[redacted]
Sleepy Hollow, NY 10591
May 30, 2022

Draft Scoping Plan Comments
NYSERDA
17 Columbia Circle
Albany, NY 12203-6399

Dear NYSERDA:

My comments in this letter discuss how we can have a reliable and sustainable electric grid powered by renewables, without needing to rely on backup energy from fossil fuels and nuclear power.

The main argument against a renewable energy grid put forth by fossil fuel and nuclear proponents is that the wind is not always blowing and the sun is not always shining. Ergo there will be periods, such as extended cold spells, summer heat waves, days of continual rain, when the grid will not be able to provide needed electricity. During these times we need firm dispatchable resources, i.e., natural gas, oil, nuclear energy, to power the grid – or so the argument goes.

I would argue that there are alternatives to these firm dispatchable resources. And in any event even these firm dispatchable resources are of no use when the grid or parts thereof are non-functional due to severe weather events, improperly maintained distribution lines, cyber attacks, or other reasons.

A reliable and sustainable grid powered solely by renewable energy would have the following components:

Increased supply to the grid:

1) Massive development of renewables, especially solar on built environments, along with upgrades to the distribution grid to enable interconnection of renewables
2) Short term energy storage
3) Long-duration energy storage
4) Increased transmission capability from upstate to downstate

Reduced demand on the grid:

5) Standalone EV Charging
6) Demand/response and energy efficiency programs

Backup when the grid is down:

7) Backup generators with green hydrogen fuel cells
8) Solar-powered emergency shelters and microgrids

1) **Massive development of renewables, especially solar on built environments.** The state's current strategy for increasing renewable energy sources is to build large-scale solar and wind farms in upstate New York. I would argue that ***development of small scale solar on built environments is equally important.*** I refer you to the work of Dr. Richard Perez, a researcher at

the University at Albany's Atmospheric Sciences Research Center. Among other topics, his webinar on "Big Solar in New York" [1] identifies built environments in New York state that are suitable for solar installations deployed without functional modification:

- Rooftops (commercial/residential/industrial buildings): 185 sq. miles
- Power lines rights of way: 161 sq. miles
- Gas pipelines rights of way: 21 sq. miles
- Railroads rights of way: 21 sq miles
- Expressways rights of way (center lanes): 12 sq. miles
- Landfills/industrial/mining exclusion zones: 29 sq. miles
- Parking lots: 24 sq. miles

Dr. Perez also discusses locations where solar can be sited with minor functional modifications. In summary, he proposes that 95% of New York's grid can be powered by wind and solar, with the remaining 5% by natural gas. I would point out that he does not mention hydropower, which currently provides 5-10% of the state's electricity. I would also argue that long-duration storage, as discussed below, could also provide some of that remaining 5%.

It is also essential for small-scale solar installations to be connected to the grid at reasonable cost. Plans for some proposed solar installations, such as one in the Anthony Wayne Recreation Area on the Palisades Parkway, have been abandoned because the cost to connect to the grid is prohibitive. Modifications to the distribution grid are essential, and the costs should be borne, at least in part, by New York state funds.

2) **Short-term energy storage.** Development of this component, in the form of lithium-ion batteries, is well under way in New York state. Lithium-ion batteries hold a charge for 4-8 hours and can provide electricity overnight or for short time durations.

3) **Long-duration energy storage.** There is hardly any mention of long-duration energy storage in the Draft Scoping Plan – and there should be. Long-duration storage can supply electricity to the grid for days or weeks. ***Instead of looking at alternative fuels like hydrogen and RNG to power the grid, we should be going all out on long-duration storage.*** It will be hard and it will be expensive, but it is essential. And although lithium-ion batteries currently dominate the energy storage market, they are best suited for short-term storage, and both their production and disposal have significant environmental concerns.

   Along with these comments I am submitting a survey paper on various forms of long-duration energy storage. In the paper I draw four conclusions:

   - ***There is no one perfect solution.*** Some of the more advanced concepts have many advantages but have not been yet fully proven or commercialized.
   - ***Long-duration storage should be an essential part of large-scale wind and solar installations.*** Wind and solar power that needs to be curtailed must have a place to go, namely, long-duration storage. Provision for on-site storage should be part of these large-scale projects.
   - ***CLCPA should be modified to specify the amount of long-duration storage that is needed.*** CLCPA specifies 3,000 MW of energy storage by 2030, but does not specifically address long-duration storage. Battery storage by itself is not sufficient.
   - ***There should be an incentive and financing program for long-duration storage.*** In addition to bills to subsidize hydrogen (e.g., S3281/A3788), there should be comparable bills to subsidize long-duration storage.

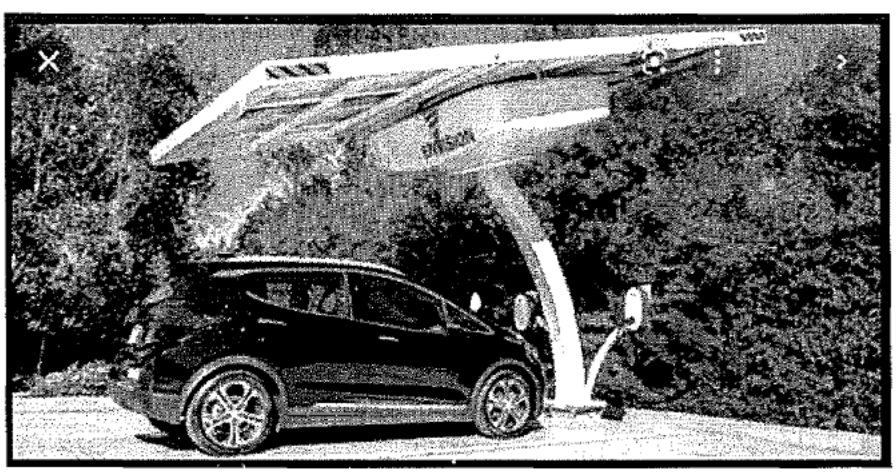
4) **Increased transmission capability from upstate to downstate.** It is well known that electric generation in upstate New York (Zones A-F) is much greater than demand and, conversely, electric generation in downstate (Zones G-J) is far less than demand.. This imbalance has been addressed in the past by transmitting upstate-generated power to downstate. In past years wind curtailment was necessary because of transmission bottlenecks which limited the amount of electricity that could be transferred.

But since 2012 transmission upgrade projects have been initiated that would allow more upstate-generated power to flow to downstate. [2,3,4] These are shown in Table 1.

Table 1. Transmission Upgrades in Progress and Completed

Name	Authorizing Proceeding	Additional MW of Capacity Provided	Anticipated In-Service Date
Segment A (Central East) Interface	PSC Case 12-T-0502	350	December 2023
Segment B (UPNY/SENY) Interface	PSC Case 12-T-0502	900	December 2023
New York Energy Solution (NYES)	NYISO AC Proceeding (FERC Order 1000)		2023
Completed Projects			
Ramapo to Rock Tavern Transmission Line	PSC Case 12-E-0503		2016
Fraser to Coopers Corners Reconductoring (MSSC)	PSC Case 12-E-0503		2016
Staten Island Unbottling	PSC Case 12-E-0503		2016

5) **Standalone EV charging.** ***Standalone solar-powered EV charging stations should be deployed on a large scale.*** These stations are manufactured by several companies, including Envision Solar and EV ARC. The units are transportable, off-grid, and require no construction, permitting, or electrical work.



A Representative Standalone EV Charging Station

6) **Demand/Response and Energy Efficiency programs.** Demand/response programs such as those ordered by the PSC in 2012 are intended to reduce the load on the grid during periods of peak demand so that blackouts can be avoided without the need for standby generation.

In November 30, 2012, the PSC directed Con Edison to develop a contingency plan for the potential closure of Indian Point (Case 12-E-0503). The order specified that the plan should consider, among other things, distributed renewable generation, demand response, and combined heat and power projects. Con Ed's plan called for 100 MW of permanent demand reduction through energy efficiency and demand reduction (EE/DR) and an additional 25 MW through combined heat and power.

Through Quarter Two of 2020, achieved EE/DR and CHP projects account for approximately 130.3 MW; the program therefore has achieved 5.3 MW in excess of the 125 MW program goal. The program has been fully implemented with the 130.3 MW total completion.

Other New York electric utilities in addition to Con Edison have implemented demand/response programs. National Grid has implemented a demand/response program for its commercial and industrial customers that allows customers to select winter or summer periods of high demand for reducing their energy usage. Central Hudson has two different programs: one exclusively for customers located in specific energy constrained areas, and one for customers anywhere in the Central Hudson service territory.

Demand/response programs need to be implemented widely across the state.

7) **Backup generators with green hydrogen fuel cells.** Generators using hydrogen fuel cells rather than gasoline or diesel are currently manufactured by companies such as GenSure and Altergy. These generators will be necessary for institutions such as hospitals that must have backup power in situations when the grid goes down. The essential point here is that the hydrogen fuel cells must be produced using green hydrogen – hydrogen generated by the steam methane reforming process would defeat the goal of reducing emissions.

It would be necessary to ensure that an adequate supply of green hydrogen fuel cells is available to operate such generators.

8) **Solar-powered emergency shelters and microgrids.** Emergency shelters provide power for essential services such as phone charging, EV charging, emergency housing and meals when the grid is down, whether due to severe weather or other conditions. In 2018, for example, SUNY New Paltz completed installation of six separate solar PV arrays (five roof-mounted and two ground-mounted systems) totaling 278 KW, along with a battery storage unit [5,6]. The battery storage unit will be used at times of high electric demand and during emergencies or power outages to support the college's designated emergency shelter for the campus and community at the college's Elting Gymnasium.

New York should provide for establishing similar emergency shelters throughout the state. Local libraries, gymnasiums of local schools, and other easily accessible public buildings are ideal sites for such shelters.

A microgrid is a resiliency zone – it is essentially a smaller grid that can operate independently, disconnecting from the larger grid during outages. In 2021 Green Mountain Power (GMP) broke ground on a cutting-edge utility microgrid in Panton, Vermon, which will use an existing 4.9-megawatt solar facility with utility-scale batteries already up and running in the town. [7,8] This project is unique because GMP is believed to be the first utility in the country to island a distribution circuit using inverter-based sources with no reliance on fossil fuel generation backup.

In the event of storm damage or a prolonged grid outage, the Panton microgrid will enable backup power from the batteries and solar panels to flow to a network of customers served by the traditional grid. The concept is called "islanding," and it creates backup power that can work independently from the larger electric system when needed. In Panton, the tracker solar panels follow the Sun and can stretch the battery backup power for days, if necessary.

This will keep the power on during outages for about 50 customers in Panton to start, with the planned possible expansion of the coverage area to include another 900 customers on that circuit. The batteries are also used to lower costs for all GMP customers during peak energy times.

New York should emulate Vermont's example and establish utility microgrids operating on solar power.

To summarize, New York's electric grid can be reliable and sustainable and powered solely by renewable energy if it has the following characteristics:

1) Massive development of renewables, especially solar on built environments, along with upgrades to the distribution grid to enable interconnection of renewables
2) Short term energy storage
3) Long-duration energy storage
4) Increased transmission capability from upstate to downstate
5) Standalone EV Charging
6) Demand/response and energy efficiency programs
7) Backup generators with green hydrogen fuel cells
8) Solar-powered emergency shelters and microgrids

I strongly believe that an electric grid powered by renewable energy is technically possible. Unfortunately I'm not sure that it's politically possible – political in this context meaning the powerful efforts of fossil fuel interests, cryptocurrency miners, and labor unions (among others) to maintain the status quo and continue with current ways of doing things. Without a doubt change is hard. I see overcoming this resistance to change as the major challenge of our task to reduce greenhouse gas emissions.

Thank you for your consideration of my comments.

Laura Burkhardt

Laura Burkhardt
[redacted]

References

[1] USES Webinar: Big Solar in NY webinar 10.15.2020 - YouTube

[2] Order Addressing Public Policy Transmission Need for AC Transmission Upgrades; 1/24/2017.

[3] PRESS RELEASE | NYISO Board Selects Transmission Projects to Meet Public Policy Need - NYISO, April 8, 2019

[4] NY Transco Project Profiles_DRAFT_112520

[5] SUNY New Paltz | Sustainability | Renewable Energy

[6] SUNY New Paltz unveils new, state-of-the-art solar energy system – SUNY New Paltz News

[7] GMP Announces Pioneering Microgrid in Panton, Vt., Designed to Keep the Lights on with Clean, Local Power During Outages - Green Mountain Power

[8] Vermont Is Remaking its Power Grid to Fight Climate Change | Time

Long Duration Energy Storage Technologies: A Survey

Laura Burkhardt
Rev. 2 – June 18, 2021

1. Introduction

As we proceed slowly but surely towards an electric grid that's powered solely by renewables, dispatchable solar, uncurtailed wind, and other forms of clean energy are requiring longer and longer durations of storage to integrate them to the grid. Lithium ion batteries will be a part of our grid for many years to come, but their storage typically lasts for only 4 hours. We will need storage that can provide electricity to the grid for many hours or days and even weeks.

There is a growing list of contenders, with diverse technologies and at different stages of commercialization. This paper will first describe existing, well-known technologies and then move on to more recent and less well-tested developments.

2. Definition of Terms [1,2]

This section defines the terms that are used when discussing and comparing storage technologies.

Power and Energy – **Power**, usually measured in kilowatts (kW) or megawatts (MW), is the load that a storage system or generator can serve at any instant in time. It is important to distinguish this from **energy**, measured in kilowatt-hours (kWh) or megawatt-hours (MWh), which is the amount of power that can flow over time.

Capacity – This term means something different for a power plant vs. a storage system. The capacity of a power plant (**power capacity**) refers to the amount of power that it can generate (MW). But the capacity of a storage system (**energy capacity**) refers to the volume of energy it can store (MWh).

Storage Duration. **Storage duration** is the amount of time storage can discharge at its power capacity before depleting its energy capacity. For example, a battery with 1 MW of power capacity and 4 MWh of usable energy capacity will have a storage duration of four hours.

Storage Duration (hours) = Energy Capacity (MWh) / Power Capacity (MW)

This concept is also referred to as **discharge time**, defined as the amount of time a storage technology can maintain its output. In Table 1 below, the term Discharge Time is used; values for power and discharge time are given but not the values for energy capacity.

Depth of Discharge - Depth of discharge is the percentage of capacity discharged. Deep discharges (>50% DOD) shorten the lives of some batteries, while others operate best this way.

Cycle life/lifetime is the amount of time or cycles a battery storage system can provide regular charging and discharging before failure or significant degradation.

Energy Density is the amount of energy stored in a given system or region of space per unit of volume. High energy density is better than low energy density because it requires less space to store or hold a given amount of energy.

Levelized Cost of Storage (LCOS). This is the cost of kWh or MWh of electricity discharged from a storage device when accounting for all costs incurred and energy produced throughout the lifetime of the device.

Adiabatic/Isothermal [2a, 2b]. These concepts are used in more advanced forms of compressed air energy storage (CAES) as ways of overcoming some of the limitations of the original systems.

- An **adiabatic** process is a thermodynamic change whereby no heat is exchanged between a system and its surroundings. In an advanced CAES implementation the heat generated by the compression process is captured and fed back into the compressed gas during the expansion phase, thus improving the system's round trip efficiency and eliminating the need to reheat with natural gas.
- An **isothermal** process is one in which the temperature of the system remains constant. Isothermal CAES requires the heat to be removed continuously from the air during the compression cycle and added continuously during expansion. This is technologically challenging, and there are currently no commercial isothermal CAES implementations.

3. Comparison of the Technologies

Table 1 summarizes the characteristics of the technologies that will be discussed in this document. Lithium ion batteries are included for comparison purposes only, as these batteries are currently not considered practical for long-duration storage.

Table 1. Comparison of Energy Storage Technologies

	Max Power Rating (MW)	Discharge Time	Max *Cycles* or Lifetime	Energy Density (watt-hour per liter)	Round Trip Efficiency	Levelized Cost of Storage (LCOS)	Ref	Company
Li-ion Battery	100	1 min – 8 hrs	*1,000 – 10,000*	200 - 400	85 – 95%	$285 - 518/MWh	3	
Pumped Hydro	3,000	4 – 16 hrs	30 – 60 years	0.2 - 2	70 – 85%	$152 - 198/MWh	3	
Compressed Air	1,000	2 – 30 hrs	20 – 40 years	2 - 6	40 – 70%	$0.12/kWh ($120/MWh)	3	
Hydrogen	100	mins - week	5 – 30 years	600 (at 200bar)	25 – 33%[1]		3	
Liquid-Air Storage (LAES)		4 hrs – 4 weeks			<50%	$100/MWh today $50/MWh in 10 yrs		Highview Power
Thermal Energy Storage – Siemens Gamesa		2 Weeks (GWh)			40 – 50%			Siemens Gamesa
Thermal Energy Storage – Stiesdal Storage		12 hrs – 7 days				$50/MWh	6	Stiesdal Storage Technologies
Aqueous Air Battery		150 hrs			50%		7	Form Energy
Advanced Compressed Air (A-CAES)								Hydrostor
Stacked Blocks	80		30+ years		85-90%	$171 – 310/MWh	8,9	Energy Vault

[1]Reference [1] gives the round-trip efficiency of hydrogen as 25-45%. But when hydrogen is used to generate electricity via a modified natural-gas generation plant its efficiency is less. The Fourth Supplement to Danskammer's Application to build a new gas-fired plant states that 5 TWh of curtailed wind used for electrolysis would generate an amount of hydrogen that would produce 1.7 TWh of electricity when burned in their turbines (based on their proprietary information). Using readily available data the amount of hydrogen produced by 5 TWh via electrolysis would generate 1.2 TWh of electricity when burned in a turbine.

Table 1. Comparison of Energy Storage Technologies (cont.)

	Max Power Rating (MW)	Discharge Time	Max *Cycles* or Lifetime	Energy Density (watt-hour per liter)	Round Trip Efficiency	Levelized Cost of Storage (LCOS)	Ref	Company
Mountain Gravity Energy Storage		150 hrs			50%	$50 – 100/MWh	29	International Institute for Applied Systems Analysis
Advanced Rail Energy Storage			40+ years					Advanced Rail Energy Storage
Small Slope Pumped Storage Hydropower	10 – 50 MW	2-10 hrs						RheEnergise
Pumped Storage Hydropower using Submersible Pump Turbine								Obermeyer Hydro, Inc.

4. Details About Each Technology

- **Lithium Ion Batteries**

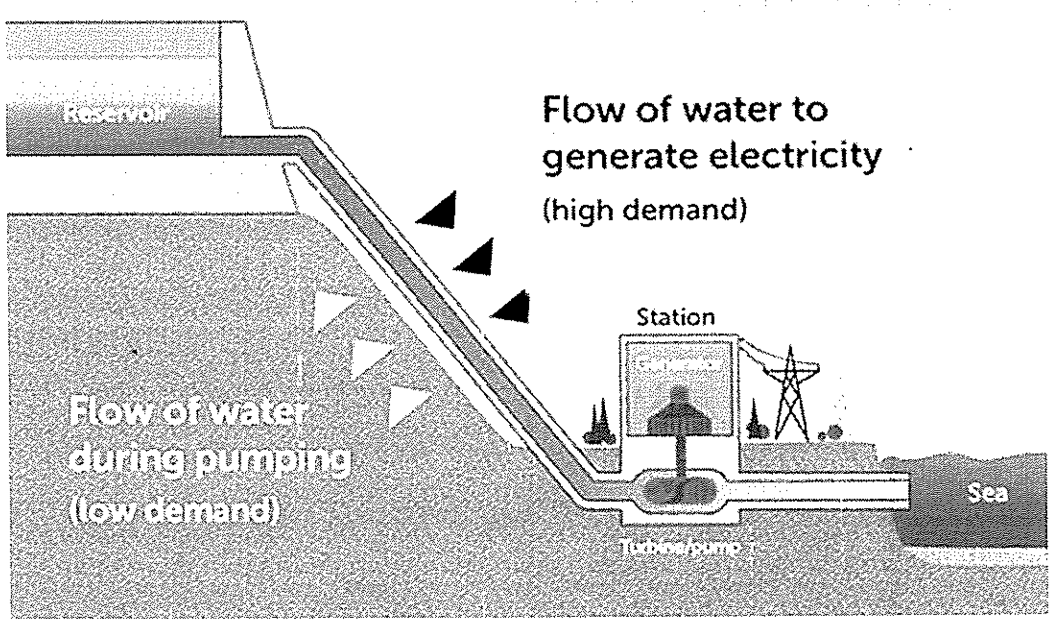
  Rechargeable batteries are generally considered to be insufficient for long-term power. Lithium-ion batteries currently dominate the energy storage market, but they are better suited for short-term storage because the charge they hold dissipates over time. Storing sufficient energy for months or years would require many batteries, which is too expensive to be a feasible option. [28]

  For grid-level power, lithium-ion batteries present a long list of shortcomings: [4]

  - Short-term storage: Most battery-based solutions store energy from one to four hours. Longer-lasting solutions (12+ hours) are not cost-effective.
  - Limited battery life: Batteries last for a finite number of recharge cycles, and their life is shorter in cold weather use.
  - Overheating risk: The risks are seen when operating temperatures are high, and when batteries are charged in freezing temperatures.
  - Environmental concerns of lithium: Production of lithium batteries is energy intense with a high carbon footprint, and the disposal of such batteries is an environmental concern. Lithium at a large scale is associated with resource depletion, global warming, ecological toxicity, and human health impacts.

- **Pumped Hydro** [10]

  Pumped hydro physically moves water from a low to a high reservoir. The water descends, when needed, to generate electricity. This is a well-known and utilized concept and still provides some 95 percent of U.S. grid storage, according to the U.S. Department of Energy.



Notional Diagram of Pumped Hydro

Strengths:

- Once built, these systems boast a very low cost of storage.
- They hold massive amounts of energy compared to even the world's biggest battery.

Weaknesses.

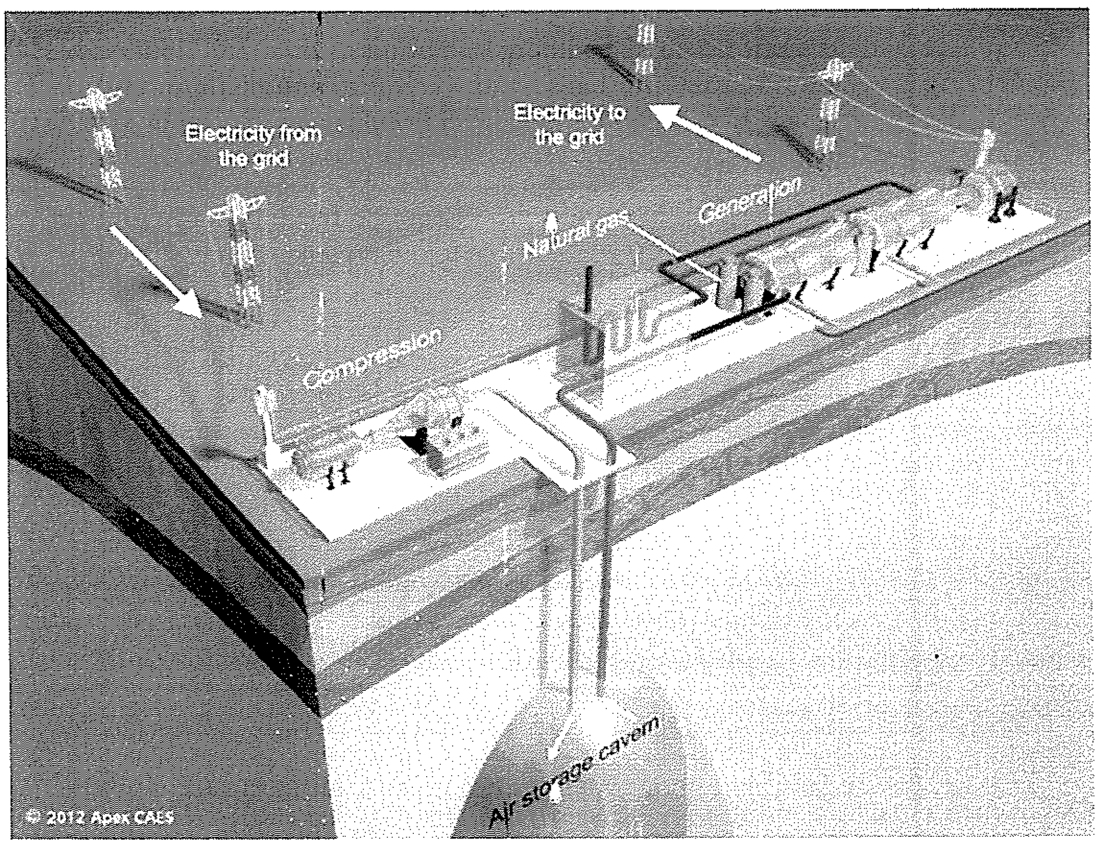
- These systems require mountains and reservoirs.
- It is extremely difficult to build new pumped-hydro storage plants, due to the permitting implications of large water-based infrastructure and recent difficulty in executing massive construction projects in general.

Examples:

- Blenheim-Gilboa Pumped Storage Power Station in upstate NY. This facility has a capacity of 1,134 MW and became operational in 1973.

- **Compressed Air Energy Storage** [11]

  Compressed-air energy storage (CAES) plants operate by using motors to drive compressors, which compress air to be stored in suitable storage vessels. The energy stored in the compressed air can be released to drive an expander, which in turn drives a generator to produce electricity. A typical CAES system is shown in the following figure.



Compressed Air Energy Storage System by Apex *[12]*

Strengths:

- o Compared with other energy storage technologies, CAES plants have a very large power rating and storage capacity, low self-discharge, and a long lifetime.

Weaknesses.

- o Conventional CAES plants have a relatively low roundtrip efficiency. However, research studies into more advanced CAES concepts, such as adiabatic and isothermal CAES, seek to improve this.
- o They require large areas for storage. The examples below utilize large underground salt caverns as storage vessels. Such areas may not be readily available in NYS.
- o Fossil fuel is used in the re-heating phase of the system.

Examples:

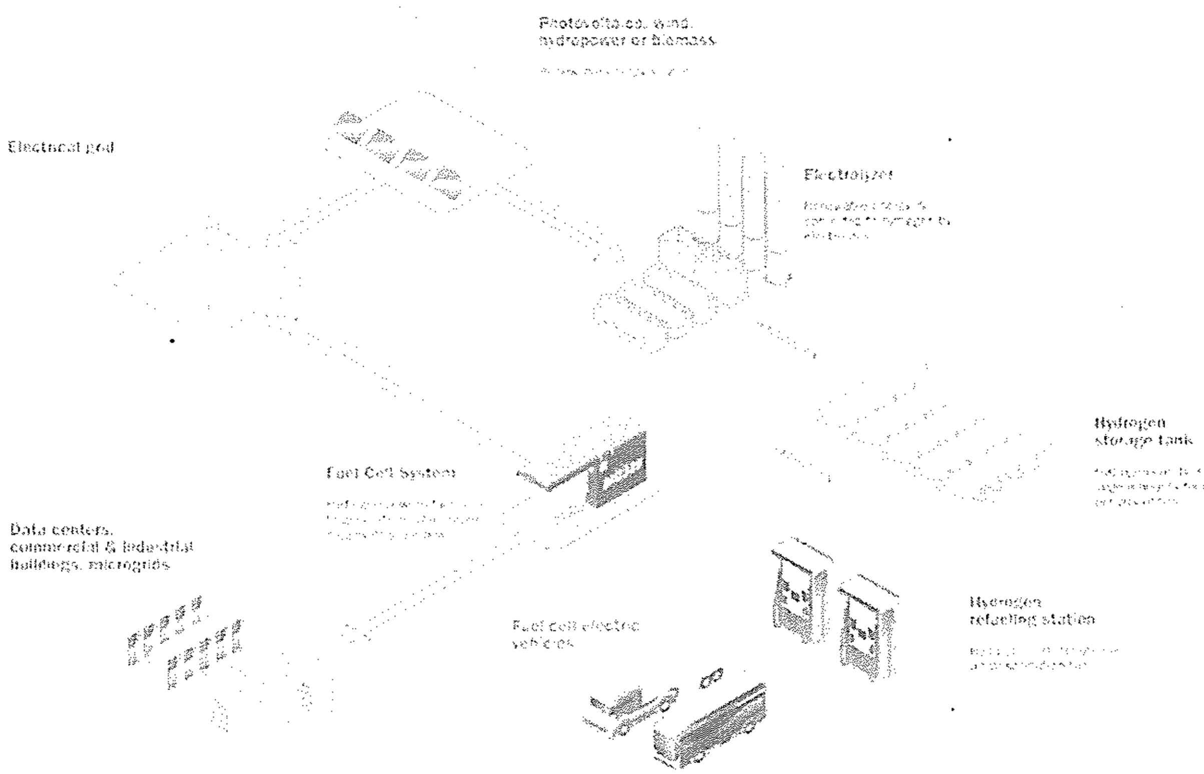
- o A plant in Huntorf, Germany, with a rated generation capacity of 290 MW. Its storage area is 532,000 cubic meters (431.3 acre feet).
- o A plant in McIntosh, Alabama, USA, with a generation capacity of 110 MW. Its storage area is 270,000 cubic meters (218.9 acre feet).

- **Hydrogen** [4, 5, 13]

Hydrogen energy storage is a form of chemical energy storage in which electrical power is used to produce hydrogen by the electrolysis of water. The hydrogen must then be stored, potentially in underground caverns for large-scale energy storage, although steel containers can be used for smaller scale storage. The energy is released by using the hydrogen as fuel in a combustion engine or a fuel cell. Hydrogen can be used as fuel for piston engines, gas turbines, or hydrogen fuel cells, the latter offering the best efficiency. Hydrogen energy storage is of interest because the gas forms the basis for the hydrogen economy in which it replaces fossil fuel in many combustion applications.

The widespread use of hydrogen in the global economy faces two important challenges: (1) the production of hydrogen from low-carbon sources is costly, and (2) the development of the hydrogen infrastructure is slow and holding back widespread adoption. Cost of building hydrogen distribution infrastructure and transport over large distances are major economic barriers to the implementation of hydrogen-based technologies. Additionally, large-scale central production will depend on market volumes to evolve in order to compensate for the capital expenditures of building up capacity. In future, carbon-neutral hydrogen could be produced by water electrolysis using electricity based on renewables. [43]

The figure below shows the flow of hydrogen from production to storage to end use.



Hydrogen from Production to Storage to End Use [4]

Strengths

- Hydrogen can replace fossil fuel in many combustion applications where electrification may not be practical; it can be used as fuel for fuel cell cars or as feedstock for the chemical and petrochemical industry.
- Potential for interseasonal storage

Weaknesses

- Very low round trip efficiency
- Need for underground caverns as storage. These would need to be co-located with large wind and solar installations in order to capture the curtailed wind or solar.
- Need to develop substantial hydrogen infrastructure.

Examples

- 5 MW PEM electrolyzer by Cummins for Douglas County Public Utility District in Washington state. This electrolyzer will be dedicated to producing hydrogen from renewable energy. Expected to be operational in 2021.
- 20 MW PEM electrolysis plant by Cummins in Becancour, Canada for Air Liquide. Planned to be operational sometime in 2021.
- 1.2 MW PEM electrolysis plant by Cummins established in Denmark in 2018.

- **Liquid-Air Energy Storage** [14, 15]

  Highview Power is a UK startup developing an energy storage system that uses liquid-air technology (LAES). In this technology electricity is used to cool air down to -196°C, shrinking its volume by a factor of 700. This frozen liquid air is then stored in low-pressure vacuum-insulated steel tanks — the kind that house liquefied natural gas. When this cryogenically frozen air is exposed to ambient temperatures, it turns back into a gas and rapidly expands, with the rush of air from this 700-fold expansion directly driving an electricity-generating turbine.

  Strengths

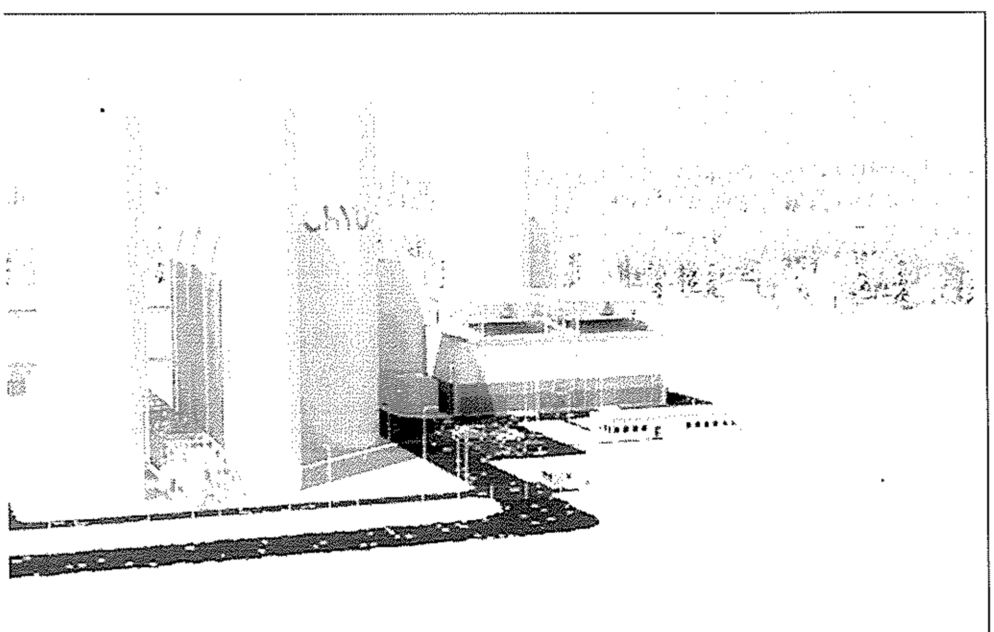
  - This is a long-duration energy storage solution available today that is locatable and can offer multiple gigawatt-hours of storage (i.e., weeks' worth of storage, not just hours or days).
  - Relies on low-risk, proven technology, generates zero emissions, has zero water impact.
  - Can be delivered at a cost of approximately half the current cost of traditional lithium-ion batteries.

  Weaknesses *[22]*

  - Low round trip efficiency, probably under 50%, which is much lower than that of batteries and pumped hydro.
  - LAES is only practical on a relatively large scale.

  Examples

  - U.S. project (50 MW, 400 MWh) in northern Vermont by Highview Power, construction begun 2021
  - U.K. project (50 MW), in Carrington, Northern England, by Highview Power, construction begun 2021
  - Pilsworth Grid Scale Demonstrator Plant, Bury, Greater Manchester, England.

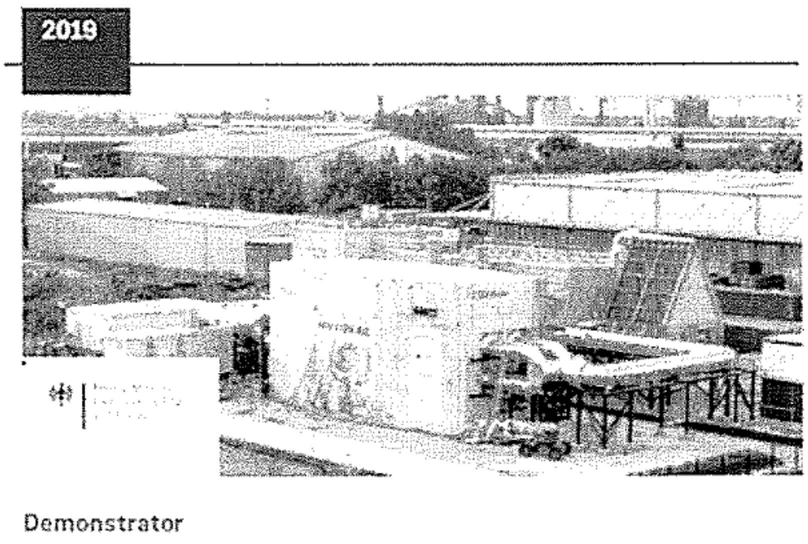


Highview Plant in Northern Vermont

- **Thermal Energy Storage by Siemens Gamesa** [16, 17, 17a]

  In a thermal energy storage (TES) system, energy is stored as heat in some form of medium for future use. There are three main types of TES systems: sensible heat storage, latent energy storage, and thermal-chemical storage. Compared to the other options, *sensible heat storage* is relatively inexpensive and much less complicated; it is also the only option to have significant commercial availability in the power sector. Latent energy storage and thermal-chemical storage systems are expensive and as of now are largely experimental.

  In a sensible heat TES system, a liquid or solid storage medium—such as water, molten salts, sand, or rocks—is heated or cooled to store energy. One such system has been developed by Siemens Gamesa, and construction of a pilot plant in Hamburg, Germany, is underway.



Demonstrator with 30 MWh storage capacity and 5.4 MW resistive heater in Hamburg

This plant would convert electrical energy into hot air using a resistance heater and a blower to heat about 1,000 tonnes of volcanic rock to 750°C. When required, the facility would convert the stored thermal energy back into electricity using a steam turbine. Due to efficient insulation, the heat can be stored for a week or longer — at a fraction of the costs of battery storage. Siemens Gamesa says the pilot plant can store up to 130 MWh for a week.

Strengths [18]

- The time required to design and build a TES facility is shortened because the system relies on conventional technology and uses components that are already widely used in the power and processing industries – such as turbines, compressors, heat exchangers, and electrical generators.
- All of the options for medium (the substance that absorbs the heat in the tank) are environmentally friendly – chemical and toxin-free.
- The medium that fills the storage tank consists of materials that are abundant and inexpensive – such as molten salts, water, or gravel.
- A facility can be installed anywhere in the world, regardless of geography.
- It can be scaled up or down to meet the location's grid storage needs.

- The technology can store more energy in a given volume (has a higher energy density) than pumped hydro dams.
- Uses off-the-shelf equipment that does not degrade in any way – unlike lithium-ion batteries. The components have a long lifetime – they last for decades before needing to be replaced.

Weaknesses

- Technology not yet completely proven or commercialized.

Examples

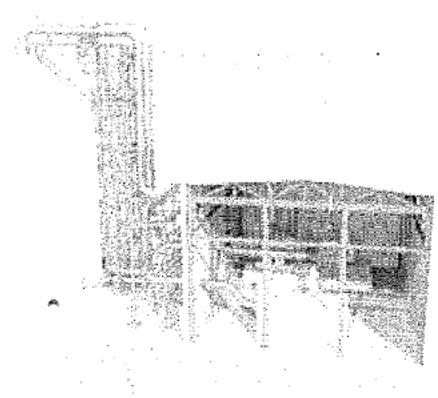
- Siemens Gamesa's first commercial projects of up to 500 MWh in 2022

- **Thermal Energy Storage by Stiesdal Storage** [19]

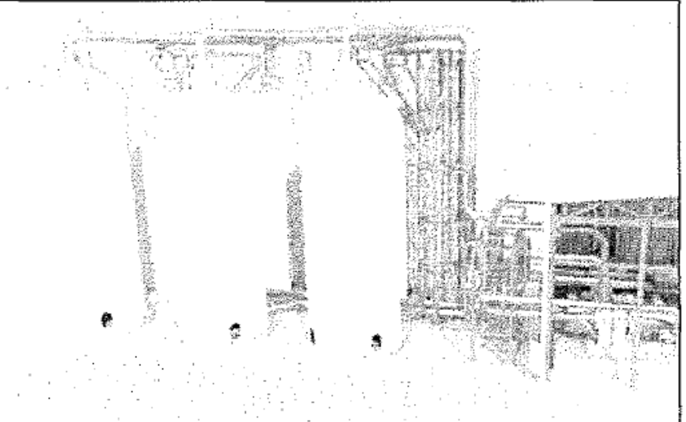
The GridScale energy storage system by Stiesdal Storage Technologies is a pumped thermal energy storage system that uses crushed basalt rock (which is abundant and low-cost) as a storage medium. The technology heats up pea-sized crushed stones in insulated steel tanks using an innovative pump-based system and releases the stored energy via a turbine to produce electricity. It has undergone tests at the Technical University of Denmark (DTU), but will now be trialled at a solar array in the Zealand region on the Baltic Sea, as well being incorporated in a Danish Energy Agency 'GridScale' project.

The system's main components are a turboexpander unit with pre-pressure compressor, controls etc., a filter unit with air filters and manifolds, and two rows of standardized storage reservoirs. The storage duration is adjusted with the number of storage tanks. Power rating is adjusted with the number of parallel units.

The GridScale range covers both the 12-18 h duration required for day-to-day smoothing of solar PV, and the 3 to 7 days duration required for smoothing of wind power over gaps caused by low wind periods..



The GridScale energy storage plant, consisting of an adjustable number of storage tanks and the GridScale-specific charge-discharge system.



GridScale is built for modular adaptation to local demands. The storage duration is adjusted with the number of storage tanks.

Strengths

- A facility can be installed anywhere in the world, regardless of geography.
- It can be scaled up or down to meet the location's grid storage needs.
- The medium that fills the storage tank (crushed basalt rock) is abundant and inexpensive.
- The GridScale range covers both the 12-18 h duration required for day-to-day smoothing of solar PV, and the 3 to 7 days duration required for smoothing of wind power over gaps caused by low wind periods..
- Stone can store large volumes of energy in a relatively small space, and it can withstand innumerable rounds of charging and discharging of the storage.
- The facilities can be placed at solar farms and offshore wind farms, at substations and industrial facilities, and perhaps on the future wind energy islands.

Weaknesses

- Technology not yet completely proven or commercialized

Examples

- Trial project solar array in the Zealand region on the Baltic Sea (April 2021)
- Trial project for Danish Energy Agency

- **Aqueous Air Storage** [20, 21]

Last year an agreement was announced between Form Energy, a long-duration energy storage startup funded by Bill Gates' Breakthrough Energy Ventures and other investors, and Green River Energy in Minnesota for the installation of a 1 MW/150 MWh "aqueous air battery" to be installed and operational in 2023. Unfortunately not much is known about Form Energy's product. Press releases say only that it "leverages some of the safest, cheapest, most abundant materials on the planet". In a 2019 interview a professor of materials science working at the company hinted about the chemistry of the new batteries: "We're looking for batteries that can use either metals or other elements that are much lower cost [compared to lithium, nickel, cobalt, iron, manganese, all of which are used in lithium-ion batteries], and an example of that would be sulfur." The implication is that this new battery system can be fueled by sulphur and water.

A research paper published in 2017 describes an "air-breathing aqueous sulfur flow battery" that can provide 100+ hours of energy storage. [40]

Strengths

- Cheaper than lithium-ion batteries
- Does not require metals and elements that have high environmental impacts, i.e., resource depletion, global warming, ecological toxicity, and human health impacts.

Weaknesses

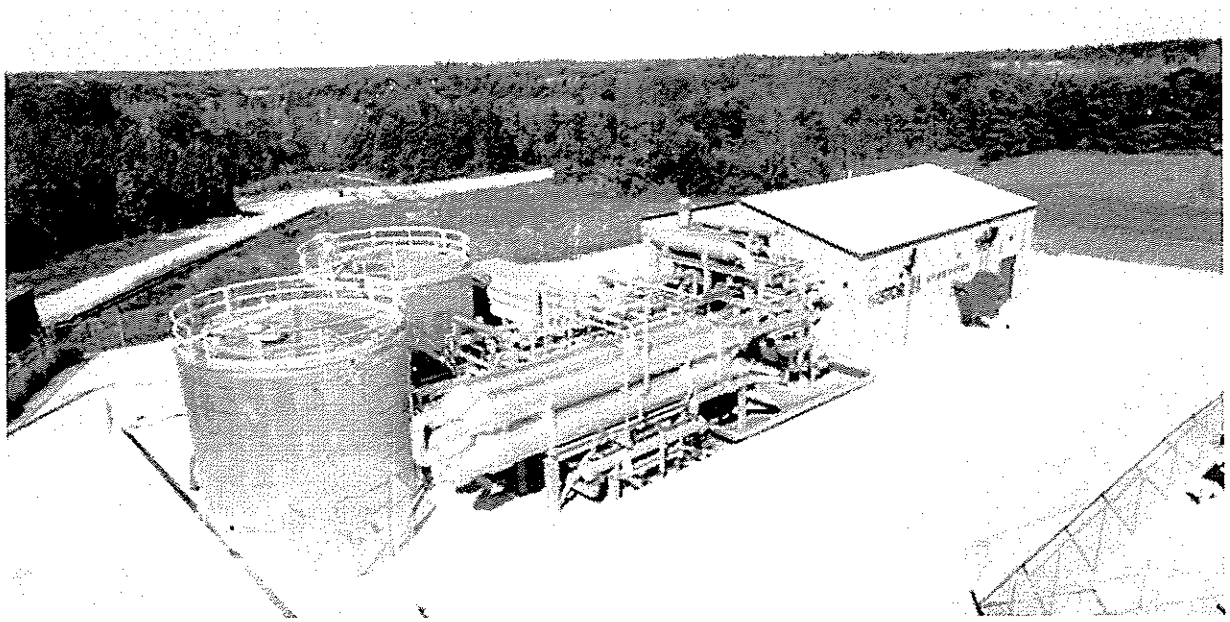
- Power output is low.

Examples

- Form Energy's first commercial project is a 1 MW, grid-connected storage system capable of delivering its rated power continuously for 150 hours with Minnesota-based utility Great River Energy. [30] The system is expected to be deployed before 2023.

- **Advanced CAES** [22, 23]

  Advanced Compressed Air Energy Storage (A-CAES) is a technology developed by Hydrostor, a company based in Toronto, Canada. In this technology there are 4 steps. (1) Renewable energy is used to run a compressor and produce heated compressed air. (2) Heat is extracted from the air stream and stored inside a proprietary thermal store, preserving the energy for use later in the cycle. (3) The compressed air is stored in a purpose-built cavern where hydrostatic compensation is used to maintain the system at a constant pressure during operation. (4) Hydrostatic pressure forces air to the surface where it is recombined with the stored heat and expanded through a turbine to generate electricity on demand



Strengths

- Lowest installed cost per kWh for large-scale, long-duration energy storage (100+ MW)
- 50+ year system life, with no replacements required and nearly unlimited cycling
- Low operating costs, and increased efficiency over traditional CAES systems
- Proprietary purpose-built air caverns allow for flexible project siting
- No toxic material, contaminants, or thermal impacts on environment; suitable for urban settings
- Uses well-proven mechanical equipment from Tier 1 OEM suppliers and proven construction techniques
- Adiabatic thermal storage system uses no fossil fuels and results in no emissions

Weaknesses

- Technology not yet fully commercialized.

Examples

- o Goderich A-CAES Facility in Goderich, Ontario, Canada is the world's first commercially contracted Advanced-CAES facility.
- o Toronto Island Demonstration Facility developed in 2015 with utility host Toronto Hydro. This is the world's first grid-connected adiabatic CAES facility.
- o 13 projects by Hydrostor in the pipeline in US, Canada and Australia.

- **Stacked Blocks** [24, 25, 26, 27]

The stacked block storage developed by Energy Vault is an electricity storage battery consisting of blocks of concrete that weigh 35 tons each and a six-arm crane with a novel design. These "bricks" are stacked one on top of the other in the shape of a tower, like pieces of Lego, to store up power when there is surplus production of electricity from wind turbines and solar panels. The bricks are unloaded again, using the force of gravity to produce electricity, when other power sources are absent. The loading and unloading operations are controlled by a software program which is able to adjust for any swaying of the blocks in high winds.

The battery is based on principles that have already been applied for decades at hydro power stations using a pump system which exploits the altitude difference between two reservoirs. This solution by Energy Vault replaces the water with custom made composite blocks which are made using industrial waste materials, including materials diverted from landfills.

This system is modular and flexible; plant capability ranges from 20-35-80 MWh of storage capacity and a 4-8MW discharge of continuous power for 8-16 hours.

Strengths

- o Round-trip efficiency of 85%
- o A plant can operate for 30 years with little maintenance and almost no fade in capacity.
- o The concrete blocks are constructed with waste materials.

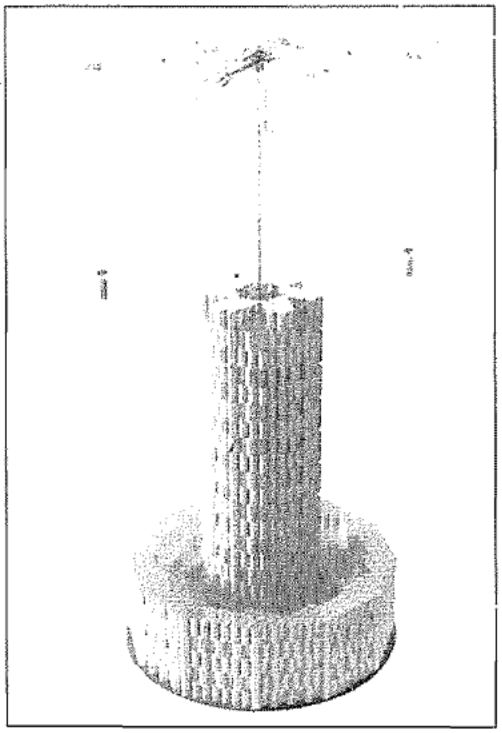
Weaknesses

- o Energy Vault's concrete blocks will have to be built on-site, and each 35 MWh system would need a circular piece of land about 100 meters (300 feet, i.e., the size of a football field) in diameter. Batteries need a fraction of that space to store the same amount of energy. But there's a niche for such plants in places that have abundant access to land and building material.

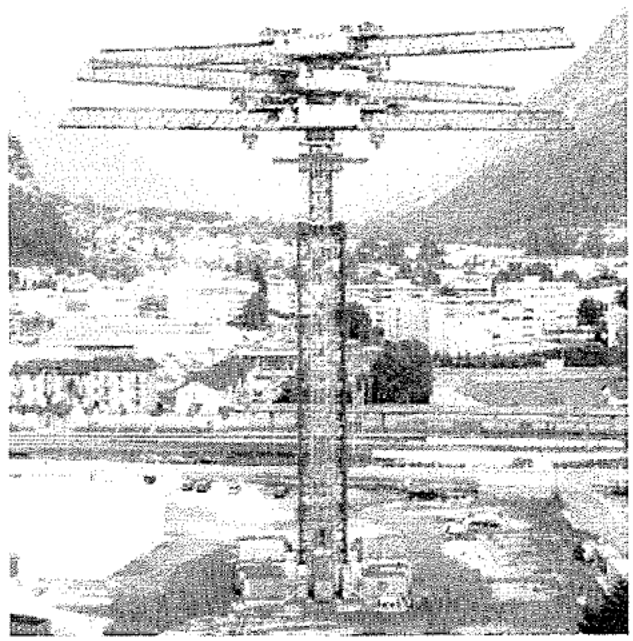
- o A number of shortcomings are described in [27]. They include the carbon footprint from producing the steel and concrete necessary to build the plant, the effect of wind on the crane lifting the blocks, and other weaknesses of the system.

Examples:

- o Commercial Demonstration Unit, Ticino, Switzerland
- o Tata Power 35 MW, somewhere in Italy, operational by 2019. No indications that it is up and running yet.



Notional Diagram of Stacked Blocks



Commercial Demonstration Unit, Switzerland [24]

- **Mountain Gravity Energy Storage [28, 29, 30]**

Mountain Gravity Energy Storage (MGES) is a gravity-based concept, similar to pumped hydro and stacked blocks. This system is proposed by Julian Hunt, an engineering scientist at the International Institute for Applied Systems Analysis in Austria, and his team. This system uses an electric motor to lift a solid mass to a high elevation in the charging mode; it then releases that mass to rotate the electricity generator whenever needed (i.e., discharging). The technology is already mature and applied in different applications such as in the construction, recreational sites, and mining industries. The difference is that the motor in MGES also generates electricity when lowering the elevation of the mass. The media for energy storage can be either sand or gravel or similar material resting on the top of a mountain, which allows the system to store energy in long-term cycles, even in a yearly scale. MGES cost varies from $50 -100/MWh of stored energy and $1–2 M/MW of installed capacity.

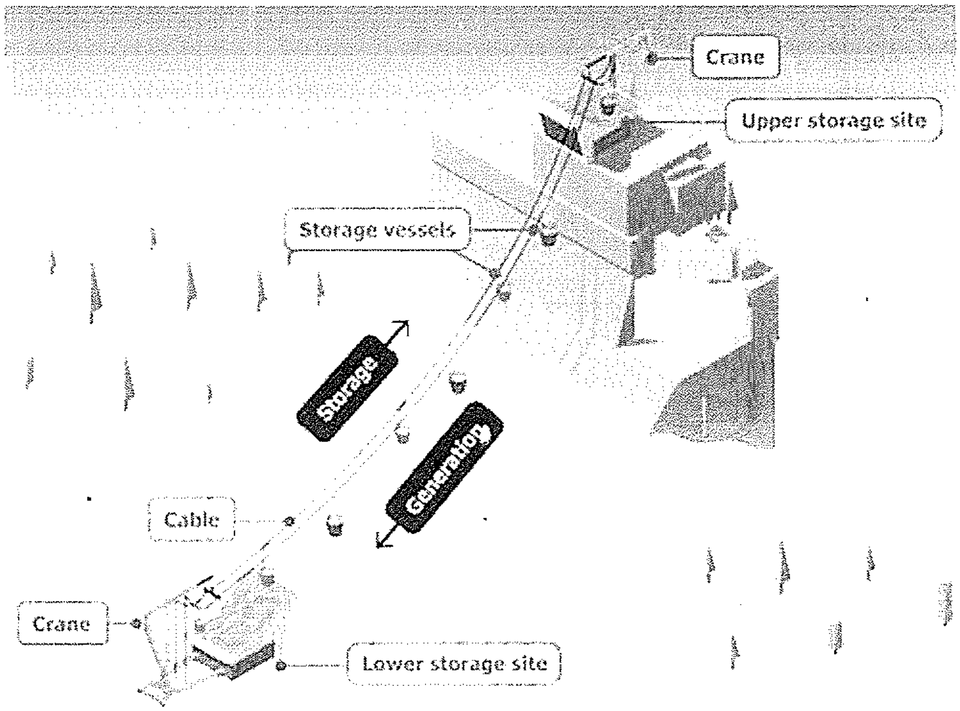


Diagram of Mountain Gravity Energy Storage

Strengths

- A feasible option for micro-grids, for example, small islands and isolated areas, and power systems where electricity costs are high, demand for energy storage is smaller than 20 MW, and there are monthly or seasonal storage requirements.
- Can provide seasonal storage in locations where there is no water for pumped storage solutions.

Weaknesses

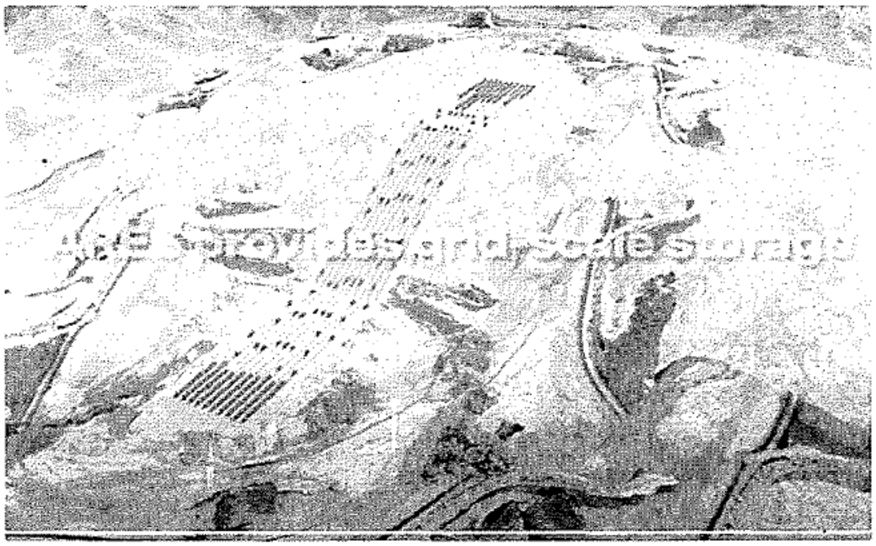
- Less suitable for systems with large storage needs (i.e., greater than 20 MW)
- Requires mountains; smaller height difference results in smaller storage capacity.

Examples

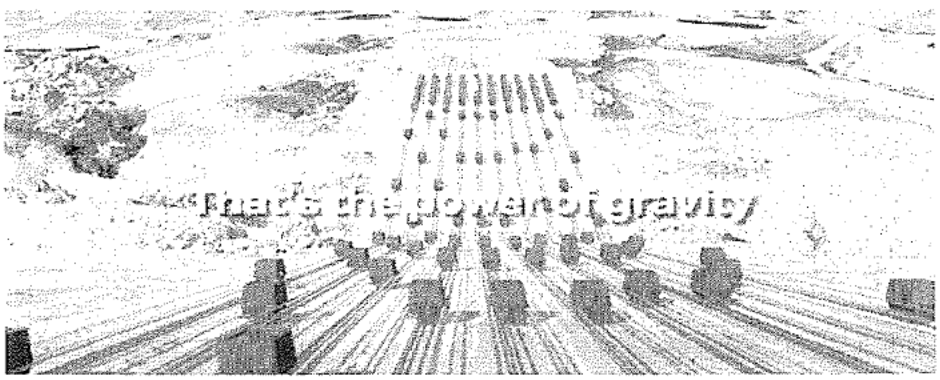
- None. For now this is a novel and interesting concept that hasn't quite reach fruition.

- **Advanced Rail Energy Storage** [32]

This system by Advanced Rail Energy Storage (ARES) is another storage system that uses the potential mechanical energy due to gravity. This system requires a slope with rail tracks that transport heavily loaded cars up and down the slope. Electricity from the grid powers the cars up the slope; then the cars can be lowered down the slope to generate electricity for the grid. The layout of this system at the company's demonstration plant in Nevada is shown below.

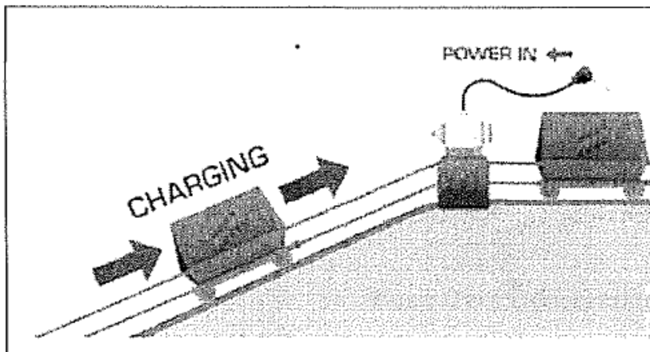


Overview of Tracks and Cars at Nevada Site

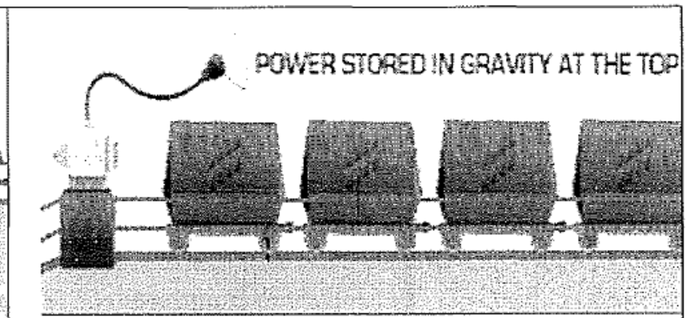


Mass Cars Descending (i.e., Generating Electricity)

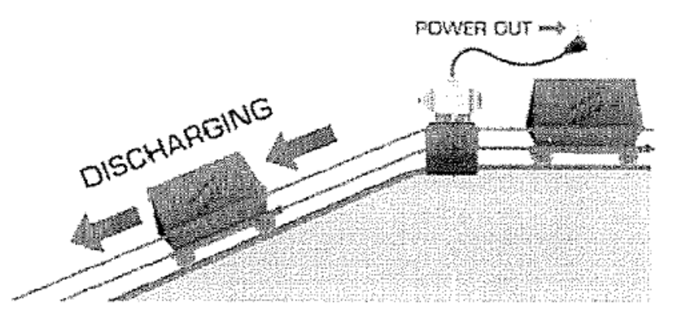
The figures below show the steps in storing and discharging electricity. First, electricity from the gird is used to power a highly efficient electric motor that lifts a heavy mass car uphill. At the top of the slope the car rests, holding potential energy. In the final step electricity is generated as the mass car is lowered, turning the reversible motor backwards and acting as a generator of power.



Step 1: Electricity is pulled from the grid to turn a highly efficient electric motor lifting a heavy mass car uphill.



Step 2: The mass car at maximum elevation resulting in maximum potential energy.



Step 3: Electricity is reproduced as the mass car is lowered, turning the reversible motor backwards and acting as a generator of power.

Strengths

- Uses no fossil fuel or water.
- Produces zero emissions or hazardous waste.
- Has a 40+ year service life with no degradation or thermal runaway.

Weaknesses

- Requires a very large land area.

Examples

- 50 MW plant in Nevada

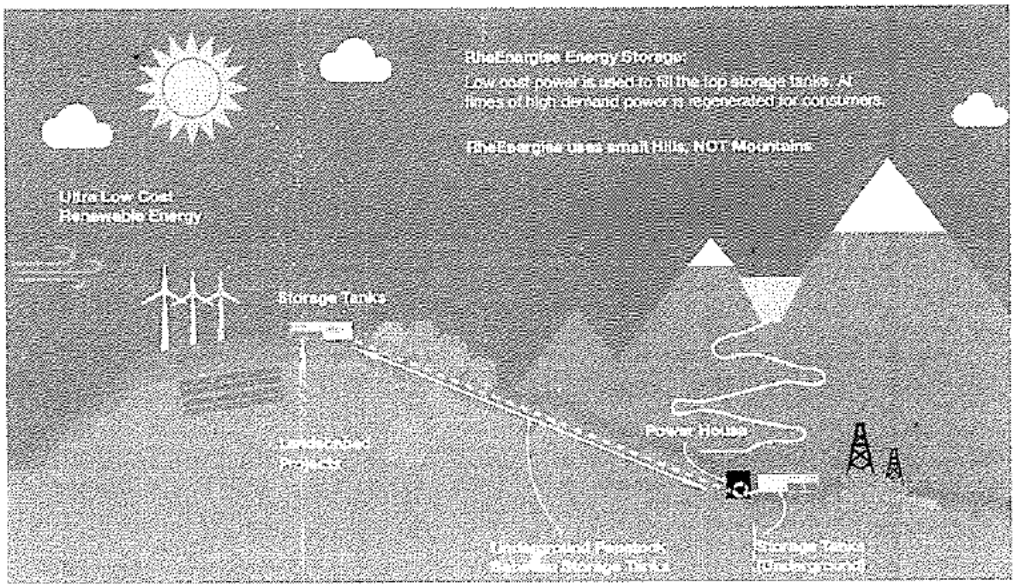
- **Small Slope Pumped Storage Hydropower** [33]

A UK company, RheEnergise, has created a pumped-hydro energy storage system which it is calling High-Density Hydro. The RheEnergise systems could operate across smaller elevation changes than conventional hydro power systems.

Like conventional pumped hydro, the system would use excess energy – such as that generated by wind turbines on a windy day with low demand – to pump the liquid uphill from underground storage tanks. After travelling uphill through underground pipes, the liquid would then be released to power downhill turbines when electricity demand is higher.

The High-Density Hydro system uses dense liquid instead of water. The fluid is two-and-a-half-times denser than water, and could therefore potentially provide two-and-a-half-times the power of equivalent conventional systems. The liquid is a fine-milled suspended solid in water, with low viscosity and low abrasion characteristics. The base material is used in oral medication applications, in a similar way that chalk is used as a bulking agent for pills and tablets. The raw materials are common and available, including in .he UK, and the fluid could either be manufactured on-site or at a depot.

RheEnergise projects provide 10MW to 50MW power and 2 to 10 hours of storage capacity.



High-Density Hydro: Energy Storage by RheEnergize

Strengths

- Projects can be installed on hills 2.5x lower than a project using water and still achieve the same power - for example, there are so many more hills at 150m than at 375m.
- Compared to conventional pumped-hydro storage a project will be 2.5x smaller, by volume, meaning dramatically lower construction costs, faster build times, easier reinstatement and easier landscaping - projects can be entirely hidden.
- Zero emissions during operation.
- Very few end-of-life liabilities

Weaknesses

- Relatively low power.
- This is medium-duration storage rather than long-duration; so far the technology has a maximum storage capacity of 10 hours.

Examples

- ???

- **Pumped-storage hydropower (PSH) using new design submersible pump turbine in a vertical "well"** [34, 35, 36]

Obermeyer Hydro, Inc., has been awarded $1.18 million to to develop an advanced closed-loop PSH configuration as part of the U.S. Department of Energy Water Power Technologies Office's HydroNEXT initiative. Obermeyer is aiming to design a cost-effective, highly flexible PSH system that reduces project costs, shortens deployment timelines, and is optimized for U.S. energy storage requirements. A diagram of the new pump turbine can be seen on the company's website.

The company's configuration is designed to only require construction of a vertical shaft to position a submersible pump-turbine/motor-generator sufficiently deep, instead of an elaborate underground cavern that would involve much larger excavation. Simplified construction and reduced installation costs make such an installation practical at sites that up to now would not have been feasible. The simple underground structure may be constructed under a wide range of geological conditions.

Strengths

- 45% savings in construction costs as compared to conventional PSH systems
- Submersible machines are compact and factory assembled and tested, reducing on-site work and construction costs.
- Energy storage within the power converter equipment provides virtual instantaneous transition between supplying and absorbing energy from the grid.
- Geologic risk and constraints are reduced, opening more potential sites such as non-powered dams to economical development.
-

Weaknesses

- Small storage capacity

Examples

- None currently; system still in design stage.

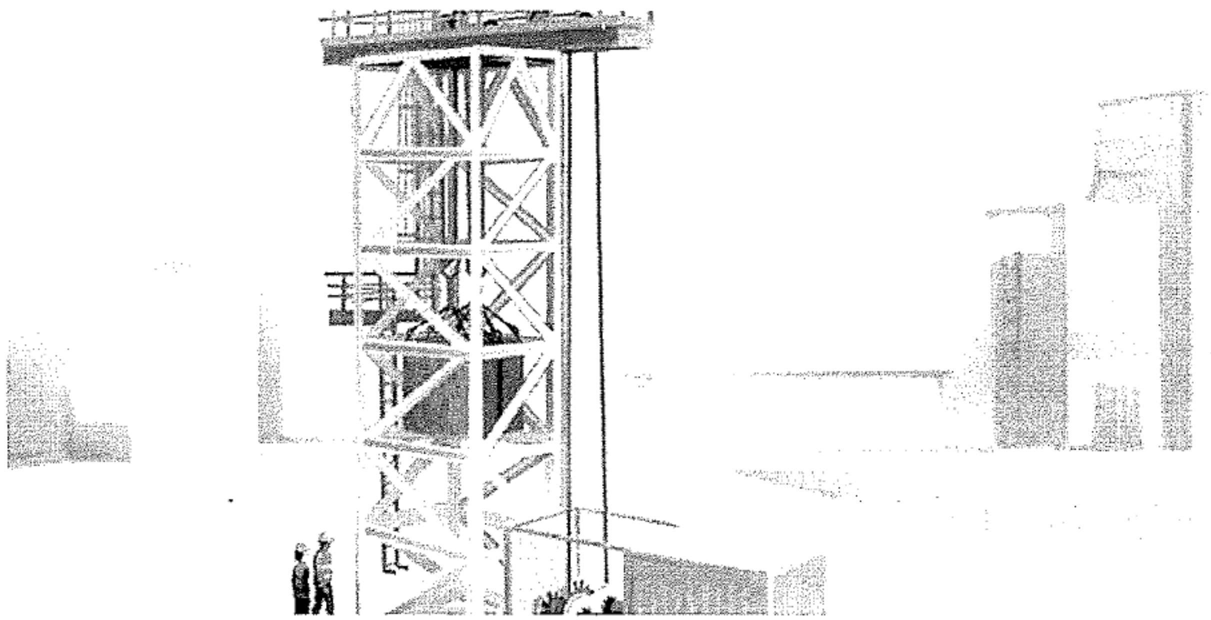
Other New Technologies

The technologies described below are not conside ed long-duration storage because their discharge time is less than 4 hours. But they could be useful replacements for lithium-ion batteries, without the negative environmental effects.

Gravity-Driven Energy Storage System by Gravitricity [31]

This system by Scotland-based Gravitricity works by raising weights as heavy as 12,000 tons into a lattice tower and releasing them into a deep shaft to discharge energy as required. A 250kW prototype of the concept is currently (August 2020) being built. The prototype will use two 25-tonnes weights suspended by steel cables. The two-month trials, which will be carried out with the system grid-connected, are expected to lead to development of a first full-scale 4MW model later in 2021. The system is expected to provide 4 MW of power for a duration of 15 minutes. The company sees the technology being deployed in repurposed mineshafts around the world.

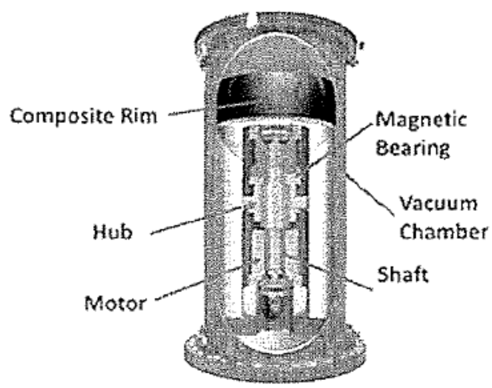
This technology is not long-duration storage but is more for the purpose of replacing lithium-ion batteries at a much lower LCOS.



Above-ground part of Gravitricity's gravity-based energy storage system. Photo by Gravitricity

Advanced Flywheel Storage [37, 38]

A flywheel is a rotating mechanical device that is used to store rotational energy that can be called up instantaneously. A flywheel battery stores electric energy by converting it into kinetic energy using a motor to spin a rotor. The motor also works as a generator; the kinetic energy can be converted back to electric energy when needed.



Source: Beacon Power, LLC

In the late 1990s and 2000s, flywheels were used mostly for short-term energy storage, providing five-to-ten-minute backup power in data centers, for example. But Ben Jawdat, the founder and CEO of Revterra, a flywheel startup based in Texas, thinks that his company has overcome the shortcomings, making flywheels capable of long-term energy storage for renewable energy.

The most important technological development in Revterra's system is in the bearing. Previous flywheel storage systems used either mechanical bearings, such as ball bearings, where the bearing physically touches the rotor, or active magnetic bearings, which eliminate friction at the cost of complex and power-hungry control systems. Both of those options ultimately result in a significant amount of the rotor's mechanical energy being lost as waste heat.

Revterra uses passive magnetic bearings that can hold a rotor in equilibrium without an external control that consumes the additional energy, thus improving the energy efficiency even further by removing the energy consumption of the bearing itself. Revterra's 100 kWh flywheel system will lose only 50 Watts when idling. In comparison, many flywheels consume over 1000 Watts, according to Jawdat. So if you charge the flywheel battery all the way and discharge completely, you would only lose about 10% of the energy, he adds.

Compared to lithium-ion batteries, flywheel batteries essentially last forever. "You can charge and discharge all day every day for 30 years, and your [flywheel] battery will still have 100% capacity," Jawdat says. "With chemical batteries, you have to keep replacing them every five to ten years," which drives up the cost for long-term usage. Revterra has built and tested a working prototype 1 kW flywheel system; the company is currently working on a commercial scale 100 kWh system.

Strengths

- Round-trip efficiency of 90%
- Durable and long-lasting

Weaknesses

- Very low power: commercial scale system under development will have only 100 kWh.

Examples

- Working prototype of a 1 kW system
- Development of a commercial scale 100 kWh system is ongoing.

5. Conclusions

- **There is no one perfect solution.** Some of the more advanced concepts have many advantages but have not been yet fully proven or commercialized.
- **Long-duration storage should be an essential part of large-scale wind and solar installations.** Wind and solar power that needs to be curtailed must have energy storage available. Provision for on-site storage should be part of these large-scale projects.
- **CLCPA should be modified to specify amount of long-duration storage that is needed.** CLCPA specifies 3,000 MW of energy storage by 2030, but does not specifically address long-duration storage. Battery storage by itself is not sufficient.
- **There should be an incentive and financing program for long-duration storage.** Instead of (or perhaps in addition to) the Parker/Cusick bill (S3281/A3788) to subsidize hydrogen, there should be a comparable bill to subsidize long-duration storage.

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