Long-Duration Utility-Scale Energy Storage

Gaseous storage systems play an important, cost-effective, and large-scale role in providing long-duration seasonal energy storage.

Executive Summary

Energy storage addresses a variety of short-term and long-term energy market needs. This paper highlights leading energy storage applications and practices in today's gas and electric energy delivery systems, with a particular focus on the role and attributes of the long-duration energy storage market segment. The paper also outlines key future energy transition considerations.

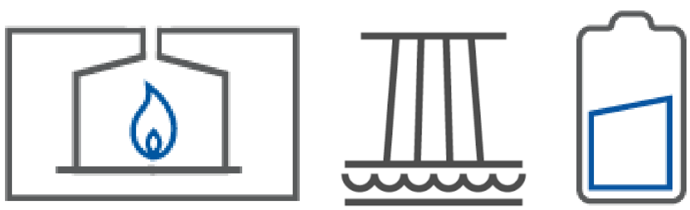

Table 1 summarizes key metrics for three primary operational energy storage systems used currently by U.S. gas and electric system operators: (1) underground gas storage, (2) pumped hydro energy storage, and (3) battery energy storage (BES). The latter two are employed exclusively for electric energy storage, while gas storage supports electric and gas systems.

Gas underground storage and pumped hydro provide long-duration energy storage services with the capability of addressing seasonal variations in supply and demand (e.g., winter or summer peak space conditioning loads). Battery energy systems typically provide short-duration (e.g., less than 24-hour) value-added services such as frequency or voltage regulation or onsite peak demand management.

Table 1: Gas & Electric Storage Performance Metrics (DOE-EIA, GTI)

Energy Storage System	Underground Gas Storage[1]	Pumped Hydro Energy Storage	Battery Energy Storage
Nominal Capacity (GW)	495	23	1.8
Peak Monthly Energy Delivered, GWh	331,800	2900	52
Peak Month Capacity Factor	23%	17%	7%
Cycle Efficiency (Losses) (%)	98.4% (1.7%)	79% (21%)	82% (18%)

[1] Underground gas storage values stated in thermal equivalents to electric GW or GWh.

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Introduction

Energy storage is used on an economy-wide basis within electric and gas utility energy delivery systems and other markets (e.g., transportation fuels) and plays a vital role in enhancing energy reliability and dampening energy price volatility. The need for robust and reliable energy storage across a range of scales, durations, and applications is fundamentally important for the energy systems of today and the future.

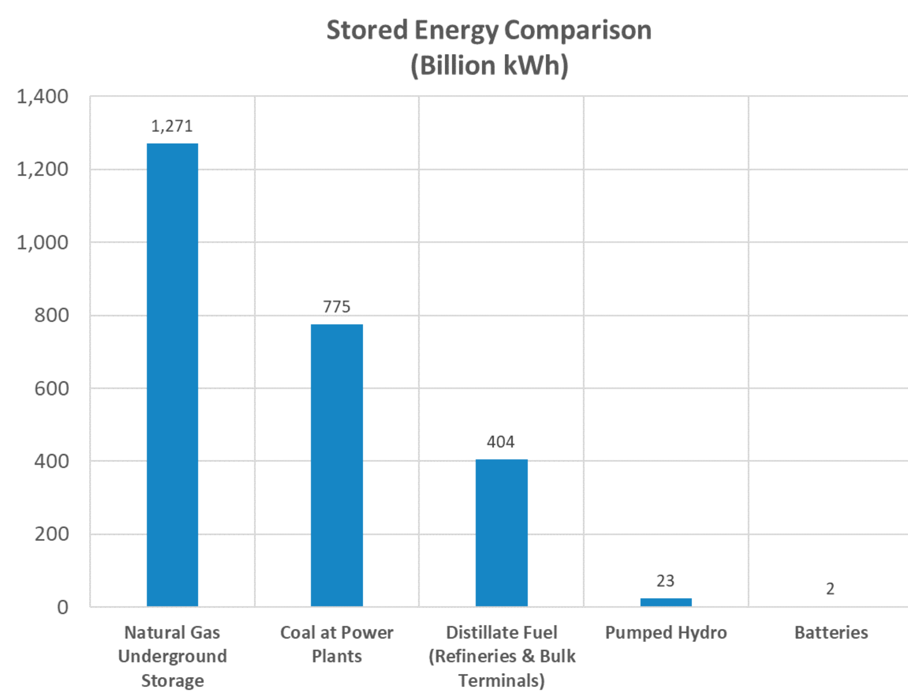
There are many energy storage options currently used in today's electric and gas energy systems, including underground gas storage, pumped hydro storage, batteries, liquefied natural gas (LNG), propane-air peak shaving, and compressed air energy storage to name a few. Additionally, these can be expanded to include distributed fuel storage for other liquid fuels (e.g., distillate fuel oil) or solid fuels (e.g., coal) – particularly located at or supporting power generation facilities.

Figure 1 shows examples of selected U.S. stored energy capacities (noting these energy forms are different, particularly comparing electricity to chemical energy carriers; distillate fuels serve stationary and transportation markets). Together, these all comprise forms of distributed energy systems that store energy for ultimate use in serving a variety of energy market needs.

Underground gas storage is the main form of gas storage

Pumped hydro storage systems currently make up over 90% of current electric energy storage, with battery energy storage (BES) deployment increasing

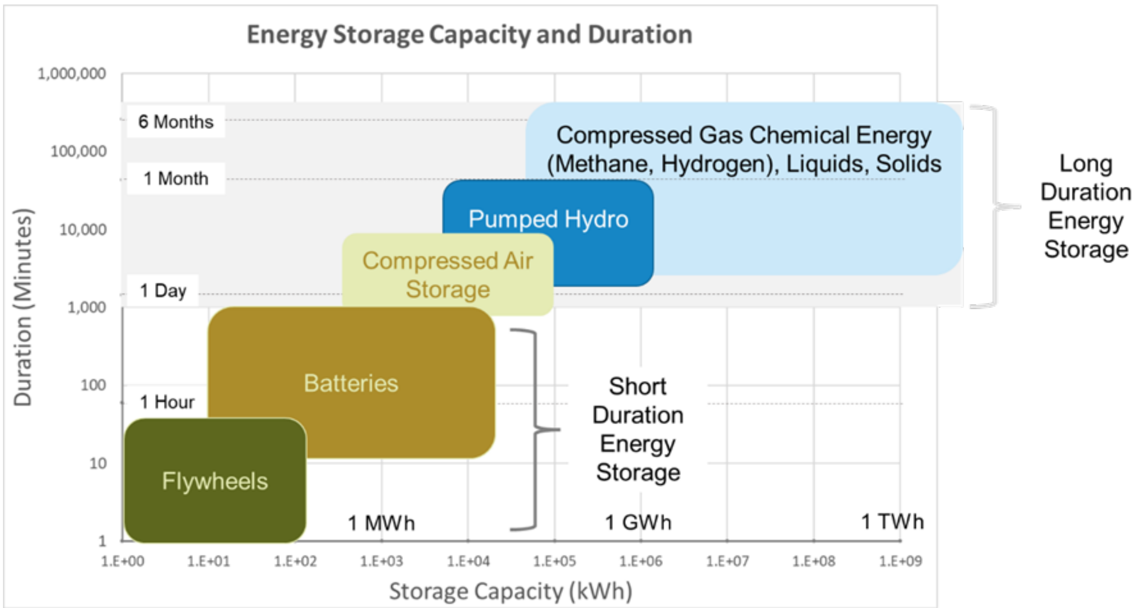
Figure 1: Comparison of Select U.S. Stored Energy Systems (DOE-EIA)



Utility-Scale Energy Storage

Figure 2 illustrates one approach to differentiating the energy storage market into two primary segments: (1) short-duration energy storage and (2) long-duration energy storage. This paper discusses three leading utility-scale energy storage systems in use today: (1) pumped hydro storage, (2) battery energy storage systems and (3) underground natural gas storage.[2] In this paper, we highlight the attributes and role of these three approaches to the long-duration energy storage segment which is vital to supporting seasonal energy system needs such as space conditioning energy loads (heating and cooling) and other demand factors influencing monthly or multi-monthly energy consumption variations.

Figure 2: Energy Storage Segments: Short and Long-Duration (adapted by GTI from National Hydropower Association report,9)



There is growing market interest in energy storage systems, driven in part by the need to help manage renewable energy intermittency challenges or in providing other value-added grid services – particularly with respect to battery energy storage systems. While there is growing interest in energy storage to address intermittency and variability in energy supply (wind, solar), energy storage in the form of fuels has always played a critical role in addressing variations in energy demand. Low- and zero-carbon fuels are well-suited to provide firm, grid-scale, long-duration energy storage in decarbonized energy systems and helping balance energy supply and demand. There is potential to leverage today's vast underground gas storage infrastructure for use with low/zero-carbon molecules and/or carbon capture as a means for reducing the cost, time, and risks of the energy transition.

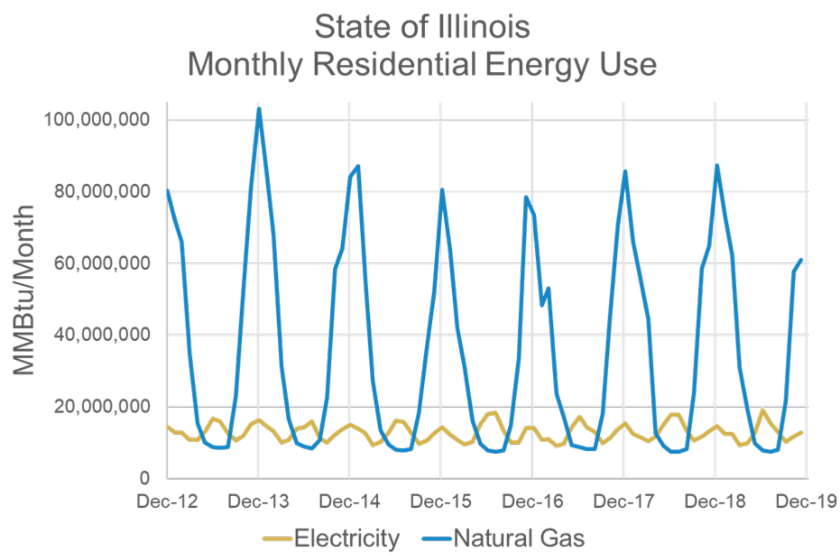
Utility-Scale Energy Storage Capacity, Monthly Usage Rates, and Discharge Time

This paper discusses key metrics for three leading operational electric and gas utility-scale energy storage systems with an emphasis on their role in addressing long-duration seasonal space conditioning (i.e., cooling and heating) loads. Metrics include: (1) system energy delivery capacity, (2) seasonal performance, and (3) system cycle efficiency.

[2] Term "utility-scale" describes larger (e.g., multi-MW) energy storage that may be owned and operated by public utility or other companies providing energy grid services to the electric and gas industries.

Gas energy storage has been used for many decades, mainly to meet intense winter seasonal space heating loads – which in most parts of the U.S. substantially exceeds space cooling energy loads. For example, Figure 3 shows monthly residential gas and electric energy use in Illinois homes over a seven-year period, with peak monthly demand for natural gas over five times larger than electric peaks. This pattern is seen in most states and is particularly pronounced in cold-weather regions, where it spans over several months. The magnitude of these end-use multi-monthly peaks are the specific reason the magnitude of underground gas storage (as shown in Figure 1) is notably larger in comparison to most other energy sources. That is, other energy markets experience lower differences in monthly or seasonal demand variation and have not needed to evolve the level of energy storage seen in gas energy delivery systems.

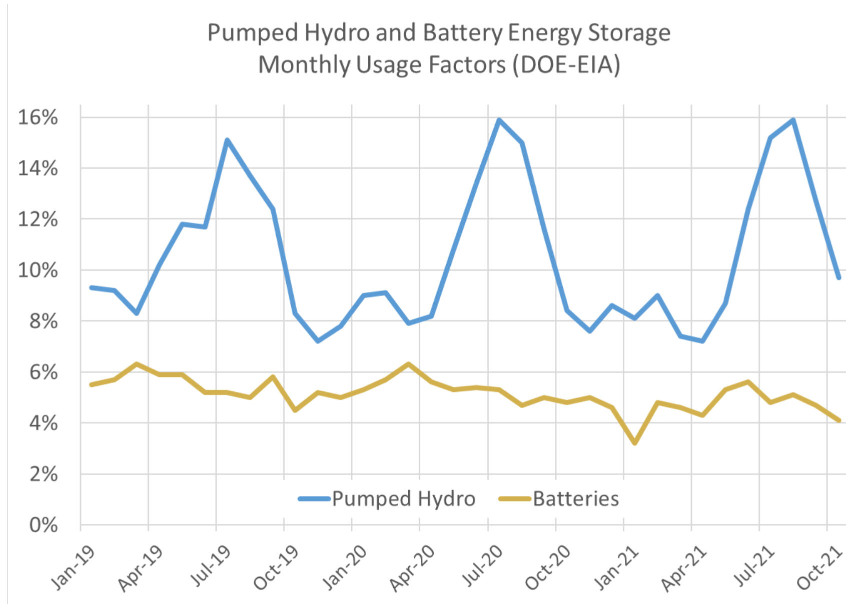
Figure 3: Seasonal Energy Use Challenges (DOE-EIA)



There are three main forms of natural gas energy storage: underground gas storage, liquefied natural gas (LNG) storage, and propane-air peakshaving plants. Underground gas storage represents over 90% of natural gas storage operating capacity and is the sole focus of natural gas storage in this paper. It is noteworthy, however, that U.S. natural gas liquefaction capacity growth for export markets may enable more stored LNG for utility, power generation, or industrial peak demand management.

Electric energy storage has traditionally used pumped hydro systems – these systems comprise over 90% of current electric energy storage. There are two key attributes of pumped hydro systems: (1) large scale and (2) seasonal operating capability (Figure 4). The seasonal capability of pumped hydro to address peak loads (now mainly for summer cooling loads with currently smaller winter peaks) underscores their role as a long-duration energy storage resource.

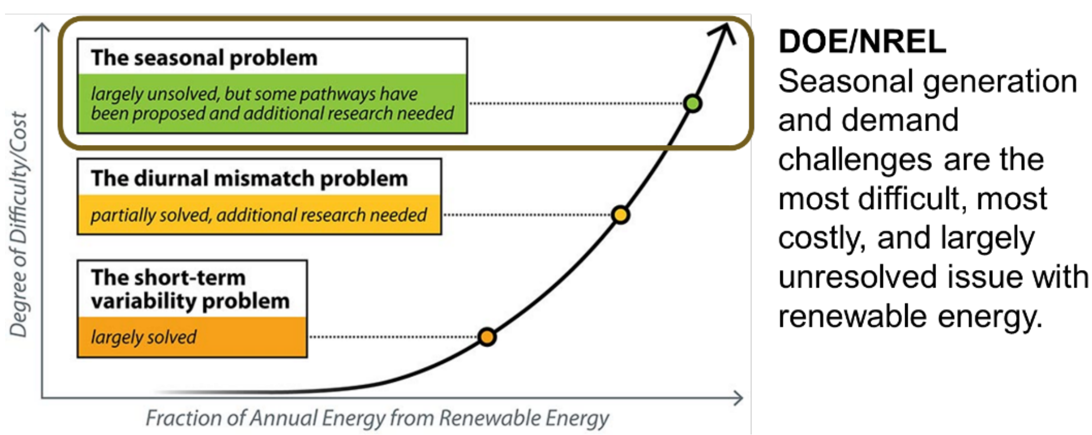
Figure 4: US Pumped Hydro and Battery Storage Monthly Usage Factor



Battery energy storage (BES) systems are gaining attention, with more BES sites installed each year. Most battery energy storage systems are installed to provide value-added services (e.g., frequency or voltage regulation), address intraday renewables intermittency, or to provide behind-the-meter peak demand management. Short-duration battery energy storage systems are particularly suited to those roles.

Based on a DOE/NREL report(7), the challenges of seasonal energy use (e.g., space conditioning loads such as cooling and heating) and seasonal energy storage are the most difficult and expensive challenge for electric systems experiencing greater generation levels from intermittent wind and solar power (Figure 5).

Figure 5: Seasonal Energy Use and Renewable Generation Challenge



Natural gas is the leading source of power generation in the U.S., playing a variety of different roles. For example, dispatchable natural gas generation is often used today as the primary option for addressing seasonal variability in electric energy demand (e.g., due to space conditioning). With respect to the short-term variability problem, fastramping gas turbines are often used now for intraday (<24 hour) grid stabilization services (e.g., to compensate for rapid changes in wind or solar generation output).

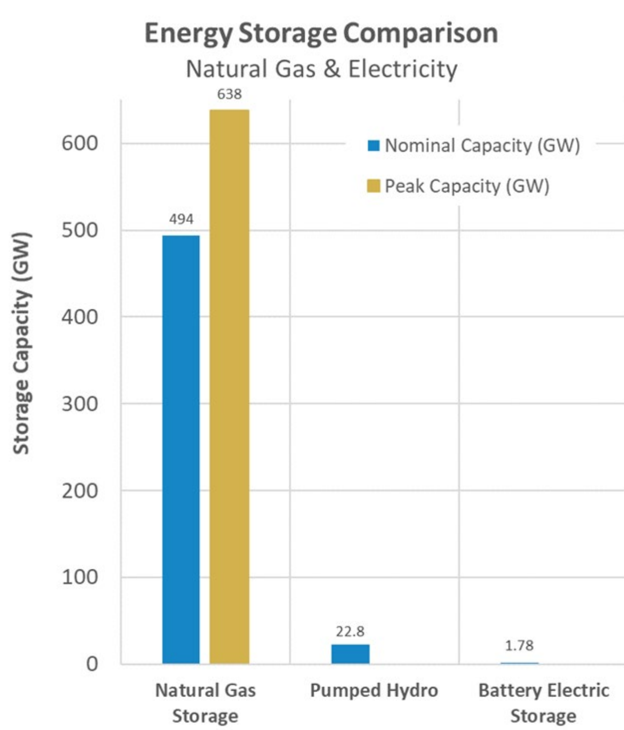
As noted by NREL, battery energy storage is well-suited to address the short-term variability challenge and diurnal mismatch concerns of renewable generation but is less technically or economically suited to addressing the long-duration (>24 hour) seasonal problem. Ongoing R&D and market experience could improve their future positioning in this area.

Table 2 and Figure 6 show DOE-EIA data for natural gas and electric energy storage system capacity. Natural gas storage working capacity is converted into capacity units (e.g., gigawatts, GW) by assuming this amount of gas could be dispensed over four months (e.g., winter season), along with suitable unit conversions that take into consideration natural gas energy content.

Table 2: Energy Storage Installed Capacity (DOE-EIA, GTI analysis)

	Number of Facilities	Working Capacity (Bcf)	Nominal Capacity (GW)	Proven One Week Peak Capacity (GW)
Natural Gas Storage	~400	4,840.2 (2018)	494.2 (2018)	638 (01/2018)
Pumped Hydro Electricity Storage	~40	--	23 (12/2020)	--
Battery Electric Storage	~200	--	1.8 (4/2021)	--

Figure 6: Nominal Energy Storage Capacity (DOE-EIA)



Gas storage facilities do not have equivalent nameplate delivery capacity as electric systems, but empirical data can be used to ascertain gas storage delivery capacity. Figure 7 shows DOE-EIA data on U.S. underground gas storage weekly send-out. In early January 2018 – during a polar vortex event – underground gas storage systems delivered 359 billion cubic feet (Bcf) of natural gas in one week. This gas flow over that time equals a sustained energy delivery capacity of about 640 GW. Based on DOE-EIA data, during January 2018 the entire natural gas system had an average delivery capacity of about 1,250 GW – gas supply plus gas from storage. From this we can infer gas storage provided about 35% of total gas use that month (including power generation). In comparison, a peak August month for the entire U.S. electricity system equals about 380,000 MWh/month – or a sustained average energy delivery capacity of about 510 GW, with only about 1% coming from electric energy storage. The difference in scale between gas storage and electric storage is substantial.

Figure 7: Peak Weekly Natural Gas Storage Send Out (Bcf/Week; DOE-EIA)

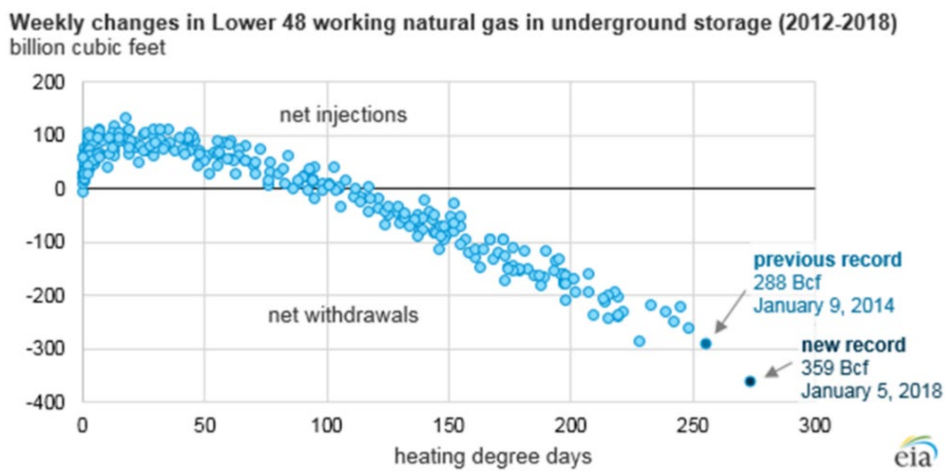


Figure 8 illustrates the differences in (1) the peak monthly average energy delivery needed for these two energy systems and (2) the relative role of energy storage in addressing peak monthly energy usage in these two systems. Gas systems overall deliver significant levels of energy in a peak month, driven by high winter space heating loads. During summer peak demand periods (driven by space cooling), electric systems currently rely partially on energy storage but more heavily on dispatchable generation power plants to ramp up output. Greater use of electric energy storage could change this relation in the future.

Natural gas underground storage systems provide a very high proportion of peak monthly energy use

Electric energy storage systems presently have a smaller role in meeting peak monthly electricity demand

Figure 8: Comparison of Peak Month Energy Delivery Capacity

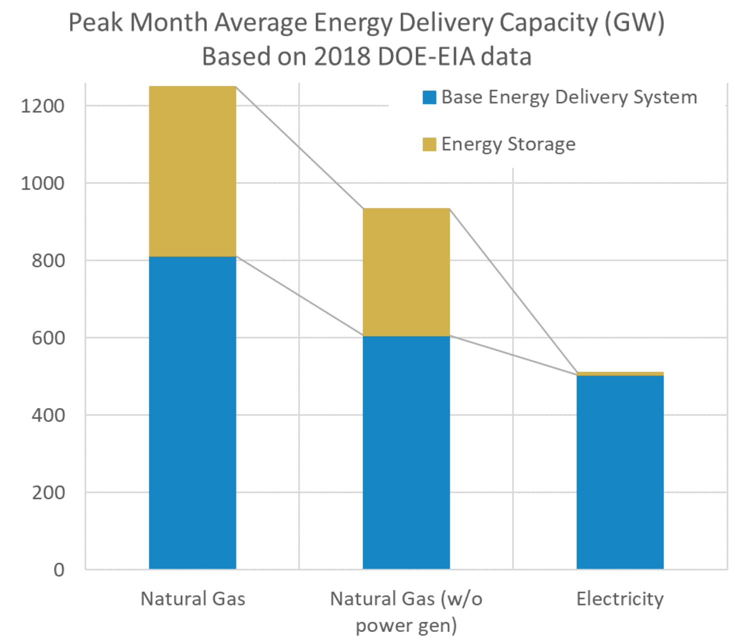


Table 3 and Figure 9 show typical monthly capacity factors (or usage factors) and discharge duration for these energy storage systems, highlighting differences in how energy storage resources are used for long-duration seasonal space conditioning peak energy demand. Underground gas storage is a leading seasonal storage resource – called on extensively during December through March and recharged during warmer months. Pumped hydro is used in all months, with a demonstrated long-duration capability to flex higher to support summer space cooling loads for example.

Table 3: Energy Storage Monthly Capacity Factors (DOE-EIA; GTI)

Energy Storage Option	Seasonality: Nominal Monthly Capacity Utilization	
	Maximum	Minimum
Underground Gas Storage	~23%	0%
Pumped Hydro	~15-17%	~7%
Battery Energy Storage	~5-7%	~3.5%

Figure 9: Nominal Energy Storage Discharge Duration

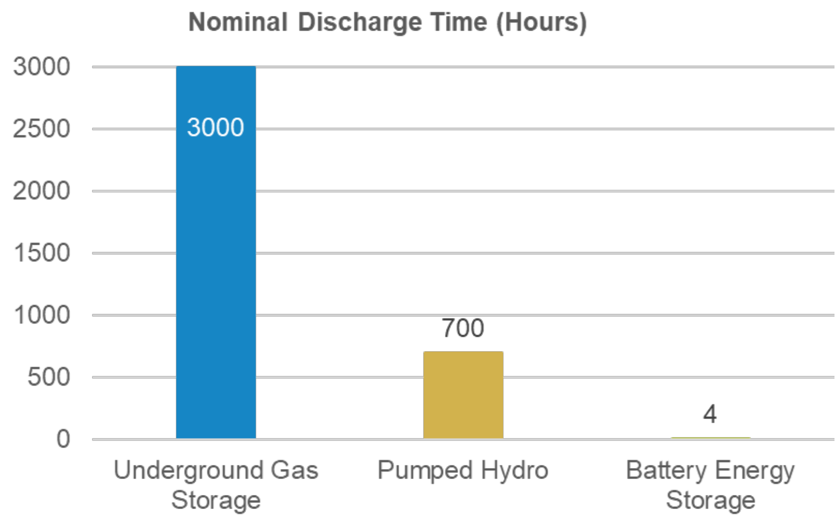
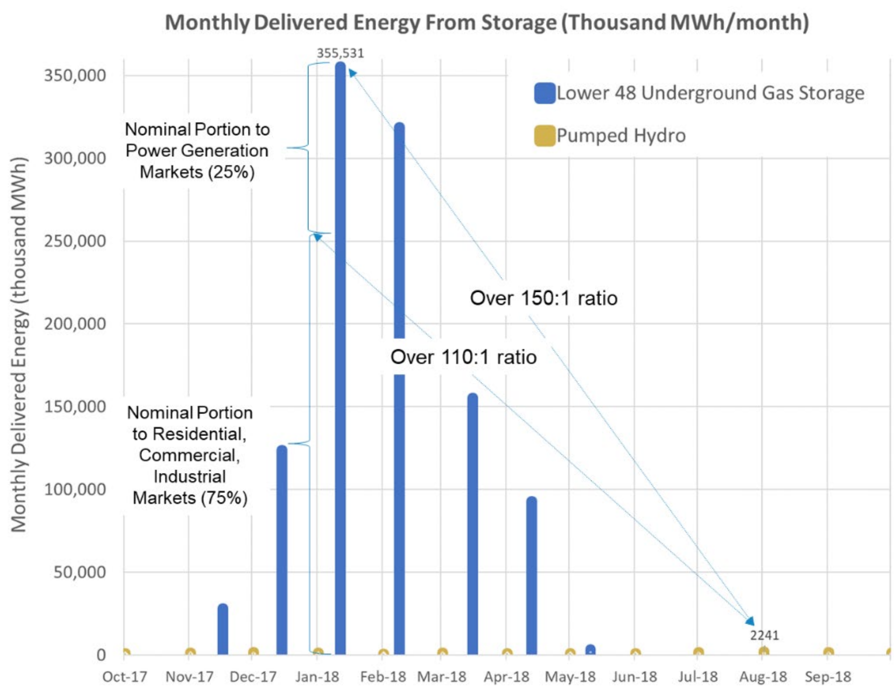


Figure 10 shows monthly gas and pumped hydro storage delivery over one year; battery energy storage is not shown because the amounts are currently small. During January 2018, peak natural gas storage energy send-out was over 150 times greater than peak pumped hydro electric energy deliveries in August 2018. These market attributes may shift in the future as battery energy storage capacity increases.

Figure 10: Monthly Energy Delivery from Storage (DOE-EIA data)



Energy Storage System Cycle Efficiency and Costs

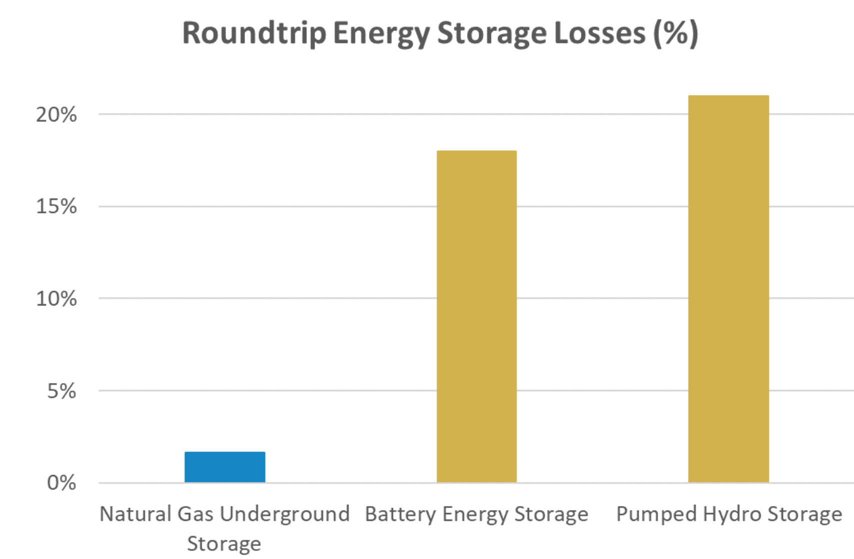
Gas and electric energy storage systems consume energy in the process of storing, converting, and returning energy back into their respective energy delivery systems (relationship shown below). Losses are equal to 1 minus the storage cycle efficiency.

$$\textbf{Storage Efficiency} = \frac{\textbf{delivered energy}}{\textbf{delivered energy + energy storage losses}}$$

For gas storage, energy losses are mainly from operating gas compressors and dehydration equipment (to remove water that absorbs into gas when stored in underground formations). For pumped hydro systems, energy is consumed by liquid pumps that elevate water as well as energy losses during conversion of water's potential energy into electricity when passing through a turbine generator. For batteries, losses occur from battery charging and discharging and from static charge losses over time. In addition, for all energy storage systems there are plant-level energy uses, sometimes referred to as parasitic losses; examples include building space conditioning, ventilation, etc.

Figure 11 shows nominal energy storage losses specific to underground gas storage and electric energy storage systems operation. Note the underground gas storage cycle efficiency is for direct delivery to gas consumers. If this were to a power plant, additional conversion losses would occur when generating electricity. Such additional power generation conversion losses could also apply to electricity going into storage depending on the specific power generation source used.

Figure 11: Nominal Energy Storage Energy Losses (DOE-EIA, GTI)



Roundtrip energy losses from electric energy storage are 8-10 times greater than underground gas storage systems

DOE-EIA Form 923 data has monthly reported information on gross and net generation energy (in MWh) for pumped hydro storage and battery energy storage systems. DOE-EIA used this information to produce a publication in February 2021 discussing the cycle efficiency for pumped hydro and battery energy storage; these data are used in Figure 11.

There is no similar Form 923 data for underground gas storage. GTI conducted a survey of gas storage operators to gather pertinent data (e.g., gas storage facility output and energy use – natural gas and electricity – for facility operations). As noted previously, this includes compression, dehydration, and other facility energy needs. Figure 12 provides detail from this survey of sixteen underground gas storage sites, with an average capacity weighted energy loss value of 1.7% (or 98.3% cycle efficiency).

Figure 12: Underground Gas Storage Energy Efficiency (GTI)

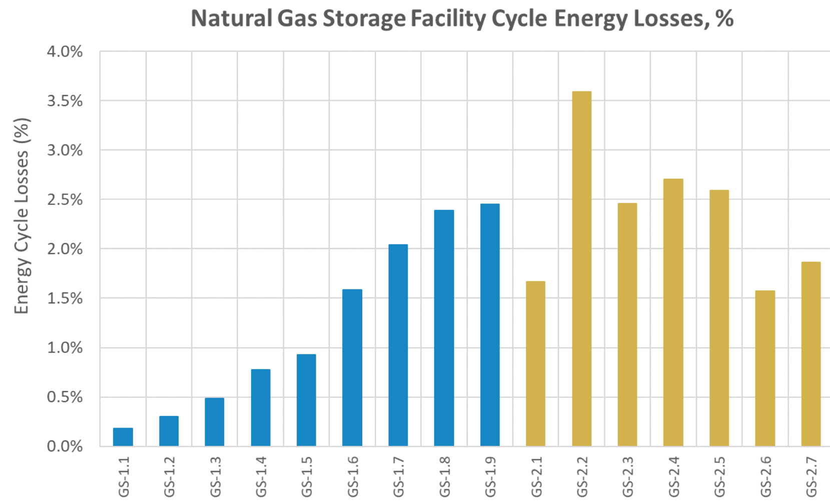
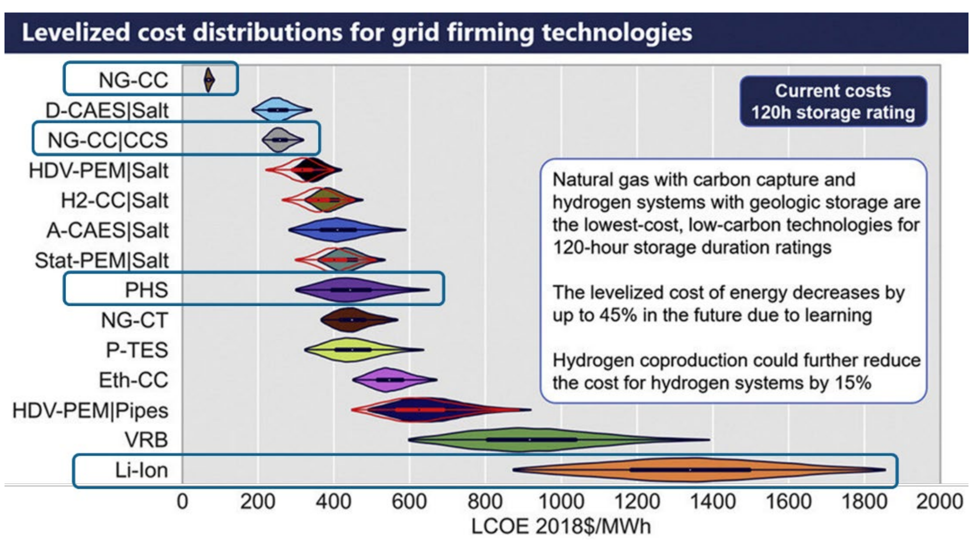


Figure 13 shows an analysis conducted by DOE/NREL on various options for longer-duration (e.g., 120-hour) storage capability(8). In this figure are highlighted four specific pathways: NG-CC (natural gas-combined cycle), NG-CC|CCS (carbon capture and storage), PHS (pumped hydro storage), and Li-ion (lithium-ion battery energy storage). Gas-based systems are on the lower end of the cost spectrum, followed by pumped hydro systems, and long-duration battery energy storage. Note these results are specific to long-duration market applications (in this analysis, a 120-hour storage rating requirement).

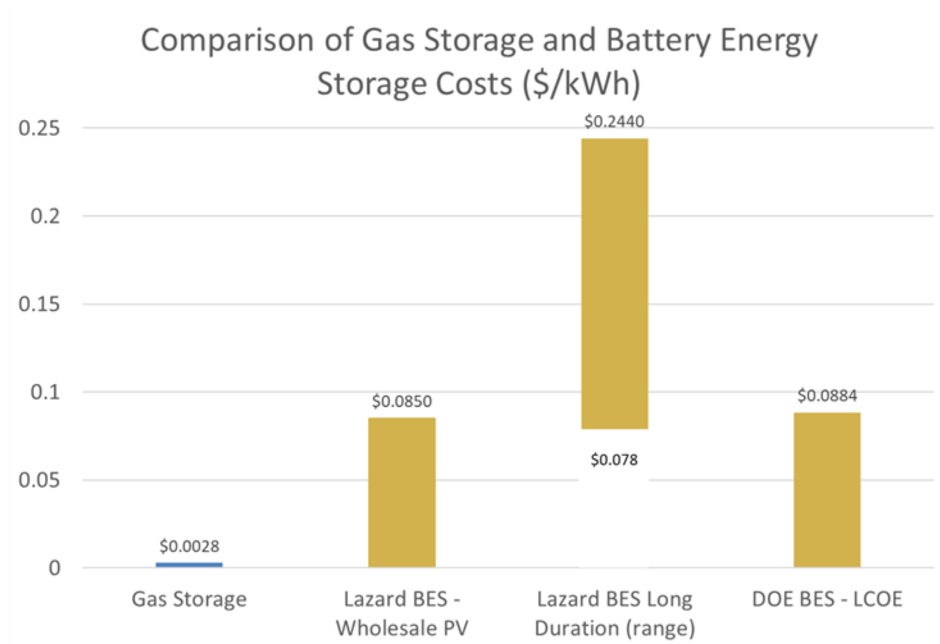
Figure 13: DOE/NREL Comparison of Current Electric Grid Energy Storage and Firming Options



One feature of Figure 13 is an assumption of 120 hours for long-duration energy storage duration. For space heating applications in cold-climate regions, the duration of underground gas storage often extends over multiple months (e.g., 3-5 months) and can last 2000-3500 hours. Market needs for space heating may necessitate exceptionally long duration energy storage. Detailed regional modeling would help determine the suitability of a 120-hour (or other value) energy storage rating under a high-penetration electric space heating scenario.

Figure 2 provides a comparison of underground gas storage costs to representative cost estimates for new battery energy storage investments (based on Lazard 2021 and DOE-EIA analyses). Typical battery energy storage costs are in the range of $0.085-$0.24/kWh. By comparison, gas storage costs (to gas consumers) are about $0.003/kWh or less than 4% of the levelized cost of battery storage systems. Gas storage is a remarkably cost-efficient way to store large amounts of energy.

Figure 14: Comparison of Gas Storage Costs and Battery Energy Storage Costs



Excludes wholesale electricity costs. Both gas storage and battery energy storage systems would generally have additional wholesale generation costs, plus transmission and distribution expenses for delivered electricity scenario; these are excluded in this figure. Note there are differences in capital basis between existing facilities built several years ago versus new technology investments. Gas storge based on actual costs to gas consumers. BES = Battery Energy Storage. BES cases from Lazard (2021) and DOE-EIA (2021).

Energy Transitions and the Long-Term Role of Gas Storage

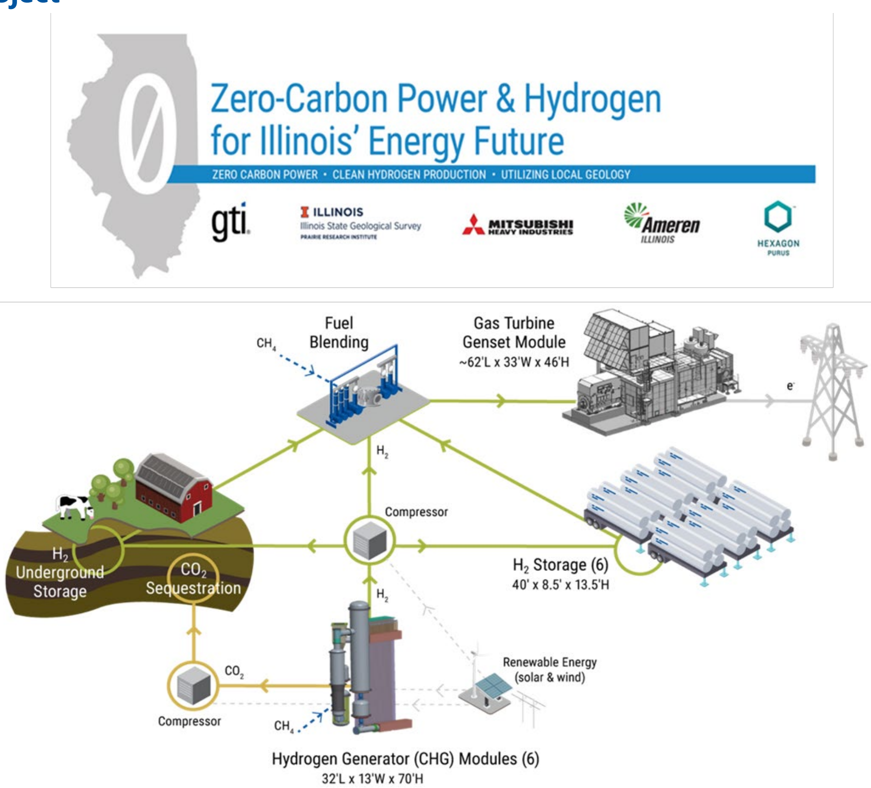
There are numerous ways in which decarbonized compressed gases can play a continued, long-term role in future integrated energy systems – particularly as cost-effective large-scale seasonal energy storage solutions. Examples of zero or low GHG compressed gas energy storage systems that can be used in the near- to long-term include:

- Using **renewable natural gas** (RNG) from bio-energy sources as supplements or replacements for conventional natural gas; this includes sources such as wastewater treatment plants, landfills, agricultural or other purpose-built digesters

- Using **carbon capture** at natural gas power plants that use a combination of pipeline gas and underground gas storage (such plants can operate on natural gas or a renewable gas or blends)
- Using **renewable or low-carbon hydrogen** (H_2) generated from wind, solar, nuclear, or natural gas reformers with integrated carbon capture and storage.
- Using **compressed air energy storage** (CAES) plants (like a facility in McIntosh, Alabama) with renewable or zero-carbon energy from wind, solar, nuclear, or natural gas power plants with carbon capture or using renewable gas.

GTI is actively involved in RD&D efforts on many of these and other forms of clean alternative energy carriers and energy storage systems. One example is a proposed Illinois-based system (Figure 14). GTI is working with the University of Illinois, the Illinois State Geological Survey at the University of Illinois, USDOE, and other partners to develop an advanced integrated energy system which generates low GHG hydrogen from natural gas with carbon sequestration, coupled with storage of hydrogen in compressed gas cylinders and in underground geologic formations. These formations are comparable to the geology in large-scale underground gas facilities.

Figure 15: GTI Zero-Carbon Power & Hydrogen Energy Storage Project



Conclusions

Energy storage systems are used in gas and electric energy delivery systems primarily to assist in managing peak energy demand; they can also be used to provide other value-added services (e.g., frequency or voltage regulation). There are three main operational large-scale utility energy storage systems employed in the U.S.: (1) underground natural gas storage, (2) pumped hydro energy storage, and (3) battery energy storage. The latter two are used for electric energy storage, while gas storage provides value to gas and electric system operators and customers.

Gas underground storage and pumped hydro can provide long-duration seasonal energy storage services (e.g., winter or summer peak space conditioning loads). Battery energy systems are mainly used for short-duration (<24 hour) grid services such as frequency or voltage regulation, onsite peak demand management, or supporting intraday renewable generation intermittency.

In terms of cycle efficiency, gas underground storage systems are more efficient than battery electric or pumped hydro energy storage systems. Underground gas storage has a typical cycle efficiency between 97-99%. Battery energy storage systems have typical real-world efficiency of 82% and pumped hydro systems are about 79% efficient (according to DOE-EIA data).

Energy storage plays a vital role in enhancing energy reliability and dampening energy price volatility. The need for robust and reliable energy storage across a range of scales, durations, and applications is fundamentally important for the energy systems today and the future. Today’s energy systems and consumers benefit greatly from the scale, long-duration seasonal performance, efficiency, and cost-effectiveness of gas energy storage. In the ongoing transition to a low-carbon integrated energy system, there is value in large-scale, long-duration energy storage currently provided by today’s gas storage systems with long-term potential for decarbonizing these systems.

For more information
contact Bill Liss,
GTI Vice President,
Energy Delivery
& Utilization
Office: 847-768-0753
Mobile: 847-312-5014
wliss@gti.energy

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