# A Long Duration Energy

# Storage Guide To

# Decarbonizing The Northeast

**November 19th, 2021**
**By: Kelly Ogiesoba**

**Paper Outline**

- Introduction
- Executive Summary
- Battery Use Cases
- The Northeast Challenge
- LDES Technologies Options
    - Electrochemical
        - Flow Batteries
        - Metal-Air Batteries
        - Zinc
    - Mechanical
        - Pumped Hydro Storage
        - Gravity Storage
        - Compressed Air
        - Thermal Energy
            - Liquid Air
            - Pumped Heat
    - Chemical
        - Hydrogen
        - LNG
        - Bioenergy
- Policy Recommendations
- Conclusion
- References

## Introduction

One of the main elements of modernizing and decarbonizing today's grid is dealing with the issue of intermittent power supplied by renewable sources, such as solar and wind. In addition, hourly, daily, weekly, monthly, and even seasonal shifts in peak electricity demand from the summer and winter periods along with excess capacity during shoulder seasons make our grids inefficient. To deal with these inefficiencies and eliminate the issues of intermittent power, we need a way to store energy to be used at any moment throughout the year. This is our best path towards decarbonizing our grid. The focus of this paper is to discuss the challenges behind energy storage, in particular long-duration grid-scale storage ("LDES") that can be dispatched on command, and lay out a recommendation for the strategy that provides the best path towards deploying LDES solutions throughout our grid in the Northeastern portion of the United States. The path forward will likely include both technological, policy, and regulatory innovations.

## Executive Summary

Today, the main sources of LDES in the northeast are pumped storage, liquified natural gas (LNG), and liquid fuels cells. Of all the long-duration energy storage solutions available, hydrogen, zinc, flow, pumped heat, and biofuels seem to have the best path for scaling in the northeast and having the most impact when taking into account cost, technology readiness levels, storage duration length, and likely policy and regulatory changes. These technologies will be able to best perform the use cases needed for longer-duration energy storage such as renewable firming and islanding. Other technologies, such as LNG can also meet the needs for LDES for an effective price but don't do the most effective job from a greenhouse gas emissions perspective. To help LDES technologies proliferate, certain policy and regulatory changes need to occur. The ones that will be most effective will be those that have a positive incentive such as tax credits, subsidies but also mandates.

## Battery Use Cases

Storage has many use cases depending on how long the power can be deployed and how quickly the power can be dispatched. Battery use case applications can be broadly bucketed into three categories: short, medium, and long-duration applications.

Short duration applications include ***frequency regulation***, stabilizing the grid frequency power output to 60 Hertz, ***volt/var support***, regulating the voltage deviations on the grid due to the real power injection from renewables such as solar and wind, ***uninterruptible power supply (UPS)***, ability to back uploads for a short duration with an extremely quick response time so lights don't flicker and electronics and other loads don't reset, and ***solar/wind or renewable smoothing***, smoothing out the input power from solar and wind sources to the grid such that the AC output from the storage slowly ramps up and down over a set period to prevent grid instability.

Medium duration applications include items such as ***Energy Arbitrage***, the process of purchasing more electricity (charging) during off-peak periods and storing the power then selling it (discharging) during peak period, ***Black Start***, the process of restoring an electric power station without using any external power source, ***transmission, and distribution (T&D) deferral***, using storage to delay or avoid a costly T&D upgrade by expanding peak capacity for up to 4 hours during peak hours, and ***demand charge management***, minimizing utility demand charges by dispatching power during high usage times.

Long duration storage, which the US Department of Energy defines as "systems that can store energy for more than 10 hours at a time" without having to recharge[1]. Long duration application includes items such as ***renewable firming***, keeping the grid stable in the face of renewable intermittent power to provide a maintained output of power from a variable power source and ***islanding/backup***, ability to continue powering a given load when the external electrical grid is no longer available – the process can last hours or days. There is a range of battery technologies that can meet this wide array of storage use cases, but not all these technologies are applicable for long-duration energy storage (LDES) that can be used in the Northeast. The storage technologies are shown in figure 1:

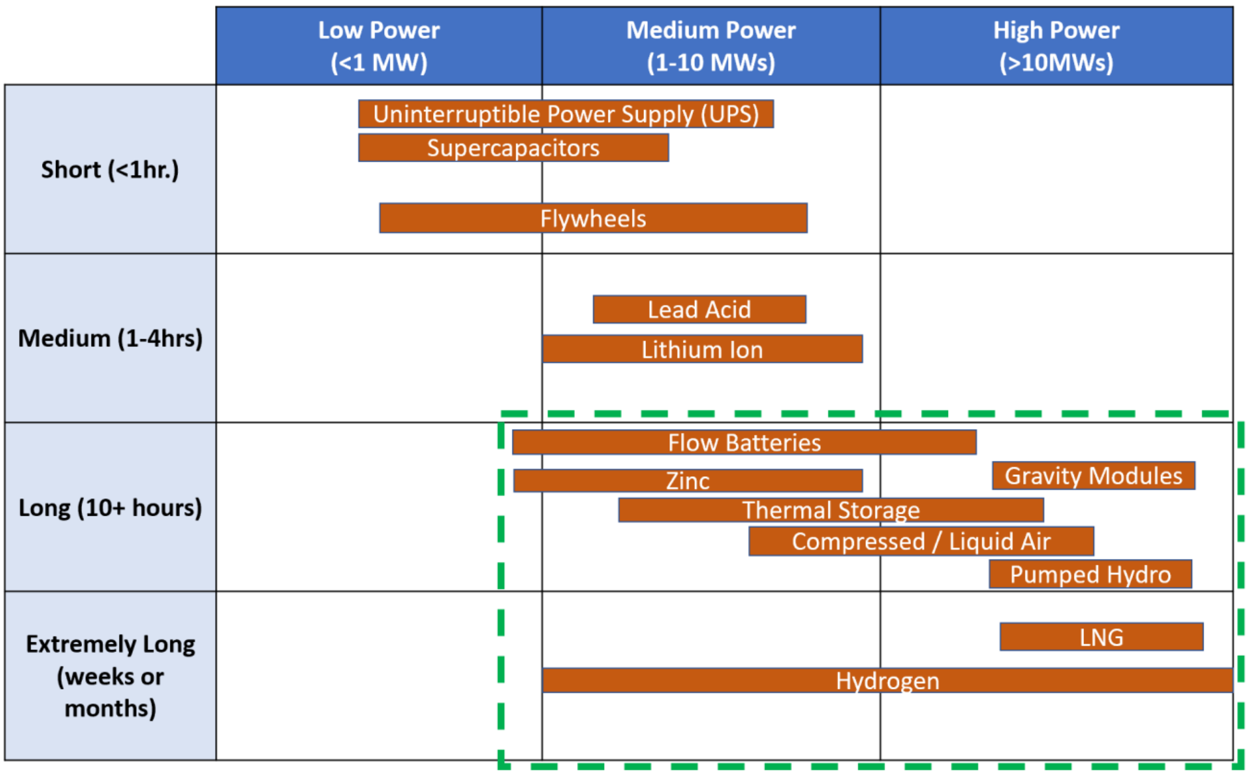



Figure 1[2]

## The Northeast Challenge

Today, in New England the primary storage for LDES is pumped hydro supplied from seasonal rainfall, LNG holdings, and kerosene storage with oil backup plants to provide peaking and to solve energy reliability concerns [3]. As the region moves towards decarbonization it hopes to find non-greenhouse gas-emitting sources for storage. In the future, the Massachusetts Department of Energy Resources confirmed they are open to bioenergy, hydrogen, methane, ammonia, compressed air, liquid air, potential energy or gravity modules, flow batteries, and liquid reservoir batteries, so these will be the possible technological solutions that will be focused on for solutions that can work in the northeast. Before being able to provide a recommendation for which technologies should be pursued in the northeast and what policy incentives could be used to drive the deployment of these technologies it is necessary to do a deep dive on each one, assessing the pros and cons, challenges, and opportunities. Lithium-ion batteries solutions are the most common battery storage technology used today, but they have their limitations, mainly duration length. It is unclear when LDES solutions will need to be deployed on mass in the northeast, but it will likely depend on when renewable penetration can take up a sizeable amount of electricity generation and causes large changes in intermittent power and when fossil generation is sharply declining – this may be around 2035[4]. There are only two grid operators in the northeast, New England ISO and NYISO, and they only give capacity value to storage up to 4 or 6 hours. No credits are given for anything longer than 6 hours, so there's little incentive for the private sector to build a product to meet that need.

**LDES Technology Options**

*Electrochemical Solutions*

*Flow Batteries:*

A flow battery is a type of battery where electrolytes flow through electrochemical cells from one or more electrolyte tanks [5]. These batteries are rechargeable They incorporate liquid electrolytes to function as a source of DC power, which is then converted to AC power. See figure 2 below for an example of a flow battery system.

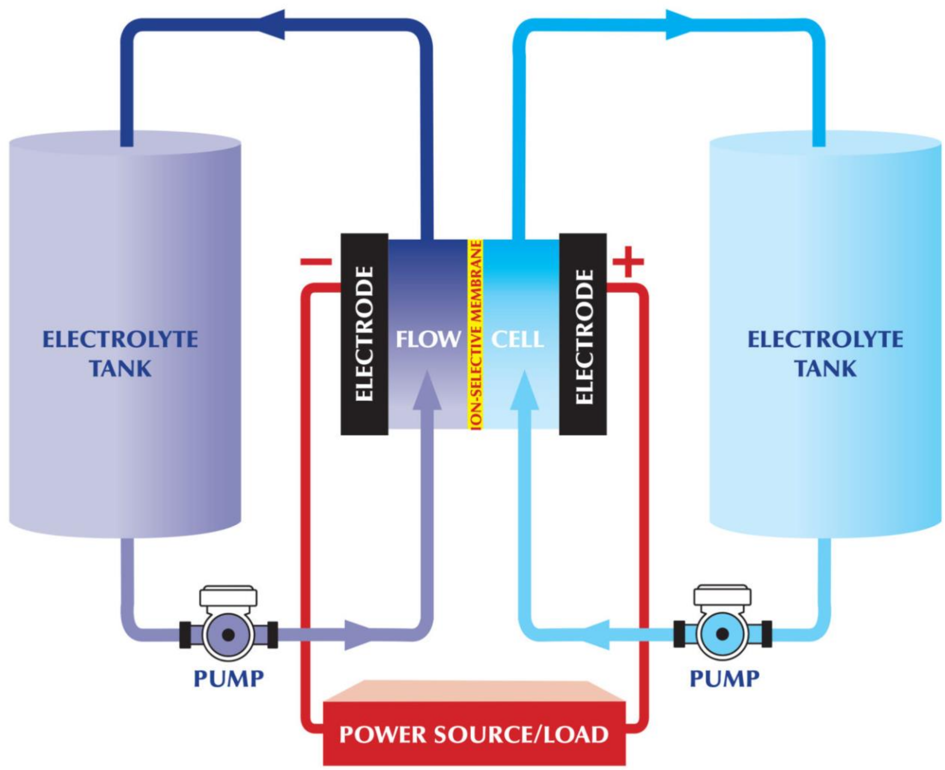



Figure 2[5]

Energy storage capacity is increased by increasing the number of electrolytes stored inside the tanks. What is unique about flow batteries, compared to a traditional lithium-ion solution, is that when maintenance guidelines are followed, flow battery performance won't degrade over the life of a project. Flow batteries have the potential to be used for black start capacity, volt/var support, demand charge management, energy arbitrage and can be paired with renewables to extend the availability of renewable energy for 10+ hours without degradation to help combat intermittency issues [6]. Round trip efficiencies are ~ 68%[7]

Costs have been declining for flow batteries, but it's not clear exactly where these prices will bottom out. Unlike lithium-ion batteries where the unit costs flatten out after 4 hours of storage, flow batteries continue to have unit cost reductions ($/kWh) up to 12 hours of storage [6]. However, flow batteries are expensive when compared to lithium-ion, which is likely why lithium-ion solutions have dominated the storage market, at least for the short duration of storage. With today's technology, flow batteries' capital costs are 2X the price of a lithium-ion solution of the same size and are not expected to hit parity in the near term. Today, a 20MW, 160MWh flow battery system is expected to cost $96M [6] This comes to $600/kWh. For broad market penetration, flow batteries must demonstrate themselves to be cost-competitive against alternative storage solutions and reduce their cost.

An exciting company in the space is ***Honeywell***. Honeywell is a US-headquartered conglomerate operating in aerospace, building technology, performance materials, and business. They have recently developed a new flow battery capable of discharging for up to 12 hours [9]. The battery will be tested on a small 400kWh system in 2022 by Duke Energy and then scaled up to a 60MWh project the following year. This battery, and flow batteries in general, aren't tied to the need to mine rare earth minerals on a massive scale to fuel mass-scale deployment. Though not technically a flow battery,

*Metal-Air Batteries:*

A metal-air battery is a battery like any other, composed of both an anode and a cathode, but the anode is made from metal, and the cathode is made from air. There is also an electrolyte that is used to create an electrical solution that is conducive to electricity. See figure 3 below for an image of a metal-air battery system.

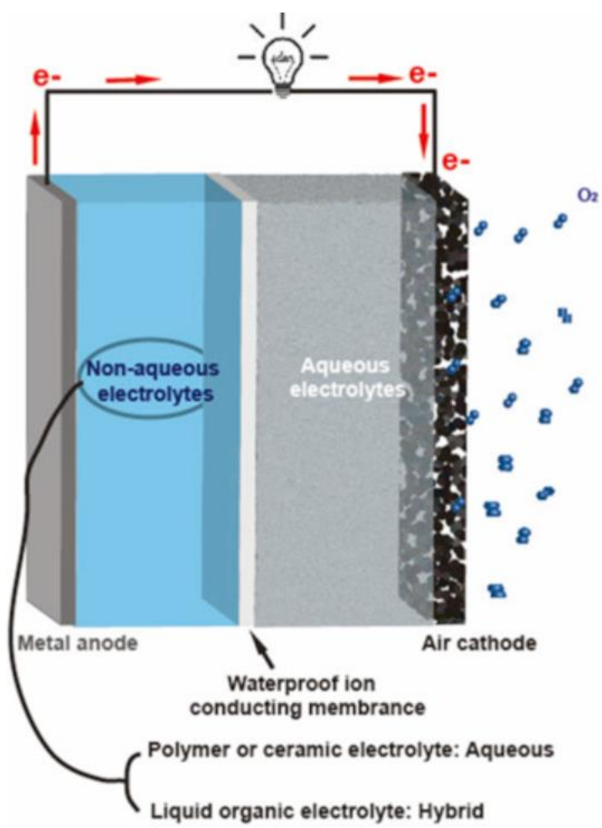



Figure 3[54]

These batteries have a theoretical cost that comes to less than $100/kWh[55]. Aqueous mental-air batteries are usually made with zinc, iron, magnesium, or aluminum while other metals are too reactive in an aqueous solution. Metals too reactive can be used for non-aqueous batteries. These include lithium, sodium, or potassium [55]. Round trip efficiencies for this technology vary widely based on the type of metal used. Zn-air and Fe-air systems have lower efficiency at around 60%, whereas Li-air systems have higher efficiency at around 75%[55][57]

***Form Energy*** is developing an aqueous metal-air battery solution aimed at delivering 1MW power for over 100 hours [10]. The expected cost of this battery at scale is $20/kWh and will be made with low-cost iron, the 2nd most mined mineral on the planet behind coal [56]. They hope to deploy their battery in 2023 or 2024. This battery, if proven successful, would certainly be a major game-changer in the LDES space as it could allow for the firming of renewables to provide almost a week of storage.

*Zinc Batteries:*

A zinc battery is a battery storage technology that relies on Zinc metal ions as the mechanism for storing energy. Like lithium-ion batteries, Zinc batteries rely on intercalation, which is the "reversible inclusion or insertion of a molecule into layered materials with layered structures" [11]. To charge, zinc metal ions move from cathode to anode. First, zinc ions from the cathode are dissolved into the electrolyte and then zinc ions are absorbed into the anode from the electrolyte [12]. See figure 4 for an example of a zinc battery system.

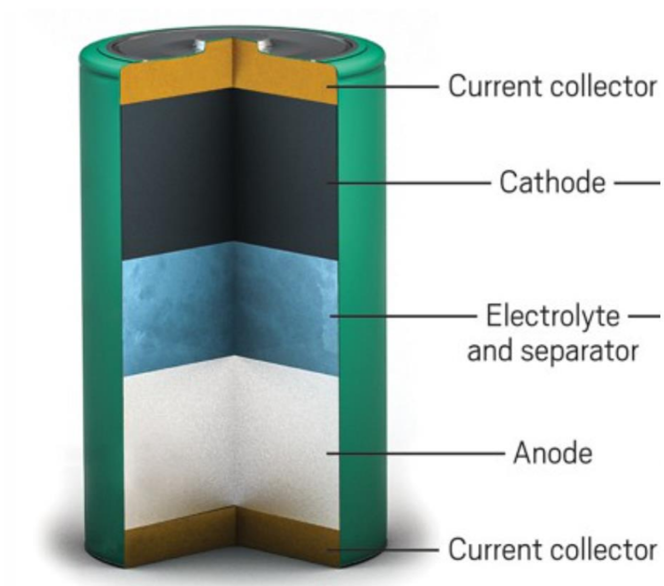



Figure 4[13]

Zinc-ion batteries have very energy-dense active materials, which allows for a lot of energy to be stored in the batteries in the electrodes. Zinc-ion batteries are water-based, so the production steps don't need to take place in a highly controlled atmosphere like lithium-ion batteries, which have a violent reactivity with water. This helps decrease their production costs. In fact, for an 8-hour zinc ion battery, the capital costs are $250/kWh, for a 32-hour system it's $100/kWh, and for a 100-hour system, it's $60/kWh. The lithium-ion alternative is $300/kWh for any storage system over 8 hours [14]. Along with being less expensive than lithium-ion alternatives, zinc-ion batteries are also safer and have a more stable and secure supply chain. Lithium-ion batteries have caught fire before such as the Arizona battery explosion in 2019[58]. It is not clear how many unreported fires have occurred from lithium-ion batteries, but from 2012-2017 there were 49 battery recalls which impacted over 4 million products [15]. In addition, many of the raw materials used to produce lithium-ion products are sourced from China. Given the growing geopolitical tensions between the United States and China, supply chain dependence on raw materials from China could lead to insecure supply chains. It also makes it difficult to monitor which materials are being used to ensure the manufacturing process is consistent. Zinc-ion batteries can be produced domestically without these constraints and can also be produced on the same production lines as lithium-ion batteries. Zinc batteries have a round trip efficiency of ~72% [7].

Two start-ups aiming to use Zinc-ion batteries to solve the long-duration energy storage problem are ***e-Zinc*** and ***Salient Energy***.

E-Zinc is a Toronto-based start-up that aims to demonstrate a long-duration zinc-ion battery for both industrial and commercial markets. CEO James Larson claims “We can do the short-duration time-of-use arbitrage and demand-charge reduction and help monetize those opportunities for customers, but we can also provide them up to two days of backup power in the face of an outage” [16]. E-Zinc has recently been awarded a $1.3M grant from the California Energy Commission, but since its founding has raised $3.4M in their seed round and more than CAD 6M of non-dilutive grants. The first deployment will be at Houweling’s commercial greenhouse in Los Angeles, California, in 2022. This will be a 40kW storage system with up to 2 days of backup power.

Salient Energy is a Nova Scotia-based zinc-ion battery start-up developer. They have a patented technology that is water-based, so the battery cannot catch on fire. They claim they have a modular battery that is 30% to 50% cheaper at scale than the lithium-ion alternative when it comes to the Levelized cost of energy storage [17]. Their product is freed from Chinese supply chains that work with much more abundant materials such as Zinc and Manganese, as opposed to lithium, cobalt, and nickel. Their product aims to have a lifespan of up to 20 years. Salient aims to work on a pilot manufacturing facility in Halifax, Nova Scotia which will become operational in 2022 and hopes to attract enough capital to build a “few hundred-megawatt hour plants” by 2024 [17]

## Mechanical Solutions

### *Gravity Storage*

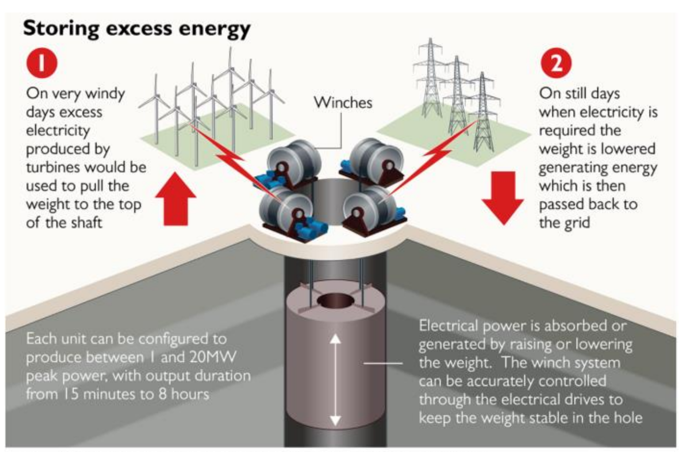
Energy can be stored as potential energy where a unit of mass is descended to discharge energy and lifted as a way to charge energy. When it comes to gravity storage, capacity increases with radius r^4, and construction costs increase with radius at r^2 [18]. The price per kW of gravity storage decreases with 1/r^2[18]. This is a strong advantage because low costs per kWh can become possible. The initial investment or CAPEX costs can be around 120 to 380 $/kWh [18]. Storage can typically be stored from anywhere between 6 and 14 hours. The main principle used is the hydraulic lifting of large rock masses, where water is pumped beneath a rocking piston. See below for an image of the gravity storage plant in figure 5.

Figure 5 [18]

The main challenge that exists for gravity storage is location. Plants need to be in areas with solid bedrock and a large body of water must be readily available.

There are other forms of gravity storage theoretical technologies where rock masses are lifted above ground or when gravity modules are dropped and lifted underground. Two innovative companies that work to design these types of storage systems are ***Gravitricity*** and ***Energy Vault***.

Gravitricity is a long-duration energy storage startup that relies on hoisting heavy weights up vertical shafts. They aim to provide consumers with an alternative solution to lithium-ion batteries and reduce the need to mine rare earth minerals to create energy storage systems. They have recently completed a small pilot in Edinburgh, Scotland, and are now preparing for a larger commercial expansion of the product. The pilot project was a 250kW system generating power using two 25-ton weights [19]. For large-scale commercial operations, they seek to install their storage systems at abandoned mine shafts and will have a capacity of 4-8MW. They hope to be able to achieve a 25-year operational life on the storage systems with no output loss or degradation. An image of the storage system is shown below in figure 6:




*Concept diagram of the gravity-based energy storage system (Credit: Gravitricity)*

Figure 6 [19]

Energy Vault's is another long-duration energy storage startup. Their technology relies on the lifting and dropping of concrete bricks. These bricks are combined with the energy vault's software algorithm and can deliver the benefits of a pumped hydro system, but with higher efficiency and a much lower price point. Energy Vault is working on building a 35MWh system with 4MW of peak power with a round trip efficiency of 90% [20]. Energy Vault has raised over $100M through a Series C round of funding. See below for an image of energy Vault's storage system in figure 7:

Figure 7 [21]

*Pumped Hydro Storage*

Pumped Hydro storage is the most common type of energy storage solution used in the market today for utility-scale storage in the United States accounting for 95% of all utility-scale storage [22]. This technology works by pushing water through a turbine to generate power and electricity. To "charge" or store power to be used later, pumps are used to elevate water into a high elevation reservoir from a lower elevation reservoir. Once the energy is needed or an operator would like to "discharge" the battery, water is released and runs through the turbines to produce power. One common application is to charge the storage system at night when the power is cheap and release the water during the day when the cost of power is much higher.

All pumped hydro can be described as open-looped or closed-looped. In an open system, the storage system is connected to a natural body of flowing water such as a river. Whereas in a closed-loop system the storage isn't connected to an outside body of flowing water. See figure 8 for the image of pumped hydro systems.

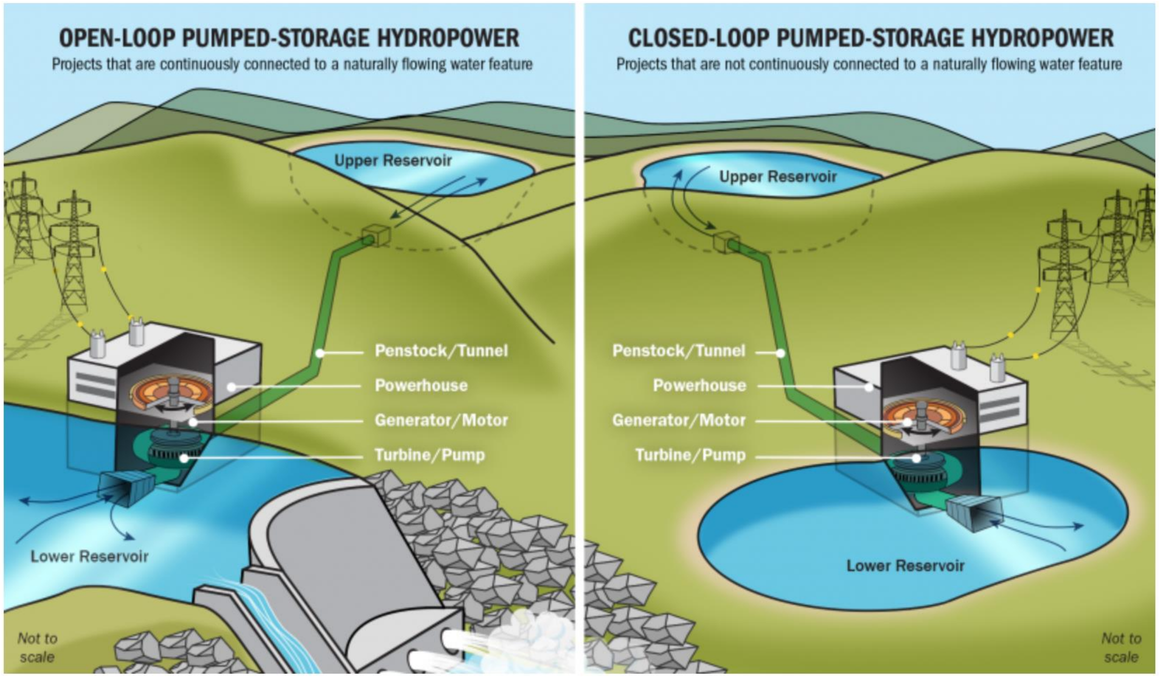



Figure 8 [22]

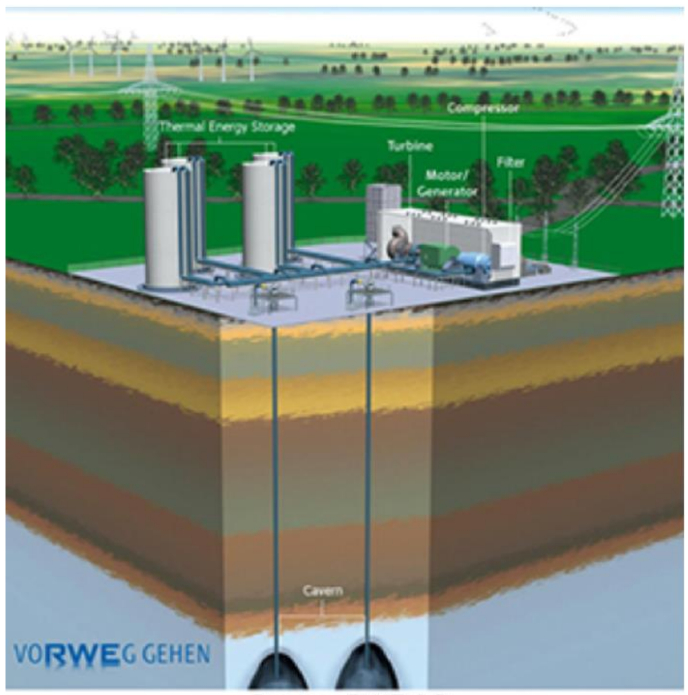
These plants tend to be efficient with a typical round-trip efficiency of around 80% [23]. These plants are not only used for capacity benefits but also for grid ancillary benefits as these plants are capable of responding to large electrical load changes within a few minutes or even seconds. These plants also tend to be capable of long-duration energy storage and can typically have between 6 and 20 hours of storage capacity and are good for a black start, spinning reserves, firming capacity, and other benefits. America currently has 43 pumped storage plants, but it has the potential to grow its pumped hydro capacity by >2X[22]. Pumped hydro has installed project costs ranging in between $106 to $200 per kWh [24]. The challenge with this technology is that there are only so many specific locations where this technology can be built and just because the storage capacity can be doubled in the US, it doesn't mean it can be doubled for as cheap a cost as has been historically done.

One interesting start-up that uses underground pumped hydro technology is ***Quidnet Energy***. Their technology is slightly different as there is no above-ground reservoir. Water is pumped into the earth to fill up the cracks in-between that held fossil fuels before. The pressurized water can then be released to spin a turbine to "discharge" power back into the grid. What makes this startup unique is that its technology can be used to convert abandoned oil and gas wells into new-age long-duration energy storage plants for renewable power [25].

*Compressed Air*

Compressed air storage is good for both large utility-scale installations that can provide benefits for the grid, but also small-scale, on-site storage solutions. When it comes to their applications, compressed air storage plants are very close to pumped-hydro plants. The difference lies in the material used to store energy. Unlike in pumped-hydro storage systems, compressed air storage uses ambient air or other forms of gas compressed and stored under pressure underground. This is how the storage system is “charged”. To “discharge” the pressurized air is heated and expanded, which drives a turbine in a generator to produce electricity [26].

Compressed air plants have two expansion methods used for extracting heat from the storage system each with its pros and cons: Diabatic and Adiabatic Method. In the diabatic method, the plants effectively operate as gas turbines, but the compression of the combustion air is separate from the actual gas turbine process. Benefits of this process include the ability to generate 3X the output for the same natural input, which is helpful for drastically cutting gas consumption, which will in turn cut carbon dioxide emissions by 40% to 60%. Efficiency levels are low and sit between 40% and 55% [26]. When using the adiabatic method, the heat of compression is recovered and used to heat the compressed air during turbine operations. It is no longer needed to burn natural gas to warm the decompressed air. Thus, the efficiency of an adiabatic system can be as high as 70%. Compressed air storage is estimated to cost $119/kWh[27]. Finally, these plants can provide up to 12 hours of storage [28]. See figure 9 below for an image of a compressed air storage plant.



Source: RWE AG

Figure 9 [26]

One prominent compressed air startup is ***Hydrostor***. Hydrostor is a Canadian-based developer of advanced compressed air storage systems for long-duration and carbon dioxide-free storage. To date, they have raised $37M since their founding in 2010. Their advanced compressed air storage system uses surplus electricity from the grid or electricity from renewable sources to run their air compressor. Hydrostor is planning to build two compressed air systems that will store up to 10 GWh of energy providing up to 12 hours of duration. The operating life of this system will be 50+ years [29]. Both plants will be built in California with the first aim to complete construction by 2026.

*Thermal Energy Storage: Liquid Air & Pumped Heat*

Thermal Energy Storage comes in two forms: Liquid Air and Pumped Heat. Liquid air energy storage uses liquified air to create an energy reserve. Air is drawn in for the surrounding environment and cooled until it liquefies and it is finally stored in a tank – this is how the system is "charged". The tanks can hold GWh of stored energy. To discharge the storage system, the liquefied air is exposed to ambient air or waste heat which brings the air back into a gaseous state. The air is pumped to high pressure and super-heated to ambient temperature to create a high-pressure gas. This gas is then used to turn a turbine and generate power [30]. The fluid (cooled gas) used is typically liquid nitrogen or liquefied oxygen, natural gas, or air. These systems are similar to pumped hydro systems when it comes to their performance characteristics, and they are well suited for long-duration applications. See figure 10 below for an image of a liquid air storage facility.


Figure 10 [31]

The above facility is being constructed by ***Highview Power*** and Encore Renewable Energy in Northern Vermont and aims to provide up to 10+ hours of storage at 50MW [32]. Highview Power is a British start-up targeting the utility market and developing long-duration energy storage solutions. Cost-wise, liquid air storage systems are very competitive and Construction project costs are between $340 and $680 per kWh [34]. Liquid air storage efficiency varies widely between 45% and 70% [35].

When it comes to pumped heat storage, electricity drives an engine. This engine is tied to two large thermal stores [30]. Thermal storage is a mechanism of storing excess heat generated from elsewhere[36]. Energy is stored by using a heat pump to pump the heat from a cold store to a hot store. This is how the storage system is charged. See figure 11 for a diagram of a typical pumped heat storage system.

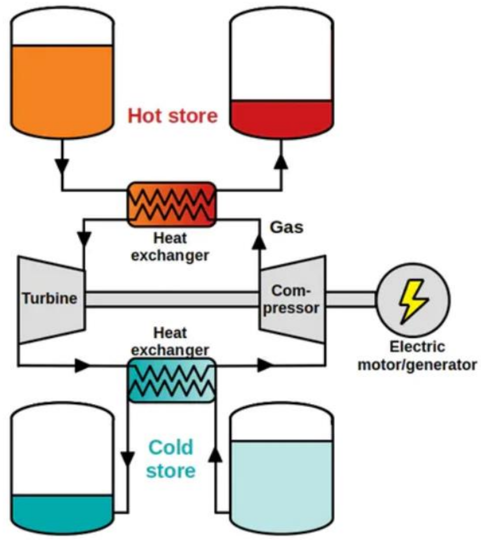
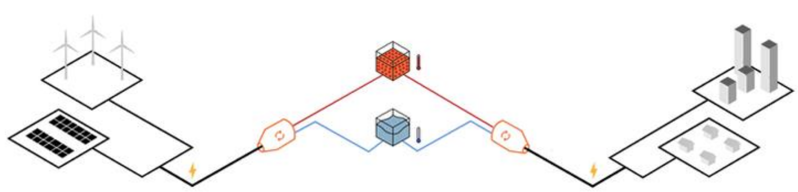



Figure 11 [37]

Pumped heat storage systems can be built for less than $100 per kWh with round trip efficiencies between 52% and 72%. Discharging duration can be up to 200 hours [60], at least in theory, though this has yet to be proven.

One prominent start-up in this space uses a pumped heat storage technology in ***Malta***. Backed by Breakthrough Energy Ventures, they've been able to put together a long-duration energy storage solution that is grid-scale (10 to 100MW) and low cost (<$100/kWh). Malta's storage system has a duration of up to 200[60]. Round trip efficiency is between 55% and 65% [38]. They are hoping to commission their storage project in Q1 2024. The system will be used for frequency response, reactive power, voltage management, inertia, and capacity. See figure 12 for Malta's recuperated air-loop heat pump system.



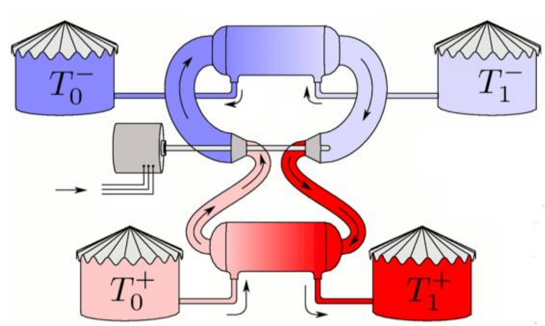


Figure 12 [38]

*Chemical Solutions*

*Hydrogen*

One of the longest duration technologies we have available for storage to address the issue of intermittent power in renewables as they increase in grid penetration is hydrogen [39]. Hydrogen storage is a process where the energy produced is used to power electrolysis. Electrolysis is a chemical process where a current is passed through a chemical solution to separate the hydrogen. See figure 13 below for a graphic showing the power to gas process for hydrogen.

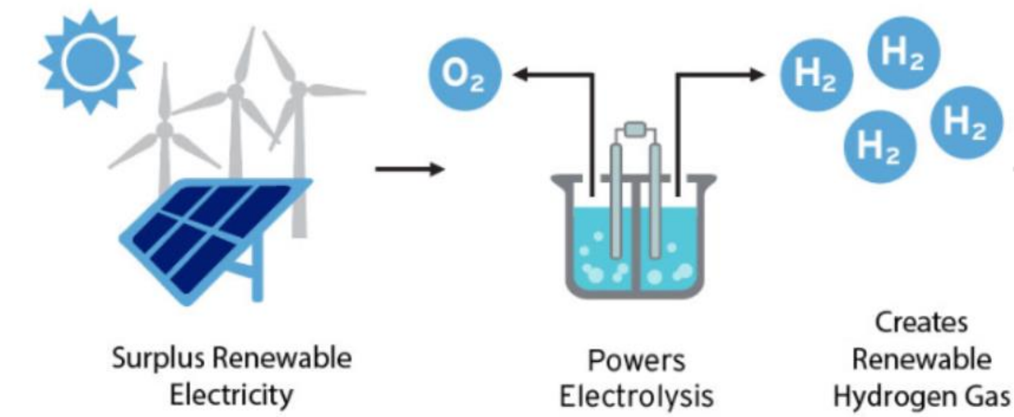



Figure 13 [39]

Once this hydrogen is separated it can be used for many things. A few use cases are to be used in stationary fuel cells, injected into natural gas pipelines, stored as compressed gas, and used for power generation. Hydrogen energy storage has the potential to last days, weeks, and even months. Hydrogen can be stored physically as either a liquid or a gas in high-pressure tanks. Very large amounts of hydrogen can also be stored in constructed underground salt caverns of up to 500,000 cubic meters at 2900 psi, which implies 100GWh of stored energy [40]. When dealing with such a large amount of storage it will be possible to have weeks of storage and even possible to balance seasonal variation in renewables. The conversion efficiency for hydrogen systems, getting from H2 to electricity, is between 65% and 90% [40].

The cost of hydrogen changes based on how it is produced. Green hydrogen produced through electrolysis costs between $10 and $13 per kg ($0.3 to $0.4 per kWh), gray hydrogen from natural gas costs $2-$6 ($0.06 to $0.18 per kWh) per kg and $6-$10 ($0.18 to $0.3 per kWh) when coupled with carbon capture and sequestration, and brown hydrogen from coal gasification costs $2-$3 ($0.06 to $0.09 per kWh) per kg and $6-$7 per kg ($0.18 to $0.21 per kWh) when coupled with carbon capture and sequestration[53]. . The challenge of hydrogen comes down to weight, volume, and efficiency. The weight and volume of hydrogen storage systems are currently far too big since hydrogen isn't that dense. This causes the need to take up lots of space to store the element. Another problem is the cost to produce hydrogen from renewable energy. This remains costly. There is also a lack of hydrogen infrastructure which holds back adoption [40].

There is a working hydrogen plant in Ontario, Canada. This is a 2.5MW Markham Energy storage facility that provides grid services to the Ontario ISO and was built by ***Hydrogenics Corporation (now owned by Cummins)***. Hydrogenics is a globally recognized developer and provider of hydrogen generation and fuel cell products [43]. This plant is North America's first multi-megawatt power-to-gas facility

*Liquified Natural Gas (LNG)*

Liquified Natural Gas (LNG) is another way to store energy. This is a natural gas that has been cooled to a liquid state. This takes place at -260 degrees Fahrenheit. Liquifying natural gas makes it easy to transport the material long distances and to areas, pipelines are unable to reach [44]. See figure 14 for the image of an LNG tank.

Figure – 14 [45]

LNG can be used as a supplemental backup to complement renewables and the intermittent power they generate. Currently, in New England, one of the primary storage technologies used for long-duration energy storage is LNG. There are very few maintenance costs for LNG to store the gas in the tanks. Once the LNG is in the tank, it's in the tank. It costs approximately 60-75 cents per MMBTUs per month to store LNG [46] and the price of the fuel in North America is $2.50 to $2.77 per MMBTU or <$1 per kg [47]. Conversion efficiencies of LNG storage after the liquid is turned back into a gas is ~45%[61]. The only issue with LNG is the fact that this form of storage once the gas is re-gasified and burned will release CO2 emissions. Far fewer emissions than coal or oil, but emissions, nonetheless.

*Bioenergy*

Biomass, such as crops, can be converted into electricity and power by burning them. A process is similar to fossil fuels. It is possible to also use bacterial decay as another form of converting biomass into usable energy [49]. Conversion of biomass into a gas or liquid fuel is one final way the technology can be used for energy. Biomass can be used to offset the need to burn coal, oil, or other fossil fuels at power plants which helps lower the carbon intensity of generating electricity and reducing CO2 emissions. See image 15 for a figure of a biomass power plant:

Figure 15 – Sumitomo Corporation, Largest wood biomass plant in Japan

Biopower can be used as a long-duration storage alternative to boost the reliability of the electrical grid and increase the flexibility of electrical generation. In the United States, direct combustion is the main way energy is generated from biomass plants. Small scale biomass energy plants have an installation cost of \$3000 to \$4000 per KW, and an LCOE of \$0.08 to \$0.15 per kWh[63]. The cost of delivered wood chips (fuel) would be \$30/ton or <\$1/kg[64]. Efficiencies range between 35% and 85% depending on the conversion technology. See below for a comparison of the LDES technologies originally outlined in figure 1.

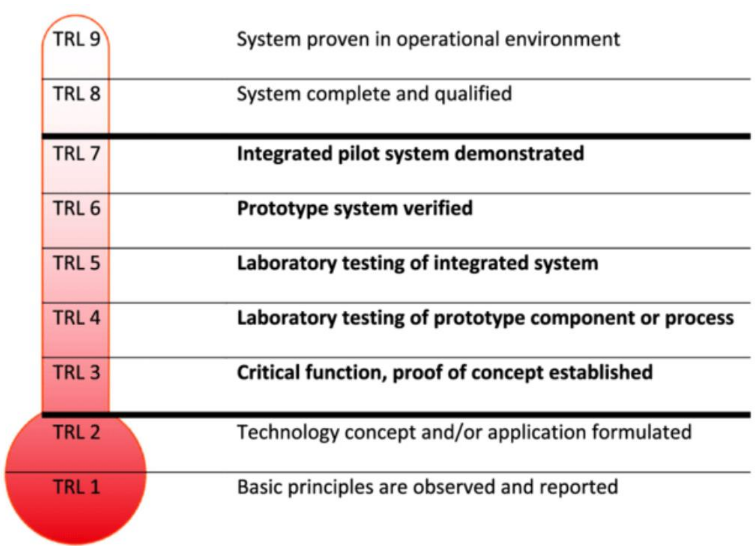
**LDES Technology Comparisons**

Each of the different long-duration energy storage solutions has different pros and cons. When we compare them across multiple dimensions from cost, technology readiness level (TRL), duration, greenhouse gas (GHG) impact, and societal resistance we find that some storage technologies are better suited to tackle the storage challenge than others.

| Technology | Cost ($/kWh) | Cost ($/kg) | TRL | Target Duration | Efficiency | Societal Resistance |
|---|---|---|---|---|---|---|
| Flow Batteries | 600 | N/A | 7[7] | < 1day | 65% to 75% | Little to None |
| Metal-Air | 20 to 100 | N/A | 4-5[56] | < 1 week | 60% to 75% | Little to None |
| Zinc | 60 to 250 | N/A | 5[7] | 2 days | 72%[7] | Little to None |
| Pumped Hydro | 106 to 200[24] | N/A | 8[7] | < 1 day | 80%[7] | High |
| Gravity | 120 to 380 | N/A | 5[21] | < 1 day | 80% to 90%[51] | Low |
| Compressed Air | 119[27] | N/A | 7[7] | < 1 day | 52%[7] | Little to None |
| Liquid Air | 340 to 680 | N/A | 8[52] | < 1 day | 45% to 70% | Little to None |
| Pumped Heat | 100 | N/A | 5 to 7 | ~1 week | 52% to 72% | Little to None |
| Hydrogen | N/A | 2 to 13 | 7 | Months | 65% to 90% | Low |
| LNG | N/A | <1 | 9 | Months | 45% | High |
| Bioenergy | N/A | <1 | 9 | Months | 35% to 85% | High |

Note: For rechargeable storage systems (Flow, Metal-air, Zinc, Hydro, Gravity, Compressed Air, Liquid Air, and Pumped Heat) efficiencies are round trip efficiencies. For fuel type storage systems (bioenergy, hydrogen, and LNG) efficiencies are conversion efficiencies from the fuel source into usable electricity and power.

TRL levels are defined as such:



Many of the storage options above aren't at a suitable TRL level or aren't able to offer multiple days or weeks of storage to deal with the need of seasonal demand changes. Other options are too costly, such as liquid air and others have low-efficiency levels or high society resistance. Of the storage technology options in the northeast that exist, hydrogen seems to be the most promising in its ability to offer extremely long energy storage in the range of weeks and even months. It's able to do this at a competitive cost compared to other storage options and pilot projects have already been demonstrated. The main issue here is societal acceptance. People seem to have a fear of hydrogen and a fear of transporting large amounts of it if it's near them. They have a perception that hydrogen is dangerous [62]. This can be mitigated by having a strong public campaign touting the benefits and the safety of using hydrogen to meet our energy needs [59]. Other promising options include zinc batteries, flow batteries, and pumped heat.

**Possible Policy Suggestions**

To help proliferate all storage technologies in general the following policy and market changes could be helpful if implemented:

- Creation of an LDES storage market with strong incentives that value seasonal storage and carbon offsets
- Subsidies for LDES, that scale down as industry grows
- State and federal incentives, such as tax credits
- Grants and R&D funding
- State or federal mandates requiring utilities to procure their resources from a larger percentage of clean sources

These changes will incentivize the private sector to act, not from fear of being penalized (i.e. carbon taxes), but for the hope of being rewarded. Although carbon taxes may be warranted, there seems to be political resistance to such a policy.

**Conclusion**

Many LDES solutions exist that can work for the Northeast. Hydrogen appears to be best for extremely long energy storage challenges requiring multiple weeks or months of storage, while flow, zinc, and pumped hydro, appear to be best for < 1-day storage. Pumped heat and metal-air batteries are the best medium-duration LDES solution to get about a week of storage. Cost, TRL, and societal blowback tend to be the largest roadblocks for LDES along with not enough renewable energy generation on the grid yet. Policy and market solutions aimed at providing an incentive to build LDES can boost and expedite the rate of LDES solutions proliferating and might do so better than policies that punish businesses for not building LDES products.

**References**


[1] - https://www.energy.gov/articles/secretary-granholm-announces-new-goal-cut-costs-long-duration-energy-storage-90-percent

[2] - https://www.wri.org/research/role-long-duration-energy-storage-deep-decarbonization-policy-considerations

[3] – Interview with Massachusetts Department of Energy Resources

[4] – Interview with First Light Power

[5] - https://flowbatteryforum.com/what-is-a-flow-battery/

[6] - https://www.powermag.com/flow-batteries-energy-storage-option-for-a-variety-of-uses/

[7] - https://www.energy.gov/sites/default/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf

[8] - https://spectrum.ieee.org/what-energy-storage-would-have-to-cost-for-a-renewable-grid

[9] - https://www.energy-storage.news/honeywell-says-flow-battery-can-meet-utility-sectors-core-need-for-long-duration-energy-storage/

[10] - https://formenergy.com/wp-content/uploads/2020/05/Form-Energy_-GREPilotPress-Release.pdf

[11] - https://www.sciencedirect.com/book/9780127473802/intercalation-chemistry

[12] - https://www.powermag.com/zinc-ion-batteries-are-a-scalable-alternative-to-lithium-ion/

[13] - https://cen.acs.org/materials/energy-storage/Zinc-ion-batteries-reach-higher/99/i5

[14] - https://www.rechargenews.com/transition/new-zinc-air-battery-is-cheaper-safer-and-far-longer-lasting-than-lithium-ion/2-1-812068

[15] - https://www.altenergymag.com/story/2020/11/the-zinc-ion-batterys-role-in-the-energy-storage-industry-/34128/

[16] - https://www.greentechmedia.com/articles/read/can-a-novel-zinc-battery-deliver-clean-multi-day-backup-power

[17] - https://www.rechargenews.com/transition/zinc-ion-batteries-up-to-50-cheaper-than-lithium-ion-with-no-raw-materials-concerns/2-1-939768

[18] - https://heindl-energy.com/

[19] - https://www.nsenergybusiness.com/news/company-news/gravitricity-demonstration-project/

[20] - https://www.energy-storage.news/energy-vault-raises-us100m-investment-for-energy-storage-using-massive-cranes/

[21] - https://www.energyvault.com/

[22] - https://www.energy.gov/eere/water/pumped-storage-hydropower

[23]- https://energystorage.org/why-energy-storage/technologies/pumped-hydropower/

[24] - https://www.greentechmedia.com/articles/read/pumped-hydro-moves-to-retain-storage-market-leadership

[25] - https://www.quidnetenergy.com/

[26] - https://energystorage.org/why-energy-storage/technologies/compressed-air-energy-storage-caes/

[27] - https://www.pv-magazine.com/2020/12/23/us-energy-storage-strategy-includes-tech-cost-estimates/

[28] - https://www.utilitydive.com/news/hydrostor-building-up-to-1-gw-compressed-air-storage-californias-long-duration-needs/599460/

[29] - https://newatlas.com/energy/hydrostor-compressed-air-energy-storage/

[30] - https://energystorage.org/why-energy-storage/technologies/liquid-air-energy-storage-laes/

[31] - https://highviewpower.com/plants/

[32] - https://www.energy-storage.news/highview-power-unveils-plan-for-first-500mwh-liquid-air-storage-project-in-latin-america/

[33] - https://www.rechargenews.com/transition/liquid-air-storage-offers-cheapest-route-to-24-hour-wind-and-solar/2-1-635666

[34] - https://www.pv-magazine.com/2021/08/02/a-closer-look-at-liquid-air-energy-storage/

[35] - https://www.sciencedirect.com/science/article/pii/S2666792421000391

[36] - https://energysavingtrust.org.uk/advice/thermal-energy-stores/

[37] - https://energypost.eu/pumped-thermal-electricity-storage-grid-scale-cheap-materials-known-tech-compact-install-anywhere/

[38] - https://www.sandia.gov/ess-ssl/wp-content/uploads/2021/LDES/Ben_Bollinger.pdf

[39] - https://www.fchea.org/in-transition/2019/7/22/unlocking-the-potential-of-hydrogen-energy-storage

[40] - https://energystorage.org/why-energy-storage/technologies/hydrogen-energy-storage/

[41] - https://www.mdpi.com/1996-1073/11/10/2825/htm

[42] - https://www.sandia.gov/ess-ssl/wp-content/uploads/2020/12/ESHB_Ch11_Hydrogen_Headley.pdf

[43] - https://www.globenewswire.com/news-release/2015/03/30/720027/10126785/en/Hydrogenics-Awarded-4-4-Million-in-Projects-From-the-California-Energy-Commission.html

[44] - https://www.energy.gov/fecm/liquefied-natural-gas-lng

[45] - https://www.transtechenergy.com/lng-cryogenic-storage-tanks

[46] - https://www.worldoil.com/news/2019/5/17/tankers-sought-to-store-abundant-lng-as-traders-wait-for-better-prices

[47] - https://www.statista.com/statistics/252984/landed-prices-of-liquefied-natural-gas-in-selected-regions-worldwide/

[48] - https://www.hydrocarbonprocessing.com/magazine/2018/july-2018/bonus-report-lng-technology/liquefaction-technology-selection-for-baseload-lng-plants

[49] - https://www.energy.gov/eere/bioenergy/bioenergy-basics

[50] - https://www.sumitomocorp.com/en/jp/business/case/group/cc-30482

[51] - https://helena.org/projects/energy-vault

[52] - https://www.pv-magazine.com/2021/08/02/a-closer-look-at-liquid-air-energy-storage/

[53] - https://www.sgh2energy.com/economics

[54] - https://www.sciencedirect.com/science/article/pii/S246802571630019X

[55] - https://www.osti.gov/pages/servlets/purl/1373737

[56] – Interview with CEO of Form Energy

[57] - https://www.umsicht.fraunhofer.de/en/projects/iron-air-battery.html#:~:text=A%20new%20type%20of%20iron,500%20full%20charge%2Fdischarge%20cycles.

[58] - https://www.azcentral.com/story/money/business/energy/2020/07/27/aps-battery-explosion-surprise-new-report-findings/5523361002/

[59] – Interview with Engie

[60] - https://www.renewableenergyworld.com/storage/chevron-backs-long-duration-thermal-energy-storage-developer-malta/#gref

[61] - https://www.eia.gov/todayinenergy/detail.php?id=44436#:~:text=The%20technology%20and%20the%20type,into%20net%20generation%20of%20electricity.

[62] - https://www.weforum.org/agenda/2019/04/why-don-t-the-public-see-hydrogen-as-a-safe-energy-source/

[63] - https://www.wbdg.org/resources/biomass-electricity-generation

[64] - https://www.esf.edu/wus/documents/primer_on_wood_biomass_for_energy.pdf