2020 Grid Energy Storage Technology Cost and Performance Assessment

Kendall Mongird, Vilayanur Viswanathan, Jan Alam, Charlie Vartanian, Vincent Sprenkle*, Pacific Northwest National Laboratory.

Richard Baxter, Mustang Prairie Energy

* vincent.sprenkle@pnnl.gov

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ENERGY STORAGE GRAND CHALLENGE
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Acronyms

AC	alternating current
Ah	ampere-hour
BESS	battery energy storage system
BLS	U.S. Bureau of Labor Statistics
BMS	battery management system
BOP	balance of plant
BOS	balance of system
C&C	controls & communication
C&I	civil and infrastructure
CAES	compressed-air energy storage
DC	direct current
DOD	depth of discharge
DOE	U.S. Department of Energy
E/P	energy to power
EPC	engineering, procurement, and construction
EPRI	Electric Power Research Institute
ESGC	Energy Storage Grand Challenge
ESS	energy storage system
EV	electric vehicle
GW	gigawatts
HESS	hydrogen energy storage system
hr	hour
HVAC	heating, ventilation, and air conditioning
kW	kilowatt
kWe	kilowatt-electric
kWh	kilowatt-hour
LCOE	levelized cost of energy
LFP	lithium-ion iron phosphate
MW	megawatt
MWh	megawatt-hour
NHA	National Hydropower Association
NMC	nickel manganese cobalt
NRE	non-recurring engineering
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PCS	power conversion system
PEM	polymer electrolyte membrane
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydro
PV	photovoltaic
R&D	research & development
RFB	redox flow battery
RTE	round-trip efficiency

SB	storage block
SBOS	storage balance of system
SCADA	sensors, supervisory control, and data acquisition
SM	storage module
SOC	state of charge
USD	U.S. dollars
V	volt
Wh	watt-hour

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Hydrogen

There are multiple hydrogen energy storage (HESS) configurations that may be useful in different use cases. The configuration analyzed in this report is bidirectional utilizing fuel cells. This configuration further involves using a polymer electrolyte membrane (PEM) electrolyzer to generate hydrogen from water with an electrical current (releasing oxygen as a byproduct) before compressing and storing the hydrogen in underground salt caverns until needed. The hydrogen is later re-electrified using the fuel cells to produce electricity.

Capital Cost

Hydrogen generation using electrolyzers can monetize variable energy sources and enable long-duration storage of energy that would otherwise be curtailed (Hunter et al., In Press). Hydrogen can be blended with natural gas in gas turbines to generate electricity and has the potential to replace natural gas as the fuel in these systems to offer a cleaner alternative (Lindstrand, 2019).

As an example of commercially deployable electrolyzers, Siemens has a 17.5 MW electrolyzer, the Silyzer 300, consisting of 24 modules and generating a maximum of 2,000 kg of hydrogen per hour at an efficiency of 75% (Siemens AG, 2018). When these are connected in parallel, electrolyzer systems rated at several hundred MWs can be deployed. Siemens has electrolyzer plants in Germany, Dubai, and other locations, with multiple projects in Europe (H2Future, 2020a, 2020b; HYBRIT Development, 2020). The Silyzer plant operates at atmospheric pressure which provides a variety of benefits such as a direct reduction of iron in steel plants, while other electrolyzers operate at 8-30 bars (Schlesog, 2020). While this work currently only examines bidirectional use of hydrogen, use in other industries such as steel making, fertilizer, glass manufacture, and microchips is expected to provide economies of scale for electrolyzers moving forward (U.S. DOE, 2020).

HESS consists of three major components:

- Charging system includes electrolyzer modules, BOP, water-handling units, mass flow controllers, electrolyzer management system, compressor, and rectifier.
- Discharging system is comprised of stationary fuel cell modules, BOP, gas-handling units, blowers, mass flow controllers, fuel cell management system, and inverter.
- Storage system typically includes pipes or a cavern.

Electrolyzer hardware capital costs consist of stacks and BOP. The life of the BOP is expected to be 20-25 years, corresponding to life of compressors and air and fuel delivery systems (Purchasing, Undated; Rundle, 2012), while the life of the electrolyzer depends on operating profile. The capital costs for hydrogen systems, along with EPC and O&M costs, are project-specific and can vary substantially.

Bidirectional usage for hydrogen is not limited to electricity generation by fuel cells; gas turbines or engines can also be used. Though there are various hydrogen technology configurations, the one included in this report is a stationary bidirectional HESS that uses a PEM electrolyzer, a salt cavern for storage, and stationary fuel cells. Cost estimates and projections for this technology were based on extensive literature review and analysis reported in Information on response time capability was provided from the literature regarding dynamic modeling and validation of electrolyzers (Hovsapian, Kurtz, Panwar, Medam, & Hanson, 2019).

To reconcile cost metrics in Hunter et al. (In Press)with the methodology used for other storage technologies in this report, the following categories were estimated for HESS using lithium-ion BESS values for categories where information was unavailable:

- C&C added $1.5/kW, same as for 100 MW lithium-ion battery system.
- Systems integration included in 50% markup.
- EPC included in 50% markup and 25% installation.
- Project development included in 50% markup and 25% installation.
- Grid integration including transformers, meters, safety disconnects, and nominal labor costs added at $19.89/kW, same as for 100 MW lithium-ion battery system.

Table 1 shows input values for capital cost obtained from Hunter et al. (In Press) for a 100 MW, 120-hour HESS. These costs include 50% markup and 25% installation and are assumed equivalent to system integration, EPC, and project development combined.

Table 1. Hydrogen Energy Storage Costs by Component – 2018 and 2030 Values, Adapted from Hunter et al. (In Press)

Mode	Component	2018 Assumption	2030 Estimate
Charging	PEM electrolyzer (kilowatt Electric [kWe])	$1,500	$440
	Rectifier cost (kW)	$130	$100
	Compressor cost (kW)	$40	$40
Discharging	Stationary PEM fuel cell (kW)	$1,320	$1,000
	Inverter (kW)	$67	$45
Storage	Hydrogen salt caverns (kWh)	$2	$1.69

Cavern cost for hydrogen systems has been estimated to be between $2-10/kWh based on previous efforts developing caverns for CAES systems. Discussions with a CAES developer indicated that, based on depth and salt thickness, cavern cost of $2/kWh can be realized. However, where caverns are not very deep and salt thickness is lower, the cost can be as high as $10/kWh, with bedded salt caverns costing even higher (Farley, 2020a). For more information on cavern costs, see the detailed discussion in the CAES section.

Table 2 provides a detailed cost breakdown for various categories and performance metrics, with references for each category.

Table 2. Price Breakdown for Various Categories and Performance Metrics for HESS

Cost Category	Nominal Size	2018 Price	Content	Additional Notes	Source(s)
Electrolyzer	100 MW	$1503/kWe	Estimated 2018 capital cost	Part of SB	Hunter et al. (In Press)
Rectifier	100 MW	$130/kW	Estimated 2018 capital cost	Part of power equipment	
Compressor	See notes	$32.7/kWh	Estimated 2018 capital cost	Part of BOP or BOS, compressor rating to support 100 MW electrolyzer hydrogen output	
Stationary PEM fuel cell	100 MW	$1,320/kW	Estimated 2018 capital cost	Part of SB	
Inverter	100 MW	$67/kW	Estimated 2018 capital cost	Part of power equipment.	
Cavern	1,000 MWh[(a)]	$3.66/kWh	Cavern capital cost	Salt dome	Bailie (2020a, 2020b, 2020c, 2020d, 2020e); Farley (2020a, 2020b); Wright (2012); Hunter et al. (In Press)
C&C	100 MW	$1.5/kW	Source estimate for C&C	PNNL approach used for scaling across various power levels	Baxter (2020b)
Grid integration	100 MW	$19.9/kW	Source estimate for grid integration	PNNL approach for scaling across various power levels	Baxter (2020a)
Fixed O&M for electrolyzer	100 MW	$14.5/kW-year	Estimate for fixed O&M	Includes $0.8/MWh for parts replacement converted to $1.7/kW-year	Hunter et al. (In Press)
Fixed O&M for stationary fuel cell	100 MW	$13.4/kW-year	Estimate for fixed O&M	Includes $0.8/MWh for parts replacement converted to $0.63/kW-year	
Fixed O&M for cavern storage	100 MW	$0.60/kW-year	Estimate for fixed O&M	2.1% of cavern capital cost	

Cost Category	Nominal Size	2018 Price	Content	Additional Notes	Source(s)
Basic variable O&M	100 MW, 10 hour	$0.51/MWh	Variable basic O&M cost	Average of basic variable O&M costs from sources	Aquino, Zuelch, and Koss (2017); Black & Veatch (2012); Hunter et al. (In Press); Mongird et al. (2019); Raiford (2020); Wright (2012)
Performance metrics – RTE	100 MW	35%	RTE for a 100 MW system		Hunter et al. (In Press)
Performance metrics – electrolyzer calendar life	100 MW	30 years	Electrolyzer calendar life in years		
Performance metrics – electrolyzer durability (hours)	100 MW	60,000 hours	Electrolyzer durability in hours		
Performance metrics – electrolyzer calendar life	100 MW	30 years	Electrolyzer calendar life in years		
Performance metrics – electrolyzer durability (hours)	100 MW	40,000 hours	Electrolyzer durability in hours		
Performance metrics – response time	100 MW	< 1 second	HESS response time ion seconds		Hovsapian et al. (2019)

[a] For this study, we are using a maximum of 10 hours of storage. Hence, for a 100 MW system, the cavern size happens to be 1,000 MWh. Hunter et al. (In Press) uses 120 hours of storage, and, therefore, they use 12,000 MWh. The use of 1,000 MWh is necessary for us to do a comparison across technologies for the same 10-hour duration.

Table 3 provides breakdown for a 100 MW, 10-hour HESS system, calculated from the estimates provided in Hunter et al. (In Press) with additional cost components and adjustments described previously. In addition to calculating estimates using the provided low cavern cost ($2/kWh), the estimates have also used a moderate $3.66/kWh cavern cost to match that of CAES following the average of various estimates described in that section. For HESS, the low, nominal, and high end for cavern costs used $2/kWh, $3.66/kWh, and $10/kWh, respectively. Additionally, multipliers of 0.9 and 1.1 were used to establish the low and high ranges for other components. For 2030 cavern costs, the NREL number was changed proportionately based on 2020 cavern costs used to establish the price range.

Table 3. Costs by Component for a 100 MW, 10-hour HESS System, Adapted from (Hunter et al., In Press)

Category	Cost Component	Low 2020 Values	Low 2030 Values	Moderate 2020 Values	Moderate 2030 Values	High 2020 Values	High 2030 Values
PEM electrolyzer	Capital cost ($/kW)	1,353	393	1,503	437	1,653	481
	Rectifier cost ($/kW)	117	84	130	94	143	103
	Compressor cost ($/kW)	35	35	39.3	39.3	43	43
Storage	Storage ($/kWh)	2	1.69	3.66	3.09	10	8.45
	Storage DOD (%)	70%	70%	70%	70%	70%	70%
	Effective storage ($/kWh)	2.86	2.4	5.23	4.44	14.29	12.10
Stationary fuel cell	Capital cost ($/kW)	1,188	854	1,320	949	1,452	1,044
	Inverter ($/kW)	60	41	67	45	74	50
C&C ($/kW)		1.35	0.95	1.5	1.06	1.65	1.16
Grid integration ($/kW)		18	15	19.89	16.3	22	18
Grand total ($/kW)		**2,793**	**1,440**	**3,117**	**1,612**	**3,488**	**1,824**
Grand total ($/kWh)		**279**	**144**	**312**	**161**	**349**	**182**

O&M Costs

Table 4 shows O&M values for a HESS from the long-duration energy storage study in Hunter et al. (In Press). It should be noted that Hunter et al. incorporates property tax, insurance, licensing, and permitting costs into hydrogen O&M estimates. To remain consistent with the methodology of the other technologies considered in this report, O&M costs without these additional additives are considered. Both values are provided in Table 4. Correspondence with a CAES developer indicated that incorporating these cost items into CAES O&M is not uncommon (Farley, 2020a).

Table 4. HESS O&M Costs by Category, Adapted from Hunter et al. (In Press)

O&M Cost Category	Electrolyzer	Stationary PEM Fuel Cell	Storage
Fixed O&M - including property tax, insurance, licensing, and permitting ($/kW-year)	47.9	37.6	
Fixed O&M - without property tax, insurance, licensing, and permitting ($/kW-year)	12.8	12.8	
Stack replacement-related variable O&M ($/MWh)	0.8	0.8	
Storage O&M (% of storage capital cost)			2.1%
Basic variable O&M ($/kWh)	$0.0005	$0.0005	

While there is limited information available for basic variable O&M cost of HESS, these costs are assumed to be similar to CAES where basic variable O&M involves water, lubrication oil, and miscellaneous items. For the electrolyzer and fuel cells, these costs may also include spare parts and compressor/blower lubrication.

Additional variable O&M costs consists of those required for stack replacement. Both basic variable O&M and stack replacement variable O&M costs depend on cumulative energy throughput. Throughput was calculated for the electrolyzer and fuel cell from the desired capacity factor and calendar life. For the electrolyzer, using a design capacity factor of 24%, the 60,000-hour durability stated in Hunter et al. (In Press) is reached in 28.5 years, less than the estimated 30-year calendar life. Hence, the cumulative energy throughput was calculated using a 60,000-hour durability at 24% capacity factor and was found to be 6,000 GWh. For the fuel cell, at the design capacity factor of 9%, the 40,000-hour durability provided in Hunter et al. (In Press) is reached only after 50 years, surpassing the stated calendar life of 30 years. Therefore, the cumulative energy is calculated using a 9% capacity factor for 30 years and was estimated to be 2,370 GWh.

For basic variable O&M, there is inconsistent nomenclature regarding what this category consists of. Due to the lack of detailed justification regarding what comprises basic variable O&M for each technology, this work sets the basic variable O&M to be $0.5125/MWh and is derived here based on the average across various technologies (**Error! Reference source not found.**). Depending on duty cycle, the e nergy throughput will vary, thus affecting total basic variable O&M costs.

Table 5. Variable O&M Estimate Calculation for Energy Storage Systems

Reference(s)	Technology	Value ($/MWh)
Raiford (2020)	Lead Acid	1
Hunter et al. (In Press)	Hydrogen	0.5
Aquino et al. (2017); Wright (2012); Black & Veatch (2012)	CAES	0.25
Mongird et al. (2019)	Non-specific	0.30
	Average	**0.5125**

Table 6 shows the individual O&M cost for each component in $/kW-year with totals in the final column. The fixed O&M range for 2020 was 0.9 to 1.1 times the nominal values for each category.

Table 6. HESS O&M Costs by Component, Adapted from Hunter et al. (In Press) and PNNL Assumptions[(b) (c)]

O&M Cost Category	Electrolyzer	Stationary Fuel Cell	Storage	Total
Fixed O&M ($/kW-year)	12.8	12.8		25.6
Stack replacement-related O&M[(a)] ($/kW-year)	1.68	0.63		2.31
Storage O&M[(b)] ($/kW-year)			0.60	0.6
Total fixed O&M ($/kW-year)	**14.48**	**13.43**	**0.60**	**28.51**
Baseline variable O&M[(c)] ($/kWh)	0.0005125	0.0005125		0.001

(a) $1.3/MWh charged or discharged, (b) Based on 2.1% of storage capital expenditure, (c) $0.0005/kWh charged or discharged

Performance Metrics

System efficiency depends on compression needs, storage type, and auxiliary load such as cooling. According to Hunter et al. (In Press), the total RTE for the hydrogen system considered in this analysis is approximately 35%.

The calendar life for hydrogen is estimated to be 30 years (Hunter et al., In Press). Note that the calendar life for the electrolyzer and fuel cell stacks should not be confused with the 20-25 year life for BOP components such as compressors and air and fuel delivery systems mentioned earlier. This corresponds to a cycle life of approximately 10,400 cycles when one cycle per day and 5% downtime are assumed. The response time for hydrogen is estimated to be < 1 second, as provided in Hovsapian et al. (2019)

Losses due to RTE were estimated based on an assumed electricity cost of $0.03/kWh and an RTE of 35%. Following these two items, it can be determined that the cost due to RTE losses is $0.056/kWh.

R&D Trends in Hydrogen Energy Storage Systems

While high capital costs and low RTE have been a roadblock to HESS deployment in the past, there is opportunity for reduction in PEM electrolyzer and fuel cell costs with R&D to improve performance and cost of catalysts and membranes, coupled with economies of scale. The following focus areas for R&D are anticipated:

- Currently, the design life for fuel cells used in busses is 20,000 operating hours, while for stationary energy storage is expected to be 40,000 hours (Hunter et al., In Press). However, considering HESS are expected to have a discharge capacity factor of 5-10%, this translates to 13,000-26,000 operating hours for a desired 30-year calendar life. Hence, HESS can leverage the developments in transportation fuel cells, much as lithium-ion BESS leverages developments in EV batteries. Additionally, R&D in heavy-duty vehicle PEM fuel cells is focused on a price target of $60/kW which offers opportunities for significant price reduction from HESS.
- Salt caverns with the desired depth and width cost $2/kWh, while bedded salt caverns, prevalent in Michigan, Arizona, and Colorado, cost > $10/kWh due to lack of depth (Farley, 2020a). The required cavern size, and hence cost, is dependent on the regional generation mix. Therefore, efforts to reduce cost of storage via engineering design are expected to gain traction.
- As long-duration energy storage (diurnal and seasonal) becomes more relevant, it is important to quantify cost for incremental storage in the cavern. The incremental cost for CAES storage is estimated to be $0.12/kWh. The cavern for the 324 MW, 16000 MWh Bethel Energy Center project has a capacity of 4 million barrels. To increase the size by 20%, a 63-day leaching at 3000 gallons per minute is needed, estimated to cost $383,000 including electricity, water and labor (Naeve, 2020), which amounts to $0.12/kWh, or $1.2/kW for the 324 MW plant. Hence, as long duration storage becomes prevalent, increasing the storage capacity of existing salt domes by solution mining is expected to gain traction due to its cost-effectiveness.
- The largest existing cavern has a volume of 17 million barrels (Naeve, 2020), which corresponds to about 64,000 MWh of storage. The Bethel Energy Center cavern can be expanded to 10

million barrels, while ATMOS Energy is developing a 10-million-barrel cavern on the west of the existing Bethel dome, corresponding to nearly 40,000 MWh of storage. As demand for long-term storage increases, it is expected that caverns of similar size will be developed.

- There are about 130 caverns at Mt. Belview constructed on a large salt done, with web thickness between caverns much less than the 250 to 300 ft required today. For large projects, it is expected that multiple caverns within a single salt dome will be developed and connected in parallel.

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