

Underground Pumped Hydroelectric Storage: A Feasibility Study

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Abstract

In this report, we argue that it is feasible for an energy storage technology called Underground Pumped Hydroelectric Storage to play a fundamental role in our fight against climate change.

For context, we discuss how energy sources like wind and solar are expected to replace fossil fuels, which will increase the variability of our grid's supply, which in turn will drive an exponential growth in demand for energy storage.

We then argue that underground pumped hydro technology could provide plentiful energy storage at the most affordable cost. We demonstrate that over a time frame of 40 years, this solution could be an order of magnitude cheaper than chemical battery solutions like Lithium Ion.

Recent studies have concluded that stationary energy storage demand is expected to grow exponentially in the coming decades. This growth will require half a trillion dollars of investments over the next two decades, and this will still not be enough to support our renewable energy goals. One study estimates that if the United States transitioned to 80% wind and solar energy, the necessary energy storage would cost \$2.5 trillion.¹

This report will demonstrate that underground pumped hydro could meet our energy storage demand at a significantly lower cost than lithium ion batteries. We believe that underground pumped hydro could capture a large part of this rapidly growing market. We advocate for the immediate development of this technology on sites deemed suitable for profitable installations.

We only get one home.
We only get one planet.
There's no plan B.

– *President Barack Obama*²

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1 Introduction

Climate change poses a dire threat to humanity. The research is clear: If we do not mitigate this risk soon, climate damages will escalate beyond our control.

In this report, we examine why it will be critical in our fight against climate change to build an enormous capacity of energy storage in the coming decades. We will then advocate for a particular technology called Underground Pumped Hydro Energy Storage. We will demonstrate that this technology has unexplored potential for providing plentiful energy storage at the most affordable cost.

1.1 Climate Change: Risk and Opportunity

The 2018 US National Climate Assessment Report concludes that if we do not mitigate climate change, we face “substantial damages to the economy, environment, and human health over the coming decades.”³ This is not a political issue. Even if health and environmental factors are omitted from discussion, projected economic costs are a sufficient cause on their own to justify urgent climate investments.

According to a report by The Universal Ecological Fund, by the next decade, climate damages will cost the United States \$360 billion a year on average. That’s half of the expected growth of the economy.⁴ The report affirms that “The benefits of taking climate action outweigh the escalating economic losses and health damages.”⁴ Plain and simple, it is cheaper to deal with climate change than to ignore it.

1.2 Green New Deals: Cities Aim for 100% Renewable Energy by 2050

“There’s been a global culture shift around clean energy,”⁵ concludes The Solutions Project, an organization whose board includes Mark Jacobson, a professor of civil and environmental engineering at Stanford. The Solutions Project (TSP)

reports that:⁵

- Hundreds of major companies have committed to go 100% renewable.
- 70% of people now “agree that we should produce 100% of our electricity from renewable sources in the near future.”
- Six cities are already running on 100% renewable energy, and over 100 U.S. cities have made the 100% commitment.

As depicted in the map below, over a hundred cities across the U.S. have drafted their own “Green New Deal” promises, pledging to become carbon neutral by 2050. These cities include San Francisco⁶ and New York.⁷ In this paper, we will use these two cities as case studies in order to depict how proposed solutions might work for these real use cases.

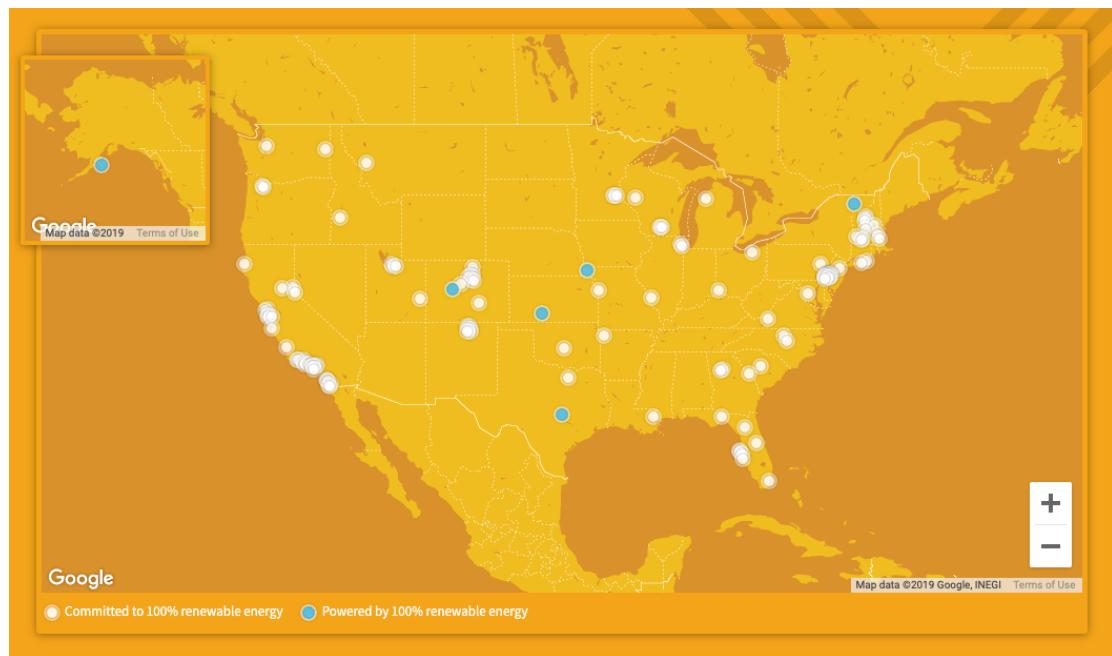


Figure 1: The Solutions Project - cities pledging zero carbon by 2050⁵

Before Mark Jacobson joined The Solutions Project, he co-authored a report in 2015 which concluded that we can and should convert the United States to 100% renewable energy by 2050. In the report (Jacobson report), he says this transition would be, “technically and economically feasible with little downside,”⁸ and that the transition would provide massive benefits including:⁸

- A reduction of each state’s end-use power demand by about 39%
- A net gain of 2 million additional long term jobs
- Saving tens of thousands of annual premature deaths related to air pollution
- Saving an estimated \$2-\$7 trillion per year in 2050 global warming costs to the world due to U.S. emissions
- Saving each U.S. resident \$260 per year in energy costs (\$2013 dollars)

By quantifying and explaining the net benefits of going carbon neutral, the Jacobson report said it hoped to “reduce social and political barriers to implementing clean-energy policies.”⁸

In writing our report, we take inspiration from Jacobson’s cause-driven research. In our report, we intend to highlight a particular technology which could solve a troubling problem with projected renewable energy growth. This technology, called Underground Pumped Hydro Energy Storage, or UPHS, could be our best hope to solve a looming shortage of energy storage. If this shortage is not covered, it will hinder future expansions of wind and solar energy.

1.3 Introducing Underground Pumped Hydro Energy Storage

UPHS was thoroughly researched and validated in the 1980s. But it seems the idea has been largely forgotten since. In our report, we will resurface the conclusions of this past research and show how UPHS might play a critical role in our fight against climate change.

Our report will first discuss Pumped Hydro Energy Storage in general (see explainer below: “What is Pumped Hydro?”).

Then, we will focus specifically on underground pumped hydro (UPHS) which is a variation of pumped hydro energy storage (PHS). Citing existing research, we will argue that UPHS is a promising alternative to today’s energy storage solutions.

Even though UPHS has never been built on a large scale, research has shown it to be technically feasible and cost competitive. It combines well understood engineering principles without any risky new technologies. And it has a lower ecological footprint than traditional PHS which could prove invaluable for surviving the gauntlets of development approvals which often doom traditional PHS projects.

1.4 San Francisco and New York City Commit to Green New Deals

San Francisco and New York City have both recently pledged that their cities would transition to 100% clean electricity by 2050.⁶⁷

New York City's Green New Deal is outlined in the "A Livable Climate" section of their "OneNYC 2050" report published in 2019. Their report promises:

"Our multifaceted strategy for action is ambitious and far-reaching — as it must be....It will require innovation to find less expensive and more effective solutions; creative financing and financial investment; and partnerships across communities, sectors, geographies, and all levels of government."⁹ – OneNYC 2050 Report

The NYC report acknowledges the need for increased energy storage. It states, "[deployment of wind and solar power] must expand rapidly in the next 20 years, and will need to be complemented by a significant expansion in energy storage."⁹ It states further, "Energy storage resources will be required to balance the intermittent nature of renewable power generation, and we want to have 500 MW of storage available by 2025."

500 MW is an ambitious goal for New York City considering that as of 2017, they only had 5 MWh of storage.¹⁰ Yet, even if NYC met this goal, it would still provide only a 2.8% buffer for their total power usage (See Appendix). As we'll see below, this may not be enough power storage to support a large increase of

wind and solar generation.

San Francisco also recently published a technical report which outlines their roadmap to achieve net zero emissions by 2050.¹¹ “Every generation is defined by how they tackled a seemingly-insurmountable obstacle, and climate degradation is our generational marker,” said San Francisco Supervisor Ahsha Safai as the city announced their commitment for net zero emissions by 2050.¹²

San Francisco’s report only briefly mentions their future energy storage needs, but other research offers more detail. A 2017 report by the Bay Area Council Economic Institute (BACEI report) discusses California’s energy storage needs in general:

“The need for energy storage and the energy storage market are growing rapidly as renewable generation, energy policies, and greenhouse gas reduction goals impact how the grid needs to be managed.”¹³ –
Bay Area Council Economic Institute

According to the report, in order for California to reach their target of 50 percent renewable energy by 2030, the state will need about 2.2 GW of additional energy storage capacity to add to their existing 4.2 GW (as of 2017).¹³

Using San Francisco and New York City as case studies, this report will examine how underground pumped hydro energy storage could help large cities meet their growing demand of energy storage. We will assess the enormous energy storage capacity needed to achieve the city’s promised goals of 100% renewable energy. And we will advocate that UPHS may be the cities’ best option to supply their required energy storage volume.

2 Why Energy Storage?

Renewable energy sources like wind and solar have matured into a small but significant share of the energy market. These renewables are expanding rapidly, helping reduce the greenhouse gases which contribute to climate change. But even as a small market, these new energy sources have caused a troublesome side-effect on our energy supply. Since the sun doesn't always shine and the wind doesn't always blow, renewables increase the variability of our net power supply.

This simple effect has a complicated impact on our energy grid. Our grid cannot tolerate variability. To avoid surges or rolling blackouts, the grid must maintain a constant balance of supply and demand. And with our current infrastructure, there is very little wiggle room.

It has been well reported for years that there is an important correlation between energy storage and renewable electricity. In a 2010 technical report, the U.S. National Renewable Energy Laboratory (NREL) concluded: “It is clear that high penetration of variable generation increases the need for all flexibility options including storage, and it also creates market opportunities for these technologies.”¹⁴

These market opportunities become clear when we examine the costly inefficiencies that arise from a lack of energy storage. Even at today’s levels of variable generation, curtailment is becoming an expensive problem. This issue is explained in detail by the BACEI report referenced earlier:

“During overgeneration conditions primarily driven by an oversupply of solar, the power being generated is in excess of real-time demand. This leads to what is referred to as the “duck curve”...which projects the supply-demand gap produced by variable power. The “belly” of the duck shows lowest net load, when solar generation is highest, followed by the afternoon upward ramp or “neck” of the duck. In the absence of an ability to store that excess energy, overgeneration is

currently being addressed by curtailment—the purposeful reduction of renewable generation in order to keep the grid stable. This is done by decreasing the output from a wind or solar plant or disconnecting the plant altogether. Curtailment can be done for large renewable power plants but not for smaller or distributed systems like rooftop solar.”¹³

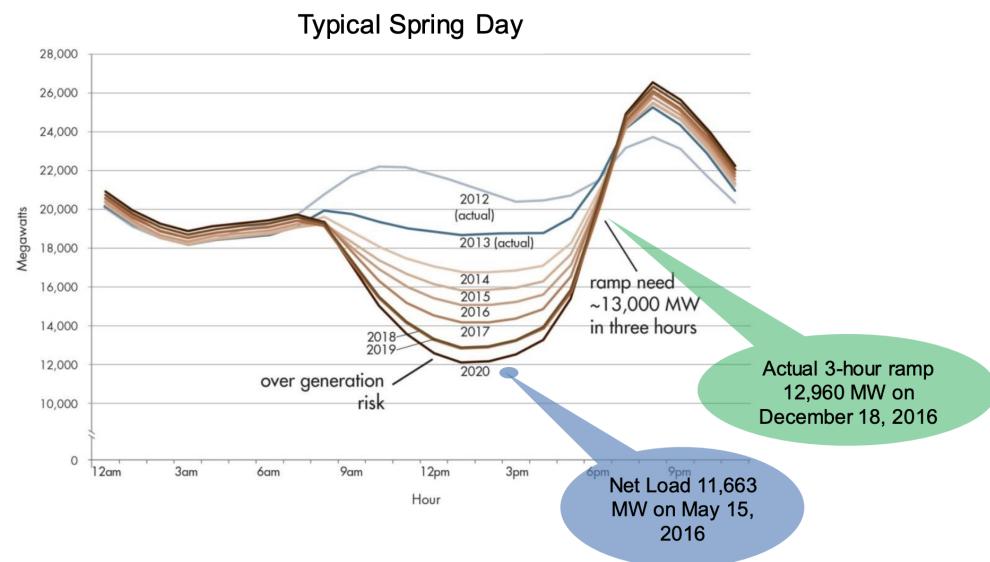


Figure 3. CAISO duck chart (source: CAISO)

Figure 2: Graph illustrating a “duck curve.” Source: California ISO¹⁵

Without sufficient energy storage capacity, our grid must instead rely on so called peaker plants in order to avoid rolling blackouts during peak loads. Fossil fuel burning peaker plants are inefficient and expensive because they must remain inactive most of the time and kick into production only when the grid’s demand spikes to peak load. Energy storage solutions are cleaner alternatives, and due to a drop in battery prices, they are becoming price competitive as well. The market is beginning to respond to this new reality. Initiatives across the United States are beginning to replace these polluting peaker plants with chemical battery facilities.^{16,17}

2.1 The State of our Energy Storage

In the United States, our energy storage capacity is only 2.5% of total electric power. For comparison, 10% of delivered power in Europe and 15% of delivered power in Japan are cycled through energy storage facilities.¹⁸

With such a low capacity of energy storage, we are ill prepared to handle an increase in variable energy generation. As mentioned above, some initiatives have begun to address local energy storage problems with chemical battery facilities. But this is on a very small scale.

Looking at the big picture, nearly all of our storage capacity (94%) is generated from pumped storage.¹⁹ Chemical batteries on the other hand, are less than 5% of the market; only about 0.1% of our grid's power can be stored in chemical batteries today.

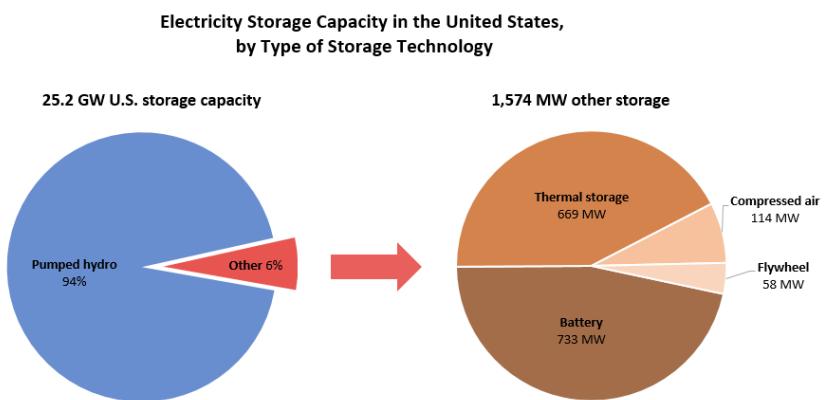


Figure 3: Illustration from EPA.gov¹⁹

Despite technological advances in chemical battery efficiency, they are not cost competitive with pumped hydro at large scales. Some research speculates that chemical battery technology will improve enough to compete on price with pumped storage,²⁰ but this is far from certain. There are many factors involved with such calculations, and other research concludes that pumped storage will remain cheaper.²¹ As we will demonstrate, underground pumped hydro could be even cheaper than traditional pumped storage, and this would give it a further competitive edge on lithium ion solutions. This will be explained in more detail below.

2.2 What is Pumped Hydro?

Pumped Hydro Storage (PHS) is a system comprised of two large water reservoirs with a difference in elevation between them. This system creates a battery from the gravitational potential difference of water pumped between them. During periods of high electricity demand, power is generated by dropping water down through a hydropower dam turbine. During periods of low demand, the upper reservoir is recharged by using lower-cost electricity to pump water back up.

Pumped hydro energy storage is affordable and efficient. PHS plants can last half a century or more, and their round-trip efficiencies can exceed 80%.¹⁸

The BACEI report summarizes:

“For bulk or grid-scale power management applications, pumped storage is widely considered to be the most demonstrated and most economic technology, with the capacity to provide over a gigawatt of power over durations of 12 hours or more.”¹³ – BACEI report

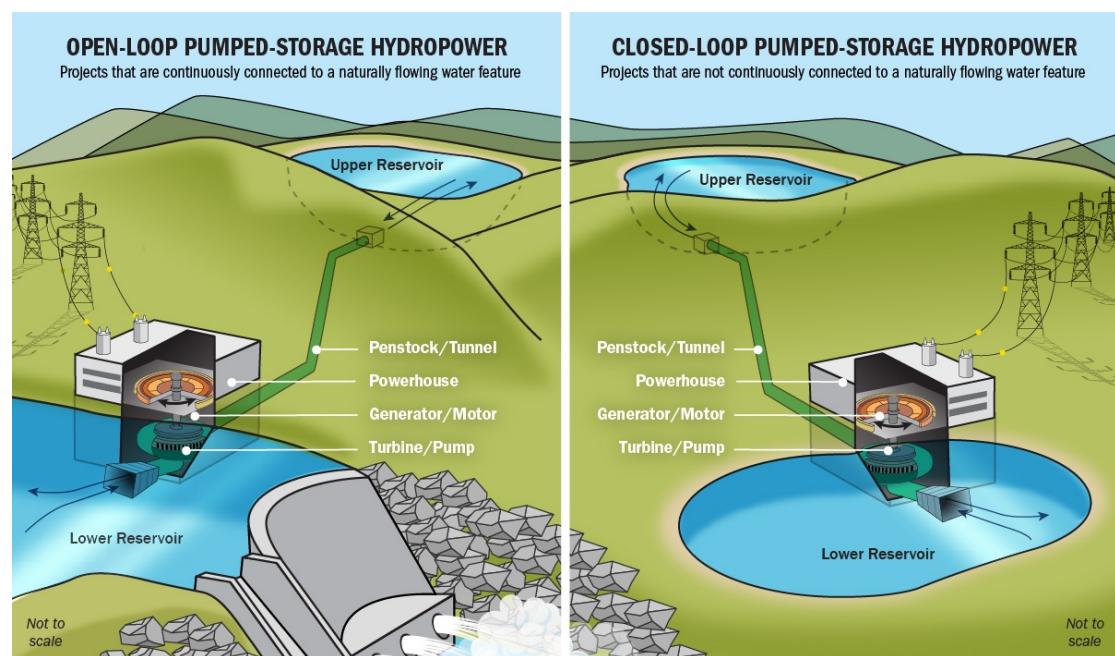


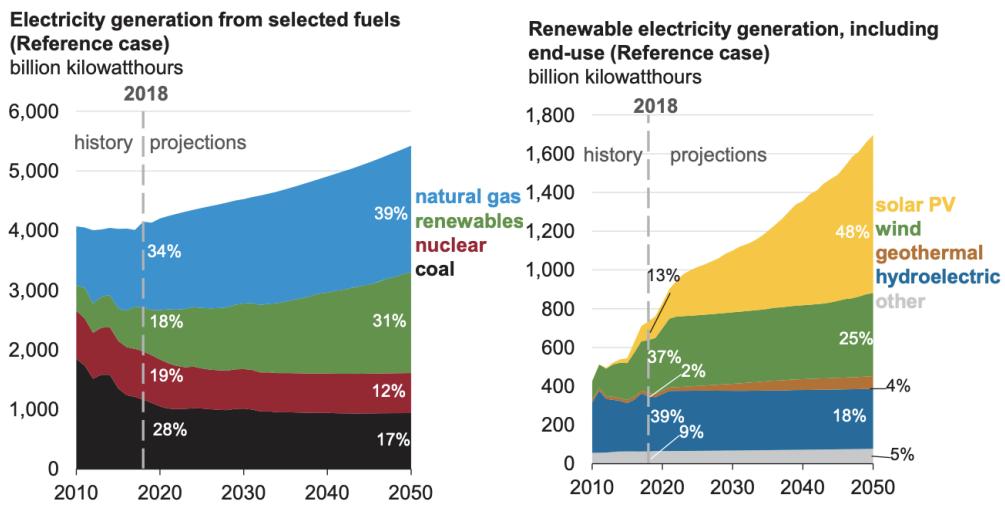
Figure 4: Illustration from energy.gov.²²

As of 2017, the U.S. had a total of about 20 GW of conventional pumped storage hydropower spread across more than 40 facilities.¹³ But as we'll see in the following sections, demand for energy storage capacity is expected to rise exponentially.

2.3 Keeping up with Wind and Solar

According to the U.S. Energy Information Administration (EIA), renewable energy resources such as solar and wind are currently the fastest growing sources of U.S. electricity generation.²³

Electricity generation from natural gas and renewables increases, and the shares of nuclear and coal generation decrease—



U.S. Energy Information Administration

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Figure 5: Illustration from a 2019 EIA.gov report.²³

As illustrated in the graph above, the EIA report projects that renewable energy will nearly double its market share by 2050.

This should be wonderful news for green energy advocates. But there's a problem. Because wind and solar energy add so much variability to grid demand, this projected growth might not even be possible without an accompanied growth of energy storage capacity. And this problem gets exponentially worse as renewable energy captures larger market share.

2.4 The Uphill Battle to 100% Renewable Energy

“The sun doesn’t always shine and the wind doesn’t always blow.” This truism is an oft-used reminder of renewable energy variability. Let’s consider what it means in practice. Imagine if we relied only on solar energy, how much energy storage would we need? On each sunny day we would need to capture almost twice the demand of our entire grid so we could store half to use at night. And what about cloudy days?

As explained by researchers from San Diego, California, “While there have been many visions for a rapid shift to an all solar and wind power grid, one of the central critiques of those visions is that they are often unrealistic in their assumptions about the need for massive multi-day, multi-week and inter-seasonal energy storage of electricity.”²¹

A 2018 article from the MIT Technology Review crunched the numbers to determine more realistic figures behind such a shift to solar and wind. Taking California as an example, the article concludes that our future energy storage needs will be astronomically expensive, especially if we rely on chemical batteries. The article cites a 2016 analysis²⁴ in which researchers found “steeply diminishing returns when a lot of battery storage is added to the grid.”¹

2.5 Lithium-ion Energy Storage: A Good First Step, but Bad at Scale

As prices drop for lithium-ion batteries, chemical battery storage has proved to be a viable replacement for fossil-fuel peaker plants. This is an important next step for energy storage growth; each retired peaker plant will save money and reduce pollutants. But unfortunately, chemical batteries are not well suited to solve energy storage on large scales.

The MIT Technology Review article explains that, “much beyond this role [of replacing peaker plants], batteries run into real problems.”¹ The article continues,

“Not only is lithium-ion technology too expensive for this role, but limited battery life means it’s not well suited to filling gaps during the days, weeks, and even months when wind and solar generation flags.”¹ Quoting MIT researcher Jesse Jenkins, the article explains that “when renewables reach high levels on the grid, you need far, far more wind and solar plants to crank out enough excess power during peak times to keep the grid operating through those long seasonal dips. That, in turn, requires banks upon banks of batteries that can store it all away until it’s needed....And that ends up being astronomically expensive.”¹

2.6 Lithium-ion Energy Storage: Projected Costs for California Case Study

California is already on track to get 50 percent of its electricity from clean sources by 2020, and the state is considering a bill pushing them to 100 percent by 2045. The MIT Technology Review article examines the correlated costs of battery storage which would be needed to support this growth.

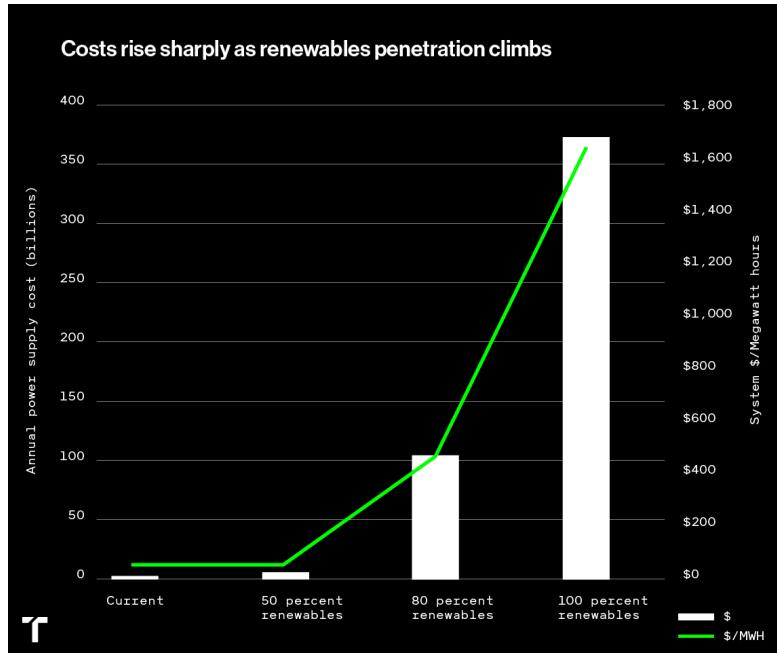


Figure 6: Illustration from technologyreview.com.¹

As depicted in the graph above, if California’s roadmap depended on current battery technology, their energy storage costs would rise exponentially, from \$49 per megawatt-hour of generation at 50 percent to \$1,612 at 100 percent. And

that's assuming lithium-ion batteries will cost roughly a third what they do now. The article sites a study from Energy & Environmental Science which found a similar result and concluded that in order for the U.S. to reach just 80 percent of US electricity demand with wind and solar, the required energy storage would cost more than \$2.5 trillion.¹ Furthermore, the short life span of lithium-ion batteries could make this a reoccurring cost which we would need to spend about every 10-20 years. And chemical batteries have never been widely deployed at grid scale, so they remain an unproven and therefore risky new technology. For these reasons, it's possible that chemical batteries might never be a feasible solution to support our future grid-scale energy storage needs. Underground pumped storage on the other hand, is based on well understood technologies and proven grid-scale energy storage solutions.

2.7 Pumped Hydro Storage is Still King

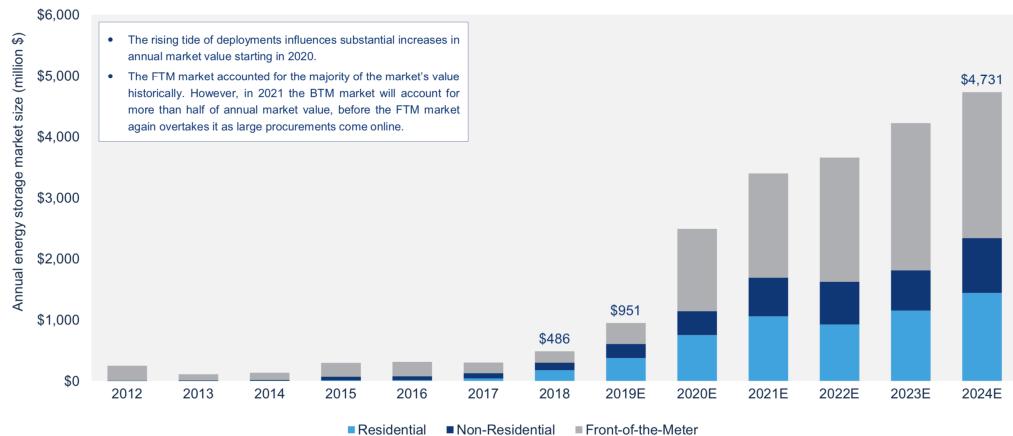
If chemical batteries can't offer a scalable solution to fill market demand for energy storage, what technologies will?

According to a market report by Wood Mackenzie, U.S. deployments of stationary energy storage will grow exponentially in the coming decades. (It's important to note that their definition of stationary energy storage does not even include pumped hydro storage which comprises most of the world's energy storage. We'll revisit this point shortly.) The report shows that stationary energy storage nearly doubled in 2018, growing 80% from 2017.²⁵ The authors state: "The [U.S. Energy storage] market will double from 2018 to 2019, then nearly triple from 2019 to 2020." Looking further, the "U.S. energy storage annual deployments will reach 4.4 GW by 2024." This signals a 14-fold growth between 2018 and 2024.

U.S. energy storage will be a \$4.7 billion market in 2024

Value set to grow 5x between 2018 and 2020

U.S. annual energy storage market size, 2012-2024E (million \$)



Source: Wood Mackenzie Power & Renewables. Note: Market size is reported as energy storage system deployment revenues (product of deployments and installed system prices).

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Figure 7: Page from a 2018 Wood Mackenzie report²⁵

The BloombergNEF (Bloomberg New Energy Finance) research team forecasts even larger energy storage growth for stationary energy storage in the coming decades. They project exponential world-wide growth of stationary energy storage from 9GW deployed as of 2018 to 1,095GW by 2040. In their words:

“This 122-fold boom of stationary energy storage over the next two decades will require \$662 billion of investment, according to BNEF estimates. It will be made possible by further sharp declines in the cost of lithium-ion batteries, on top of an 85% reduction in the 2010-18 period.”²⁶

As prefaced above, it’s important to note that these reports are only examining stationary energy storage which does not include pumped hydro. Our world’s stationary energy storage capacity is currently only about 9 GW which is only a small percentage of the world’s 160 GW of overall energy storage comprised mostly of pumped hydro.²⁷ There are various reasons why pumped hydro storage might be excluded in these reports. Two likely reasons are A: the steep upfront investment costs of PHS and B: the diminishing availability of sites for new dam

construction. However, this sentiment is shifting back in favor of pumped storage. In the 2018 Lazard Energy Storage report, PHS was excluded along with other technologies which the report considered to have “limited current or future commercial deployment expectations.”²⁸ (It has been omitted from the report since 2016 even though in 2016 it was shown to have one of the lowest unsubsidized levelized costs.²⁹) But this is expected to change this year as the 2019 version of the report is presently expected to add PHS back into consideration.²¹ This renewed validation for pumped hydro reflects growing interest in new pumped hydro projects. It may also be influenced by newfound interest in proposals for underground pumped hydro installations using existing underground abandoned mines. (See below: *Underground Pumped Hydro in Abandoned Mines*)

2.8 A Booming Energy Storage Market

The nascent energy storage market looks poised for incredible growth. Public awareness is just beginning to spread through new high-profile initiatives. One such project is a \$3 billion pumped storage retrofit being planned for the Hoover Dam. According to the New York Times,

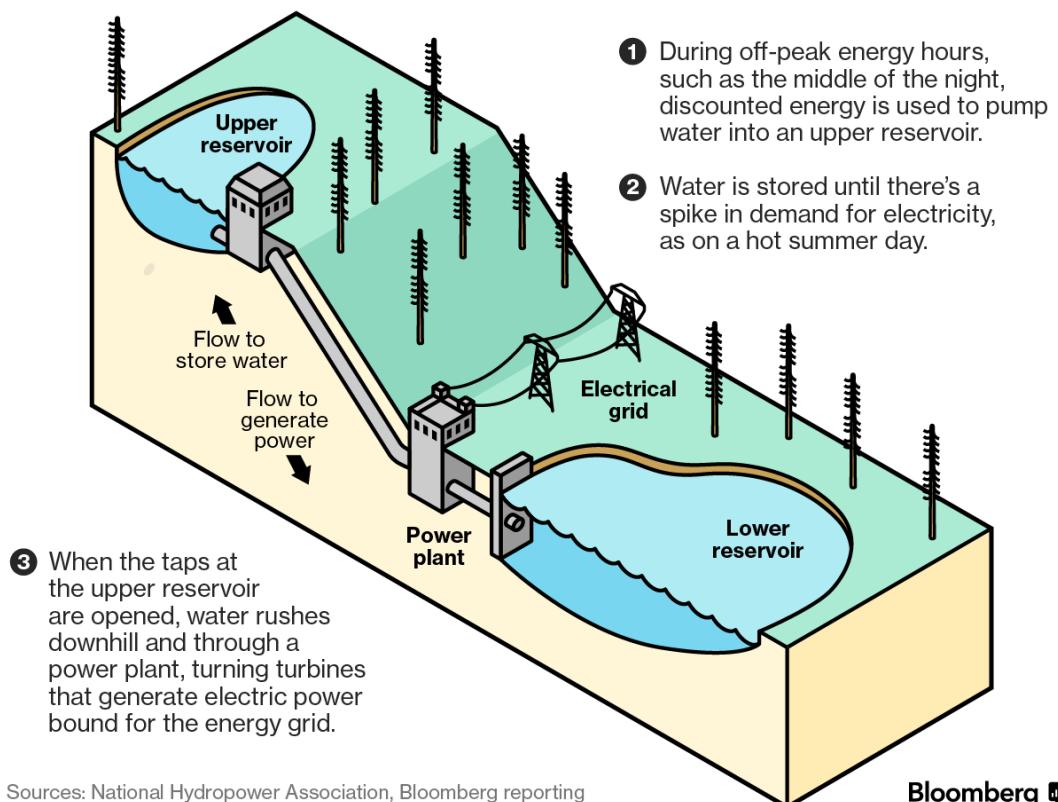
“Using Hoover Dam to help manage the electricity grid has been mentioned informally over the last 15 years. But no one pursued the idea seriously until about a year ago, as California began grappling with the need to better manage its soaring alternative-electricity production — part of weaning itself from coal-fired and nuclear power plants.”³⁰

The Hoover Dam retrofit is a part of a larger boom in pumped hydro energy storage projects. In the next section we’ll examine why pumped hydro could soon lead a surge of growth in the stored energy market.

3 Why Pumped Hydro Energy Storage?

As discussed above, 94% of the world's energy storage capacity comes from pumped hydro storage.¹⁹ Pumped hydro is affordable and effective with round-trip efficiencies sometimes exceeding 80%.³¹

How a Pumped-Storage Hydroelectric Power Station Works



Sources: National Hydropower Association, Bloomberg reporting

Bloomberg

Figure 8: Graphic from Bloomberg³²

A Bloomberg article from 2018 called “The world’s most beautiful Battery,” calls pumped hydro the “unsung hero’ of electricity storage solutions.”³³ The article details how pumped hydro plants were once a “little-seen corner of the electricity grid.” And now “they’re getting fresh attention across Europe and the U.S. as governments struggle to accommodate the surging supplies from wind and solar.”³³

3.1 The Clear Leader of Bulk Energy Storage

Although there are many other kinds of energy storage deployed around the world,³⁴ and each of these are uniquely suited to specialized purposes, they are not used for bulk energy storage on a grid scale. Flywheels for example are “mainly used for power management rather than longer-term energy storage.”¹⁸

A report from the University of Michigan, drawing on research from the U.S. DOE, offers a nice summary of Pumped Hydro’s position amongst other alternatives.

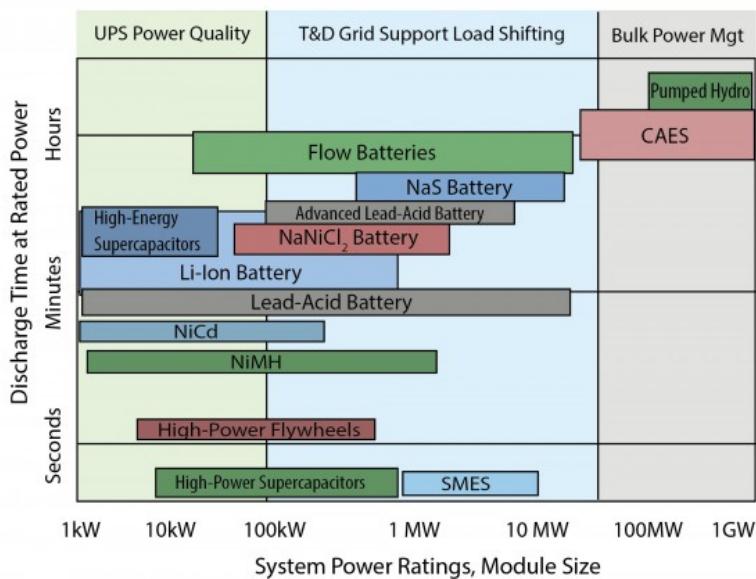


Figure 9: Characteristics of energy storage technologies¹⁸

As shown in the figure above, there are only two proven technologies that work for Bulk Power Management. The only other solution besides PHS is one called CAES, or Compressed Air Storage.

3.2 What About Compressed Air Storage?

Compressed Air Storage (CAES) is indeed a feasible competitor to Pumped Hydro for delivering grid-scale bulk energy storage. However CAES has some disadvantages which disqualify it from being considered here. Most importantly

CAES uses fossil fuels as a part of its process, so it's not carbon neutral. As explained by the NREL report mentioned above: "CAES technology is based on conventional gas turbine technology and uses the elastic potential energy of compressed air. Energy is stored by compressing air in an airtight underground storage cavern. To extract the stored energy, compressed air is drawn from the storage vessel, heated, and then expanded through a high-pressure turbine that captures some of the energy in the compressed air. The air is then mixed with fuel and combusted, with the exhaust expanded through a low-pressure gas turbine."¹⁴ Because CAES is not carbon neutral and requires an unusual site location, we will not consider it further. However, the NREL report does indicate that alternative designs may mitigate these limitations in the future. So perhaps CAES can be revisited in the future.

3.3 What About Other Novel Solutions?

There is always a chance that a young new technology will surprise the industry with rapid successful development. Here we examine some interesting but unproven ideas. Some of these may prove feasible for bulk energy storage in the coming years.

- Advanced Rail Energy Storage: ARES is reported to provide long duration (8+ hours) of storage, round trip efficiency of over 80 percent, and leveled cost comparable to pumped storage. Its principal challenges have to do with price uncertainty and technology adoption.¹³
- Flow Batteries: Flow batteries store energy in electroactive solutions. Flow batteries offer advantages in terms of longer duration, longer cycle life, improved safety due to the non-flammable, non-toxic nature of the materials used, and potentially larger scale. Flow batteries, however, are still largely at the demonstration stage of technological development and prices remain high.¹³
- Sodium Sulfur Batteries: This technology is close to market. But reliability and safety issues remain a challenge. These concerns were highlighted when NGK Energy Storage's sodium sulfur batteries caught fire in 2011.¹³

- Lead-acid batteries: Lead-acid batteries are slightly more expensive than sodium sulfur batteries, with higher life cycle cost. The main disadvantage of lead-acid is lower energy density and limited cycle life.¹³

While these ideas deserve research and attention, it would be dangerous to assume that unproven technologies like these may save us. Considering our urgent need for additional energy storage, it is critical to acknowledge that pumped hydro is still our only proven source of zero-carbon bulk energy storage. Therefore, to minimize risk, we must rapidly develop more pumped hydro even as we explore alternative options.

3.4 A PHS Case Study: The Kaprun Hydroelectric Station

In “The world’s most beautiful Battery” mentioned above, the article celebrates one particular hydro plant called the Kaprun hydroelectric station. Located high in the Austrian Alps, the Kaprun station offers a shining example of pumped hydro’s success.



Figure 10: A photo of the Kaprun high mountain reservoirs³³

At 70 years old, the Kaprun plant is still a valuable workhorse just as relevant in today's changing energy market. The plant boasts 830 megawatts of capacity, enough power to supply almost 100,000 households for more than a week.³³

As demonstrated by Kaprun, pumped hydro storage technology is not only elegant and powerful, but also proven and durable. A similar plant built today would outlast a chemical battery plant many times over. Plants like Kaprun have inspired new growth in PHS. But the technology is now "at a tricky in-between stage," says Jonas Rooze, a BloombergNEF analyst.³³ He believes the industry "will probably have to reinvent how they operate several times to capture value from the ever-evolving system."³³ He says that "There's capacity to build in Europe but right now it's not in the money....For all of these projects you need a long-term vision."³³ In other words, these large scale energy storage solutions still hold great promise, but only if we have the foresight to pledge large funds for long-term investments.

3.5 A new Era for Pumped Hydro

In a more recent Bloomberg article, journalist David R Baker makes a case that the time is indeed ripe for new long term visions to take on our newly evolving system. Baker identifies that "renewed interest is surging" in pumped storage technology.³² According to the article, "The Federal Energy Regulatory Commission has issued 34 preliminary permits for companies and government agencies exploring projects in New York, Pennsylvania, Wyoming and elsewhere. Another 16 applications are pending."³²

3.6 Pumped Hydro Pros and Cons

Baker's article also offers succinct summaries of the pros and cons of pumped storage. Quoting Neena Kuzmich, a project manager for a proposed pumped storage facility near San Diego, Baker captures the sentiment behind this resurgence.

In Kuzmich's words, "It's not as glamorous as a battery. But it's a tried and true technology that provides the volume that we need." To illustrate the downside of pumped hydro, Baker cites BloombergNEF: "The projects can cost more than \$1 billion to build....Plus, securing permits, building dams and boring tunnels can take 10 years. And since the process often involves flooding valleys, most projects face resistance." Baker reports that nine pumped hydro projects have been proposed in California. But even the project which is furthest along has met fierce opposition from environmentalists. Federal regulators approved the project in 2014 but construction has yet to begin.³²

3.7 Towards a long-term vision for Pumped Storage

In section 2 we demonstrated that energy storage is critically important for decarbonizing our energy grid and curbing climate change. Section 3 has argued that pumped hydro is the best path forward for grid-scale investments in energy storage. In the following sections, we will make the case for a particular variation of pumped storage which could help bring the technology to market sooner. This variation takes the novel approach of replacing a lower reservoir with deep underground tunnels.

4 Why Underground Pumped Hydro Energy Storage?

Underground Pumped Hydro Energy Storage, or UPHS, is simply a pumped hydro solution which replaces the lower reservoir with an underground cavity mined from hard rock. This is not a new idea. Even though it has never been implemented on a large scale, the concept is well researched. In 1984, the Pacific Northwest Laboratory (sponsored by the US Department of Energy) authored a research paper called, “Underground Pumped Hydroelectric Storage.” The report (PNL report) concluded that “the UPHS concept is technically feasible and economically viable.”³⁵ It summarizes: “Underground pumped hydroelectric energy storage was conceived as a modification of surface pumped storage to eliminate dependence upon fortuitous topography, provide higher hydraulic heads, and reduce environmental concerns.”³⁵

The PNL report analyzes the economic feasibility of the design concluding that, “A UPHS plant offers substantial savings in investment cost over coal-fired cycling plants and savings in system production costs over gas turbines.”³⁵ Regarding capacity potential it determines: “A UPHS plant would be in the range of 1000 to 3000 MW. This storage level is compatible with the load-leveling requirements of a greater metropolitan area with population of 1 million or more.”³⁶

These are striking conclusions. They make it clear that UPHS is, at the very least, a legitimate contender for our future’s vast energy storage needs. And as such, this idea surely deserves further exploration. In the following section, we will examine past and current research on the technology.

5 Underground Pumped Hydro Storage, Past Research

In the 1984 PNL report mentioned above, the authors were optimistic about underground pumped hydro storage. The report concluded that, “while a project utilizing sub-surface reservoirs has yet to be completed, these types of projects are attractive due to their perceived site availability and their potential for reduced environmental impacts.”³⁶ So, it may seem surprising that in the thirty-five years since the report, UPHS has never been developed. Why?

Although it’s outside the scope of this report to analyze exactly why UPHS has not gained adoption, it is plausible that the reasons have not changed since the PNL report was published. As the report explained at the time, “Despite optimistic forecasts of technical and economic feasibility, so far no utility has committed funds to the design and construction of a UPHS plant....Even though UPHS has some environmental advantages over conventional pumped storage, higher cost remains an impediment to significant market penetration in the near future.”³⁶

The cost differences allude to were actually small, if even higher at all. The report notes that, “some feasibility studies” estimate capital cost to be “somewhat greater” than for conventional storage.³⁶ On the other hand, it noted a different study (the Charles T. Main Study) found that “Underground pumped hydroelectric storage compares favorably with conventional pumped storage” with costs being essentially the same.³⁶

Still, the small difference, compounded with the risk of a new technology, must have been significant enough to deter interest. To this day, no major UPHS projects have been built. This was confirmed by at least one 2017 research paper which reported “no bibliographic evidence of UPSH plants constructed.”³⁷ But this could soon change as our current market conditions rapidly evolve.

5.1 Past Research, Predicting Today's Market

In the PNL report's closing section, the authors looked to the future, predicting which "changes in the electricity generating environment" would be necessary for the adoption of PHES. Here is the full list of changes which would be "likely to influence organizations toward UPHS commitments".³⁶

1. increase in the availability of capital and decreased interest rates
2. increasing load growth within metropolitan areas
3. trend toward joint ownership of large projects
4. successful demonstration of advanced high-head reversible pump turbines
5. full utilization of available and environmentally acceptable surface pumped hydro sites
6. implementation of regulatory reforms to enable return on capital committed to construction of new facilities
7. development of uniform institutional and legal procedures applicable to artificial surface and subsurface reservoirs
8. demonstration of complete remote operability of the subterranean powerhouse in all modes of operation.

Let's analyze and diagnose whether our current market has made such changes over the last few decades. For organization, we'll break this list into categories.

Market demand: (see item 2 above) Load growth has indeed increased since 1984.³⁸ But more importantly, a sharp increase in variable load is expected to accelerate market demand for energy storage.

Evolution of Research and Technology: (see 4 and 8) Pumped Hydro technology has continued to advance in the last few decades. Research in advanced high-head turbines continues to increase load potentials.^{39,40} And where head height exceeds pump limitations, a multi-step approach can be used with intermediate reservoirs and powerhouses relieving head pressure from turbines below.³⁶ Additionally, tunnel boring technology is faster and more efficient today which could significantly lower past cost estimates.^{41,42}

Exhaustion of potential traditional Pumped Hydro: (5) As discussed in the "Quest for Bigger Batteries" Bloomberg article, our current energy storage has already manifested

a spike in pumped hydro permit applications. And many of these projects are stalled by fierce opposition driven by environmental concerns. So indeed, this fight over a shortage of feasible sites for traditional pumped storage has already begun. This problem will only get worse as the demand for energy storage grows year over year as projected. Under this shortage of traditional PHS sites, UPHS's environmental advantages could quickly justify slight additional upfront costs.

Regulation and Government Cooperation: (6 and 7) Climate change has finally pressed governments and regulators to take urgent action. New York City and other governments have made bold commitments to mitigate risk through energy reform. Governments could soon view UPHS as a critical tool for attaining these goals. Especially within this political climate, regulators should be amenable towards such an environment-friendly technology.

Investor Interest: (1 and 3) Although past research like the PNL report concluded that UPHS technology was “technically feasible and economically viable,” they understood that long construction time would challenge investors. The PNL report found that “Beyond the technical considerations...the quality of the bond market and availability of support through a utility consortium may ultimately determine economic practical capability.” In other words, it acknowledged that UPHS was just barely competitive with existing technologies. So due to long construction time and large upfront costs, UPHS was an infeasible investment for all but the largest of investors with the patience to leverage favorable loan conditions and industry cooperation. Until today, these conditions have been prohibitive for large-scale UPHS projects. But under today’s rapidly changing political and energy market climates, the conditions could be ripe for this idea.

In conclusion, the energy market has indeed changed considerably since the PNL report was published in 1984. Technology has steadily evolved. The energy storage market is on the verge of exponential growth. Governments have promised energy market reform and have begun to inject capital into large-scale energy initiatives. These aligning factors could spin pumped hydro into a lucrative emerging market. With a convincing opportunity for long-term returns, UPHS could find an audience of patient investors with deep pockets.

6 Underground Pumped Hydro, Current Research

Considering that past research had already demonstrated the feasibility of underground pumped storage, the current state of UPHS research is disappointing. There are only a handful of small, experimental projects in development today which could be considered UPHS.

6.1 Underground Gravity Storage With Heavy Piston Design

One experimental design for underground energy storage involves a heavy “piston” of heavy rock mined from a vertical shaft. This design was once mentioned by science celebrity Bill Nye as an idea that he was “thoroughly charmed by”⁴³ 6:50. The idea is developed by a company called Gravity Power. This piston concept is not really a UPHS design though. Because, while water is pumped into a drilled vertical shaft, the weight of water is not utilized to store energy. The water is pumped in a closed loop with water above and below the piston. The water really only serves to pressurize the shaft in order to lift the piston weight. In fact, the water’s net weight is actually pumped in the opposite direction as the piston’s weight, so it seems to actually detract from the efficiency of the system.⁴⁴

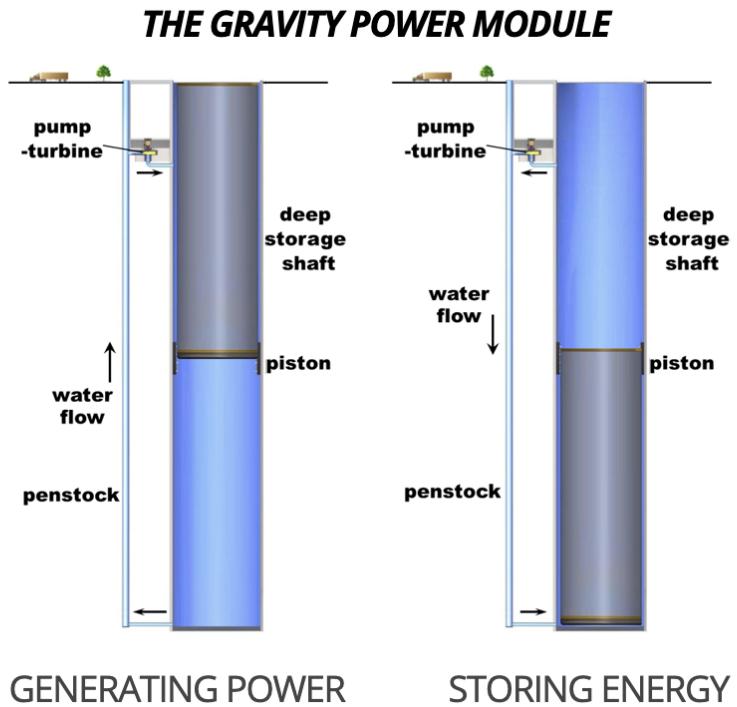


Figure 11: Diagram of Gravity Power, LLC's scheme⁴⁵

Our calculations raise doubt as to whether this design could be superior to underground pumped hydro. Because while the rock density might be about 2.5 times the density of water, the piston's bulk would restrict both its volume and the potential height it could travel, reducing its advantage. So it seems that this design would perform worse than UPHS, offering less storage capacity per meter of tunnel. (See Appendix: *Calculations for Pumped Storage with Heavy Piston Design*). We do concede however that this piston design eliminates the need for an upper reservoir. So perhaps the idea could still prove valuable for some locations where an upper reservoir is not possible.

6.2 Underground Pumped Hydro in Abandoned Mines

It seems that most UPHS projects in development today have set their sights on abandoned mines and rock quarries which offer an existing lower reservoir. There are multiple reports of such projects being researched and proposed, but it's unclear how many of these projects are actually getting completed. Some of these projects are:^{36, 46–48}

- 1** Elmhurst Quarry Pumped Storage Project (designed to be 50-250 MW)
- 2** Riverbank Wisacasset Energy Center (1,000 MW)
- 3** Prosper-Haniel coal mine in Germany (200 MW)
- 4** Kidston Pumped Storage Hydro Project in Queensland, Australia (250 MW)
- 5** Bendigo Mines Pumped Hydro Project (30 MW)

Compared to the drilled UPHS projects proposed in the PNL report which were as large as 3,000 MW with a 10 hour capacity,³⁵ these projects slated for abandoned mines have smaller capacities, usually by an order of magnitude.

This report's authors were not able to determine how cost-competitive it would be to develop a bundle of smaller pit mine sites rather than developing one single centralized PHES site. But it does seem that there are ample mine sites around the world which would be suitable. There are about half a million abandoned mines in the United States.⁴⁹ And according to hydroworld.com, there are thousands of abandoned rock quarries in the US National Park system alone. And these could be "converted into pumped storage facilities with less civil work than a greenfield development and minimal environmental impact."⁵⁰ So it seems feasible that the supply of mines is plentiful. However, it's unclear what the average depths and volumes of these mines are as this report's authors have not yet been able to find a database that included those figures. It seems that a typical coal mine depth might be around 300-600m,⁵¹ which is significantly less than the 1500m or greater depths proposed by the 1984 paper.

6.3 UPHS Summary of Current Research

In summary, there are no active research projects exploring grid-scale underground pumped storage as proposed in the 1984 PNL report. In the following section we'll argue that this is a missed opportunity, and that changing market conditions could make this technology more feasible and profitable than ever before.

7 Why UPHS is Feasible Today

As discussed above, underground pumped storage has been rigorously studied and generally determined to be “technically feasible and economically viable.”³⁵ To reach this conclusion, the PNL report drew on multiple case studies including, the Charles T. Main Study, the Argonne National Laboratory/Allis Chalmers Studies, the Potomac Electric Power Company Study, and the Commonwealth Edison/Harza Study. Citing the Charles T. Main Study, the PNL report states:

“Underground pumped hydroelectric storage compares favorably with conventional pumped storage. The construction costs were found to be essentially the same [i.e., in the range of \$300 to \$350/kW (1978 dollars)]. Operating and maintenance (O&M) costs are essentially the same, possibly favoring UPHS.”³⁵

And further highlights some benefits of UPHS which could make it more advantageous than traditional pumped storage in some scenarios.

Underground pumped hydroelectric storage should appeal to a utility company in lieu of conventional pumped storage in that it minimizes site selection and acceptance problems; develops greater head and capacity; is more applicable in water-scarce areas; and lowers transmission costs and line losses by being located near load centers.³⁵

In spite of these advantages, no one has built any UPHS over the past few decades. It’s possible that the idea was simply forgotten about and never considered until now. But as detailed above (see *Past Research, Predicting Today’s Market*), it’s likely that sub optimal market conditions have kept the idea out of development. We believe that these conditions are recently turning in favor of UPHS.

7.1 A Convergence of Favorable Factors for UPHS

In the *Past Research* sections above, we outlined the factors which were predicted “likely to influence organizations toward UPHS commitments.” These factors are much better aligned to favor UPHS today than they were in 1984.

As already mentioned, “renewed interest is surging” in traditional pumped hydro storage technology (see *A new Era for Pumped Hydro* above). Developers are rushing to secure project permits in anticipation of parabolic growth in the energy storage market (see *Wood Mackenzie* report above). However, this spiking demand faces resistance from an exhaustion of ideal sites and an increase in environmental concerns. These factors were cited by the PNL report as market drivers for UPHS.

Technological advances also favor UPHS. Tunnel boring technology and high-head turbine technology have evolved considerably. High-head turbine research has continued to optimize efficiency, though these gains are likely small. On the other hand, tunnel boring technology is poised for huge gains in efficiency, largely thanks to Elon Musk’s *The Boring Company*. According to Musk, the company’s modified boring machine called Linestorm can dig 2-3 times faster than a conventional machine. And a radical new design called Prufrock will be expected to dig 10-15 times faster than the conventional competition.⁵² (video 52:03)

According to Elon Musk, Prufrock, the fully Boring Company designed machine will be, aspirationally, 15 times faster than current boring machines. Very likely 10 times faster.

The new design is expected to parallelize basic functions, allowing for excavation, wall reinforcement, and earth removal to all be executed simultaneously. In Musk’s own words, they intend to “automate segment direction,” incorporate a “passing lane” for incoming and outgoing materials, and implement a “fast muck

dump.” Of course some experts are skeptical about these unproven claims.⁵³ But if Musk is able to deliver on such speed improvements, it could drop digging costs by a factor of 10. This could in turn drastically reduce the cost of underground pumped storage since the cost is largely driven by tunneling costs. According to the PNL report, the lower reservoir of a UPHS plant likely represents about 30% of the overall project cost.³⁵

7.2 UPHS, Less Risky than Grid-scale Li-ion

As discussed above, PHS is the only well-established energy storage method proven to work at grid-scale. UPHS is just a special case of PHS. It uses the same pumped hydro technologies, and it adds only well-established digging technologies. Therefore, even though UPHS has never been built on a large scale, the technology is comprised of very well understood engineering principles. Since it does not use any new technologies, it is low risk design. This is repeatedly emphasized in the PNL report:

“Proven boring techniques are available with which to confirm geologic site suitability. Numerous successfully constructed deep room and pillar mines in the United States exemplify the major techniques required to construct the shafts, adits, tunnels, and underground caverns associated with UPHS. ... Excavations of equivalent volumes of rock have been made previously from a variety of host rocks, and integrity with time has been clearly established. ... The results of subsurface investigations and office studies have provided a firm basis upon which a definite project can be established.”³⁵

UPHS is further validated by existing projects which have successfully implemented pumped hydro in deep abandoned mines. (See *Underground Pumped Hydro in Abandoned Mines*)

Conversely, lithium ion batteries have never been implemented at grid scale

and there is significant risk that they might never be a cost effective solution at scale. According to researchers working with the San Diego County Water Authority, “There remains substantial uncertainty especially for battery projects because nearly all of the operational experience with these technologies is for much smaller systems operating over shorter time horizons (typically 1-2 years).”²¹ The paper further highlights some of these risks of chemical battery technology:

“The technology is newer, business models are still evolving, and low-risk long-term contracts are therefore less widely used. For these reasons, today’s battery projects typically involve more risk and thus a greater role for equity (and higher costs of raising capital).... In the real world, the useful storage in a battery system is often lower than the rated capacity because today’s battery systems often suffer damage at full discharge. A recent project in Southern California, for example, purchased a 50MW rated battery system to yield reliably only 20MW of capacity....Looking across all the reputable studies of battery systems it is clear that significant uncertainties remain around the real cost of battery storage systems. Those unknowns are particularly large for battery systems deployed in ways that are unfamiliar and untested—especially for large-scale, long-duration storage.”²¹

7.3 Biggest Challenges for UPHS Today

We presume that the largest obstacles facing UPHS developers today would be current unfavorable regulations, and any market aversion to long-term investments. Yet, both of these issues are steadily improving in today’s political climate as governments and corporations rush to fulfill their decarbonization promises. The City of New York for example, is throwing real money behind these efforts. In their oneNYC report, they promise:

“We will continue to coordinate with public and private partners to

create market opportunities for emerging technology and innovation, while helping to remove the technical, financial, and regulatory barriers that limit scale.”⁹ – oneNYC report

And New York State has sponsored a financial entity called NY Green Bank to accelerate clean energy deployment. From the Green Bank website, “NY Green Bank is a State-sponsored, specialized financial entity working with the private sector to increase investments into New York’s clean energy markets, creating a more efficient, reliable and sustainable energy system.”⁵⁴ According to the Coalition for Green Capital, in June 2017 the New York Green Bank became profitable after just a few years of operation. They had made investments of \$409.4 million to support projects with a total cost of between \$1.2 and \$1.4 billion.⁵⁵

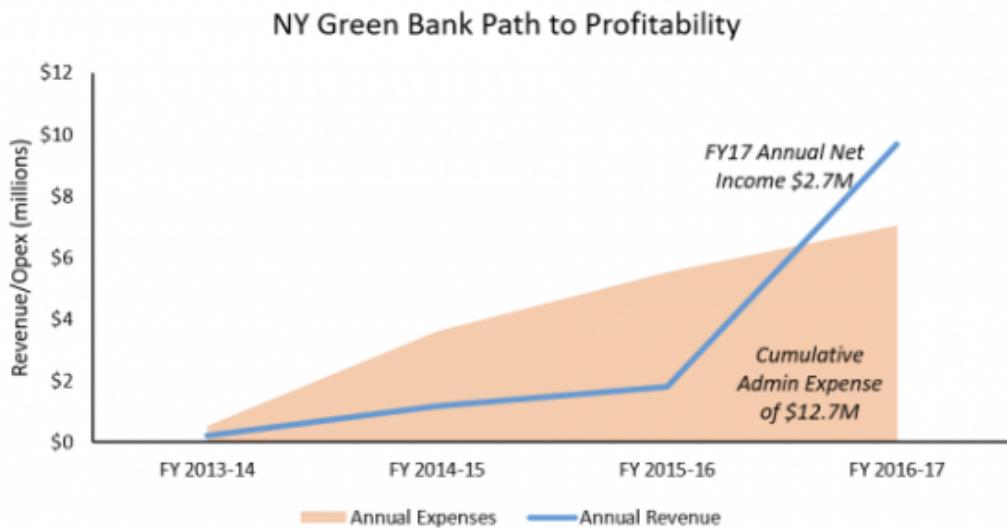


Figure 12: The New York Green Bank became profitable in 2017 just a few years after its launch.⁵⁵

8 UPHS Case Study Technical Specifications

The PNL report cites the Potomac Electric Power Company Study as “without a doubt, the definitive design study for UPHS,” which it says, “will provide the baseline against which all UPHS development in the future will be referenced.” This study (PEPC study) which was also sponsored by the US Department of Energy, provides detailed technical designs.

The study conducted cost comparisons of various configurations for a 2000-MW plant. And it concluded that a two-step multi-pump design was optimal because it optimized head height and therefore minimized the volume of lower reservoir excavation.³⁵

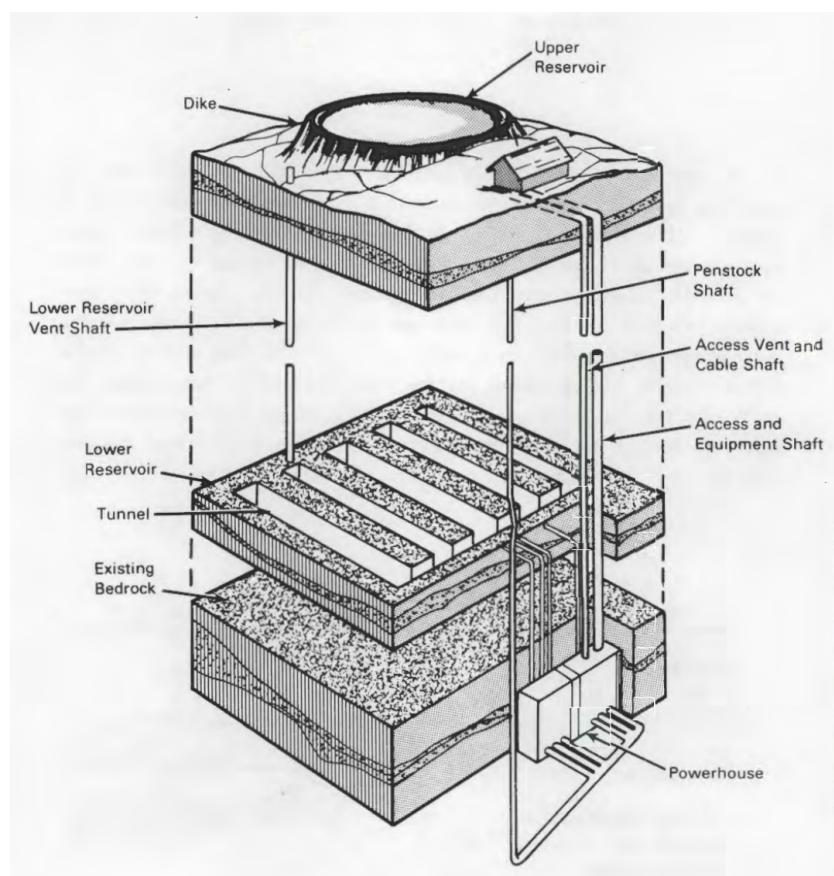


Figure 13: Image from the Pacific Northwest Laboratory Report: Three-Dimensional Conception of UPHS Plant (adapted from Allen et al. 1980)³⁵

8.1 PEPC Study: Two-Step Design with Reversible Pump-turbines

The PEPC study's optimized design called for single-stage reversible pump-turbines with identical layout and design. Each step consisted of three pump-turbine/motor-generator sets, each of 333-MW rating and each operating at 720 rpm under a nominal head of 762 m (2500 ft). With two steps combined, the overall nominal head was 1525 m (5000 ft). The study acknowledges that future technological development could significantly raise the head height or achieve the same head height in only one step.

8.2 PEPC Study: General Architecture

In addition to the main vertical penstock shaft, four other shafts were planned, ranging in depth from 1525 to 1677 m (5000 to 5500 ft). Three of these shafts were to contain hoisting conveyances for main power transmission, and control cables. The fourth, an air vent shaft, was to allow atmospheric air admission to and from the lower and intermediate reservoirs.

Construction of all shafts was to be accomplished by sinking from the surface using conventional drilling and blasting methods.

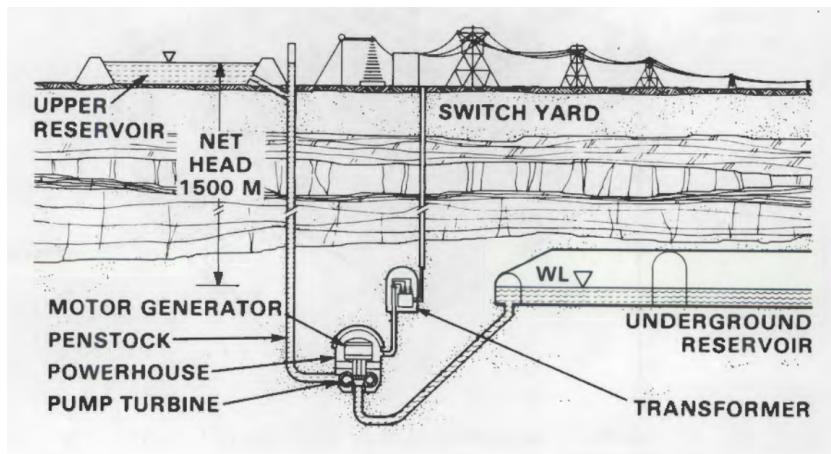


Figure 14: Image from the Pacific Northwest Laboratory Report: Cross Section of UPHS plant³⁵

8.3 PEPC Study: Penstock Specifications

The vertical penstocks were to have diameters of 5.8 m (19ft) and be designed for a maximum flow of 153 (m^3/sec) (5400 cfs).

The penstock walls were to have rock bolt support and a permanent concrete lining provided with a drainage system. The penstocks were to turn to the horizontal at the powerhouse levels, and concrete-lined manifolds were to form three 3.35-m (11-ft) diameter penstocks at each level. An 88-m (290-ft) length of the penstocks upstream from the powerhouses were to be lined with 7-cm (2 3/4-in.) thick high-strength steel lines that have flanged connection penstock valves upstream of the pump-turbine spiral cases.

8.4 PEPC Study: Excavated Tunnel Specifications

The PEPC study's excavation plan included 12 tunnels of substantial cross section, 26 x 20 m (85 x 65 ft), interconnected by smaller air and water collector tunnels at the extreme ends of the reservoir system.

The excavation volume was to be 6,012,900 m^3 (7,860,000 yd^3), which included 2.3% for "safety" storage to prevent overfilling of the lower reservoir, and a further 0.3% for freeboard. The main tunnels in the lower reservoir were to be oriented with their axes approximately perpendicular to the strike of the rock foliation in order to provide more desirable conditions for rock support of the larger spans. All of the storage caverns within the lower reservoir were to have curved side walls to reduce tensile stress zones. They were to be constructed at grades allowing free drainage upon dewatering. Provision was allowed for isolation of any one third of the reservoir with "stoplogs" to permit reservoir cavern inspection without disrupting plant operation.

9 UPHS Site Selection Considerations

The geology of the United States is sufficiently well known to determine areas of favorable development for UPHS. Site exploration can be aided from existent databases and interactive maps.

9.1 UPHS Site Selection: Geology

According to the PNL report, the lower reservoir of a UPHS system must be mined from rock which is essentially impervious. Pervious water-bearing sandstones, such as the artesian Dakota formation of the Great Plains, are not suitable for UPHS. Almost all other rocks are so dense as to be impervious for all practical purposes.³⁵

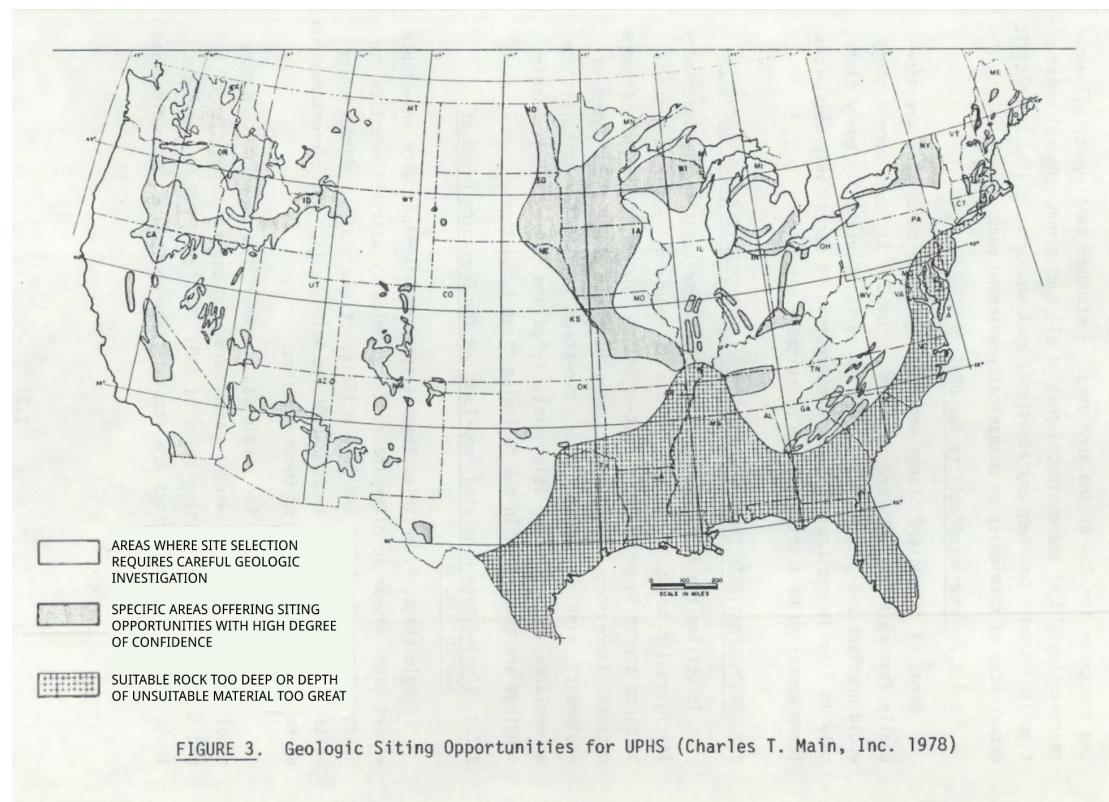


Figure 15: Image from the Pacific Northwest Laboratory Report: suitable U.S. locations for UPHS (text enlarged).³⁵

As shown in the map above, most States in the US have at least some suitable areas for UPHS. Most areas require bore hole sampling to verify a site's geology

down to the required depths.

For closer inspection of sites which are likely to be suitable, a detailed geologic map may be consulted.

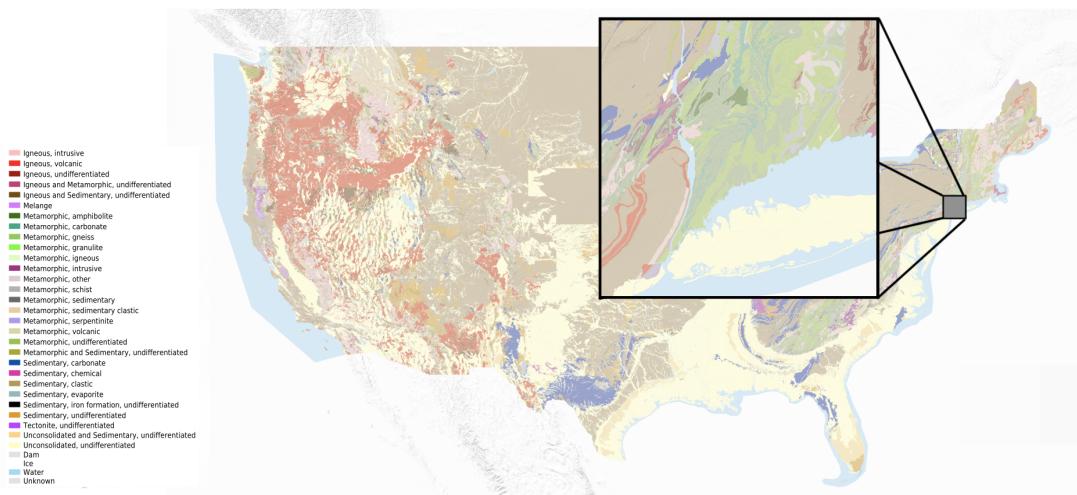


Figure 16: Geologic map of the U.S. with a close up of the NYC area – usgs.gov⁵⁶

In the geologic map above, the New York City Area is shown to have a diverse mix of geology just north of the city which should include suitable sites for UPHS.

9.2 UPHS Site Selection: GIS Analysis of Water and Elevation

The Australian National University has recently compiled an amazing database and interactive map based on their research of potential sites for pumped hydro energy storage (PHS, also known as PHES). They found these sites using GIS algorithms. Based on factors like elevation, proximity, area, and volume, they calculated hypothetical pairs of upper and lower regions considering both existing dams and potential dammable areas. In their words:

“We found about 616,000 potentially feasible PHES sites with storage potential of about 23 million Gigawatt-hours (GWh) by using geographic information system (GIS) analysis. This is about one hundred times greater than required to support a 100% global renewable electricity system.”

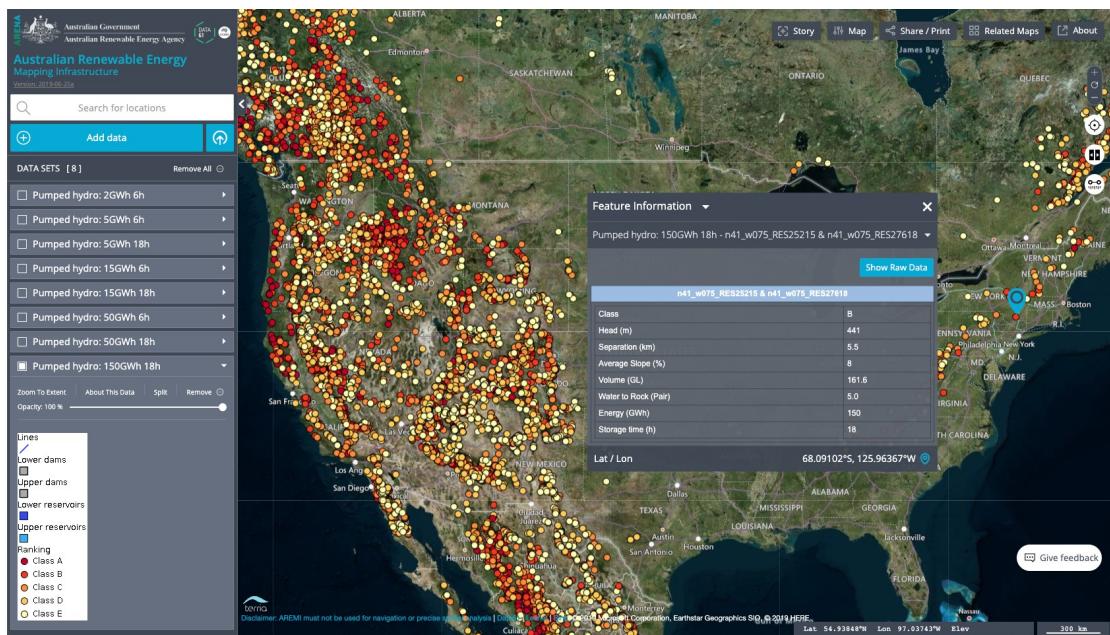


Figure 17: Australian National University PHES Atlas - global search tool⁵⁷

This map only considers sites for traditional PHS, not UPHS. But it can of course also aid in the research of potential sites for underground pumped hydro. This is especially true because the most optimal UPHS sites will likely make use of an existing dam or PHS site.

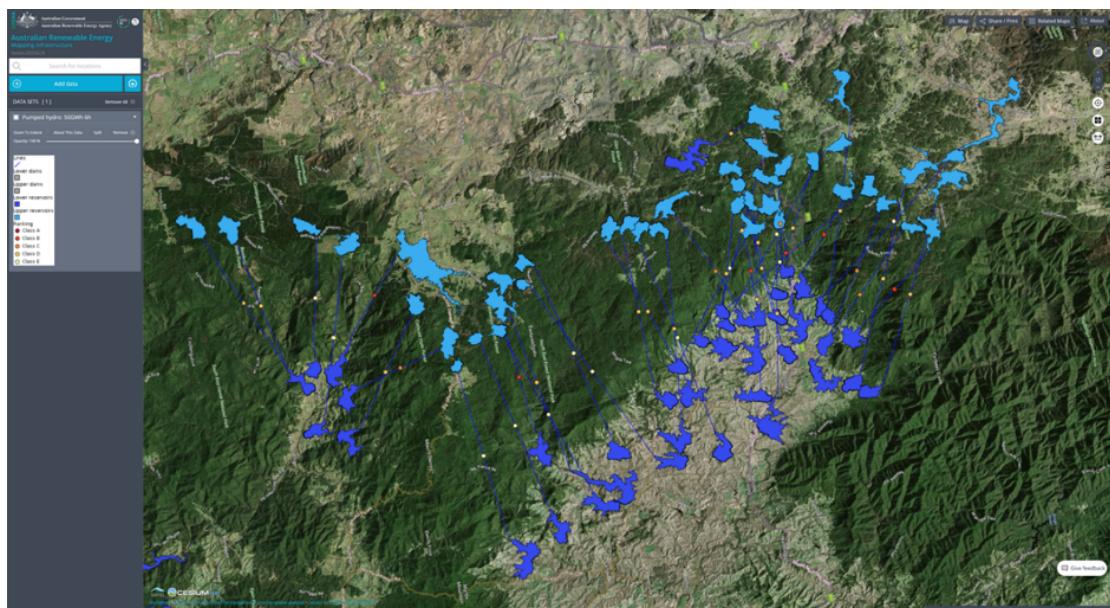


Figure 18: Australian National University PHES Atlas - hypothetical PHS site overlay layer⁵⁷

9.3 UPHS Site Selection: Consideration of Sea Water Usage

Sea water pumped storage is a very interesting modified form of pumped storage which uses the ocean as one of its reservoirs. The first project to successfully employ this design was the Okinawa Yanbaru Seawater Pumped Storage Power Station in Japan.⁵⁸



Figure 19: Birds eye view of the Okinawa Yanbaru Seawater Pumped Storage Power Station in Japan⁵⁹

The Okinawa station was built in 1999 by the Japanese Ministry of Economy, Trade and Industry. It operated until 2016 when it was shut down because the demand for electric power in Okinawa had not grown as predicted.⁶⁰

The Okinawa plant had 30 MW of storage. The lower reservoir was the Philippine Sea. The water was pumped 136 m up to an artificially excavated octagonal reservoir. Because sea water is highly corrosive, the penstock and tailrace were constructed with fibre-reinforced plastic instead of steel, and the surface of the upper reservoir was covered with an impermeable liner to prevent seawater from leaking and damaging the surrounding vegetation. The pump turbine was partially made of seawater-resistant stainless steel.⁵⁸ The outlet of the tailrace was surrounded by tetra-pods for protection from waves.⁵⁹ Further research on the sea water pumped storage discusses other important factors such as preventing barnacle adhesion from reducing pump efficiency.⁵⁹

10 UPHS: New Innovations and Hybrid Designs

In this section we will propose various innovations and hybrid designs based on existing technologies which could further enhance the efficiency of underground pumped hydro energy storage.

*... * Redacted **

UPHS could also be used to augment the capacity of existing traditional PHS sites. The UPHS plant could be installed beside the lower reservoir to effectively raise the head of the combined system and increase the overall potential storage capacity.

*... * Redacted **

The PHES Atlas project mentioned above has said that future versions of their study will include brownfield sites (existing reservoirs, old mining sites). It's feasible that these brownfield sites could be used as either upper or lower reservoirs for potential PHES sites.

** Redacted remainder of section. For further information and partnership opportunities, contact Eric Chaves at syllablehq.com.*

11 UPHS: Optimized Site Selection

** Redacted. For further information and partnership opportunities, contact Eric Chaves at syllablehq.com.*

12 UPHS: Estimated Costs and ROI

This section discusses the estimated costs of underground pumped hydro energy storage. It cites current research validating some of the figures from the PNL report on which we have drawn heavily. We calculate costs based on LCOE (sometimes also called LCOS) meaning levelized cost of energy/storage. LCOE is the minimum constant price of electricity required over the lifetime of a plant in order to cover its costs.

Although we could not find any existing LCOE calculations for UPHS systems, we did find various calculations for PHS in general. Based on data from the PNL report, we calculated our own LCOE for UPHS which we determined to be about \$0.063/kWh, or ¢6.3/kWh (after adjusting for inflation). This will be discussed in more detail below.

According to the PNL report, the LCOEs for UPHS and traditional PHS should be about the same. So it's worth noting that our calculated LCOE is quite a bit lower than contemporary estimates for non-underground PHS. Contemporary estimates for PHS are closer to \$150/MWh or \$175/MWh. See Appendix: *Comparison of researched LCOE for PHS, UPHS, and Li-ion Batteries*. Further research is needed to analyze this price gap and determine which details account for the difference. It's possible that our calculation based on 1980s figures is based on optimal conditions, whereas the contemporary estimations are based on average results from real projects, some of which may have suffered from sub-optimal conditions and cost overruns.

12.1 UPHS Construction Cost (Installed Cost)

According to the PNL report, the total direct cost of a UPHS plant built in 1983 would be estimated at $\$500 * 10^6$ for a 1000-MW plant in 1983 dollars.³⁵ (about \$1.3 billion in today's dollars.⁶¹) Note that this works out to \$1,300/kW.

As cited above, this cost compares favorably with conventional pumped storage. (\$300-\$350/kW in \$1978,³⁵ which is about \$1,180-\$1,375/kW \$2019⁶¹).

We can cross reference these numbers with more recent studies. According to a 2012 report by the International Renewable Energy Agency (2012 IRENA report), the installed costs for Large Hydro Plants were as low as \$1,050/kW (\$1,176/kW in \$2019). The costs were as high as \$7,650/kW (\$8,568 in \$2019).⁶² This large range is partly due to outliers with very large cost overruns. For our purposes of validating prices from the PNL report, we will just note that the low end construction cost for contemporary PHS (\$1,176/kW) is indeed comparable to the PNL report's low end construction cost for UPHS (\$1,180/kW).

12.2 UPHS Operations and Maintenance (O&M) Costs

As cited above, the PNL report estimated that operating and maintenance (O&M) costs for UPHS should be essentially the same as traditional pumped storage, possibly favoring UPHS.³⁵ According to the 2012 IRENA report, the yearly operations and maintenance costs for PHS are about 2 – 2.5% of the installed cost.

12.3 UPHS Levelized Cost of Renewables Combined with Energy Storage

In a recent study published by MIT, researchers analyze profiles of energy storage which would be needed for low-carbon energy sources like wind and solar to meet grid demand in a cost-competitive market.

The study (MIT study) samples four locations in the United States in order to represent a diversity of potential energy capacity profiles for solar and wind across the country. The study determined that energy storage capacity costs would need to fall to \$20/kWh in order to allow a wind-solar mix to provide baseload electricity at competitive costs with existing power plants.

In order to account for the unique inter- and intra-year energy resource varia-

tions, the calculations considered 20 years of solar and wind fluctuations for each area. To compare the real costs of each technology, the study calculates the leveled cost of shaped electricity (LCOSE). Shaped electricity cost refers to the price of electricity bundled into contracts and priced for specific locations and times. The leveled cost refers to the minimum constant price of electricity which would be required over the lifetime of a plant in order to cover its costs.

The study considers two different classes of energy storage which it denotes as Tech I and Tech II. Tech I consists of cost efficient technologies like pumped hydroelectric storage (PHS), compressed air energy storage (CAES), and proposed flow battery technologies using highly abundant and low-cost elemental constituents. Tech II consists of future Li-ion batteries after further cost reduction, and possibly other closed battery technologies, flywheels, and supercapacitors.⁶³

The study calculates various market scenarios in which a cost-optimal mix of wind, solar, and energy storage would reach costcompetitiveness with various existing energy sources.

The following list shows various Tech I energy storage price points which could pair with wind and solar in order to undercut corresponding current technologies.

1. At \$10-20/kWh energy storage: nuclear fission baseload electricity (\$0.075/kWh)
2. At \$5/kWh energy storage: peaker natural gas plant (\$0.077/kWh)
3. At \$30–70/kWh energy storage: generic baseload (\$0.10/kWh)
4. At \$30–90/kWh energy storage: generic intermediate (\$0.10/kWh)
5. At \$10–30/kWh energy storage: generic bipeaker (\$0.10/kWh)
6. At \$10–30/kWh energy storage: generic peaker electricity (\$0.10/kWh)

The study concludes that Tech I energy storage could hit these rates (e.g. PHS), but Tech II storage could not (e.g. Li-ion chemical batteries)

The study then acknowledges however that Tech II battery storage could still be a compatible option for wind+solar+storage mixes, but not without giving up

100% availability. This is because of the increasingly high costs of energy storage (diminishing returns of investment) as availability requirements approach 100%.

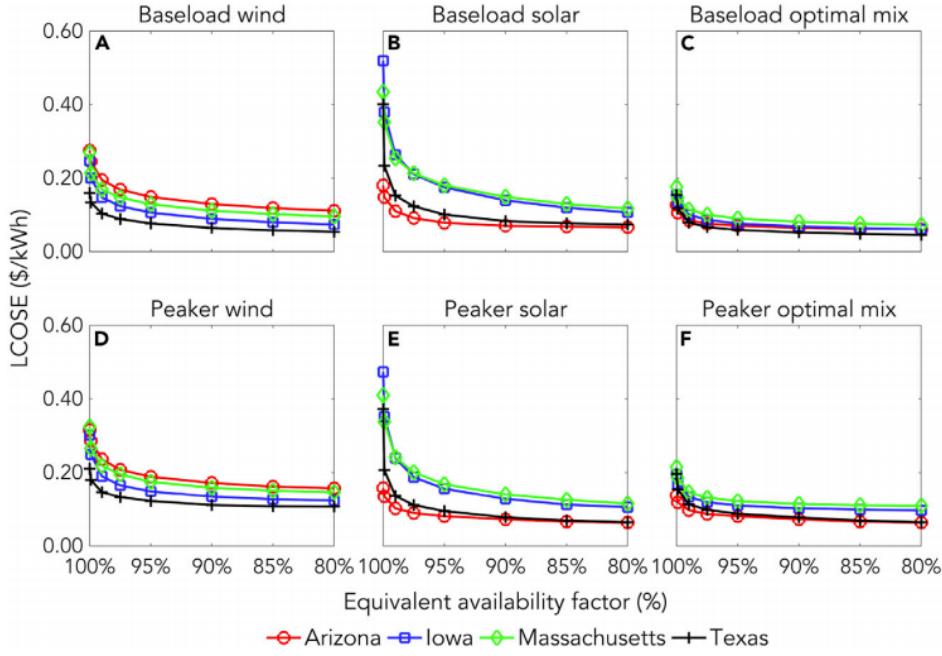


Figure 20: Electricity Cost Dependence on Equivalent Availability Factor for Tech II –⁶³

As shown in the charts above, the energy storage cost rate of change is steep close to 100% EAF (equivalent availability factor), but then it levels out. As the MIT study explains, these charts illustrate how an availability reduction of just 5%, can drastically reduce energy prices and raise our energy capacity cost target from \$20/kWh to \$150/kWh.

At \$150/kWh, Tech II storage solutions like Li-ion chemical batteries could be feasible for some regions. This would of course require some other energy solution to provide availability for the remaining 5% of the time which is a non-trivial problem to solve.

12.4 UPHS: Estimated Levelized Cost of Energy

The levelized cost of a power plant is the minimum constant price of electricity required over the lifetime of a plant in order to cover its costs. We can calculate

an estimated Levelized Cost of Energy Estimations using a simplified formula.

$$sLCOE = (\text{overnight capital cost} * \text{capital recovery factor} + \text{fixed O\&M cost}) / ((24*365) * \text{capacity factor})^{64}$$

The *overnight capital cost* is the initial construction costs. The *capital recovery factor* is driven by interest rates and years of operation. The *capacity factor* is the percentage of time that the plant produces energy. The full details of the calculation can be found in the appendix. (See Appendix: *Calculation of LCOE for UPHS*).

Our calculations show that a 1,000 MW UPHS installation has an LCOE of about \$0.063/kWh, or 6.3¢/kWh.

It's important to remember that PHES is not energy generation, but energy storage. So we cannot interpret this value simply as the cost of grid energy. Instead, we interpret this LCOE as a premium cost added to existing grid energy generation. The UPHS LCOE is the minimum cost which would be added to the cost of a variable energy supply.

There are multiple scenarios in which it makes sense for variable energy markets to purchase power with this premium. For example, this premium could still be much cheaper than peak power rate penalties, and it could be cheaper than the costs of curtailment.

13 UPHS: Optimistic Estimated Costs and ROI

In this section we build on our previous estimated costs of underground pumped hydro energy storage. Here we will speculate on additional cost savings which, optimistically, we believe could be gained from some or all of the following: capitalizing on current low interest rates, utilizing existing dams, and saving on cheaper tunnel costs with improved tunnel boring technology.

We acknowledge that the estimates in this section are speculative. But we hope to demonstrate that these costs are at least feasible under ideal circumstances. We hope that by demonstrating the feasibility of much cheaper prices, we inspire further exploration to validate these optimistic assumptions.

13.1 UPHS Estimates: Low Interest Rates

As expressed in the 2012 IRENA report, “given that hydropower is capital-intensive, has low O&M costs and no fuel costs, the LCOE [(levelized cost of electricity)] is very sensitive to investment costs and interest rates but less sensitive to lifetime, given the lifetime range typical for hydropower.”⁶² In other words, the cost of hydro is largely dependent on favorable financing rates.

Long term interest rates are currently very low in the US, which give an advantage to long term projects like pumped hydro.



Figure 21: The 30 Year US Treasury Rate is 2.26% as of Aug 09, 2019. This is well below the long term average of 5.10%⁶⁵

According to the 2012 IRENA report, if the cost of capital (or discount rate) decreased from 10% to 3%, the LCOE costs are approximately cut in half.⁶²

13.2 UPHS Estimates: Utilization of Existing Dams

Above, we estimated the total install cost of UPHS to be about \$1,300/kW. However, it could be possible to lower this cost by adding UPHS to an existing dam. In the 2017 IRENA report, the typical install costs for hydropower projects are estimated in a large range: from a low of \$500/kW to a high of around \$4,500/kW. And the report estimates that a plant built onto an existing dam could cost as low as \$450/kW.

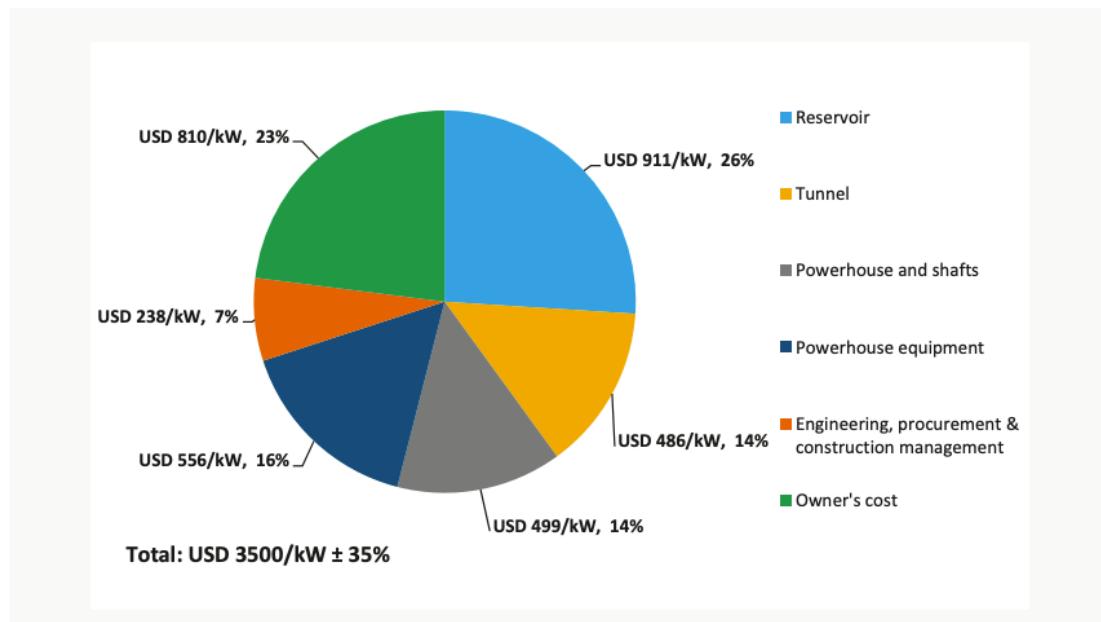


FIGURE 4.5: COST BREAKDOWN OF AN INDICATIVE 500 MW GREENFIELD HYDROPOWER PROJECT IN THE UNITED STATES

Source: Black and Veatch, 2012.

Figure 22: Cost breakdown of a typical greenfield hydropower project in the US⁶²

As shown in the pie chart above, these savings would presumably come from reducing the 26% reservoir costs of a greenfield development.

If we presume that a UPHS facility could benefit from similar savings, we can deduct 25% from our previous UPHS construction estimate of \$1.3 billion. This

gives us a construction cost of \$975 million.

$$\$1,300,000,000 - (\$1,300,000,000 * .25) \approx \$975,000,000$$

13.3 UPHS Estimates: Cheaper Tunnel Costs

It's estimated that about 30% of overall UPHS project costs are spent on digging the lower reservoir. The vertical shafts are comparably small in volume and should not add much more digging cost. See Appendix: *Calculation of Vertical Shaft Volume and Cost*

As cited above, Elon Musk's Boring Company has been developing improved tunneling machines which have the potential to drastically reduce the time and cost of mining. The Boring Company claims that their technology will soon add a 10-15-fold performance gains. Although these claims certainly cannot be taken on faith without rigorous demonstration, it does make sense that performance gains should follow from the process streamlining that the company is developing. For the sake of argument, we'll choose an optimistic estimation that digging could become five times faster and cheaper than it was at the time of the 1984 PNL report when UPHS costs were calculated.

13.4 UPHS Calculated Optimistic Estimated Cost

With the optimistic figures above, we can re-calculate a potential lower cost of UPHS than our initial calculation. The full details of this calculation can be found in the appendix. See Appendix: *Calculation of LCOE for UPHS (Optimistic)*.

Our calculations show that under optimistic market conditions, it's feasible that a 1,000 MW UPHS installation could have an LCOE of about \$0.017/kWh, or 1.7¢/kWh.

Again, we stress that this estimation includes some speculative assumptions.

And more research is needed to attach more confidence to this number. But if any of our optimistic assumptions prove correct and UPHS could drop from a LCOE of 6.3¢/kWh to a price closer to 1.7¢/kWh, it would be extremely competitive, making it much easier for wind and solar growth to capture market share well past 50% of the energy market.

14 UPHS Versus Lithium Ion Chemical Batteries

In the section above called *Why Energy Storage?*, we discussed some of the problems with Li-ion chemical batteries and why they might not be suited for grid-scale energy storage. In this section, we'll explore this question in more detail. And we'll demonstrate why UPHS could be a far cheaper alternative.

The BloombergNEF research team recently published their Energy Outlook 2019 Report. The report's summary cites that the levelized cost of (Li-ion battery) storage will fall from today's \$187/MWh cost to around \$67/MWh by 2040.⁶⁶ They predict: "By the mid-2020s, batteries are the most cost-competitive source of peaking generation. By 2030, they challenge the duopoly of coal and gas for the provision of dispatchable generation – so producing when the sun does not shine and the wind does not blow."⁶⁶

But these levelized costs are much higher than those for PHS or UPHS. Today's cost of \$187/MWh (\$0.187/kwh) is about three times more expensive than our more conservative estimate for UPHS at \$0.063/kWh. And even by 2040, the cost of Li-ion batteries would still be more expensive at \$67/MWh (\$0.067/kW) than our conservative estimate for UPHS at \$0.063/kWh.

But it gets worse. Li-ion battery life has a max of 7-10 years at best, and degrades steadily even in early years.⁶⁷

In the article above about the Hoover dam, the New York Times quotes chemistry professor Sri Narayan who believes lifespans are likely even shorter in the

real world. He said, “With lithium-ion batteries, you have durability issues...If they last five to 10 years, that would be a stretch, especially because we expect to use these facilities at full capacity.”³⁰

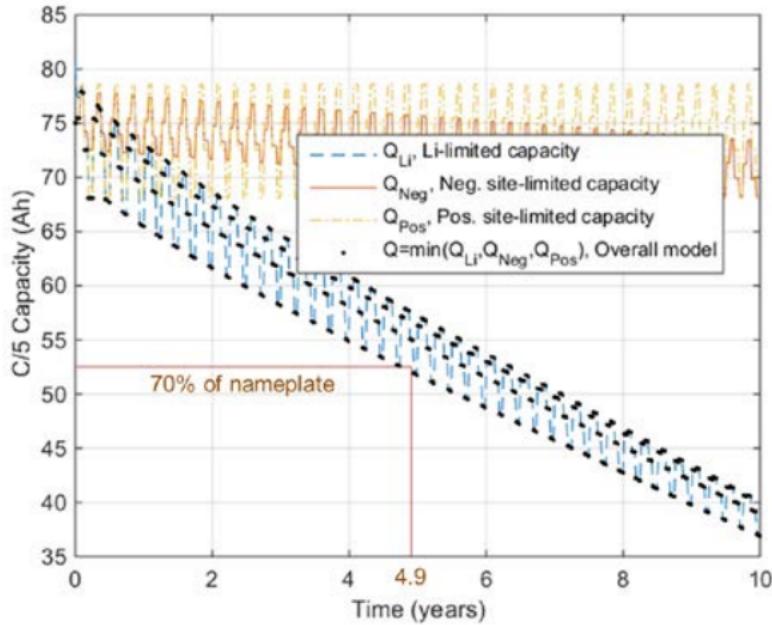


Fig. 8. Simulated battery capacity fade under self-consumption mode operation with seasonal ambient temperature variation of 18/28/12/5°C for spring/summer/fall/winter seasons, respectively.

Figure 23: Battery Life for Grid-Scale Li-Ion Batteries⁶⁷

With a 5-10 year lifespan, a LCOE of \$67/MWh for Li-ion by 2040 looks much less enticing. Because this could mean that the equivalent LCOE for a 40 year operating storage plant could be about \$332/MWh for Li-ion. There is some hope for Li-ion as research suggests that recent technological advances could push battery life to 20 years with little degradation. But even these most optimistic predictions for Li-ion are not enough to make it cheaper than UPHS over 40 years. On the other hand, optimistic predictions for UPHS could make it 3-15 times cheaper than Li-ion over 40 years. See Appendix: *LCOE comparisons for UPHS vs Li-ion Batteries*.

And, we have further problems with Li-ion batteries. Researchers are not even sure that our planet can supply all the materials needed to produce enough bat-

teries. According to research by the University of Technology Sydney, by 2050, “demand from renewable energy and storage technologies could exceed reserves for cobalt, lithium and nickel, and reach 50% of reserves for indium, silver, tellurium.”

Figure A: Cumulative demand from renewable energy and storage by 2050 relative to reserves in three scenarios for selected battery metals (left) and solar PV metals (right)

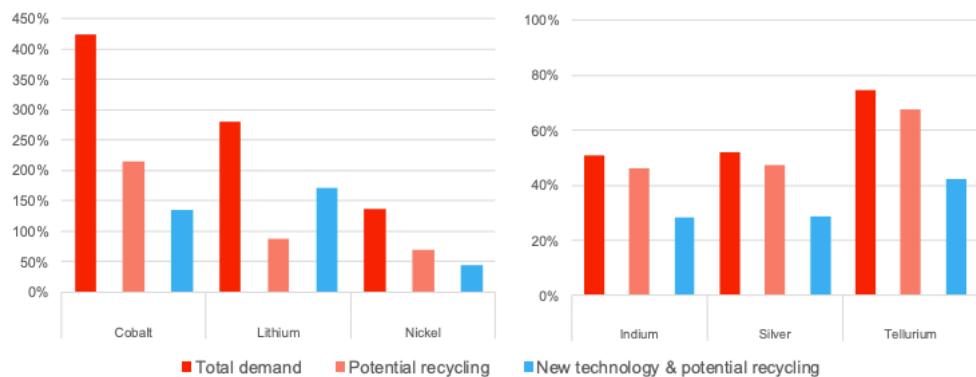


Figure 24: Cumulative demand from renewable energy and storage by 2050 relative to reserves - UTS 2019⁶⁸

According to that report (Institute for Sustainable Futures report), some materials will experience a threatened supply even sooner.

“The rapid increase in demand for cobalt, lithium and rare earths is of the most concern. Demand for lithium and rare earths from lithium-ion batteries for EVs and storage exceeds current production rates by 2022 (for all uses).”⁶⁸

Furthermore, chemical batteries are a known source of pollution. It will be important to monitor and better understand the repercussions of such pollution as mining increases. Here is one story highlighted by the Institute for Sustainable Futures report:

“Although not well documented, there have been ongoing negative social environmental impacts in China, which at one point was producing 97% of the world’s supply [of rare earth ores]. The town of Baotou, in Inner Mongolia, processes rare earths from the Bayan Obo mine, a 48

square kilometre open-pit mine that is the largest source of rare earths in China, as well as producing iron ore. Here wastewater from the tailings dams has polluted groundwater, which has led to crop failures and the displacement of farming communities.”⁶⁸

14.1 UPHS Plus Lithium Ion Batteries

Despite some downsides of Li-ion batteries, they are still a crucial technology which will help us increase global battery storage and increase renewable energy resources. As stated earlier, chemical batteries are particularly good for replacing peaker-plants on a local scale. We outline the downsides of Li-ion only to illustrate that the technology is probably not as well suited for grid-scale energy storage compared to other options.

Further, we demonstrate that underground pumped hydro energy storage could be a more effective solution than Li-ion batteries – by an order of magnitude on long-term scales.

15 Conclusion

Climate change is a dire threat. In this report we have explained why it is critical to build an enormous capacity of energy storage over the coming decades. And we have argued that underground pumped hydro storage could be our most affordable means of accomplishing this task. Over the next 40 years, UPHS technology is estimated to be cheaper than Li-ion batteries, even under the most optimistic circumstances for Li-ion technological advancements. On the other hand, optimistic predictions for UPHS could make it 3-15 times cheaper than Li-ion over 40 years.

Without overstatement, civilization is in a state of climate emergency. Our fight against climate change will demand a global, multi-faceted effort. This challenge is our generation’s “moonshot mission.”

Underground pumped storage technology could help sway a tipping point from either trillions of dollars in climate damages, or billions of dollars in economic gains. We should immediately pursue further research of this technology.

We must invest in long-term climate solutions, immediately. If we do this, we still have a chance to inherit a future with a healthier climate and a stronger economy.

“We’re the first generation to feel the impact of climate change.

We’re the last generation that can do something about it.”²

– President Barack Obama

16 Appendix

16.1 Calculations for Pumped Storage with Heavy Piston Design

As mentioned above, a company called Gravity Power is developing an energy storage design which involves a heavy piston suspended in a vertical shaft filled with water. The system employs a closed loop of water with a pump and a power generator. The system can cycle water in both directions. Energy is expended to lift the piston by pumping water under it. Energy can be recaptured by allowing the weight of the piston to push the water back up through a turbine. When the piston falls, the water gathers in the space above the piston.

With these assumptions about the piston design, our calculations below demonstrate that this design should be less efficient than underground pumped hydro energy storage.

Let's begin with the basic equation for gravitational potential energy where E is energy, m is mass, g is the gravitational constant, and h is height.

$$E = mgh$$

We replace mass with volume times density (ρ) where volume is represented by the height (h) times area (a).

$$E = (h * a * \rho) * g * h$$

The piston design system includes two densities. We will define the density of the rock piston as (ρ_p) and the density of the water as (ρ_w).

The piston and water volumes both occupy the entire cross section area of the shaft. The potential energy of each piece depends on each of their heights and the distance (d) that each travels. We must remember that when the piston drops,

the water is lifted above the piston. So the water's potential energy must be subtracted from the piston's. Using subscripts p for piston and w for water, we have:

$$E_{net} = (h_p * a * \rho_p) * g * d_p - (h_w * a * \rho_w) * g * d_w$$

We introduce f as the fraction of the shaft height which the piston will occupy. We can then translate the heights of the piston (h_p) and height traveled by the piston (d_p) as functions of f .

$$h_p = hf, \quad d_p = h - hf$$

Because the water occupies the rest of the volume around the piston, we can also define the height of the water and the height traveled by the water as:

$$h_w = h - hf, \quad d_w = hf$$

These are naturally the inverse values as the piston, because each element must travel the distance of the other's height to balance the volume of the closed system.

Now let's revisit our Energy equation and begin substitution.

$$E_{net} = (h_p * a * \rho_p) * g * d_p - (h_w * a * \rho_w) * g * d_w$$

Refactoring, we have:

$$E_{net} = ag(\rho_p(hf)(h - hf) - \rho_w(h - hf)(hf))$$

We note the common factor of $(hf)(h - hf)$, and refactor again.

$$E_{net} = ag((hf)(h - hf)(\rho_p - \rho_w))$$

Since rock is about 2.5 denser than water we have

$$\rho_p = 2.5\rho_w$$

So

$$E_{net} = ag((hf)(h - hf)(2.5\rho_w - \rho_w))$$

Simplifying

$$E_{net} = ag(fh^2 - h^2f^2)(1.5\rho_w)$$

Refactoring

$$E_{net} = 1.5ag\rho_w h^2(f - f^2)$$

Inspecting this equation, we see that the maximal f value is .5. So we conclude that the piston should be half the height of the shaft. This gives us:

$$E_{net} = 1.5ag\rho_w h^2(.5 - (.5)^2)$$

or

$$E_{net} = 0.375ag\rho_w h^2$$

Now let's compare this result to the potential Energy E_{UPHS} of the shaft filled with just water and no rock piston. We note that the water will, on average, only rise half the height of the shaft as it empties to ground level at the top of the shaft. We use our equation above but with new values for water using a subscript u. So our water has a height h_u and distance traveled d_u .

$$E_{UPHS} = (h_u * a * \rho_w) * g * d_u$$

The water is the full height of the column and will travel half the height on average.

$$h_u = h, d_u = .5h$$

So we have

$$E_{UPHS} = ag\rho_w(h)(.5h)$$

or

$$E_{UPHS} = .5ag\rho_w h^2$$

We can see that this is an improvement over E_{net} for the piston design. With common values for $ag\rho_w h^2$, the improvement of UPHS over this piston design appears to be

$$(0.5/0.375) - 1 = 0.\bar{3}$$

In other words, UPHS should give an improvement of about 33% over this piston design. With this result, the piston design does not seem to be compelling alternative to UPHS. We do concede however that this piston design eliminates the need for an upper reservoir. So perhaps the idea could still prove valuable for some locations where an upper reservoir is not possible.

16.2 Calculation of New York City Daily Energy Usage

New York State's Total Annual Energy usage in 2017 was about 905 trillion Btu.⁶⁹ This is equivalent to 265,229,319 MWh.

According to the New York Times, “nearly 60 percent of the state’s electricity is consumed in the New York City area.”²⁷ This number is validated by the eia.gov report which says “two-thirds of the state’s power demand is in the New York City and Long Island region”.⁶⁹ So we will use 60% and consider this the New York City Area not including Long Island. This gives us

$$265,229,319MWh * .6/365 \approx 435,993MWh$$

The New York City area consumes approximately 435,993MWh of power daily,

or

$$435,993 \text{ MWh} / 24 \approx 18,166 \text{ MWh}$$

18,166MWh per hour

New York City has pledged to have 500 MW of storage available by 2025. But as we can see

$$500 \text{ MW} * 1 \text{ hour} / 18,166 \text{ MWh} \approx 0.0275 \approx 2.8\%$$

This will only yield about 2.8% of NYC's total power consumption in storage energy.

16.3 Calculation of Vertical Shaft Volume and Cost

In the PNL report, it was estimated that the lower reservoir of a UPHS installation might have a volume of about $6,012,900 \text{ m}^3$. The volume of the vertical shafts is not given, but the dimensions are. The PNL report mentions there could be 4 shafts with diameters of 5.8 m ranging in depth from 1525 to 1677 m.³⁵ We'll use 1600 m as an average value. This gives us an estimated volume for each shaft:

$$\pi r^2 * h = \pi (5.8/2)^2 * 1600 \approx 42,273 \text{ m}^3$$

For all four shafts, this gives us $169,092 \text{ m}^3$

$$42,273 \text{ m}^3 * 4 = 169,092 \text{ m}^3$$

We note that according to these estimates, the mined vertical volume is about 3% of the total volume.

$$169,092 \text{ m}^3 / (6,012,900 \text{ m}^3 + 169,092 \text{ m}^3) \approx 0.03$$

The PNL report estimates that the lower reservoir of a UPHS plant would likely represent about 30% of the overall project cost.³⁵ Given that the vertical shafts represent only 3% of the overall mined volume, we consider it negligible for the purposes of our rough estimations. We'll estimate that all the digging still represents about 30% of the overall cost.

16.4 Calculation of LCOE for UPHS

According to the PNL report, the total direct cost of a UPHS plant built in 1983 would be estimated at $\$500 * 10^6$ for a 1000-MW plant in 1983 dollars.³⁵ (about \$1.3 billion in today's dollars.⁶¹). Note that this works out to \$1,300/kW.

We will base our LCOE calculation on this UPHS construction cost of \$1,300,000,000 for a 1000-MW plant.

Our calculation will use NREL's formula for Simple Levelized Cost of Energy:

$$sLCOE = \{(overnight capital cost * capital recovery factor + fixed O&M cost) / (8760 * capacity factor)\} + (fuel cost * heat rate) + variable O&M cost.⁶⁴$$

We'll remove variable O&M cost and fuel cost which are not relevant for pumped hydro. We assume a capacity factor of 30%. We define overnight capital cost as C_i dollars per installed kilowatt (\$/kW). We assume a lifetime of 40 years. We'll assume the fixed O&M costs are $(2.5\% * C_i)$ dollars per kilowatt-year (\$/kW-yr). We define capital recovery factor as CRF, which per NREL, is defined as the following where i is the interest rate and n is the number of years.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

This gives us:

$$LCOE = ((C_i * CRF) + (.025 * C_i)) / (8760 * .3)$$

We will assume a conservative rate of 10% interest. At 10% interest over 40 years, our CRF is about 0.1023

$$CRF = \frac{0.1(1 + 0.1)^{40}}{(1 + 0.1)^{40} - 1} = 0.10225941441$$

Which gives us:

$$LCOE = (0.1023C_i + .025C_i) / 2628$$

which reduces to

$$LCOE \approx 0.00004844C_i$$

Using our initial cost above, we determine our value of C_i in dollars per installed kilowatt. Our value is for a 1,000MW capacity plant (1,000,000kW).

$$C_i = \$1,300,000,000 / 1,000,000kW = \$1300/kW$$

This gives us a LCOE for UPHS of about \$0.063/kWh, or ¢6.3/kWh

$$LCOE \approx \$0.00004844 * 1300 / kWh \approx \$0.063 / kWh$$

We note that this estimate may be simplified and idealized. We also note that it is about 2.4 times cheaper than the lowest contemporary estimate we could find for pumped hydro storage.

$$0.15 / 0.063 \approx 2.4$$

This discrepancy could be due to a number of factors. One factor could be

that contemporary estimates of pumped hydro projects may average out the costs of actual built projects. Some of these built projects may have suffered from cost overruns, or they may have been built on less suitable locations with smaller overall capacities which would have lost economies of scale. Underground pumped storage could arguably avoid such risks as it is not as site dependent.

see *Comparison of researched LCOE for PHS, UPHS, and Li-ion Batteries*.

16.5 Calculation of LCOE for UPHS (Optimistic)

Here we will re-calculate the above LCOE using more optimistic predictions.

The original estimated cost of UPHS construction was \$1,300,000,000. We speculate that this cost could be feasibly lowered by 25% if a UPHS plant was built onto an existing dam. This brings the cost down to \$975,000,000.

We divide this into two costs: The cost of tunneling and everything else.

Tunneling was estimated to be 30% of \$1.3 billion, or \$390 Million

$$\$1,300,000,000 * .3 = \$390,000,000$$

Subtracting this out from the base cost, we see that non-tunnel costs are \$585 Million.

$$\$975,000,000 - \$390,000,000 = \$585,000,000$$

As discussed previously, we presume that tunneling costs could be 5 times cheaper thanks to technological efficiencies. This would reduce tunnel costs to \$78 Million.

$$\$390,000,000 / 5 = \$78,000,000$$

Adding these costs back together we get \$663 Million.

$$\$78,000,000 + \$585,000,000 = \$663,000,000$$

We take note that this price is just about half of our original estimated construction cost.

$$\$663,000,000/\$1,300,000,000 = .51 \approx .5$$

To determine our LCOE, we'll use the same NREL formula mentioned above. We'll again remove variable O&M cost and fuel cost. We'll assume a lifetime of 40 years which is conservative for PHS. All other assumptions are the same including a capacity factor of 30%.

As discussed above, the current 30 Year US Treasury Rate is very low at 2.26%. We will use an optimistic value of 3% interest. At 3% interest over 40 years, our CRF is about 0.0433.

$$CRF = \frac{0.03(1 + 0.03)^{40}}{(1 + 0.03)^{40} - 1} = 0.04326237789$$

Which gives us:

$$LCOE = (0.0433C_i + .025C_i)/2628$$

which reduces to

$$LCOE \approx 0.00002599C_i$$

Using our initial cost above, we determine our value of C_i in dollars per installed kilowatt. Our value is for a 1,000MW capacity plant (1,000,000kW).

$$C_i = \$663,000,000/1,000,000kW = \$663/kW$$

This gives us a LCOE of about \$0.017/kWh, or \$17/MWh, or ¢1.7/kWh.

$$LCOE \approx \$0.00002599 * 663 / kWh \approx \$0.017 / kWh$$

16.6 Calculation of LCOE for Li-ion

Li-ion batteries currently have a lifespan of only 5-10 years.³⁰ In ideal conditions they might have a lifespan of 7-10 years.⁶⁷

Li-ion batteries have a levelized cost of \$187/MWh today. This cost is expected to more than halve in cost by 2040, reducing them to an LCOE of \$67/MWh. Assuming a linear decline in cost, the average cost will be \$127/MWh over the next twenty years.⁶⁶

$$(\$187/MWh + \$67/MWh) / 2 = \$127/MWh$$

Let's make an assumption that Li-ion prices will halve again by 2060. That would bring down the LCOE to about \$34/MWh. Again, assuming a linear decline in cost, that would give us an average cost of \$110.5/MWh over the next forty years.

$$(\$187/MWh + \$34/MWh) / 2 = \$110.5/MWh$$

We note that over the lifetime of a Li-ion battery, the capacity declines steadily in a nearly-linear fashion from about 75% to about 40% of their capacity.⁶⁷ We're not certain whether this battery capacity decline is already averaged out in estimations of LCOE, so we will ignore this. But we note that if this has not been properly taken into account, this could strengthen UPHS's advantage over Li-ion.

We will assume a ten year lifespan for Li-ion batteries. As noted above, this could be lower in practice - possibly closer to 5-7 years. As noted below, it could also be larger due to technological advancements. But this has yet to be fully

validated.

With these assumptions, we conclude that over forty years, if a Li-ion energy storage facility had to replace their batteries once a decade, their cost over forty years would be \$332/MWh.

$$\$110.5/MWh * 3 \approx \$332/MWh$$

16.7 Calculation of LCOE for Li-ion (Optimistic, dependent on Technology Advances)

As mentioned above, Li-ion batteries currently have a lifespan of only 5-10 years (see *Calculation of LCOE for Li-ion*).

New research has emerged however which suggests that lifespans of lithium ion batteries may be stretched to 20 years.⁷⁰ This research was done by Jeff Dahn and his lab, who are doing battery research for Tesla, Inc. The gains are attributed to a design which includes a next-generation “single crystal” NMC cathode and a new advanced electrolyte.

Using this new optimistic figure, we can conclude That over forty years, a Li-ion energy storage facility would only need to replace their batteries once. So their cost over forty years would be \$221/MWh.

$$\$110.5/MWh * 2 = \$221/MWh$$

We note that this figure is now within the ranges of research cited below (see *Comparison of researched LCOE for PHS, UPHS, and Li-ion Batteries*).

16.8 Comparison of researched LCOE for PHS, UPHS, and Li-ion Batteries

In the sections above, we calculated a simplified LCOE for UPHS. We determined that the LCOE was \$0.063/kWh based on research from the 1980s (See *Calculation of LCOE for UPHS*). We acknowledge that this estimate may be a simplified calculation which may ignore certain factors. Although we could find little to no contemporary research about UPHS pricing, in this section we compare our findings with more contemporary research for PHS pricing in general.

We also calculated a LCOE for Li-ion energy storage projected over 40 years. We determined that it could be somewhere between \$221/MWh and \$332/MWh. This is within the range of our research as shown below.

The Lazard Energy Storage Report is one of the most trusted industry sources for price analysis. In 2016, the report determined the following for unsubsidized levelized costs of storage at grid-scale (transmission system):²⁹

Pumped Storage:	\$152/MWh - \$198/MWh (about \$0.15/kWh - \$0.2/kWh)
Lithium-Ion:	\$267/MWh - \$561/MWh (about \$0.25/kWh - \$0.55/kWh)

As shown, in 2016, pumped storage was estimated to about 6 times cheaper than lithium-ion on average for grid-scale applications.

$$((561 - 267)/2)/((198 - 152)/2) \approx 6.4$$

Examining only the low estimates, pumped storage was estimated to be almost half the cost of lithium-ion for grid-scale applications.

$$267/152 \approx 1.8$$

Unfortunately, Lazard began omitting PHS in 2017. Despite the very low LCOS (levelized cost of storage), it seems that the Lazard report decided to lump PHS into technologies with “limited current or future commercial deployment expec-

tations.”²⁸ As discussed above, this is likely due to concerns over steep upfront costs and the diminishing availability of sites for new dam construction. However, Lazard is now expected to reincorporate PHS into the upcoming 2019 version of their report, according to researchers working with the San Diego County Water Authority.²¹

In their 2019 research paper, the same San Diego group calculated their own LCOS estimates for both PHS and Li-ion:²¹

Pumped Storage: \$177/MWh (about \$0.18/kWh)

Lithium-Ion: \$218/MWh - \$285/MWh (about \$0.22/kWh - \$0.29/kWh)

Summarizing their findings, the San Diego group concludes that even with drastic technology improvements for Li-ion, over a 40 year time frame “[Li-ion] batteries will remain overall more expensive than pumped storage — possibly 50% more expensive than pumped storage.”²¹ This is a notably different conclusion from some competing research which concludes that Li-ion will become cheaper than pumped storage. The San Diego group believes that their research is more complete. They argue that the estimated lifetime cost of Li-ion increases after considering the nuances of long term financing. They explain: “Compared with pumped storage, the capital cost for these [Li-ion] projects is lower (\$285,000/MWh to \$452,000/MWh), but that cost must be paid back more rapidly because the lifetime of these [Li-ion] projects is shorter. The overall effect is to make batteries more expensive than pumped storage when those costs are leveled over the relevant time period.”²¹

Further, the San Diego group showed that PHS projects could continue to operate beyond 50 years with relatively little maintenance cost. Building on the existing infrastructure, the second 50 years of a PHS project has an extremely low LCOS of only \$58/MWh (about \$0.06/kWh).

Summarizing this range of cost estimates: We note that our LCOS estimate for UPHS based on 1980s data is significantly lower at \$63/MWh than contemporary

estimates which show costs closer to \$150/MWh or \$175/MWh. Further research is needed to analyze this price gap and determine which details account for the difference (note that inflation has already been considered).

We acknowledge that 63-175 is a very wide range. But this should perhaps be expected considering that 1: Large UPHS projects have never been constructed before, and 2: Even contemporary research shows a fair amount of variation since it draws data from many disparate projects. Each unique project deals with diverse conditions that vary financially, geographically, and politically.

Based on this range, our conservative estimate for UPHS will be \$177/MWh. Our optimistic LCOS baseline for UPHS will be \$63/MWh, based on the 1980s PNL research. Finally, our highly-optimistic LCOS will be \$17/MWh based on other optimistic possibilities. See *Calculation of LCOE for UPHS (Optimistic)*.

Based on the ranges of LCOE estimates for Li-ion batteries, we will use \$220/MWh as a feasible, best-case scenario for Li-ion. And we'll use \$285/MWh as a still feasible conservative cost for Li-ion. It's important to note that this is not a worst case scenario by any means. In fact, it still makes many optimistic assumptions that Li-ion technology will drastically improve over the coming decades.

Summarizing all of the above:

- PHS LCOS estimates in 2016 were about 2-6 times cheaper than Li-ion.
- PHS LCOS estimates for projects planned and built in the next decade, are still expected to be cheaper than Li-ion over a 40 year time frame.
- PHS facilities can extend their lifespan for 100 years or more with very low additional cost.
- UPHS cost estimates are projected to be about the same cost or cheaper than PHS in general.

We conclude that UPHS facilities built in the near future should be at least

competitive, if not far cheaper than Li-ion facilities over the next 40-100 years.

40-year LCOE values for UPHS and Li-ion

UPHS (conservative):	\$177/MWh	Li-ion (conservative):	\$285/MWh
UPHS (optimistic):	\$63/MWh	Li-ion (optimistic):	\$220/MWh
UPHS (highly-optimistic):	\$17/MWh		

16.9 LCOE comparisons for UPHS vs Li-ion Batteries

Based on the sections above, we make direct comparisons of the 40-year LCOE predictions for UPHS and Li-ion batteries. We will calculate these based on various combinations of predicted outcomes. We note that even under the best case scenario for Li-ion, UPHS is still cheaper.

Apples to Apples

- Optimistic UPHS is 3.5 times cheaper than optimistic Li-ion (220/63)
- Conservative UPHS is 1.6 times cheaper than conservative Li-ion (285/177)

Best Cases for Li-ion

- Conservative UPHS is still 1.2 times cheaper than optimistic Li-ion (220/177)

Best Cases for UPHS

- Optimistic UPHS is 4.5 times cheaper than conservative Li-ion (285/63)
- Highly-optimistic UPHS is \sim 13 times cheaper than optimistic Li-ion (220/17)
- Highly-optimistic UPHS is \sim 17 times cheaper than conservative Li-ion (285/17)

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