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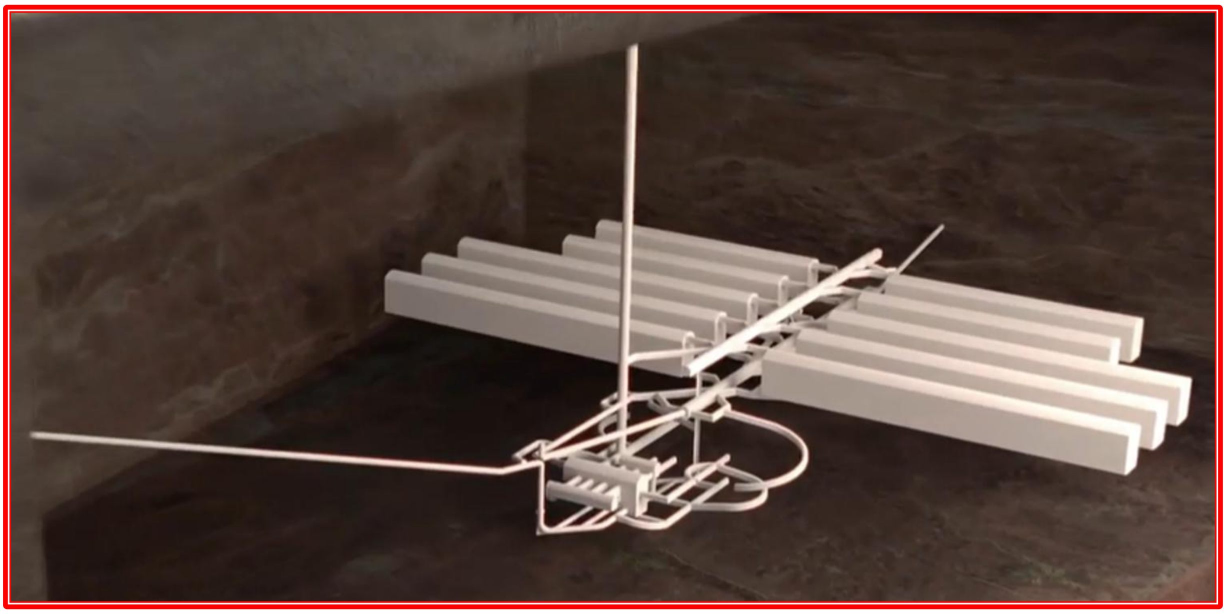
The Global Need for Underground Pumped Storage Hydro



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Acronyms and Abbreviations

BESS	Battery energy storage system
BELT	Borrow, Engineer, Lease and Transfer (variant of FELT concession)
BII	British International Investment
bn	Billion (10^9)
°C	Degree Celsius
CAES	Compressed air energy storage
Capex	Capital expenditure
Cebr	Centre for Economics and Business Research
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CO_2	Carbon dioxide
COD	Commercial operation date
COP	Conference of Parties (UNCCC)
E2H2E	Electricity to hydrogen to electricity cycle
EPC	Engineering Procurement and Construction (or Turnkey) contract
EPC+F	EPC plus finance
EU	European Union
EV	Electric vehicle
FCR	Frequency containment reserve
FELT	Finance, Engineer, Lease and Transfer (form of concession)
GB	Great Britain
GHG	Greenhouse gas
GVA.s	Gigavolt-amp-second (measure of inertia)
GW	Gigawatt (million kW)
GWh	Gigawatt-hour (million kWh)
Hz	Hertz
IEA	International Energy Agency
IHA	International Hydropower Association
IMechE	Institution of Mechanical Engineers, UK
IRENA	International Renewable Energy Agency
kg	Kilogram
km	Kilometre
L:H	Length : head (ratio)
LAPS	Location Agnostic Pumped Storage
LCE	Lithium carbonate equivalent
LCOE	Levelized cost of electricity
LDES	Long-duration energy storage (at least 8 hours of storage)
Li-ion	Lithium-ion
LNG	Liquified natural gas
m	Metre

Mpa	Megapascal
mcm	Million cubic metres
mmbtu	Million British thermal units (unit of gas)
mt	Million tonnes
MVA.s	Megavolt-amp-second (measure of inertia)
MW	Megawatt (1000 kW)
MWh	Megawatt-hour (1000 kWh)
NDC	Nationally determined contribution (under Paris Agreement)
NESO	National Energy System Operator (of GB)
NOx	Nitrogen oxides
O&M	Operation and maintenance
Opex	Operating expenditure
pa	Per annum
PHS	Pumped storage hydropower
PPA	Power purchase agreement
PV	Photovoltaic (generation)
RoCoF	Rate of change of frequency
s / sec	Second
SBR	Shaft-boring roadheader
SBC	Shaft-boring cutterhead
SC	Synchronous condenser
SCADA	Supervisory Control and Data Acquisition
SOC	State of charge
SOx	Sulphur oxides
t	Tonnes (metric = 1000 kg)
T&D	Transmission and distribution
TV	Television
TW	Terawatt (10^9 kW)
TWh	Terawatt-hour ((10^9 kWh)
U	Uranium
UN	United Nations
UNCCC	United Nations Climate Change Conference (or COP)
US / USA	United States (of America)
US$	United States Dollar
V2G	Vehicle to grid
vRE	Variable renewable energy
VRFB	Vanadium redox flow battery
XPLE	Expanded p
ZT	Zero Terrain (see Home - Zero Terrain)

Executive Summary

This report is prepared by the author, Mike McWilliams, 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 (combined with gas storage – see below) or hybridisation with batteries 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, which would be refilled later to restore the energy storage. The full development of the deep underground ZT PSH variant of 7000 MW with 24 hours electricity storage would hold over 40 million cubic metres of water, much of which could be used as emergency 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 FELT[1] 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 will limit 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 systems for mid-century and beyond, with modular, build-anywhere Zero Terrain PSH featuring prominently.

[1] Finance, Engineer, Lease and Transfer – lease-based procurement model developed by the author.

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 development. His experience includes the study, design and construction of hydropower and pumped storage projects, assessment of renewable energy technologies, least cost system planning and economic and financial modelling. 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 currently serves as a Senior Advisor for Energy at Cebr, one of London's leading economic consulting firms. Beyond these roles, Mike is an influential figure in the hydropower sector, serving as an advisor and board member at Klinchenberg—a Norfund and BII subsidiary collaborating with TotalEnergies on development and operation of hydropower projects across Africa. Additionally, he lends his expertise as a non-executive board member of Agua Imara of Norway. His influence extends globally, with the World Bank relying on his strategic guidance in hydropower and pumped storage as a Senior Advisor for strategy, planning, and project development.

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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1 Climate Change

For the past 35 years, the global community has been deeply engaged in intense discussions about anthropogenic climate change. During this same period, carbon dioxide levels in our atmosphere have continued to increase, rising from 380 ppm in 1990 to 425 ppm today. International dialogues have not been in vain, leading to significant milestones in the fight against climate change. One such milestone was the 2015 United Nations Framework Convention on Climate Change, where 196 countries came together to approve the Paris Agreement (United Nations, 2015). This landmark accord committed nations to striving for a global temperature rise of no more than 1.5°C, with a firm goal of keeping it well below 2°C above pre-industrial levels.

Under the Paris Agreement all countries are required to submit their climate action plans, known as nationally determined contributions (NDCs) setting out their targets to achieve the Paris Agreement goals. Most countries are planning radical decarbonization of their power generation, with targets to achieve Net Zero by 2050 to 2060.

2 The Energy Transition and Investment

In order to cut global GHG emissions we need to transition our basic energy uses, including transportation, heating and industrial processes, from primary fossil fuels to electricity. The author's assessment is that this will typically increase electrical energy consumption by a factor of two to three by 2050, on top of increased demand from universal access, economic growth and data centres. This assessment takes account of the improved efficiency of heat pumps compared with boilers and of electric vehicles compared with combustion engines.

The main growth in low carbon generation is in the variable renewable energy (vRE) technologies of photovoltaic solar and wind energy. The world now invests around five times as much in clean energy as it does in fossil-fuelled generation. According to IEA (IEA, 2025), global energy investment is set to reach US$ 3.3 trillion in 2025, with over US$ 2 trillion going to clean energy technologies and infrastructure. Investment in clean energy has accelerated since 2020, and spending on renewable power, grids and storage is now higher than total spending on oil, gas, and coal.

Power sector investment in solar photovoltaic (PV) technology is projected to reach US$ 450 billion in 2025, making it the largest single global energy investment, and solar remains central to the power sector's transformation.

Investments in nuclear power are expected to reach US$ 75 bn in 2025, having grown by 50% in the past 5 years.

Grids have become a bottleneck for the energy transition, but investment is rising, and is expected to hit US$ 400 billion in 2025. However grid investment is still falling behind generation, and needs to catch up if the bottleneck is to be alleviated.

Investments in battery storage are ramping up and are set to exceed US$ 65 billion in 2025. More modest investment in pumped storage hydro (PSH), which added 8.4 GW in 2024, brings the global PSH capacity to 189 GW (IHA, 2025). This represents an investment rate of around US$ 15 bn pa.

Today's investment trends are not aligned with the levels necessary for the world to limit global warming to 1.5°C above pre-industrial levels and to achieve the interim goals agreed at COP28. A huge increase in investment is needed to keep 1.5°C within reach.

According to the World Bank, investment in PHS is a key component of global energy transition strategies, especially as it is one of the most mature, reliable, and scalable storage technologies. Renewable energy investment, including energy storage, is attracting significant attention from governments, international organizations, and some private investors. In view of its critical role in decarbonisation, governments worldwide are offering incentives to attract private finance. Investment in large-scale energy storage, especially PHS, reduces long-term operational costs and strengthens the case for scaling up renewable energy sources. As a result, renewable energy companies backed by strong storage capabilities are seen as good investments for long-term returns.

In conclusion, the importance of renewable energy investment cannot be overstated, and the expansion of energy storage capabilities, particularly through pumped hydro storage, is essential for the long-term success of this transition. PHS offers a scalable, cost-effective solution to balance grids, stabilize supply, and optimize the integration of renewables, making it a compelling investment opportunity.

3 Economics Are Driving Renewables – Not Theology

In the early days of renewable energy the cost of electricity from vRE was much higher than from traditional sources such as coal, gas and nuclear. Renewable generation needed to be heavily subsidised to attract commercial investment, and this subsidy was justified based on the economics of climate change.

The cost of most forms of vRE has fallen dramatically over the past decade to the extent that vRE, on a MWh basis, is typically competitive with most traditional generation.

Many analysts, including Lazards (Lazard, 2025) in their latest LCOE version 18.0 of 2025, have shown that the current levelized costs of energy (LCOE) of unsubsidised variable renewables, especially PV in moderately to good resource areas and on-shore wind are cost-competitive with gas-fired CCGT generation.

The LCOE of PV and on-shore wind is typically around 4¢/kWh, compared with gas-fired CCGT at 5¢/kWh. However this is based on the assumption that CCGT will operate at its maximum availability of 90%, and using pipeline gas at US$3 to 4 per mmbtu. In practice CCGT on mixed nuclear-RE-fossil systems tends to operate at around 50% load factor, and as vRE penetration increases, the load factor reduces significantly, tending towards a few percent at Net Zero. For example in 2024 in California, according to the California Energy Commission, the 38,686 MW of gas-fired generation produced 86,480 GWh of energy, operating at a load factor of 25.5%. Also outside North America, many countries are now dependent on imported LNG for electricity generation, with any pipeline gas consumed by base-load heating requirements. LNG shipments currently cost around US$12.5/mmbtu, and with the cost of transfer, re-gasification and reticulation, cost at least four times the assumed cost of pipeline gas.

Taking these factors into account, the LCOE of CCGT at different load factors and cost of fuel can be calculated, as shown in Table 1.

Table 1: LCOE of various generation technologies in US¢/kWh

Technology	Capex	Opex fixed	Opex variable	Fuel	Total
Utility scale PV	3.5	0.5	-	-	4.0
On-shore wind	3.5	0.5	-	-	4.0
Off-shore winds	6.0	1.0	-	-	7.0
CCGT: 90% LF, $3.5/mmbtu	2.0	0.1	0.3	2.2	4.6
CCGT: 50% LF, $3.5/mmbtu	3.6	0.2	0.3	2.2	6.3
CCGT: 30% LF, $3.5/mmbtu	6.0	0.3	0.3	2.2	8.8
CCGT: 90% LF, $14.0/mmbtu	2.0	0.1	0.3	8.8	11.2
CCGT: 50% LF, $14.0/mmbtu	3.6	0.2	0.3	8.8	12.9
CCGT: 30% LF, $14.0/mmbtu	6.0	0.3	0.3	8.8	15.4

Source: author, based on a selection of LCOE analysts

Hence in the real world, gas-fired generation already costs up to four times as much as PV and on-shore wind energy, even without subsidies or carbon taxes. The capital cost of old CCGT plant is already sunk, so owners can bid slightly above the marginal generation cost. However for system planning, the total cost needs to be taken into account, especially as few if any existing CCGT will be in operation at the Net Zero target dates.

Of course **all energy is not equal.** Comparison of vRE energy costs with despatchable, but high carbon fossil-fuelled generation is spurious. Externalities such as grid services, transmission enhancement, security back-up, carbon emissions and pollution need to be taken into account. Nevertheless, it can be seen that there is considerable margin to provide back-up and grid enhancements for vRE and still undercut LNG-fired CCGT.

The benefit for countries that get it right, developing vRE based systems with the optimum blend of back-up and storage, are enormous. Future economies will be largely driven by the cost of energy. Robotics and AI will displace low-paid labour, and **countries with access to cheap, green and secure energy will become the industrial powers of the future** (McWilliams, 2024).

4 The Need for Storage

Fossil fuel systems have traditionally maintained large stores of primary fuels to guard against fuel supply disruptions, in order to maintain security of supply. Some of these stores, such as the US Strategic Oil Reserve, are vast in terms of energy capacity. There are also considerable quantities of energy stored in transit, or in fuel tanks waiting for use. The scale of these fossil fuel energy stores is illustrated in Table 2.

Table 2: Traditional Fossil Fuel Energy Stores

Energy Store	Energy stored (GWh)
US Strategic Oil Reserve	1,200,000
Europe gas storage	1,130,000
World LNG Fleet (assumed half full)	320,000
US vehicle fuel tanks (assumed 1/3 full)	46,500
Typical 2000 MW coal fired power station	4,000

Historically on many power systems the on-site coal reserve provided protection against extreme cold weather: whereas gas tends to be diverted away from power stations to domestic use at times of extreme heating demand, coal is always available to fuel generation.

By comparison electricity storage facilities tend to be several orders of magnitude smaller, as shown in Table 3:

Table 3: Current Electrical Energy Storage Capacity

Storage Technology	Energy stored (GWh)
Total world pumped storage hydro capacity	1,600
Total world battery storage capacity (2024)	375
Largest pumped storage (Snowy 2 under construction)	350
Largest battery storage (Edwards & Sanborn)	3

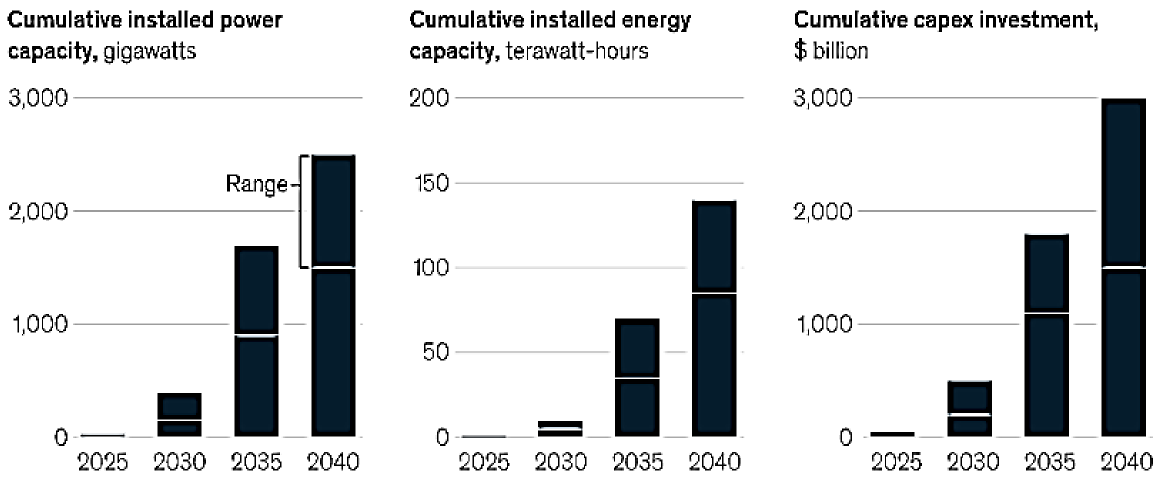
The need for strategic energy reserves to protect against fuel supply disruption is less imperative for the future decarbonized system than in the past, with adverse weather becoming the main threat to security. However weather-related disruptions, such as Dunkelflaute (long periods of dark doldrums with little wind or sun), wind droughts and long periods of cloud cover can create energy deficits running to thousands of GWh.

It is not surprising that terawatt-scale electricity storage is needed to support the future global grid.

The global market size for energy storage is set to expand significantly, with Bloomberg NEF predicting that the global energy storage market will grow to 1,095 GW/2,850 GWh by 2040. The rapid scaling of energy storage capacity is critical to accommodate the anticipated surge in renewable energy investments. Hydropower, which includes PHS, accounts for the majority of global energy storage capacity, with around 200 GW of pumped storage installed globally. This technology offers long-duration energy storage (LDES), essential for stabilizing grids dominated by variable renewable sources like wind and solar.

LDES encompasses a range of technologies—mechanical, thermal, electrochemical, and chemical—that can store energy for extended periods and scale affordably to sustain power for days or even weeks. Their ability to absorb and manage fluctuations in energy demand and supply adds flexibility to the system. This integration not only stabilizes electricity but also harmonizes the entire energy system, including heat, electricity, hydrogen, and other energy types.

Figure 1: Expected Energy Storage Capacity - McKinsey & Co



Source: McKinsey & Co

According to the authoritative report by McKinsey (McKinsey & Company, 2021), globally, 1.5 to 2.5 TW of LDES capacity may be installed by 2040, which is eight to fifteen times the total electricity storage capacity deployed now. In terms of energy, 85 to 140 TWh of storage will be required by 2040, with 80% of this in storage having over 24 hours' duration. According to the chart above, this amounts to a total investment ranging from US$1.5 trillion to US$3 trillion.

McKinsey's estimate that 10% of electricity will be passed through storage prior to consumption appears to significantly underestimate the requirement for storage. The great disparity between the demand load factor of electricity systems (typically 60% to 80%) and renewable energy generators (typically 10% to 40%) means that huge capacity margins are inevitable. For wind dominated supply, the installed capacity needs to be two to three times peak demand in a net zero system; for PV dominated supply the installed capacity needs to be four to eight times peak demand in order to produce sufficient energy for the system. The surplus capacity at times of high output needs to be time-shifted using LDES to match demand.

In a 2018 study, (Felix Cebulla, 2018) the energy storage requirements for the EU and US power grids are estimated, as illustrated in the graphs in Figure 2.For 60% vRE penetration that is predominantly PV, storage equivalent to 40% of peak demand is needed. The storage requirements presented for wind dominated systems are much lower.

A further study from Imperial College, London (Staffell, 2019) suggests that for a wind-dominated system, such as that of Great Britain, storage capacity of 35% to 40% of peak demand is needed to allow vRE to satisfy 80% of demand, as shown in Figure 3.

Figure 2: Amount of Storage needed for VRE share (Felix Cebulla, 2018 annotated by the author)

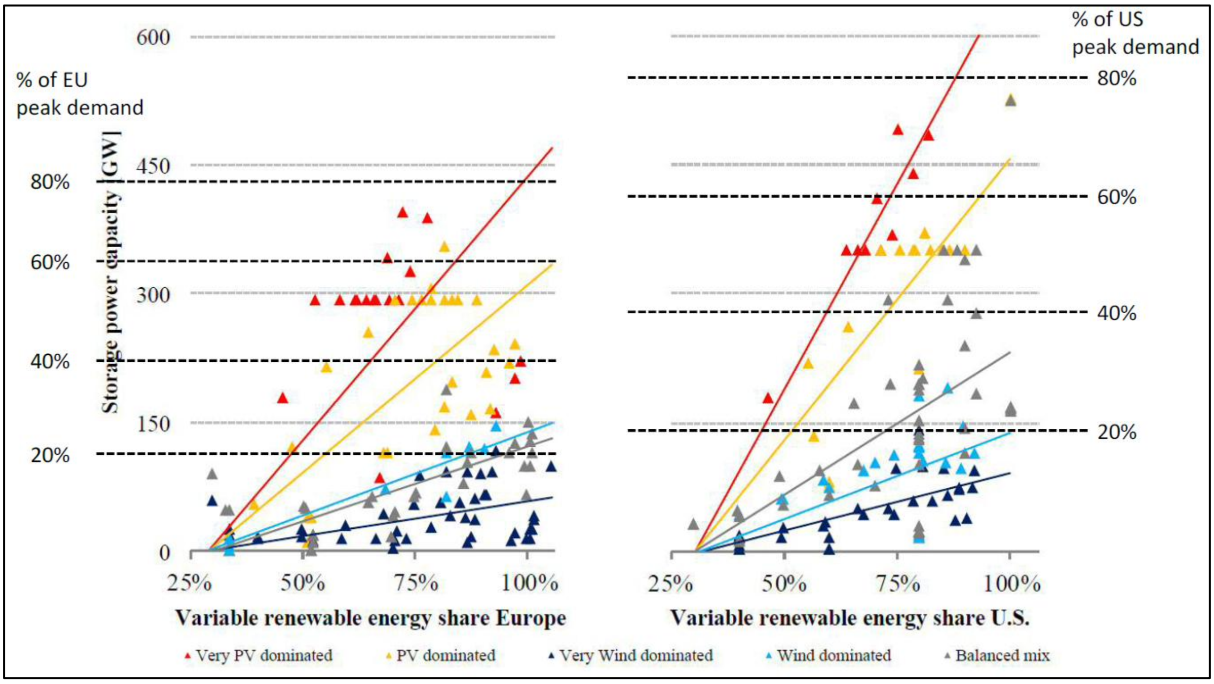
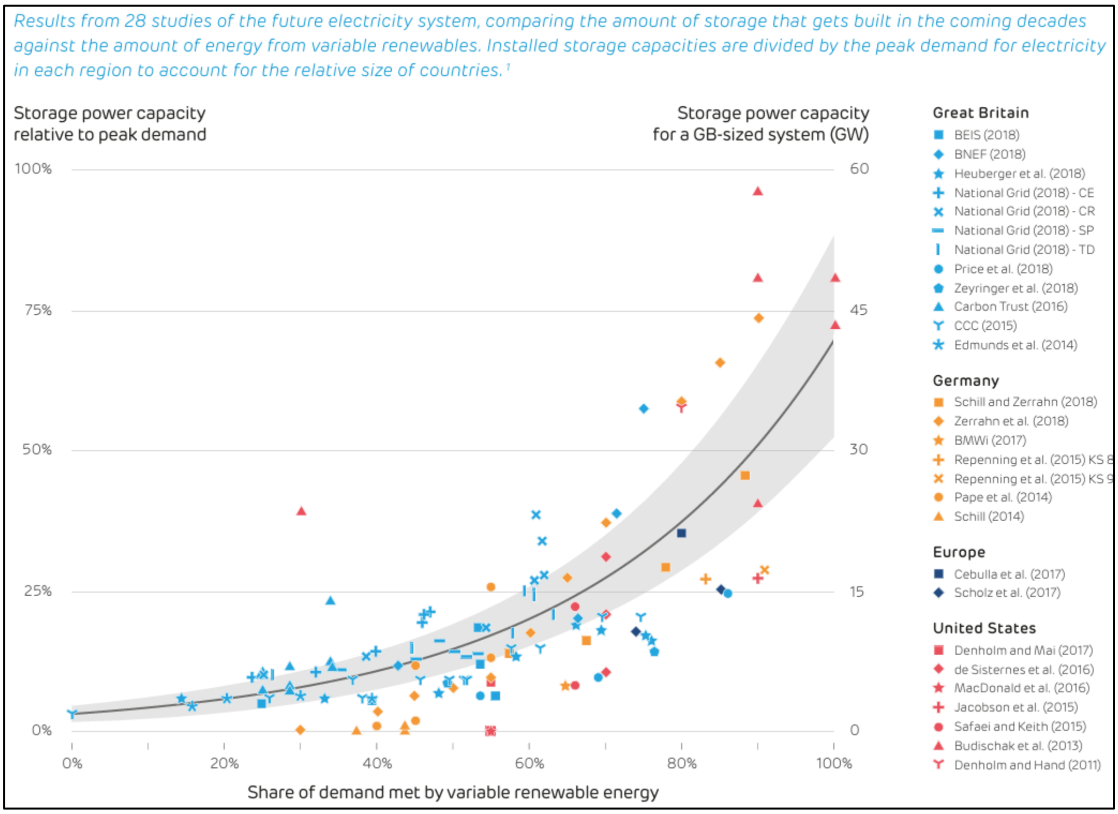


Figure 3: Storage Requirement Relative to Peak Demand by vRE Share of Demand



Source: (Staffell, 2019)

In their Australia National University (ANU) report on the potential for transition to 100% renewable energy (Blakers et al, 2019), it is estimated that 1 GW / 20 GWh of storage per million people is required to balance the grid, assuming that other measures, such as inter-regional long-distance transmission are deployed to balance weather, seasonal and time of day differences in supply and demand. Applying this to UN population projections (United Nations Department of Economic and Social Affairs, 2024) of around 10 billion at mid-century, this equates to 10,000 GW and 200,000 GWh of storage. However it seems unlikely that inter-regional transmission can provide security against weather and seasonal variations, so even more LDES would probably be needed.

Blakers also provides an alternative guide to the amount of storage needed to balance a 100% renewable large-area system: 1 day of electricity consumption. Applying this to potential Net Zero demand of 100,000 TWh pa, this would equate to around 275,000 GWh of global storage demand.

A comparison of LDES forecasts is presented in Table 4. There is broad consensus that installed capacity will need to exceed 1,000 GW by 2040, and the LDES Council forecast of a requirement for 8,000 MW of LDES (which includes thermal storage) is not far out of line with the IEA total storage demand of 5,000 GW by 2050.

Table 4: Comparison of LDES Forecasts

Source	Date	Capacity (GW)	Energy (GWh)
Bloomberg NEF	2040	1,095	2,850
McKinsey	2040	1,500 – 2,500	85,000 to 140,000
LDES Council	2030	1,000	>8,000*
	2050	8,000	>64,000*
Blakers et al	2050	10,000	200,000

** Minimum based on definition of LDES having at least 8 hours of storage.*

The author's own analysis indicates that systems which supply up to 25% of energy consumption from renewables can manage without much storage. When 50% of energy comes from variable renewables, some 25% of energy must pass through storage, and as we approach 100% renewables, some 50% of energy must be time-shifted from when it is generated to when it is used. This suggests that McKinsey's estimate of 10% of energy passing through storage before consumption is likely to underestimate the future storage requirement.

The consequences of failure to provide sufficient storage can be seen in Figure 4, where the increasing trend of curtailed renewable energy in California is apparent. Despite having installed some 16 GW of electricity storage (mainly short duration batteries) to help integrate 30 GW of vRE on its 48 GW peak demand system, CAISO curtailed 3,400 GWh of PV and wind energy in 2024.

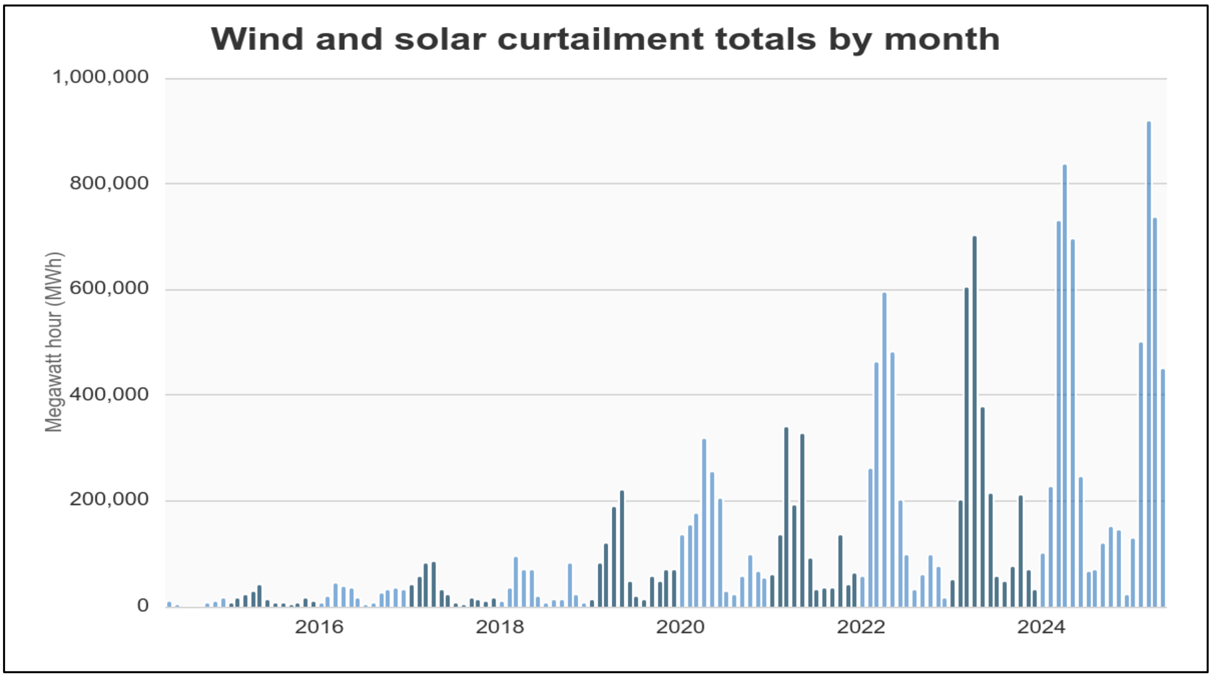
Although data for 2024 is not yet published, the data for "in-state" generation in California for 2023 in Table 5 (California Energy Commission, 2025) shows that only 25% of in-state generation came from vRE, illustrating the difficulty in achieving high levels of vRE penetration without LDES.

Table 5: California in-state generation by type (2023)

Type	In-state generation (GWh)	% of generation
Fossil	94,485	44%
Nuclear	17,714	8%
vRE	53,340	25%
other RE	50,084	23%
Total	**215,623**	**100%**

Source: California Energy Commission analysed by the author

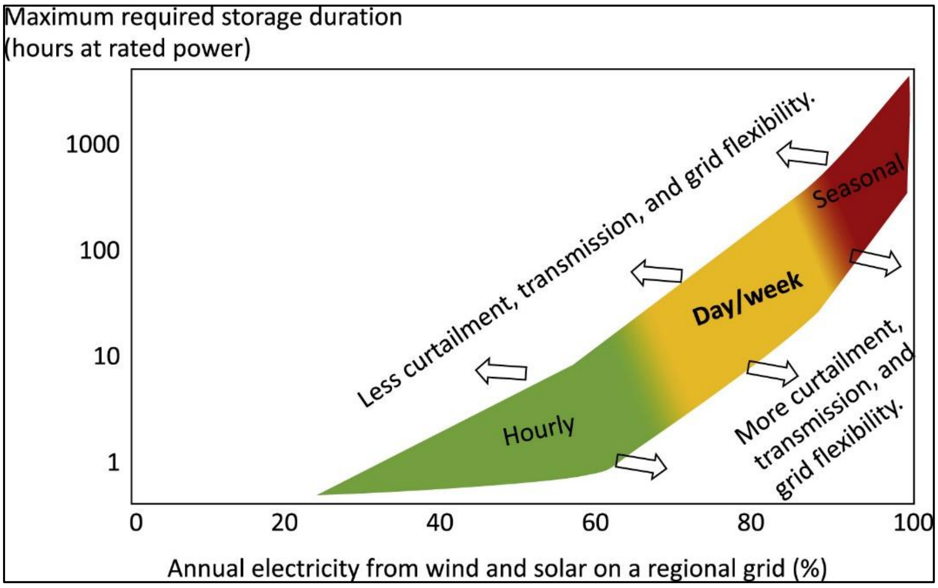
Figure 4: Curtailment of Renewables in California



Source: CAISO

As well as the storage capacity needing to increase, the duration of storage needs to increase as the proportion of electricity supplied to the grid by vRE increases. In a report by Albertus et al. (Paul Albertus, 2020), the duration of storage required as vRE penetration increases is estimated, as shown in Figure 5. This indicates that very short duration of storage, perhaps 1 to 2 hours, is needed with 40% vRE penetration to provide flexibility, reduce curtailment and minimize transmission congestion. As the proportion of electricity generated by vRE rises to 75%, the required duration of storage is 10 to 20 hours, and with 90% vRE, storage of 100 hours or more may be required.

Figure 5: Storage Duration Requirement with Increasing vRE



Source: Paul Albertus, 2020

This requirement for increased durations of storage is starting to emerge in the energy markets. For example in the GB Capacity Market, short duration electricity storage is increasingly de-rated. From Table 6 it can be seen that in the 2018 auction for delivery the following year, one hour duration storage was accredited with over 1/3 of its installed capacity, and with 4 hours of storage the full capacity was accredited. Six years later in the 2024 auction for delivery in 2028, 1 hour of storage is accredited with barely 10% of its installed capacity, and 9 hours of storage is needed to achieve full capacity.

This table reflects the increasing duration of storage needed to provide grid security as vRE penetration increases. In 2018 vRE (wind and PV) supplied some 21% of indigenous generation, and by 2023 this had grown to some 33%. This coincides with the stage of vRE penetration of the GB grid when it moved from needing very little storage to starting to require significant storage. With GB advancing its Net Zero target for electricity generation to 2030, with vRE supplying some 80% of generation, the required duration of storage for grid security will only increase[2].

Table 6: GB Capacity Market De-Rating Factors - MW accredited for a 100 MW Storage Facility

Duration of Storage (hours)	Auction: 2018		Auction: 2024	
	For 2019-20	For 2022-23	For 2025-26	For 2028-29
0.5	17.5 MW	14.9 MW	6.8 MW	5.3 MW
1.0	34.2 MW	29.4 MW	13.6 MW	10.5 MW
2.0	62.8 MW	56.7 MW	27.2 MW	20.9 MW
4.0	95.5 MW	80.0 MW	54.2 MW	41.7 MW
5.0	95.5 MW	95.5 MW	65.1 MW	52.3 MW
6.0	95.5 MW	95.5 MW	74.6 MW	62.7 MW
8.0	95.5 MW	95.5 MW	93.0MW	83.5 MW
9.0+	95.5 MW	95.5 MW	93.0 MW	93.0 MW

Source: NESO Capacity Market Auction Guidelines

According to Blakers (Blakers et al., 2019), the transition of transportation, heating, and industrial manufacturing to electric power will cause energy demand to quadruple. Applying this to current global electricity consumption, world generation at net zero in say, 2060, may be over 100,000 TWh. IEA in their report Net Zero by 2050 (International Energy Agency, 2021), under their NZE (Net Zero Energy) scenario, forecast demand of 60,000 TWh by 2050. This assumes significant demand reduction by efficiency and behavioural changes, and the use of biomass and carbon capture to provide despatchable generation, reducing the need for storage.

The author's own assessment of demand growth in industrialized countries, where underlying electricity consumption has been virtually static, indicates demand growth of two to three times due to the energy transition. Adding increased access and demand increase due to increasing wealth and affordability together with expanding needs of data centres, a global demand increase quadrupling is considered plausible.

It can be concluded that over the next 30 to 40 years global **electricity storage will need to increase from less than 2,000 GWh to 100,000 GWh or more**. This represents building some 30,000 of the

[2] It will not be possible to build the required storage by 2030, and the system operator, NESO, is planning to balance supply and demand using significant amounts of "demand-side flexibility", its euphemism for load-shedding.

world's largest BESS every 6 to 10 years (their life span), or one-off construction of 10,000 PSH projects of the size of Zero Terrain's Paldiski PSH (500 MW / 20 hours).

5 The Options – Firm Capacity or Storage?

The need for LDES is strongly correlated with the penetration of vRE. Hence the options for avoiding such huge amounts of storage while achieving Net Zero are:

i) Reduce demand
ii) Construct low-carbon base-load or predictable generation
iii) Install even more vRE and accept very large curtailment / wasted energy
iv) Interconnect regions with different timings of demand and supply

The options are considered as follows:

5.1 Reduce Demand

In most industrialized nations electricity demand growth has been fairly flat or falling over the past decade as a consequence of increased efficiency of use (incandescent to LED lighting and improved appliance/process efficiency) and off-shoring manufacturing (which transfers electricity demand elsewhere). Most of these efficiencies are now embedded in demand, and forecasts are starting to show demand increasing.

For example Grid Strategies, in their 2024 National Load Growth Forecast for the USA are reporting FERC estimates of surging growth over the next 5 years, largely as a result of data centres and manufacturing. Whereas in 2022 and 2023 total growth over the following five years was forecast to be 2.8% and 4.7% (i.e. around 0.5% and 1% pa respectively), the latest 5-year forecast is for 15.6% growth (close to 3% pa). They conclude that "The Era of Flat Power Demand is Behind US". The energy transition – electrification of heating, transport and industries – contributes little to this pre-2030 demand; most of this is reflected in later forecasts.

With improving electricity access across the developing world, increasing wealth making electricity more affordable combined with the energy transition, there is little opportunity to reduce demand. The question is whether demand growth at Net Zero can be limited to nearer three times today's consumption, or whether it will be closer to four. And of course, the more electricity that needs to pass through storage, the more needs to be generated to make up for losses.

"Demand-side Flexibility" or load-shedding can help mitigate the need for intra-day storage. However it primarily involves time-shifting demand over a period of hours to alleviate capacity (GW) constraints, and has limited benefit where daily energy supply is short, such as in Dunkelflaute conditions. With increasing dependence on electricity for all aspects of our life, such load-shedding measures will be unwelcome at best, and life-threatening at worst.

5.2 Low Carbon Base-load or Predictable Generation

Nuclear Power

Nuclear power is being promoted as one of the technologies that can provide firm, base-load low-carbon energy for the Net Zero grid. The "always-on" nature of nuclear power makes it a poor partner for variable renewables: it cannot be ramped down as the sun starts to shine or the wind blows, and cannot be ramped up as night falls or the wind drops[3]. Hence while helping to increase firm energy supply, nuclear power will result in more curtailment of vRE.

As illustrated by the French power system, it is possible to run a low-carbon grid based largely on nuclear power supported by a limited amount of storage and despatchable generation. In the early 2000s, nearly 80% of France's generation came from nuclear power (US Energy Information Administration, 2024), with fossil fuelled generation supplying less than 10%. Balancing supply and demand was facilitated by hydropower, providing around 10% of generation, and pumped storage capacity of around 10% of peak demand. By 2022 nuclear generation had dropped to around 63% of supply, with hydropower and vRE supplying 25%, leaving fossil fuels to supply the remaining 12%.

If a low-carbon grid can be supplied predominantly by nuclear power, is this the global solution to net zero energy?

Setting aside the cost and construction delays that beset most new nuclear plants (it is expected that large-scale take-up would streamline construction and reduce costs, and small modular reactors would facilitate roll-out), the problem seems to lie with nuclear fuel.

Current economic (US$130/kg U) global uranium reserves are estimated at 6.1 million tonnes (World Nuclear Association, 2024), with total recoverable reserves of 8 million tonnes. With secondary sources, waste recovery and reprocessing, a global Uranium resource of 10 million tonnes could be assumed. As it is unlikely that global build-out of nuclear plants would exceed a level where the resource is consumed in less than 50 years (i.e. without fuel guaranteed for 50 years), the maximum likely Uranium usage will be 200,000 tpa. Since some 44 GWh of electricity is produced from 1 tonne of Uranium, the maximum likely annual nuclear generation is around 9,000 TWh. With global electricity demand at Net Zero likely to exceed 100,000 TWh pa, nuclear power based on current technology is unlikely to account for much more than 10% of global electricity supply.

New nuclear technologies, such as thorium fission or fusion may come to the rescue, but these are at least 30 years away from commercial operation, and will not contribute much towards achieving Net Zero by the middle of this decade.

Biomass

Analysis by the author indicates that electricity generation from biomass could make a significant contribution to electricity supply at Net Zero. In countries such as UK, Germany, Italy and China between 5% and 10% of electricity demand at Net Zero could be produced from sustainable biomass, assuming up to 10% of land area is dedicated to biomass production. For USA the percentage is around 16%, and in Russia and Australia and the figure exceeds 80%. Although not analysed, it is expected that Canada, and the Nordic countries would have potential similar to Russia.

However land-constrained countries such as Japan and South Korea would struggle to produce 5% of their electricity needs from biomass generation.

While notionally in carbon balance, assuming that harvesting, drying, pelletisation and transportation are carbon neutral, and if combined with carbon capture and storage (CCS), the technology could be carbon negative. However with conventional combustion, pollutants such as

[3] Molten salt nuclear that separates the always-on thermal energy generation from electricity production has ramp up and down capability, but only within a daily cycle, and there currently seems little appetite in pursuing this technology.

NOx, SOx and microscopic particulates can be difficult to abate, meaning that even if biomass generation may be carbon-neutral, its sustainability credentials are questionable.

Hence while likely to make some contribution towards electricity supply at Net Zero, it is most unlikely that biomass generation will be a major electricity supplier.

Geothermal

Geothermal generation is a major generation technology in some countries with good geothermal resources, such as Kenya and Iceland, with 44% and 30% respectively of electricity generated from geothermal plants in 2022 (US Energy Information Administration, 2024). However the resource of high-grade heat for electricity generation is not sufficient for it to contribute significantly to global electricity demand, and in 2022 only 0.3% (US Energy Information Administration, 2024) of global electricity generation came from geothermal plants. There is more potential to use low-grade geothermal heat for space heating, which could displace some electricity demand.

Tidal Energy

Although not constant or despatchable, tidal generation is predictable, and over a two-week period will produce close to its average energy output. The global world tidal energy potential, including both tidal range and tidal stream, is estimated at 3,000 GW (IRENA, 2014). With a typical capacity factor of around 20%, this could yield 5,000 TWh of energy if fully developed. However tidal energy projects face significant ecological objections, and there is little sign of the technology progressing to the extent that it will have a major impact on world electricity supply.

Gas Generation with Carbon Capture

Several countries, including UK, are placing their hopes on gas-fired generation with carbon capture and storage (CCS) to produce low-carbon electricity. There are signs that up to 90% of carbon dioxide can be removed from the exhaust gases at the point of use, and the process is particularly effective in chemical plants, where high concentrations of CO_2 can be captured efficiently. Assuming that up to 90% of CO_2 can be removed at the point of use, this still leaves the problem of the upstream GHG footprint.

An increasing proportion of gas for generation is transported as liquified natural gas (LNG). In a recent report on the GHG footprint of LNG exported from the US (Howarth, 2024) estimates that the point of use accounts for only one-third of the GHG footprint, with the other two-thirds occurring during extraction, processing and transport. Capturing 90% of CO_2 at the point of combustion only deals with a small part of the GHG footprint, and it therefore seems that gas-fired generation with CCS should not be part of a Net Zero power grid.

5.3 Install a Very Large Surplus vRE Capacity

If, as it seems likely, it is not possible to construct sufficient low carbon baseload generation to meet a large proportion of global demand at Net Zero, is it possible to construct sufficient vRE without storage so that there will be enough usable energy to meet demand, even if much of the vRE needs to be curtailed or wasted?

The author modelled a typical power system in an arid equatorial region, where 45% of the typical daily demand was met by nuclear baseload and generation associated with desalination, leaving 65% of demand available for PV generation.

The modelling indicated a tipping point when PV capacity (MW) was equal to the typical daily maximum demand, with around 20% of energy delivered from vRE. Up to this point additional PV capacity would be largely absorbed by the power system without significant curtailment. However installing PV capacity above this level increasingly results in curtailment, with a maximum of 27% of energy demand being met by PV. With the PV generation being concentrated around the middle of the day, the daytime demand is quickly satisfied, leaving the surplus PV generation to be wasted, and the evening, night-time and early morning demands unmet.

The curtailment issue can be resolved by the provision of energy storage – 6 to 8 hours of storage is typically required for intra-day time shifting, although more is required to cope with prolonged overcast conditions. For 25% of demand to be met by PV, around 10% of peak system demand keeps curtailment below 5% of PV generation. Beyond that additional storage is needed to match PV penetration, with 60% penetration requiring storage capacity of almost 100% of peak demand.

The demand-supply balance of the modelled grid is significantly affected by the “always-on” nuclear power, which cannot be ramped down to accommodate more PV. This is the likely future situation on many power systems, where nuclear generation is planned as base load. Obviously, each power grid is different, with differing daily and seasonal demand curves, different generation mixes and different resource environments, but the modelling above illustrates why vRE penetration on PV dominated systems can reach 20% to 25% without much storage, and why increasing amounts of storage will be needed to progress beyond this.

The situation with wind dominated systems is more complicated to model. Analysis by the author of 34 years (1980 to 2013) of hourly wind records on the GB grid shows that output will be less than 10% of installed capacity for around 12% of the time, and less than 25% of installed capacity for over one-third of the time. At times output drops below 1%. Periods of 48 hours with output less than 10% of installed capacity are not uncommon, and the worst such wind drought with output less than 10% in the record lasted 6 days. Again without significant storage or despatchable generation, it is not possible for supply to meet demand. Simply building more vRE does not cover the shortfall.

5.4 Interconnection of regions with different timing of demand and supply

Demand

Electricity demand tends to follow a diurnal pattern, with high demand during the day and lower demand late at night and in the early hours of the morning. In particular peak demand often occurs in the early hours of the evening, although air-conditioning demand in hot climates can result in a mid-day peak. Interconnecting regions with offset peak demand timing can reduce capacity constraints. However the distances involved for such interconnections can be great. For example at the equator some 1670 km of transmission distance is needed to gain one hour of time separation; at the tropics of Cancer and Capricorn the distance is 1530 km. Artificial time zones can be utilised: for example GB and France are close to the same longitude, but have a time difference of 1 hour, with a minimum separation of 35 km. This offset enables exchange between the two grids to meet capacity constraints and reduce supply costs. This benefit may be reduced in future when time-of-day tariffs and smart-grid controls are used to level intra-day demand.

Supply

Solar energy follows a daily pattern, peaking in the middle of the day. This pattern follows the position of the sun, and hence artificial time differences do not apply: the full circumferential transmission distance is needed.

The occurrence of protracted wind droughts is typically associated with large anti-cyclonic weather patterns that result in shallow pressure gradients over extended distances. In Europe such weather patterns can cover most of the North Sea, where much of the Norther European wind energy fleet is located. While interconnections can mitigate the impacts of short duration weather events, they are less effective for the more severe large-scale events.

While interconnectors are a valuable tool to reduce average energy costs through arbitrage, they are less useful for mitigating against the effects of wind and energy droughts to enhance energy security.

5.5 The Need for Storage Cannot be Avoided

The above analysis shows that, although demand management, constructing despatchable generation and interconnectors and over-building vRE can mitigate the need for storage, and indeed will all be required as we move towards Net Zero, they will not displace the need for electricity storage, and the analysis by McKinsey (McKinsey & Company, 2021) and others remains valid.

It should be noted that although much of the analysis above is based around time-shifting supply to meet demand, the analysis by McKinsey takes into account other Flexibility Services that will be required by the grid. These include:

- Energy shifting, capacity provision, and T&D optimisation
- Optimisation of energy for industries with remote or unreliable grids
- Isolated island grid optimisation
- Firming for Power Purchase Agreements (PPAs)s
- Stability services provision, such as frequency response, inertia and spinning reserve.

The storage capacities and valuations of these services are shown in Figure 6. It should be noted that the valuations are conservative, in that the reduction in curtailed energy associated with alleviation of transmission congestion is not valued, and nor are flexibility services other than inertia.

Figure 6: Quantification and valuation of LDES Services

xx T&D optimization value; xx Value/spend measures

Value created by LDES	2040 Cumulative LDES: Installed power capacity GW	2040 Cumulative LDES: Installed energy capacity TWh	Cumulative value creation USD bn	Annual LDES capex spend USD bn
Energy shifting, capacity provision, and T&D optimization	~1,300–2,300	~80–135	~470[1]; ~300–650[2]	~175–215
Optimization of energy for industry with remote or unreliable grids	~110	4	~120	~4–5
Isolated island grids	~90–100	3	~30–35	~10
Firming for PPAs	~40	2	~5–10	<1
Stability services provision (inertia)	0	0	~5–10[3]	na[4]
Total	~1,500–2,500	~85–140	~950–1,300	~190–230

Key assumptions

1. Based on reduction in cumulative system cost vs. "No LDES Case."
2. Value of transmission and distribution expansion deferral or substitution. Figures only account for infrastructure optimization and do not quantify the value of reduction in generation curtailment costs and reduction of energy not served.
3. Other services are potential material revenue streams for LDES, but not sized in this report.
4. Inertia provided through assets that are deployed for energy generation and capacity provisions, not through additional build-out.

Source: McKinsey (McKinsey & Company, 2021)

6 Storage Options

The following section considers the options for providing LDES, considering only those technologies that are commercially viable, or are close to market readiness.

6.1 Mechanical

Pumped Storage Hydro (traditional)

According to the IHA (International Hydropower Association, 2024), over 94% of the world's LDES capacity is provided by pumped storage hydropower, with global installed capacity of nearly 200 GW. This mature technology has been helping system operators balance supply and demand for over 100 years.

Traditionally PSH has been developed to time-shift supply (arbitrage) from "always-on" (nuclear) or base-load (coal) generation. A few PSH were constructed for rapid response, such as Dinorwig in Wales, which was designed for ultra-rapid response for TV pick-ups (surges in demand at the end of popular TV programmes).

Advantages	Disadvantages
• Mature technology • Exceptional life with no degradation • Good efficiency (~80% cycle) • Easy management (energy stored is proportional to water volume) • Relatively little use of strategic metals • Wide range of ancillary services	• Long gestation time • Site specific (requires topography to provide head (difference in elevation between upper and lower reservoir) • Challenging environmental issues • Each site is different and requires a bespoke solution

Zero Terrain Pumped Storage Hydro

Zero Terrain pumped storage is a new variant of pumped storage built on flat land that offers a modular solution which can be constructed almost anywhere to suite the grid requirements and environmental considerations.

In common with most large PSH, the powerhouse is underground and the waterways are all in shafts or tunnels. The only difference is that the head is created by locating the lower reservoir in caverns excavated deep below ground near the same elevation as the powerhouse.

Since no special topography is required, and excavation techniques are available for most geological conditions, Zero Terrain PSH can be constructed almost anywhere. Two design concepts are available: **underground**, with the powerhouse and lower reservoir located at a depth of 750 metres (the current limit for use of reversible pump-turbines), and **deep underground**, with the powerhouse and lower reservoir between 1400 m and 2000 m below ground level. Further details of the concept are provided in section 8.

An example of the underground Zero Terrain PSH concept (Zero Terrain) is Energiasalv PSH at Paldiski Bay in Estonia see (Home - Zero Terrain), a fully permitted 500 MW PSH with initial storage of 8 hours, expandable to 20 hours or more.

Zero Terrain PSH has all of the benefits of traditional (topographic) PSH, and many additional positive attributes, as discussed further in sections 7 and 8.

Advantages	Disadvantages
• Mature technology (all elements are well-proven) • Exceptional life (100 years +) with no degradation • Good efficiency (~80% cycle) • Easy management (energy stored is proportional to water volume) • Relatively little use of strategic metals • Wide range of ancillary services • Modular design • Build anywhere (no specific topography or geology) • Location to suit grid connection and environment (eg brownfield site) • Avoids new HV transmission lines – reduced fire hazard in vulnerable areas and hazard to HV lines from fires • Small water volume (suits desalination: upper reservoir can be covered to avoid evaporation) • Length-head ratio near 1.0 allows ultra-fast hydraulic response • Capacity range 500 MW to 1000 MW per station • Storage up to 48 hours (i.e. maximum 48,000 MWh) – can be added incrementally	• Five-year construction period (similar to traditional PSH, but shorter planning and development period)

Compressed Air (CAES)

A range of CAES systems have been postulated: originally air was compressed using surplus energy and stored under high pressure in large natural caverns (e.g. salt caverns). When the energy was needed by the grid, it was used to supercharge a combustion engine, with the waste heat from the engine used to heat the air for expansion. Obviously for net zero such fossil fuelled systems are not acceptable.

Adiabatic CAES stores the heat from compression until the energy is needed, when it is used to heat the compressed and to drive an air-turbine. This requires the storage of heat as well as air. Systems are being developed where the air pressure is maintained using the head of a water column, although this requires water to be stored as well as air and heat. This system has all of the components of a pumped-storage scheme plus heat storage, and the system is inherently less efficient than pumped storage hydro.

Other variants are being developed using compressed carbon dioxide, and with sufficient pressure to liquify CO_2 or air.

Where natural storage is available, CAES can provide an economic storage solution, and can form part of the massive fleet of LDES that is needed.

Advantages	Disadvantages
• Long life • No degradation • Moderate cycle efficiency (>70%) • Commercial viability if natural storage is available	• Limited sites for natural storage • Complex, with may components and need to store heat as well as air (and possibly water for constant pressure)

Gravity-based (solid)

Many concepts have been developed where solid weights are hauled uphill or lifted by cranes. One concept is being used where a building is constructed, weights are lifted by cranes using surplus energy, and the energy is recovered by using the motor-generators to lower the weights.

While technically viable, this technology has no advantage in terms of cost, complexity, performance or efficiency over traditional pumped storage, other than modularity and ability to construct it anywhere – factors resolved by Zero Terrain PSH.

Advantages	Disadvantages
• No degradation • Modular / construct anywhere • Moderate efficiency (~65%)	• Complex with many components and moving parts • Expensive

6.2 Thermal

Molten Salts and other sensible heat storage

Molten salt thermal storage is used for Concentrated Solar Power systems where solar rays are reflected onto a receiver to concentrate the energy to heat a high temperature fluid – typically a molten salt or high temperature transfer fluid. Heat is retained in this fluid until the energy is required, when steam is produced in a heat exchanger to drive a conventional steam turbine.

The same approach is proposed for molten salt nuclear generation, where a molten salt is used as the heat transfer fluid. This can be stored before being used to heat steam to drive a steam turbine and generator. This enables the concept of a peaking nuclear plant, which can be a much better accompaniment to vRE than traditional nuclear generation. However, due to the cost of the salt storage and the heat loss, this storage is typically restricted to a daily cycle. However systems are being developed that will store heat over several days.

Advantages	Disadvantages
• Most efficient where input energy is already in form of heat (e.g. nuclear or CSP)	• Low energy density • Salts need to be kept in liquid phase by continuous heating to avoid freezing and blocking pipework

Latent Heat and Thermochemical Storage

Latent heat and thermochemical storage offer the potential for longer term storage with less heat loss. With latent heat storage, a phase-change material is heated to melt it from solid to liquid, using surplus energy, with energy recovery coming from the heat released on subsequent freezing of the material. The gas-to-liquid phase change can also be used.

Thermochemical storage is at an early stage of development, but has the potential for very long-duration storage, using reversible chemical reactions that absorb and generate heat.

Advantages	Disadvantages
• Potentially higher energy density than sensible heat storage • Potentially longer duration storage	• Early stage of commercial readiness

6.3 Chemical

Hydrogen including E2H2E

Electrolysis of hydrogen is a mature technology that will certainly play a role in decarbonisation of energy systems to achieve net zero. The production of hydrogen as a fuel, either for mobile or static use (e.g. transportation, space heating) is well advanced, although the technologies for safe storage and transport are still under development.

The cycle efficiency of electricity-to-hydrogen-to-electricity (E2H2E) is currently very low – of the order 40% using fuel cells for generation or 20% using combustion turbines. Even with expected improvements in efficiency of electrolysis, it seems unlikely that E2H2E can contribute significantly to intra-day storage cycles. However with the ability to store hydrogen at high pressure for extended periods (months / years) with virtually no loss of energy, E2H2E can play an important role in energy security, providing despatchable supply to cover rare Black Swan events and emergencies.

Advantages	Disadvantages
• Long duration storage (months or years) with virtually no loss • Huge energy storage (caverns at high pressure)	• Very low efficiency compared with other storage technologies

6.4 Electrochemical

Batteries including Li-ion BESS

Most new battery energy storage systems (BESS) are currently based on Lithium-ion (Li-ion) batteries, although they do not qualify as long-duration, typically having storage of four hours or less. However with cell prices falling, Li-ion based BESS could soon be economically competitive with PSH for 8-hour storage.

The characteristics of BESS and PSH are very different, making it difficult to compare them on a like-for-like basis. Both BESS and PSH are needed to achieve Net Zero, and their respective characteristics are presented in greater detail in section 7.

Metals for construction of BESS may limit battery supply, and requirements for BESS will be competing with EV demand. IRENA (Lyons, 2022) considers that the global resource for lithium of 400 million tonnes of lithium carbonate equivalent (LCE) is sufficient for 200 years at the estimated EV demand (plus minor other uses) of 2 mt LCE in 2030 (based on 40 million EV sales pa and 50 kWh of batteries per EV.) However the supply chain for mining and processing the metal may not keep up with supply, and there is a question whether all of the lithium will be battery-grade.

If Li-ion BESS is to provide say, half of the 100,000 GWh of LDES needed for Net Zero, and bearing in mind the ~10-year life of BESS cells, annual production for BESS would be 2.5 times the estimated annual demand for EVs[4]. At this rate the global lithium reserves (assuming it is all accessible and of battery grade) would be depleted in under 60 years, although this can be extended by recycling.

[4] 40 million EV with 50 kWh batteries = 2,000 GWh demand pa. Half of 100,000 GWh = 50,000 GWh, renewed every 10 years = 5,000 GWh for BESS pa.

Advantages	Disadvantages
• Rapid deployment (short development and construction period) • Ultra-fast (<1 second) active power injection (synthetic inertia) • Low cost of power (MW) • Good round-trip efficiency (~90%)	• Short life (11 years of daily cycling, but shorter if used for intra-day grid services and arbitrage) • High marginal energy (MWh) cost • Fire safety hazard • Requires strategic metals • Difficult to determine state-of-charge (SOC) • Does not provide mechanical inertia

Flow Batteries

The promising new technology of Flow Batteries is being developed for grid scale energy storage. A flow battery consists of two tanks for electrolyte storage, and a reaction cell. The electrolytes are circulated through two sides of the reaction cell separated by a membrane, and the battery is charged using surplus electricity to oxidise (release electrons) one electrolyte and reduce (gain electrons) the other electrolyte. Discharging occurs in reverse. The power (MW) output and energy storage (MWh) are independent, depending on the size of the reaction cell and storage volumes respectively.

Current versions of flow batteries are typically based on vanadium in Vanadium Redox Flow Batteries (VRFB). Commercial plant sizes up to 175 MW / 700 MWh (Xinhua Ushi ESS, China) have been developed, which are typically based on linking hundreds of small cells together. Currently some 63 m^3 of electrolyte containing 8 tonnes of Vanadium pentoxide is needed per MWh of storage capacity (Tycorun Energy, 2025). With global reserves estimated at 63 million tonnes (U.S. Geological Survey, January 2024), it seems unlikely that VFRB will contribute more than a few percent of the LDES required for Net Zero.

Advantages	Disadvantages
• Rapid deployment (short development and construction period) • Ultra-fast (<1 second) active power injection (synthetic inertia) • Little fire safety hazard (compared with Li-ion) • Extended cycle life 16,000 to 20,000 cycles (compared with 4000 hours for Li-ion) • Moderate round trip efficiency (~65%)	• High marginal energy (MWh) cost due to cost of vanadium (~US$200/MWh) and tanks • Requires strategic metals with limited supply • Difficult to determine state-of-charge (SOC) • Does not provide system (mechanical) inertia • Electrolyte needs periodic repair and rebalancing

7 Comparison between PSH and BESS

The estimated LDES requirement to achieve Net Zero is 100,000 GWh or more (refer section 3), and there do not appear to be viable options to significantly mitigate the LDES requirement in the foreseeable future (refer section 5). Although CAES and VRFB technologies are likely to contribute to the LDES needs, and E2H2H can assist with energy security, from the assessment in section 6 it appears that electrochemical batteries (initially Li-ion, but new technologies will emerge) and pumped storage hydro will provide the bulk of the requirement.

Battery storage is likely to account for much of the short-duration storage needs, along with other technologies such as flywheels (providing inertia) and ultra-capacitors (very rapid load changes without degradation, but small energy storage).

Battery Energy Storage Systems (BESS) and pumped storage hydro (PSH) share many characteristics, but also have distinct attributes, and a mixture of both is needs to successfully operate a vRE dominated grid. In addition Zero Terrain PSH and traditional (topographic) PSH have characteristics in common but also distinct attributes that are beneficial to system operators, as shown in Table 7.

Table 7: Characteristics of BESS and PSH Compared

Characteristic	BESS (Li-ion)	Traditional PSH	Zero Terrain PSH
Power (MW)	up to 800 MW	up to 3600 MW	up to 7000 MW[1]
Energy Storage (GWh)	up to 3.2 GWh	up to 350 GWh	up to 140 GWh
Hours of Storage	Typically < 4 hours	up to 175 hours	Typically 20 hours
Life: number of cycles	4000	∞	∞
@ 1 cycle / day	11 years	>100 years	>100 years
@ 2 cycles / day	6 years	>100 years	>100 years
Development period	2 years	5 years	3 years
Construction period	2 years	5 years	5 years
Efficiency (round trip)	~90%	~80%	~80%
Services			
Mechanical inertia	No	Yes	Yes
Synthetic inertia (active power < 1s)	Yes	No	No
Active power injection	< 1 sec	< 2 mins[3]	< 15 secs
Transition time (charge to discharge)	< 1 sec	< 3 mins[3]	< 30 secs
Ramp rate	~100% in 1 sec	~5% / sec	>10% / sec
Depth of Discharge	90%	100%	100%
Blackstart	(Yes)[4]	Yes	Yes
Voltage regulation	Yes	Yes	Yes
Environmental Impacts			
Social / resettlement	Small	Medium	Small
Ecology	Small	Large	Small
Strategic metals	Large	Small	Small
Cost of Storage[5]			
4-hour storage	US$350/kWh	US$350/kWh	US$450/kWh
8-hour storage	US$300/kWh	US$200/kWh	US$250/kWh
24-hour storage	US$250/kWh	US$100/kWh	US$110/kWh

Notes: *1 – seven levels of 1000 MW each in deep underground ZT PSH*
2 – 20 hours per plant (expandable to ~40 hours)
3 – typical traditional plant; ultra-fast plants like Dinorwig are much faster
4 – grid-forming inverters required
5 – costs vary considerably depending on the location, site and environment – hence only for illustration

8 Zero Terrain PSH – Description and Characteristics

As discussed in section 6.1, two design variants of zero terrain technology are available: **Underground**, with the powerhouse and lower reservoir located at a depth of 750 metres (the limited for use of reversible pump-turbines), and **Deep Underground**, with the powerhouse and lower reservoir between 1400 m and 2000 m below ground level.

8.1 Underground PSH

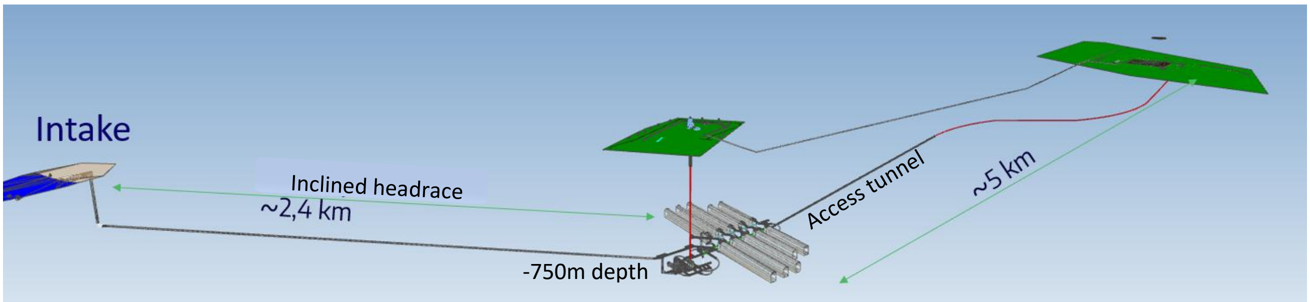
The initial project being developed at Paldiski in Estonia illustrates the Underground Zero Terrian concept, with the following characteristics:

Table 8: Characteristics of Paldiski Zero Terrain PSH, Estonia

Characteristic	Parameter	Comment
Installed Capacity	500 MW	This is about the minimum that would economically viable for the Underground Zero Terrain concept.
Hours of storage	20 hours	Initial operation can start at 8 hours of storage; storage capacity can be increased almost without limit by increasing the lower reservoir cavern volume.
Lower reservoir volume	6.0 mcm	Initial cavern volume around 2.5 mcm for 8 hours of storage at CoD; enlarged as required.
Upper reservoir	Baltic Sea	Baltic Sea is a natural water body with brackish (not saline) water and small tidal range; more typically ZT PSH would use a constructed surface reservoir.
Water	Brackish	More usually fresh water or desalinated water would be used. Suitable brackish water is uniquely available in the Baltic.
Depth to powerhouse / head	750 metres	This is currently the limit for reversible Francis pump-turbines.
Turbine type	Reversible Francis	
Fixed or variable speed	Fixed speed	Variable speed units could also be deployed (either full power converter or Doubly-fed Induction Machines) if the characteristics better suit the grid requirements. Hydraulic short-circuit between units is also possible.
Unit capacity	3 x 167 MW	Typical future units would be 4 x 250 MW
Access	Tunnel	Shaft or tunnel are both possible. At Paldiski the geology favours a tunnel.
Lower reservoir construction method	Drill-and-blast	Use of tunnelling jumbos allows excavation to proceed on multiple fronts; rate of progress can be adjusted to suit project schedule.
Commercial readiness	Pre-construction	Paldiski Zero Terrain PSH is fully permitted and procurement of project delivery partners has started (late 2024).
Unique features	Stone sales	Aggregate from the caverns is highly valued in Estonia: aggregate sales enable indefinite expansion of the lower reservoir (and hence storage capacity) at negligible cost.

The configuration of Paldiski Zero Terrain PSH is illustrated in Figure 7.

Figure 7: Section through Paldiski Zero Terrain PSH



In most applications of the concept, without the use of the Baltic Sea as the upper reservoir, the upper reservoir would be located immediately above the powerhouse. Depending on the geology, access would either be by means of a road tunnel, as at Paldiski, or a vertical shaft.

The cost of ZT underground pumped storage typically reduces as the depth of the powerhouse and lower reservoir increases, since the lower reservoir volume and size of the turbines and waterways reduces as the head increases. However currently the maximum head used for Francis turbines is 750 metres, which sets the current depth limit for this variant of Zero Terrain.

There are no hard constraints on the installed capacity or size of energy storage. However, in view of the cost of the underground infrastructure, the concept is unlikely to be economic at less than 500 MW or less than 8 hours of storage.

8.2 Deep Underground PSH

The Deep Underground variant of Zero Terrain PSH is almost identical to the Underground option, except that the greater depth and higher head means:

- Ternary Pelton units are required (separate pump and turbine on a common shaft with a fixed speed motor-generator)
- Smaller reservoirs and waterways (storage volume is proportional to the head)
- Since Pelton units must discharge above a free-water surface, and the pumps must be submerged, the operating range of the lower reservoir must be restricted to avoid excessive shaft length. The cavern height is therefore limited to 8 metres.
- Ternary units are able to operate in hydraulic short circuit mode, pumping and turbining at the same time; this allows almost full (0% to 100%) output in both pumping and generating modes, while maintaining high efficiency.
- Mode change times (pumping to generating etc) are typically quicker with Pelton units, since the shaft rotates in the same direction when pumping and generating.
- With the greater depth (1400 m and more below ground level) access by means of a road tunnel is unlikely to be economic. However the development by Herrenknecht of their shaft boring roadheader (SBR) for the mining industry enables blind shafts to be rapidly bored up to 1600 m depth with a high degree of safety in rock up to 120 MPa strength (medium hard to hard rock, including most sedimentary and some igneous rock). The recent 8 m diameter shaft sinking at Nezhinsky mine in Belarus achieved sinking rates up to 144 metres per month. For harder rock up to 250 MPa a shaft boring cutterhead (SBC) can be used.

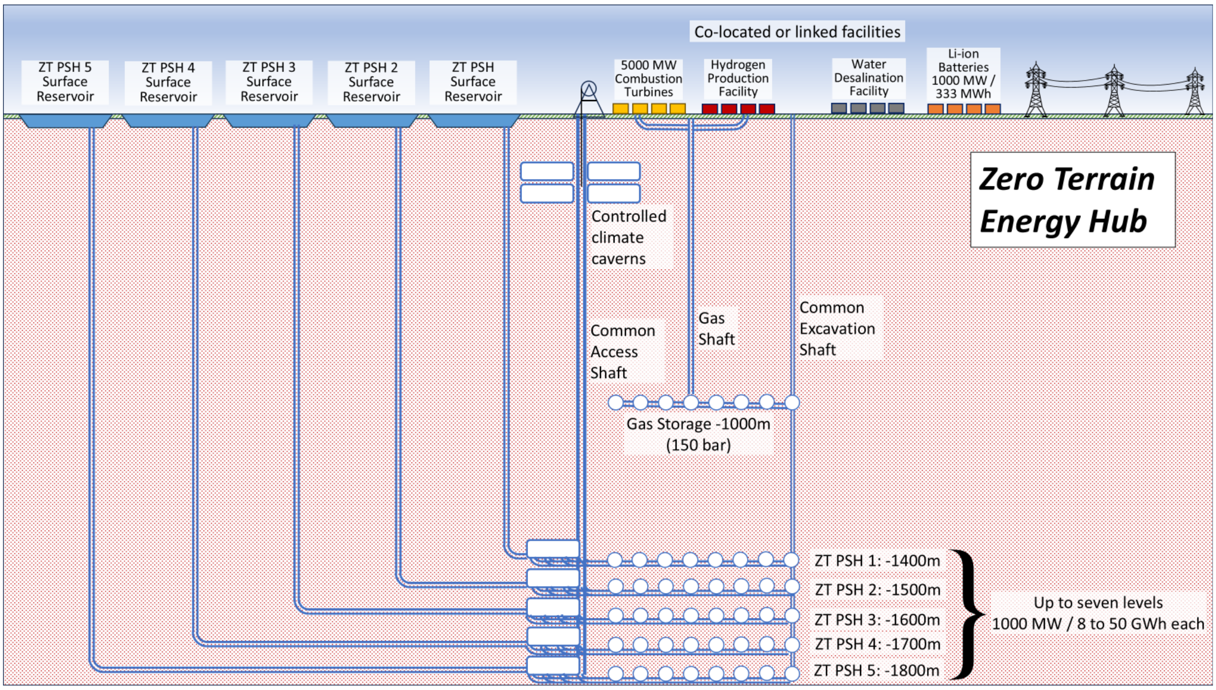
Typical characteristics for the Deep Underground variant of Zero Terrain PSH with Ternary Units are as shown in Table 9.

Table 9: Characteristics of Deep Underground Zero Terrain PSH

Characteristic	Parameter	Comment
Installed Capacity	1000 MW per plant	1000 MW is typically the minimum size to justify the associated infrastructure; Larger plants are possible, and plants can also be constructed at 100 m depth separation (eg 1400 m, 1500 m etc) using common infrastructure. With a limit or 2000 m based on current technology, up to 7 levels of 1000 MW PSH can be installed on a common access shaft.
Hours of storage	Up to 50 hours	Initial operation can start at 8 hours of storage or less; storage capacity can be increased almost without limit by increasing the upper reservoir pond and lower reservoir cavern volumes.
Lower reservoir volume	2.5 mcm	Initial cavern volume around 2.5 mcm at COD for 8 hours; enlarged up to 15.5 mcm for 50 hours as required.
Upper reservoir	2.5 mcm	Upper reservoir with volume matching the lower reservoir is created on the surface using spoil from the cavern excavation. The upper reservoir can be covered to prevent evaporation.
Water	Fresh or desalinated water	The small volume of water required lends itself to use with desalinated water in water-stressed regions.
Depth to powerhouse / head	1400 metres	Current technology for all components is available to at least 1400 m depth / head, and up to 2000 m is feasible.
Turbine type	Pelton Ternary Units	
Fixed or variable speed	Fixed speed	No advantage from variable speed due to the flexibility of hydraulic short-circuit.
Unit capacity	4 x 250 MW	250 MW is a sensible limit to restrict the size and weight of the generators and transformers to be lowered down the shaft. More units at this size are possible.
Access	Shaft	Blind shaft sinking using SBR or SBC.
Lower reservoir construction method	Drill-and-blast	Use of tunnelling jumbos allows excavation to proceed on multiple fronts; rate of progress can be adjusted to suit project schedule. Use of a TBM is possible, but it is difficult to scale up production.
Commercial readiness	Development	All elements are proven technology; most large pumped storage is underground. The head of 1400 m is at the forefront of technology and underground reservoirs are innovative.

Although the current limit of proven technology restricts the depth to 1400 m, incremental advances up to 2000 m depth are planned, based on the experience of the initial plant. Figure 8 shows the typical arrangement for the deep variant of Zero Terrain PSH, with plants on multiple levels (starting at -1400 m and at 100 m depth intervals), together with other facilities that may be associated with the plants.

Figure 8: Deep Underground variant of Zero Terrain PSH showing multiple levels and linked facilities



8.3 Safety and operation

8.3.1 Safety

Many large hydropower and pumped storage projects are predominantly underground, with long tunnels and underground powerhouses. Safety planning during construction and operation have evolved to the extent that some modern underground powerhouses only have a single access tunnel.

For ZT PSH, safety during construction and operation is a priority. During construction a high degree of mechanisation will be used, such as the shaft boring roadheader and raise-boring for shaft construction, computerised automatic jumbos with pre-programmed drilling patterns and remote-controlled mucking plant and support machinery for tunnel construction and multiple exit routes for evacuation. Many of the hazards in underground construction arise from geological uncertainties due to the linear nature of most tunnels. However with ZT PSH the tunnelling is in a small area where the geological conditions are rapidly determined, and methodology to deal with the hazards can be quickly established.

Underground excavation at depths up to 1400 metres is relatively common, including several hydropower tunnels. For example the recently completed Neelum-Jhelum HEP in Pakistan reached depths of 1900 metres below ground level, and Jinping II HEP in China reached over 2500 m depth. Civil engineering tunnels, especially for transport now exceed 2500 m depth, and mining tunnels can reach depths of 4000 m.

The main concern for deep underground excavation is the occurrence of rockbursts, when de-stressing of brittle rock during excavation can result in explosive release of energy and ejection of rock particles. Methods have ben developed for predicting and controlling rock bursts, and the use of mechanisation keeps personnel out of harm's way.

8.3.2 Operation

Like most modern hydropower and pumped storage plants, ZT PSH uses advanced and comprehensive Supervisory Control and Data Acquisition (SCADA) systems to transmit all of the control and monitoring data to a central control room, which may be at the surface or at a remote location. Hence no personnel are required in the underground power station for operating or monitoring. Periodic visits are planned, perhaps once per week, for visual inspections, but even these may soon be replaced by remote controlled robots. Hence only irregular maintenance activities require human presence. Multiple exit routes will be provided for evacuation of personnel working underground.

The Building Information Modelling (BIM) system, creating a digital twin before construction, used in design and construction of ZT PSH will also be used for operation and maintenance. All specifications, tests and maintenance records will be held in the system, and advance asset management with PAS55 / ISO 55000 methodology will minimise the probability of failures and maintain availability.

Fire safety has greatly improved for underground pumped storage with the replacement of oil-filled cables with XLPE (cross-linked polyethylene) insulation in the late 1980s. Advanced fire suppression systems are also provided, although the amount of combustible material in the powerhouse is small. Oil-filled transformers remain a fire hazard, although new dielectric fluids reduce the risk, and separation of the main transformers from other parts of the plant minimises the safety threat.

Rockfalls are a threat in conventional hydro and pumped storage projects that have long tunnels. However with ZT PSH, the high-pressure shafts and critical lengths, such as the draught tubes, are fully lined. Rock falls in the unlined lower reservoir tunnels have little effect in view of the multiple water paths and ease of remediation.

8.4 Mode change times

The main factors governing mode change times relate to the hydraulics of the waterways, and in particular the length to head ratio (L:H ratio) between the nearest free-water surface and the turbines. For reversible Francis turbines a surge shaft is typically required if the natural L:H ratio is less than 4 (typically less than 5 for conventional hydropower, but pumped storage tends to have more onerous hydraulic transients). The fastest reacting PSH, such as Dinorwig, have an L:H ratio of 2 or less.

Traditional topographic PSH used for time-shifting energy between off-peak and peak times, working in conjunction with nuclear or steam plant had little need for fast response, and hence the mode change times tend to be quite long, as shown in Table 10. However future role of PSH in integrating vRE and providing grid services means that fast-response is now essential.

The high head of Zero Terrain PSH combined with the ability to locate the upper reservoir almost immediately above the powerhouse provides a L:H ratio close to 1.0. This ensures the fastest possible response times for Zero Terrain PSH.

Examples of the mode change times for typical topographic PSH, and Zero Terrain PSH with reversible Francis turbines (Underground concept) and Pelton Ternary units with hydraulic short circuit (Deep Underground variant) are shown in Table 10, with the transitions shown in Figure 9.

Figure 9: Transitions between various PSH operating states

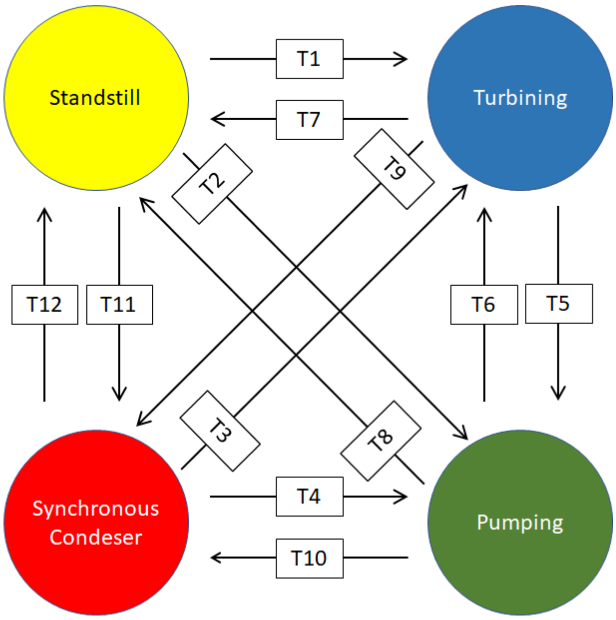


Table 10: Transition times between various PSH operating states

Transition	Description	Typical Traditional Topographic PSH	Zero Terrain Reversible Francis	Zero Terrain with Pelton Ternary + Hydraulic Short Circuit
T1	Standstill to Turbining	< 150 s	< 75 s	< 60 s
T2	Standstill to Pumping	<480 s	< 160 s	< 80 s
T3	Synchronous Condenser to Turbining	<100 s	< 16 s	< 20 s
T4	Synchronous Condenser to Pumping	< 70 s	< 30 s	< 30 s
T5	Turbining to Pumping	< 420 s	< 240 s	< 30 s
T6	Pumping to Turbining	< 200 s	< 90 s	< 30 s
T7	Turbining to Standstill	< 360 s	< 200 s	< 120 s
T8	Pumping to Standstill	< 360 s	< 160 s	< 60 s
T9	Turbining to Synchronous Condenser	< 80 s	< 30 s	< 30 s
T10	Pumping to Synchronous Condenser	< 150 s	< 30 s	< 30 s
T11	Standstill to Synchronous Condenser	< 360 s	< 120 s	< 60 s
T12	Synchronous Condenser to Standstill	< 420 s	< 200 s	< 120 s

9 Zero Terrain PSH Services

The general characteristics of Zero Terrain PSH are discussed in section 8, and the energy services that can be provided are presented below in more detail. Pumped storage hydro is often described as the “decathlon” of power system infrastructure; whereas some generation and storage provides a single service, PSH provides a wide range (more than 10) services to the grid. For this reason, it is sometimes described as "*the Grid Operator's Best Friend".*

As early as 2014, the Irish grid and system operators analysed the system services available from all their generating plant (EirGrid and SONI, 2014), and concluded that their pumped storage scheme out-performed all of their other technologies on virtually every ancillary service. However it is interesting that in the absence of new pumped storage, Ireland is having to install stand-alone synchronous condensers to support the grid, in addition to batteries and other grid infrastructure.

One of the key issues is that most other generation technologies which provide inertia must be generating, usually at 40% to 50% of rated capacity, if they are connected to the grid. Like the stand-alone synchronous condensers, PSH can be synchronised to the grid at no load, and hence it can provide inertia (and other grid support services) without displacing vRE (some conventional hydro can also do this).

9.1 Time Shifting (arbitrage)

Traditionally PSH was used in conjunction with coal and nuclear generation to time-shift off-peak generation to peak times. The low marginal generation costs of these technologies meant that cheap night-time electricity could be transformed to high-value day-time generation. The normal PSH cycle was 10 hours of pumping and 8 hours of generation, meaning that 8 hours of storage was typical. As gas started to replace coal, its higher variable cost and greater flexibility meant it was more economic to vary the output of the gas-fired plant to suit demand, and the opportunities for arbitrage reduced.

With vRE the situation is more complex. At low vRE penetration the output can typically be absorbed by the grid, displacing other generation. The need for time-shifting and opportunities for arbitrage are minimal. However as vRE penetration increases, especially in systems dominated by one vRE technology, vRE generation at times of high output starts to match or exceed demand resulting in low or negative energy values. This is most predictable in PV dominated systems, but also occurs with other technologies. For example in California it is now common to have negative day-time electricity prices. With high evening demand resulting in high tariffs, new arbitrage opportunities emerge for energy storage.

High levels of vRE penetration cannot be achieved without energy storage. On a largely PV supplied system up to 20% grid demand can be supplied by PV energy without storage, with virtually no curtailment. However 20% is the tipping point: to achieve 25% of demand by vRE without storage the PV capacity must be doubled, and 75% of the incremental PV production is curtailed[5]. The limit for PV is around 30% of demand, beyond which virtually all additional vRE is wasted. Six to 8 hours of energy storage enables daily time-shifting and can avoid most of the curtailment. However high levels of storage capacity (MW) are needed: in the extreme the PSH capacity needs to match the evening peak demand if there is no despatchable generation on the grid.

In practice longer durations of storage are beneficial for grid security and on mixed technology systems: European grid operators are planning for 20 to 40 hours of storage – a duration that is unlikely to be available from battery systems. These long durations are ideal for PSH, where more storage only requires larger reservoirs and more water, with consequently low marginal storage cost.

[5] Author's modelling of a PV dominated Gulf State electricity system.

9.2 Synchronous Inertia

A growing problem for vRE dominated systems is the lack of synchronous inertia that stems from wind and PV generation being asynchronous. While traditional generators are mechanically linked to the frequency of the grid (50 or 60 Hz), and the rotational speed of the generators and attached turbines needs to change if the grid frequences changes. Hence the rotational inertia of plant resists changes in frequency, and is an important characteristic in limiting the rate of change of frequency (RoCoF) when an imbalance event occurs.

Many grid operators do not know how much inertia is needed to avoid grid stability problems, and few know how much inertia is actually on the grid. Traditionally there was a surplus of inertia from all of the synchronous generation. On the GB grid it was calculated that 140 GVA.s of inertia was needed to avoid problems when a large generator or interconnector tripped, although this has subsequently been reduced to nearer 100 GVA.s by relaxing quality criteria. The mandatory grid frequency limit on the grid is 49.5 Hz to 50.5Hz. For a deviation of ±0.5Hz, 2% of the system inertia can be transferred before the limited is exceeded, or 2.0 GVA.s of the 100 GVA.s. For a 1000 MW disturbance the grid frequency limit would be exceeded after 2 seconds, within which time virtual inertia has to start injecting active power. In theory this is quite possible, although in real time the system operator's algorithm does not know how much active power to inject.

As the amount of synchronous generation on the grid reduces, inertia is being supplied by forcing thermal generators or synchronous hydropower to operate just to provide inertia, producing their minimum power output (typically 40% to 50% of rated output). However this minimum level of power is displacing vRE, resulting in even more curtailment.

An alternative to synchronous generators is stand-alone synchronous condensers, such as those being installed in GB. These are large fly-wheels attached to motors that mimic the effect of synchronous generators without displacing vRE.

The substantial cost of stand-alone synchronous condensers or operating thermal plant at part-load can be avoided with fixed-speed pumped storage plants, which typically have the ability to operate in synchronous condenser mode at no load. Recently the GB system operator awarded a contract to Cruachan Pumped Hydro to provide 533 MVA.s of inertia from one of its 110 MW reversible units.

Synchronous inertia should not be confused with virtual inertia, a service that can be provided by batteries, variable speed pumped storage and some vRE through ultra-rapid injection of active power into the grid. However virtual inertia requires measurement of the frequency deviation (which takes some 0.2 seconds) and power despatch or frequency adjustment (0.1 seconds) to activate. Unlike the passive response of synchronous inertia, virtual inertia provision must be staggered to avoid overshoot, and hence the real-life response times can extend to seconds.

9.3 Regulatory Capacity

A wide range of regulatory control services can be provided by pumped storage hydro. The regulatory capacity is typically double the quoted rated capacity. PSH can usually regulate from -100% in pumping to +100% in generation mode. When pumping, fixed speed reversible units can only operate at -100% (i.e. full pumping capacity), while the generation range is typically 40% to 100% of rated capacity. Ternary PSH equipped with hydraulic short circuit, as used in the deep variant of Zero Terrain PSH, can pump and turbine simultaneously, giving almost full range (0% to 100% of rated capacity) operation both for pumping and generating.

Depending on the market and the characteristics of the products, ZT pumped storage should be able to provide most balancing services. As can be seen from Table 10, the transition time for both reversible Francis ZT and the deep underground variant using ternary units from SC mode to generating or pumping is below 30 seconds. For the best case, SC to generating should be achieved in around 15 seconds.

While reversible Francis units can transition from pumping to generating in less than 90 seconds, and from generating to pumping in less than four minutes, ternary units can transition both ways in less than 30 seconds, as the direction of rotation of the shaft is the same for both pumping and generating.

While hydraulic transients can impede conventional hydropower from meeting the fast response requirements for Frequency Containment Reserve (FCR), the short waterway length and L:H ratio of ZT PSH ensure that the fastest possible response time is achieved to meet the FCR criteria.

Fast ramping can be achieved with both reversible and ternary units, with ramp rates typically greater than 10% per second. This means that a 500 MW ZT PSH can ramp faster than 50 MW per second, and the deep underground 1000 MW ZT variant can ramp faster than 100 MW per second.

Without the lifetime cycling limits of Li-ion batteries, ZT PSH can be cycled through multiple mode changes and hundreds of set-point changes per day, making it invaluable to System Operators struggling to integrate vRE.

9.4 Voltage / Reactive Power Control

Like other pumped storage plants, ZT PSH can help control the voltage level through reactive power: production or absorption of reactive power will raise or lower the grid voltage, helping to maintain it within safe limits.

Pumped storage can provide reactive power rapidly on demand, and with the ability to deliver reactive power when spinning in air (synchronous condenser mode), reactive power delivery is independent of active power.

Unlike conventional pumped storage with its topographic constraints, ZT PSH can be constructed anywhere, including locations where there is likely to be a need for reactive power.

9.5 Black Start and System Reconstruction

A growing issue, partly linked to the complexity of operating vRE dominated grids, but also related to erosion of firm capacity margins and the difficulties in keeping pace with surging electricity demand, is the propensity for system blackouts. Once the preserve of emerging economies, there is now a growing probability of total grid failure on many power systems. System operators now need to actively plan for blackstart and grid reconstruction.

Historically total system blackouts were considered a sufficiently rare event that grid reconstruction over a period of days seemed reasonable, and on many systems coal-fired generators provided the primary blackstart resource. With the increasing likelihood of blackouts, the demise of fossil fuelled generators and the increased economic and social importance of rapid supply restoration, there is more focus on re-building grids rapidly, and restoring power to regional sub-grids simultaneously.

Trials have been carried out to reconstruct grids using wind generators and battery storage equipped with grid-forming inverters. While providing plausible theoretical results, these technologies fail in the most important criterion: wind production may be very low (a likely cause of the grid failure), and batteries, if charged will have limited production duration.

In addition to the ability to start without external energisation and to form both frequency and voltage, there is a need to carefully balance supply with demand. Controllable and despatchable output is needed to match the block loading that typically introduces less than 5% of the system load at a time. Reactive power is needed to regulate the voltage, especially with long lightly loaded transmission lines and transient over-voltage from large inrush currents.

Pumped storage plants are ideally suited to provide blackstart services. However due to topographic constraints, traditional pumped storage plant is often remote for the major load centres, reducing their effectiveness. ZT PSH can be located close to load centres, and can also be located in each power island to enable local networks to be individually re-energised prior to reconnection to restore a national network.

9.6 Alleviation of Transmission Constraints

One of the most valuable services provided by ZT PSH is the alleviation of transmission constraints within or between grids, and the avoidance of transmission capacity enhancements.

In many regions the greatest renewable energy resource is remote from the largest load centres. In GB the largest wind resource is in Scotland, whereas over 60% of demand is in the Midlands and the South. The 2 GW sub-sea HVDC Eastern Greenlink 2 project is currently under construction at a cost of around US$6 bn to transfer Scottish vRE 500 km to the south. In Germany three major HVDC links are among the infrastructure planned to transmit electricity from the windy north to the industrial south. The 2 GW A-Nord underground cable project, the first half of the westernmost link, has started construction, with an estimated cost of US$1.6 bn.

With these projects sized to prevent significant vRE curtailment, there will be a problem maintaining high capacity factors. Wind energy generators typically operate with 25% to 35% capacity factor. If transmission capacity is provided to cope with peak generation, they would have a similarly low capacity factor. The problem is exacerbated when the existing network can transmit much of the base load, meaning the new line only handles the surplus power. Provision of LDES at either end of transmission lines can increase the capacity factor of existing and new-build transmission lines, reducing the need and associated cost of additional lines. While conventional pumped storage can offer some of this service, ZT PSH is inherently more suited due to its ability to be constructed where it is needed.

The saving in cost is not the only benefit: planning and permitting new lines can take many years, with environmental opposition often delaying projects. Any reduction in the need for new transmission can have huge environmental and social benefits, political advantages and reduction in opposition to vRE projects.

Another transmission issue receiving increased publicity is the role of transmission lines in starting wildfires. Using ZT PSH to increase the capacity factor of transmission lines can enhance the economic justification for upgrading these existing lines, either to underground cables or high clearance overhead lines. Where Public Safety Power Shutoffs to transmission lines are required, LDES, such as ZT PSH, at either end can reduced generation curtailments and guarantee supply to consumers, especially critical service providers.

9.7 Summary of Ancillary Services

A comparison of the services available from pumped storage and the two variants of ZT PSH is provided in Table 11 below.

Table 11: Comparison of Ancillary Services from Pumped Storage Types

Type of PSH	Synchronous Inertia	Frequency Response	Fast Ramping	Voltage/ Reactive Power Control	Blackstart / Reconstruction	Transmission Constraint Alleviation
Conventional (topographic)	✓	✓	✓	(✓)	(✓)	
ZT with Reversible Units	✓	✓	✓	✓	✓	✓
Deep ZT (Ternary Units)	✓	✓	✓	✓	✓	✓

9.8 Summary of Zero Terrain PSH Characteristics

The characteristics of Zero Terrain PSH are summarised in Table 12 below:

Table 12: Summary characteristics of Zero Terrain PSH

Characteristic	Particulars
Power	500 to 1000 MW per plant; up to 7,000 MW on one site for 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 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

10 Other Uses for Geological Infrastructure

With the establishment of sub-surface geological infrastructure for ZT PSH, there are opportunities for other underground facilities to make use of this infrastructure using the common main access shaft. Some of these facilities, such as data centres, benefit from the grid connections and energy storage associated with ZT PSH. Others primarily benefit from the access and construction activity for ZT PSH. Examples include:

10.1 Co-location of Electrical Facilities

ZT PSH will require a bi-directional high voltage transmission line and switchyard for its grid connection. For the initial project at Paldiski in Estonia this grid connection will have a minimum capacity of 500 MW; future projects are likely to have a minimum of 1000 MW. Co-locating PV facilities, gas/hydrogen-fired generation, batteries or ultra-capacitors to operate conjunctively with the PSH can optimise the use of the grid connection, and the marginal cost of increasing the capacity of the connection facilities would be low.

Pairing li-ion batteries and/or ultra-capacitors and grid-forming inverters with PSH can have benefits for system stability, providing virtual inertia to reinforce power injection in the sub-15 second period following a system disturbance. The maintenance cost of PSH can also be reduced by using batteries or capacitors to reduce the output variation of the PSH. However the limited lifetime of li-ion batteries of 3,000 to 4,000 cycles tends to preclude their use for frequently fluctuating output. Hence ultra-capacitors without this restriction are more likely for this conjunctive operation.

While pumped storage is the preferred technology for LDES, on many systems there will be a need for despatchable emergency generation. As on the future grid this will have a very low capacity factor, being used typically less than 5% of the time, gas turbines or reciprocating units will be most economic. With an objective of transitioning to net zero, a good solution will be to install plant that can initially be fired with natural gas, but in future will be fuelled with hydrogen. Co-locating the green hydrogen production facility with ZT PSH provides it with a secure and stable electricity supply. At such a low capacity factor, the inefficiency of the electricity to hydrogen to electricity (E2H2E) cycle will be of little significance. Co-locating this gas plant with ZT PSH and geological gas storage as discussed in 10.2 below, will create an energy hub of great benefit to the grid.

10.2 Gas Storage

The most economic gas storage facilities use naturally occurring caverns – typically salt caverns. Where natural salt caverns are not available, solution mining can be used to excavate storage economically in suitable salt strata, although with significant environmental impacts. However such caverns where available, may not be located at suitable depth to achieve economic storage pressure, and the high diffusivity of hydrogen can lead to leakage.

Using the access and construction facilities created for ZT PSH, caverns for storage of gas can be excavated to provide secure gas storage. When paired with combustion engines or gas turbines at the surface, it provides an excellent emergency generation facility. Initially natural gas can be stored, but the long-term aim is to transition to hydrogen storage, with the full E2H2E cycle on site. A 1.0 mcm cavern at 150 to 200 bar would store some 500 GWh of hydrogen energy, providing over 100 GWh of electrical energy or 100 hours from a 1 GW of hydrogen generation capacity.

10.3 Flow Batteries

As discussed in section 6.4, flow batteries such as vanadium redox flow batteries, are likely to contribute to the huge global LDES requirement. Flow batteries require a significant storage volume for the two electrolyte cells, and ideally the electrolyte is maintained at a reasonably constant temperature. Hence underground caverns can provide a good solution for electrolyte storage as well as the reaction cell and power controller.

For a 100 MW Vanadium Redox flow battery having 20 hours of storage (i.e. 2000 MWh), the required volume of electrolyte storage is around 120,000 m³. While this is very manageable underground, on the surface it would require over 1000 tanks of 6 m diameter and 4 m high. Maintenance of constant temperature underground is easier than on the surface, especially in regions of extreme climates.

Again the use of the ZT PSH grid connection can improve the economics of the flow battery installation.

10.4 Constant and Controlled Environment Facilities

A feature of underground infrastructure is the constant temperature of the surrounding rock. While deep underground the temperature may be high, closer to the surface it is usually moderate and ideal for controlled environment facilities. This is a particular benefit in regions of extreme temperature, such as the high temperature and humidity encountered in summer in the Middle East, or the extreme cold in winter in Canada and the Nordic countries.

In addition to environment, geological infrastructure is typically less susceptible to seismic activity.

Among the facilities that can benefit from location underground are:

- **Data centres:** As well as providing a controlled environment, underground data centres as part of ZT infrastructure benefit from constant high-quality electricity supply, access to water and good security through controlled access.
- **Agricultural facilities**: Geological infrastructure can provide a controlled environment for hydroponics and other advanced agricultural solutions. This is of particular benefit in regions of extreme heat or cold, offering year-round growing, with secure access to electricity and water.
- **Secure storage**: Underground storage for documents, valuables and artworks can benefit controlled environment and security.

10.5 Military and Critical Infrastructure

Military facilities and critical infrastructure can be located underground to provide security against attack and unauthorised access, as well as having access to secure electrical and water supplies.

10.6 Strategic Water Reserve

The water used in the pumped storage can provide several million cubic metres of strategic water reserve at no extra cost. Water can be “borrowed” from the storage reservoirs at times of shortage, to be re-filled later to restore the electrical storage capacity when supplies become available again. The full development of the deep underground ZT PSH variant of 7000 MW with 24 hours electricity storage would hold over 40 million cubic metres of water, much of which could be used as an emergency reserve.

The concept of an underground strategic water store is millennia old, with examples such as the 80,000 m³ Basilica Cistern in Istanbul. In Abu Dhabi some 26 million m³ of water is stored in a strategic reserve at Liwa, providing 90 days of reserve supply at a reported cost of US$435 million.

10.7 Source of Aggregate

In Estonia most rock available at the surface is limestone, which degrades when used in construction such as road surfacing. More resistant rock has to be imported from neighbouring countries. The gneiss extracted during excavation of the underground PSH caverns will provide millions of cubic metres of high-quality aggregate. Similar benefits may be available elsewhere to subsidise the cost of the excavation.

10.8 Visually Intrusive or Noisy Facilities

Visually intrusive or noisy facilities can be located underground to avoid environmental disturbance. Also the large quantity of rock removed during excavation of the underground works provides opportunities for landscaping: bunds can be constructed around the ZT facilities early during construction to minimise disturbance from construction activities. Also bunds can be used to ensure resilience against flooding of the ZT infrastructure.

10.9 Parking and EV Charging

In addition to providing a moderate temperature and secure environment and saving land area, the secure electrical supply enables high voltage vehicle charging for large numbers of vehicles. There is also potential for vehicle-to-grid (V2G) connections, enabling vehicle batteries to be used for grid storage.

11 Regulatory Changes to Promote PSH

The key lesson emerging from recent grid disruptions is that power systems need to be meticulously planned and managed, in view of the complexity of operating grids supplied by vRE. **Whereas traditional grids supplied by dependable, despatchable generation with high inertia were inherently robust, grids of the future will be fragile**. The issue is of particular concern for de-regulated electricity markets, where market forces drive which projects are developed and how they are operated. This worked reasonably well in historic markets, where different technologies had different fuel costs and efficiencies, and cost-supply elasticities worked to maintain secure and reliable systems. In the future, when virtually all generation has zero marginal cost, these elasticities break down; paying more does not make the wind blow or the sun shine.

11.1 PSH as Grid Infrastructure

As discussed in the previous sections, PSH will be a critical component of the future power grid, enabling the system operator to provide economic and dependable electricity to consumers. The system planners need to configure PSH to meet the demands of the grid, both in terms of energy storage and the grid services provided, and then to operate it for optimised grid benefit. Since many of the services provided by PSH are mutually exclusive and cannot be stacked, the facilities need to be operated strategically to minimise the system cost and maximise system security, rather than maximising commercial revenue.

Models need to be implemented that provide the system operator with full control of the planning and operation of PSH.

Among the benefits of ZT PSH is the ability to locate it almost anywhere to suit the grid requirements, and the rapid response time is of huge value to the system operator for balancing the system.

11.2 Leasing or EPC+F

Regulatory models where the PSH owner derives his income from energy arbitrage and selling services tend to result in projects located, configured and operated for maximum commercial profit, based on the market at the time the project is planned. Services that are not monetised are unlikely to be taken into account, and the future needs of the system receive little consideration.

A better model enables the system planner / operator to configure the project precisely to the future needs of the power system, and then to operate it for optimum system benefit. This ensures the most economic system consistent with grid security for the benefit of consumers.

Models that enable the system planner to define the PSH parameters and then use private sector finance and expertise to deliver the projects include leasing (such as FELT[6] and BELT) and EPC+F. In both of these models the system planner has full control of the PSH configuration, bringing the project to EPC tender stage (defining the owner's requirements) before going to the market. Under these models the system operator has full control of the facility; the owner's revenue or the EPC contractor's reimbursement are unaffected by how it is operated.

Capacity payments, becoming common for IPP hydropower, allow some degree of flexibility of operation. However availability and O&M costs depend on how the facility is operated: one mode change is the equivalent of hundreds of hours of steady-state operation, and aggressive use of PSH capabilities can result in extra down-time for maintenance. Hence capacity payments that are based on availability tend to have restrictions on operation, limiting the system operator's flexibility.

12 Conclusions

As discussed above, the need for long-duration energy storage (LDES) to support the integration of vRE will be huge over the next few decades; pumped storage is ideally placed to provide this service, and Zero Terrain PHS has the characteristics that make wide-scale deployment of PHS possible.

In particular:

- By 2060 more than 5,000 GW and over 100 TWh of LDES will be required to support vRE; most of this is new capacity – 10,000 projects the size of ZT Paldiski PSH (500 MW / 20 hours).
- The duration of storage is increasing: whereas previously 1 to 2 hours of BESS was adequate, upwards of 10 hours is now required.
- In addition to storage; other services are needed to run the grid including mechanical inertia, balancing services, voltage and reactive power control and blackstart / reconstruction.
- Pumped storage is ideal for providing this LDES and the critical grid services, but the bespoke nature and environmental impacts are problematic
- ZT PHS which can be constructed almost anywhere, is modular, and can be deployed rapidly, seems to be the most appropriate technology to enable the massive roll-out of vRE that is needed.
- The geological infrastructure of Zero Terrain can have multiple uses, with the technology at the centre of an invaluable energy hub, as well as housing other important infrastructure.
- ZT PHS enables the large-scale deployment of vRE, and makes sure that largely vRE based grids can be stable and secure.

[6] FELT or Finance, Engineer, Lease and Transfer is a model developed by Mike McWilliams – see MCWe FELT and MCW-e FELT paper; BELT (Borrow Engineer Lease and Transfer – see BELT paper) is a variant of FELT aimed at reducing the cost of public infrastructure.

- By supporting vRE deployment, ZT PSH ensures the least cost of energy, helping national economic growth and boosting energy intensive industries.
- The geological infrastructure provided by ZT PSH can enhance national economic development and self-sufficiency.
- De-regulated electricity markets need to be reconfigured to allow the system operator to specify the characteristics of their infrastructure and facilities, and to have full flexibility in operating the plants.

It is clear that large-scale deployment of Zero Terrain PSH is needed now to enable decarbonisation of the world's electricity grids to continue, and to minimise the cost of reliable electricity supplies. The countries that make the right choices – developing secure, stable and cost-effective grids with a balance of low-carbon generation, BESS and pumped storage, will become the leaders in industrial production and technology deployment.

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