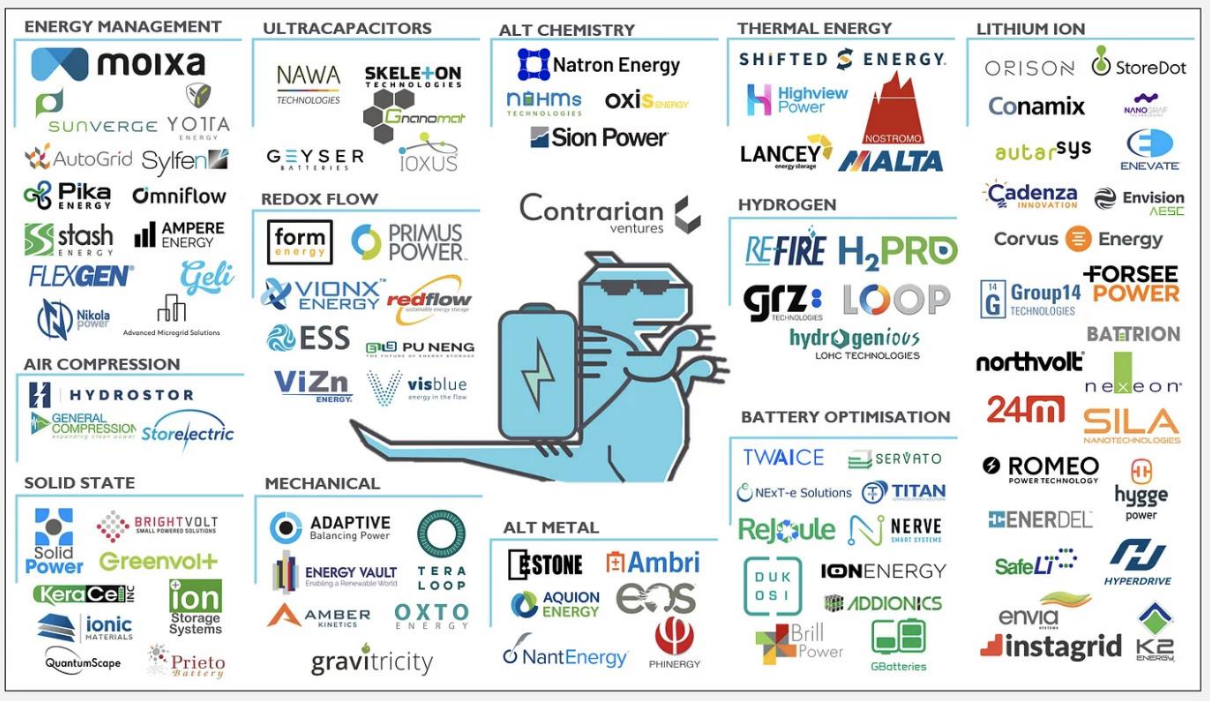
[54] Net-zero power – long duration energy storage for a renewable grid; LDES Council & McKinsey

[55] LDES - Net Zero Industry Report; LDES Council & Roland Berger

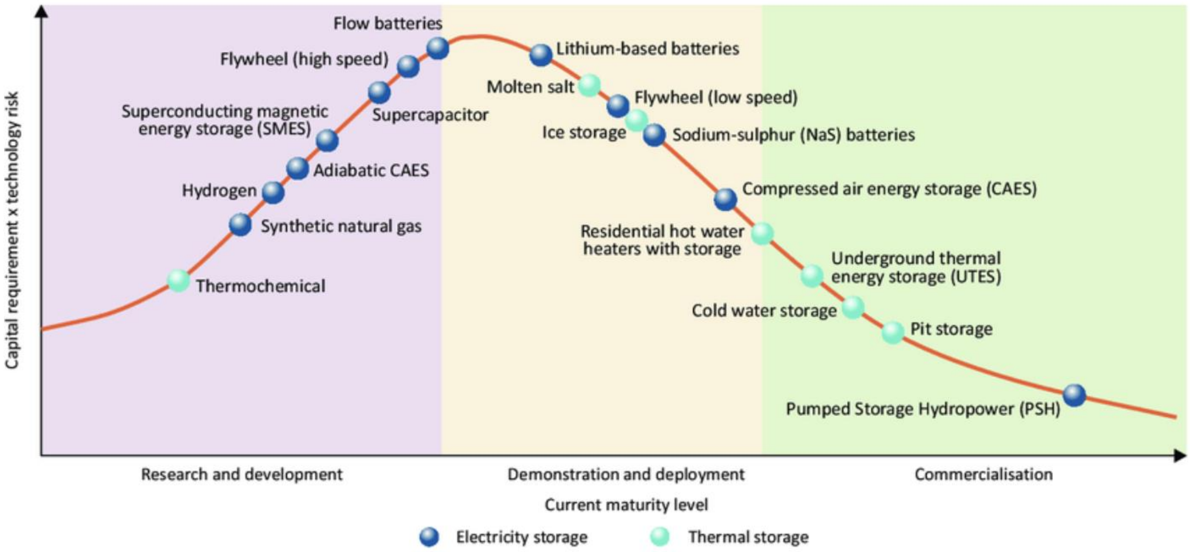
[56] https://www.ctvc.co/ldes-long-duration-energy-storage-tech/

Appendix I. Energy Storage Start-up Map



https://medium.com/contrarian-view/global-energy-storage-startup-map-76bfddaa9c86

Appendix II. Maturity of Energy Storage Technologies



https://www.researchgate.net/figure/Maturity-of-energy-storage-technologies_fig1_261848307