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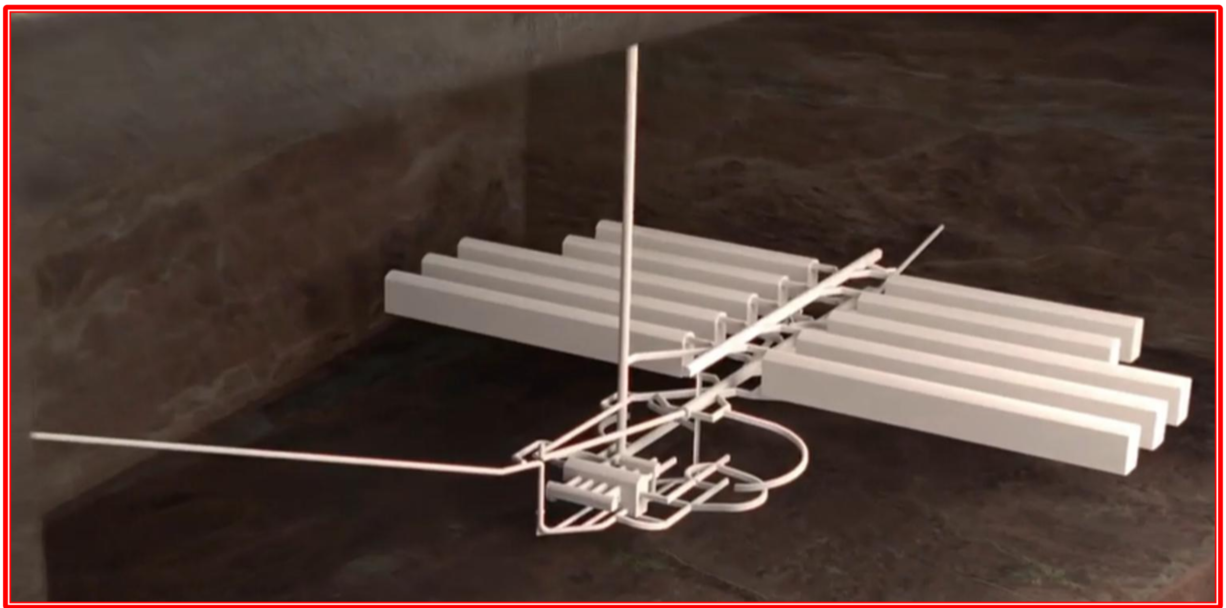
The Global Need for Underground Pumped Storage Hydro

Executive Summary



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This is the Executive summary of the report "The Global Need for Underground Pumped Storage Hydro" prepared by Mike McWilliams. The full report is available on the website of McWilliams Energy at www.mcw-e.com.

About the author

Mike McWilliams is a hydropower engineer with over 45 years of experience in the industry, specializing in power planning, renewable energy, hybrid systems and commercial developments. He is the originator of LAPS, the Location Agnostic Pumped Storage concept, which is part of Zero Terrain's offering.

Mike McWilliams is the proprietor of McWilliams Energy, his own energy advisory firm, which partners with the International Forum on Pumped Storage. He is a senior advisor to World Bank on hydropower and pumped storage, and is Senior Advisor for Energy at Cebr, one of London's leading economic consulting firms. He is an advisor and board member at Klinchenberg—a Norfund and BII subsidiary collaborating with TotalEnergies on development and operation of hydropower projects across Africa, and board member of Agua Imara of Norway.

Mike has authored numerous papers on hydropower and pumped storage, including the Pumped Storage chapter in Elsevier's Comprehensive Renewable Energy Encyclopaedia – published March 2022, and he has twice delivered the prestigious Thomas Lowe Gray lecture at IMechE in London, on the role of pumped storage.

In 2024, Mike McWilliams was selected to join the Zero Terrain Global Advisory Board.

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This report has prepared to highlight the requirements of future energy grids, not only for long-duration energy storage (LDES), but for a wide array of critical services needed to keep electricity supplies secure, stable and affordable, as we strive to decarbonise our energy systems. The particular focus of this report is on modular, build-anywhere underground pumped storage hydro, such as that being developed by Zero Terrain.

Climate Change and the Energy Transition

In 2015 most of the world's nations signed up to the UNFCC Paris Agreement, which committed them to striving to limit global temperature rise to 1.5°C, with a firm goal of keeping it well below 2°C above pre-industrial levels. As a consequence most countries are decarbonising their energy systems, targeting Net Zero for electricity generation by 2050 to 2060.

However it is not just because of this commitment that most electricity systems are transitioning from fossil fuels to renewable energy; on most systems renewable generation is now cheaper than electricity from traditional plant. However to reduce the overall system cost of electricity, it is necessary to plan the grid infrastructure carefully and optimise the services provided by each facility.

Need for Storage

Fossil fuel based systems traditionally held huge stores of primary fuels to guard against supply disruptions. For example US oil and EU gas reserves each exceed 1 million GWh. This compares with current (2025) global electricity storage of some 2,000 GWh, 80% of which is in pumped storage hydro facilities. A huge increase in electricity storage is needed to provide an equivalent degree of resilience.

Various analysts have estimated the amount of storage needed as we approach Net Zero for electricity generation. Estimated global LDES requirements range up to 10,000 GW and 200,000 GWh, with typically 20 hours of storage. These figures do not appear out of line when the experience in California is taken into consideration: the system is suffering major curtailment despite 16 GW of mainly short-duration storage helping to integrate 30 GW of vRE on its 48 GW peak demand system, as it struggles to get vRE much above 25% of generation.

If a lower-end global demand of 100,000 GWh of LDES is assumed, this still represents 10,000 projects the size of Zero Terrain's underground Paldiski PSH, with its 500 MW and 20 hours of storage.

Storage Options

There are many options to provide electricity storage, each with its own characteristics:

- **Ultra-capacitors** can provide very short term storage with long life spans;
- **Chemical batteries** such as Li-ion can provide short-term storage, typically up to four hours, and virtual inertia (sub-second injection of active power into the grid). However they have short lifespan (~6 years if cycled twice per day), safety risk and mining of their components presents environmental challenges;
- **Compressed air storage** is complex, with the need to store compressed air, heat and water in constant pressure systems;
- **Flow batteries** provide potential for the future, but with current technology based on vanadium, supply constrains are likely to limit their capacity;

- **Hydrogen gas storage with combustion turbines** offers a good solution for emergency and insurance of supplies. However the very low cycle efficiency of E2H2E makes it unsuitable for daily use;
- **Conventional (topographic) pumped storage hydro** is one of the best solutions, and accounts for over 80% of current global electricity storage. However it depends on good sites in mountainous regions, which are often remote from load centres and with high ecological and cultural value. Development and construction periods are protracted, and environmental objections often block development.
- **Underground pumped storage hydro,** such as that being developed by Zero Terrain, has all of the benefits of topographic PSH, but is modular and can be built almost anywhere. Hence environmentally sensitive sites can be avoided, plants can be located to suit the grid requirements, and pre-construction time can be reduced. The number of plants is unlimited, and individual sites can be developed with up to 7000 MW and 170,000 MWh capacity.

It is clear that we will need all of the LDES that we can produce., with room for all technologies. However for efficient deployment the technology needs to be gigawatt scale, economic, modular, constructable almost anywhere and with storage potential of 20 hours or more. Only underground PSH, such as Zero Terrain, meets these criteria.

Zero Terrain Pumped Storage

The fully permitted Zero Terrain underground pumped storage site at Paldiski in Estonia is being developed with 500 MW installed capacity and initially 8 hours of storage that can be expanded to 20 hours or more (up to 40 hours currently envisaged) when needed.

Although it acts as a good demonstrator for the technology, it has some features that are unique due to its evolution history: it uses the brackish water of the Baltic Sea as the upper reservoir, the lower reservoir was originally planned as an underground mine for gneiss aggregate for which there is strong demand in Estonia. Although it was sub-economic as a mine, it means the lower reservoir, and hence energy storage capacity, can be expanded at negligible marginal cost.

The deep underground variant of Zero Terrain, with the lower reservoir at 1400 m depth below ground level, takes the Paldiski technology further. With greater head (1400 m instead of 750 m) the reservoirs, waterways and plant are proportionately smaller. With less water used due to the ultra-high head, desalinated water is practical, and the upper reservoir can be covered to avoid evaporation. It is therefore highly appropriate for water stressed regions that are often most suitable for vRE.

By using ternary pump-turbine units with hydraulic short circuit, a continuous range of pumping and turbining is possible from 0 MW up to the installed capacity of the station (i.e. for a single plant -1000 MW to +1000 MW).

In common with other pumped storage plant and some conventional hydro, ZT PSH can operate in synchronous condenser mode – synchronised to the grid at no load. This means that it does not have to generate to provide grid services such as inertia, reactive power, voltage control and spinning reserve, and therefore does not displace vRE causing curtailment.

With the upper reservoir located directly above the power cavern, the headrace has the absolute minimum length, giving a length:head ratio of close to unity. This gives the best possible hydraulic performance, and ensures industry leading mode-change and ramping times.

Paldiski ZT PSH will have mode change times in line with the best reversible pump-turbine units such as Dinorwig in Wales, ramping to full output from spinning in air in less than 20 seconds. The Ternary units of the deep underground variant will have even faster response times, and can change from pumping to turbining in less than 30 seconds, as there is no need to stop and reverse the direction of shaft rotation. Both variants can ramp faster than 10% per second, allowing rapid injection of power to compensate for variation in output by other generators and changes in demand.

Underground PSH, although new in concept, pulls together well-proven technologies in common use: the powerhouses of most large pumped-storage schemes are underground; the pump-turbine units are the same; the surface reservoir and waterways are standard; only the underground reservoir is different in that it is excavated rather than on the surface. However the lower reservoir behaves in the same way as in conventional PSH – it is essentially a lake in a series of caverns, as found in many natural caves.

The ability to excavate deep blind shafts safety is relatively new technology developed for the mining industry. Indeed it was Herrenknecht's development of its innovative shaft boring roadheader (SBR) that inspired the author to develop the deep underground PSH concept known as LAPS (Location agnostic pumped storage). Shafts can now be sunk without personnel at the bottom of the shaft to depths over 1500 m, at rates up to 140 m per month.

The range of services provided by ZT PSH means that other stand-alone infrastructure, such as synchronous condensers, do not need to be built. PSH has been described as the *decathlon* of power system infrastructure for its range of capabilities, and is the "*Grid Operator's Best Friend*".

Among the services provided by ZT PSH are:

- **Arbitrage:** (time-shifting low value energy to high value periods).
- **Synchronous Inertia:** reducing the rate of change of frequency following imbalance events.
- **Power regulation:** (100% up/down) including frequency response, spinning reserve, load following and fast ramping.
- **Blackstart and system reconstruction**: enabling progress and controllable re-building.
- **Transmission constraint alleviation**: allowing the full capacity to be used continuously.

By avoiding the need to build stand-alone facilities to provide these services and optimising the use of other grid infrastructure, ZT PSH can significantly reduce the overall cost of electricity.

A summary of the characteristics of Zero Terrain PSH is shown in the following table:

Characteristic	Particulars
Power	500 to 1000 MW per plant; up to 7,000 MW on one site for the deep underground variant.
Storage	Starting at 8 hours, but expandable to 24 hours or more as needed.
Location	Virtually anywhere with room for surface facilities (~1 km^2 for basic unit + 0.25 km^2 per 10,000 MWh of additional storage).
Modularity	Two basic designs – reversible Francis at 750m depth; Ternary Pelton at 1400 m depth and more.
Water	300 m^3 per MWh deep underground (-1400m); 550 m^3 per MWh for Reversible Francis (-750m). Desalinated water can be used; upper reservoir can be covered to prevent evaporation.
Environment	Site can be selected to minimise environmental and social impacts and avoid lengthy transmission lines. Ground water studies are needed.
Safety	Highly mechanised construction minimises hazards; few safety hazards during operation.
Services	Wide range of grid support services including synchronous inertia, frequency response, fast ramping and load following, reactive power, blackstart and transmission optimisation.
Cost	~USD 2 bn for 1000 MW / 8000 MWh; ~USD 30 million per additional 1000 MWh
Development period	3 years studies and licencing; 5 years construction

Other Uses for Geological Infrastructure

While ZT PSH is highly valuable in its role in long-duration energy storage and as a grid service provider by reducing the cost of electricity and boosting national economies, the geological infrastructure created by Zero Terrain can have other economic uses including:

- **Co-location of electrical facilities** such as combustion turbines (with gas storage – see below) or hybridisation with batteries and/or ultra-capacitors, using the grid connections.
- **Gas storage caverns**, initially for natural gas and later for hydrogen, supplying co-located combustion turbines for emergency use.
- **Flow battery electrolyte tanks**, housing large volumes of electrolyte and the reaction cell.
- **Constant, controlled and secure environment** for data centres, agriculture and storage, with reliable electricity and water supplies and controlled access.
- **Military and critical infrastructure**, with controlled access, security against attack and secure electricity and water supplies.
- **Strategic water reserve:** the ability to "borrow" water from the PSH at times of critical need, to be refilled later to restore the energy storage capacity. The full development of the deep underground ZT PSH variant of 7000 MW with 24 hours electricity storage holds over 40 million cubic metres of water, much of which could be used as an emergency water reserve.
- **Source of aggregate:** strata can be selected for the caverns to supply valuable aggregate, as in the case of Paldiski.
- **Visually intrusive or noisy facilities**, using spoil for landscaping and visual / noise barriers or location underground.
- **Parking and EV charging:** maintaining vehicles in a moderate environment and using the high power capacity on site for charging large numbers of vehicles, while also enabling V2G.

Most of these uses are complementary to the LDES function, and indeed several benefit from the electricity supply security, grid access and large volumes of water on site.

Regulatory Changes Needed

While integrated power systems under central control of a power utility or government ministry have the ability to plan their system, and to procure facilities such as ZT PSH, deregulated markets have more difficulty.

The auction system used in many deregulated markets worked well with traditional generation, where only energy needed to be procured, and the inherent elasticities of different fuel types and differing thermal efficiencies enabled the market to design the grid. With most future generation having zero or negative (in the case of nuclear) marginal cost, these elasticities have disappeared: a higher price does not make the sun shine or the wind blow more.

Further, the complexity of operating a vRE supplied grid means that multiple services are needed – in sophisticated markets twenty or more services must be procured. Buying these individually through auctions at different times with different delivery periods is highly inefficient, ensuring the highest possible cost of electricity.

It is almost impossible to ensure that like-for-like services are competing: projects are at different locations, have different characteristics and operate for different periods. The market needs to change, reverting to formal planning, with facilities being designed and operated by a central authority. The private sector can participate in project delivery and maintaining facilities, if desired.

Models exist that allow a power utility to define and procure projects such as LDES (including ZT PSH) while using the private sector for delivery and, if needed, financing the projects. Traditional EPC enables the utility to specify its requirements in detail, and using EPC+F or lease-based FELT brings commercial finance with construction.

Conclusions

The report establishes the huge requirements for LDES, considers the options and assesses the solutions, and concludes that many different types of long- and short-duration energy storage will be needed. By meticulously planning the grid infrastructure (including the generation plant) and optimising the services provided by each facility, the cost of electricity can be minimised, providing major economic benefits to nations adopting this approach.

As the “Grid Operator’s Best Friend”, pumped storage is the ideal solution to provide large amounts of energy storage and grid support services. However the bespoke nature of conventional pumped storage, difficulty in licencing and shortage of good topographic sites limits its rate of development.

Without a modular, build-anywhere grid scale solution such as Zero Terrain Pumped Storage Hydro it seems unlikely that we can make meaningful progress with decarbonising the world’s energy systems. At best, the cost of electricity will continue to rise, and security of supply will diminish.

Grid operators and strategic consumers should be planning their power systems for mid-century and beyond, with modular, build-anywhere Zero Terrain PSH featuring prominently.

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