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Optimizing Renewable Energy Storage Systems to Accelerate Sustainable Data Center Deployment

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ABSTRACT

Behind-the-meter generation from variable renewable energy is a potential pathway for new data centers to obtain power more quickly and more sustainably than interconnecting to existing electrical grids. Energy storage is needed to accommodate the variability of wind and solar energy across multiple timescales. Hydrogen from electrolysis and ammonia made from this hydrogen can be used as fuel for dispatchable power generation while offering lower $/MWh storage costs than batteries. In this work, we analyze the economics of using hydrogen, and/or ammonia along with batteries in hybrid energy storage systems to enable data centers to be powered by 100% renewables. We perform this analysis using an optimization model for the selection, sizing, and coordinated hourly operation of constituent energy storage technologies toward minimizing the levelized cost of energy (LCOE). The model uses an hourly resolution scheduling horizon of five years to account for hourly, seasonal, and interannual renewable variability. We use this model to specifically analyze the economics of to 5 MW, 50 MW, and 500 MW sustainable data center energy systems in three relevant American locations. We find that including ammonia energy storage in hybrid systems with batteries and hydrogen enables lower LCOE across all scales and locations by reducing energy storage capital investments despite deploying an order-of-magnitude more storage capacity while also enabling less investment in renewable generation. Ammonia is used for seasonal and interannual energy storage and its inclusion in these hybrid storage systems is most advantageous for larger-scale data centers in locations with high wind potential.

Keywords: Optimization, Energy Storage, Renewable and Sustainable Energy, Technoeconomic Analysis, Alternative Fuels

INTRODUCTION

In the United States, the development of renewable generation projects outpaces the addition of the new transmission infrastructure needed to maximize the use of this renewable power within existing electrical grids [1]. In fact, the average wait time for grid interconnection requests for U.S.-based generation projects is five years [2]. The wait time of this interconnection queue is similar for large industrial customers who wish to purchase power from the grid. As a result, new industrial power users who wish to more quickly begin operations prefer "behind-the-meter" power supply wherein they are directly connected to a generation source. Data centers are an increasingly important example of these industrial consumers. At present, they are being rapidly deployed to facilitate the growing adoption of artificial intelligence. By 2030, data centers are projected to be responsible for at least 10% of total U.S. energy consumption [3, 4]. Using behind-the-meter renewables to provide power for data centers provides an opportunity to ensure that this growing customer segment is sustainable from an energy perspective while also lessening the impact of interconnection constraints on the continued development of renewable generation projects.

Energy storage technologies are a necessary aspect of meeting data center power demands, which are generally constant over time, using variable renewable energy. This variability manifests over multiple timescales from within a day to between consecutive years. Batteries are the most well-developed energy storage technology and are well-suited for managing short-term variability, but their deployment is limited by high energy storage costs for long-term supply-demand imbalances. As such, previous research on energy storage systems for data centers has considered the use of dispatchable fossil-based generation to limit the required size of battery installations [5, 6]. Hydrogen obtained from water via renewable-powered electrolysis can act as dispatchable fuel source without incurring any carbon dioxide emissions upon reconversion to electrical power. The economics of hydrogen energy storage have previously been investigated in the context of data centers [7, 8]. In [7], hydrogen storage was used in a grid-connected data center to facilitate demand response. In [8], hydrogen storage was coupled with bifacial PV in Arctic locations to enable 100% renewable operation. To this end, over 1, 000 metric tons (mt) of hydrogen storage was needed, which may not be suitable for all locations. Furthermore, analysis in [8] did not consider interannual solar generation variability, the management of which could require even more energy storage capacity in a behind-the-meter, 100% renewables system.

Converting hydrogen to ammonia by combining it with nitrogen separated from air can facilitate higher energy storage capacities than hydrogen itself. Ammonia energy storage has been of particular interest over the past decade for high capacity, long duration energy storage due to higher achievable storage volumes as well as lower storage costs [9]. As with hydrogen, ammonia can be used for dispatchable power generation via fuel cells or combustion [10, 11]. To our knowledge, the economics of ammonia energy storage in the context of data centers have not been previously analyzed. We have previously investigated the economics of ammonia energy storage for 100% renewable energy storage in 1 MW residential microgrids U.S. throughout the continental U.S. [12] and combined heat and power systems in remote U.S. locations [13]. Ammonia energy storage economics have also been analyzed in facilitating the energy transition of different provinces in Spain [14], enabling exclusively solar power to meet 4 MW residential power demand in Florence, Italy [15], and using ammonia for both energy storage and export in Can Dao, an archipelago off Vietnam's Southern Coast [16].

These previous efforts employed quantitative modeling approaches to determine the best deployment of ammonia energy storage to manage renewable variability. Specifically, these works used optimization models wherein technology selection, sizing, and operational scheduling decisions are made simultaneously toward lowest cost. This is the state-of-the-art approach for modeling renewables-based chemical production and utilization [17, 18]. In the context of ammonia energy storage, this optimization approach has been implemented using mixed integer linear programming (MILP) models solved via branch-and-cut algorithms [12-14, 16] or using software based on hierarchical operational rules for scheduling [15].

Scheduling decisions in these optimization models are typically made over a yearlong horizon with hourly resolution, including in [12-16]. This allows optimal energy storage system design to account for renewable variability across hourly to seasonal timescales. A representative year which agglomerates multiple years of historical or forecasted weather data is usually selected for this purpose. However, previous work on ammonia energy storage has not considered interannual variability in renewable generation. In general, renewable potential can vary considerably over consecutive years and its consideration in the design of renewable energy systems can increase reliability [19]. Interannual variability has only been previously considered in the economic analysis of renewable ammonia production [20]. We hypothesize that ammonia's low storage cost can facilitate economical interannual energy storage.

In this work, we investigate the economics of using hydrogen and/or ammonia along with batteries in hybrid energy storage systems to facilitate meeting data center power demands using only renewable energy. We specifically formulate a combined design and scheduling model which employs multiple years of historical, hourly resolution time series data to capture interannual renewable variability as well as hourly and seasonal variability which have been considered in previous work. We use this model to analyze the optimal economics of sustainable data center energy systems at 5 MW, 50 MW, and 500 MW power demand scales in three American metropolitan areas: Northern Virginia (NoVa), Dallas-Fort Worth (DFW), and Las Vegas. The goal of this work is to determine the merit of hydrogen and ammonia energy storage toward providing economical and sustainable energy for data centers, the most rapidly growing segment of industrial power consumption.

CASE STUDY DESCRIPTION

Battery-H_2-NH_3 Energy Storage

The energy storage system we analyze in this work must meet data center power demand using energy generated exclusively from wind and solar resources and energy storage (see Figure 1). Energy can be stored directly in its electrical form using battery storage. It can also be used to produce hydrogen via water electrolysis which can be stored as gas at 200 bar and used for dispatchable power generation. Electrical energy can also be used to separate nitrogen from air and combine it with hydrogen to make ammonia, the synthesis of which is also electrically powered. Ammonia can be stored as liquid and used for dispatchable power generation.

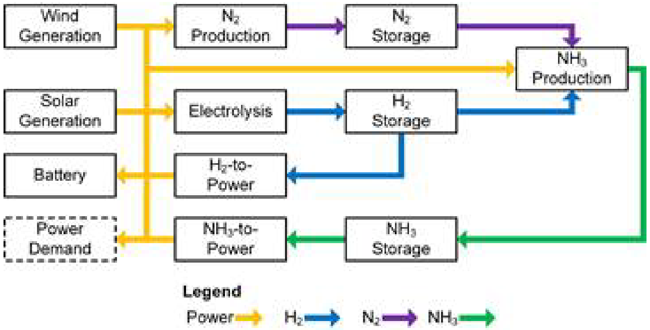

Figure 1. Conceptual diagram of 100% renewable energy system with battery, hydrogen, and ammonia energy storage pathways.

Combined Optimal Sizing & Scheduling Model

The optimization model we use minimizes the levelized cost of energy (LCOE) of meeting data center power demands using behind-the-meter renewables and hybrid energy storage. The LCOE includes capital investments (CapEx) of all technologies in Figure 1, annualized by a capital recovery factor (CRF), as well as annual operating costs (OpEx):

$$LCOE\left(\frac{\$}{MWh}\right) = \frac{CapEx \times CRF + OpEx}{Demand} \quad (1)$$

The model simultaneously optimizes the selection, sizing, and operational scheduling of all constituent technologies in Figure 1. Optimal scheduling decisions for battery state-of-charge and charge/discharge rates, chemical production rates and storage inventories, and dispatchable power generation rates are made across a multi-year horizon of hourly resolution renewable availability time series data.

Hourly power balance constraints ensure that renewable generation plus battery discharge plus dispatchable hydrogen- or ammonia-fueled power generation meet or exceed constant data center power demand plus battery charge plus chemical production power demands. Hourly mass balance equations for hydrogen and ammonia govern the accumulation of their storage inventory between consecutive hours. This storage inventory is constrained to be cyclical between the first and last hour of the multi-year operating horizon. Chemical production and dispatchable power generation technologies are constrained to operating limits defined by their respective operational flexibility. This model is formulated as a MILP and solved using CPLEX in GAMS. Please see our previous work [12] for more technical details, including model equations.

U.S. Data Centers Case Study Data

We perform a case study considering data centers with power demand scales of 5 MW, 50 MW, and 500 MW in NoVa, Dallas-Fort Worth, and Las Vegas. NoVa has highest current data center capacity in United States. DFW and Las Vegas respectively have high wind and solar potential, and data center capacity is rapidly growing in both metropolitan areas. We optimize the LCOE of meeting data center power demands via (i) battery, (ii) battery-hydrogen, and (iii) battery-hydrogen-ammonia energy storage systems using five years of historical renewable generation data from 2019 to 2024 in each location. The annual average wind and solar capacity factors in NoVa, DFW, and Las Vegas are respectively 39%, 45%, and 27% and 16%, 18%, and 22% [21].

Table 1: Capital and operating cost coefficients for renewable generation, battery charge/discharge capacity and electrolysis at different power demand scales. Data for all technologies except for electrolysis are from [22] while electrolysis data are from [23].

Technology at Demand Scale (MW)	CapEx ($MM/MW)	OpEx (%CapEx)
Wind (5)	2.04	1.86
Wind (>50)	1.41	2.08
PV (5)	1.49	1.06
PV (>50)	1.19	1.51
Battery - Power (5)	0.88	2.41
Battery - Power (>50)	0.43	2.15
Electrolysis (5)	1.99	2.5
Electrolysis (50)	1.37	2.5
Electrolysis (500)	0.94	2.5
ICE Genset (5)	1.27	2.0
CCGT (>50)	1.43	2.2

The capital and operating costs of energy system technologies depend on scale (see Table 1). Battery energy capacity (in MWh) has a capital cost of $0.18/MWh and $0.26/MWh respectively at the 5 MW and >50 MW demand scales [22]. Batteries have a charge efficiency of 90% and a discharge efficiency of 95%. PEM electrolysis is considered in this work for its wide operating range and fast dynamics. Its energy efficiency is assumed to be 51 MWh/mtH_2 [23]. High pressure gaseous hydrogen storage has a capital cost of $0.9MM/mt$H_2$. Reconversion of hydrogen and ammonia to electrical power occurs through combustion in internal combustion engine gensets at the 5 MW scale and combined cycle gas turbine (CCGT) plants at 50 MW and 500 MW scales. ICE genset and CCGT efficiencies are respectively 35% and 60% of LHV. ICE gensets have 90% turndown (i.e., can operate between 10% and 100% of installed capacity) while CCGTs have 60% turndown. The capital costs of nitrogen and ammonia production are subject to conventional power law cost scaling (see Table 2). Each technology has an annual operating cost of 2% of capital cost. Nitrogen and ammonia storage have capital costs of $5x10^{-2}MM/mt$N_2$ and $1.5x10^{-3}MM/mt$NH_3$ respectively [24].

Total energy system capital cost is annualized by a

Table 2: Capital cost correlations and performance data for nitrogen and ammonia production technologies [24].

	Capacity (mt/y)	CapEx (MM$)	Scaling Exponent	Efficiency (MWh/mt)	Turndown (%)
Pressure swing adsorption (PSA)	10,000	6.6	0.75	0.25	90
Cryogenic distillation	197,500	29.5	0.55	0.18	50
Haber-Bosch synthesis	237,500	89	0.65	0.45	90

Table 3: Optimal LCOE, renewable generation and energy storage capacity, and renewable curtailment for 50 MW data centers in Northern Virginia. Hydrogen and ammonia storage capacities in MWh are based on LHV.

Storage Pathway	Battery	Battery-H_2	Battery-H_2-NH_3
LCOE ($/MWh)	328	185	140
Wind (MW)	192	198	124
PV (MW)	556	130	104
Battery (MWh)	2,115	405	441
H_2 Storage (MWh)	0	8,382	255
NH_3 Storage (MWh)	0	0	43,340
Wind Curtailment (%)	62	33	10
PV Curtailment (%)	73	22	17

CRF of 0.073 y^{-1}. This corresponds to a project lifetime of 30 years with a 6.04% weighted average cost of capital (WACC). This is the average WACC for green and sustainable energy projects in the United States [25].

RESULTS AND DISCUSSION

Incorporating hydrogen and ammonia as lower cost energy storage media into hybrid renewable energy storage systems for sustainable data centers results in meaningfully lower LCOE than using battery storage alone (see Table 3). Combining hydrogen storage with battery storage results in a 44% LCOE reduction. This is driven by considerably lower solar generation and battery costs. Battery energy storage is too expensive to include enough capacity to store close to all generated MWh of renewable energy specifically due to variability over longer timescales. The battery-only energy storage system thus overbuilds solar generation to enable more demand to be met via direct generation and respectively curtails 62% and 73% of wind and solar over its modeled operational lifetime. Nonetheless, more than 2 GWh of battery storage is still required. In contrast, the battery-hydrogen system installs around 4x more total energy storage capacity despite 5x less battery capacity than the battery system to facilitate more effective renewable utilization. The optimal solar generation capacity for the battery-hydrogen system is 77% less than the battery-only system while optimal wind and solar curtailment are 33% and 22% respectively. Overall, the hybrid battery-hydrogen system still uses batteries for short-term storage and hydrogen for longer-term storage.

Using ammonia in a hybrid battery-hydrogen-ammonia energy system further reduces the LCOE by 24%. The same general trends as described in the previous paragraph are more pronounced. Ammonia's low storage cost results in approximately 20x more total optimal storage capacity than the battery-only system as well as approximately 5x more total storage capacity than the battery-hydrogen system despite 97% less hydrogen storage. Consequently, renewable energy generation capacities and curtailment are both reduced relative to the energy systems where energy storage technologies have higher $/MWh storage costs. Comparing battery-hydrogen and battery-hydrogen-ammonia systems specifically, we note that incorporating ammonia allows for considerably more effective use of wind energy with 37% less wind capacity installed and wind curtailment reduced from 33% to 10%. Wind potential in NoVa exhibits more seasonal and interannual variability than solar potential, and ammonia is more cost effective at balancing supply-demand mismatches that occur over longer timescales.

Interestingly, the optimal hybrid battery-hydrogen-ammonia energy system does not install any hydrogen-to-power capacity. In this system, the installed hydrogen storage only acts as a buffer between electrolysis and the less flexible Haber-Bosch synthesis. This occurs because, for the combustion technologies considered in this work, the roundtrip efficiency of the hydrogen storage pathway is only 39% compared to 32% for the ammonia storage pathway, but hydrogen storage cost is 100x higher on a $/MWh basis. Ultimately, the hybrid battery-hydrogen-ammonia system uses battery storage for short-term cycling and ammonia for longer-duration storage with hydrogen only acting as an intermediate. Specifically, batteries are cycled on short timescales to take advantage of their high roundtrip efficiency. Figure 2

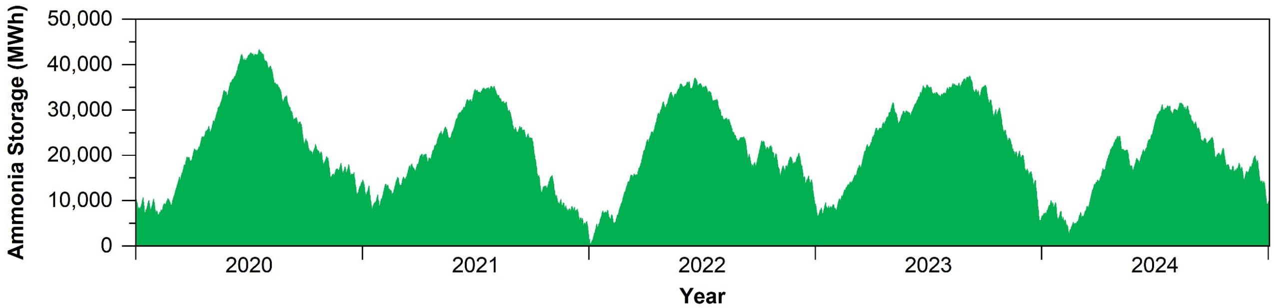

Figure 2. Optimal ammonia energy storage schedule for 50 MW data center using battery-hydrogen-ammonia storage pathway in Northern Virginia. Ammonia storage capacity in MWh based on LHV.

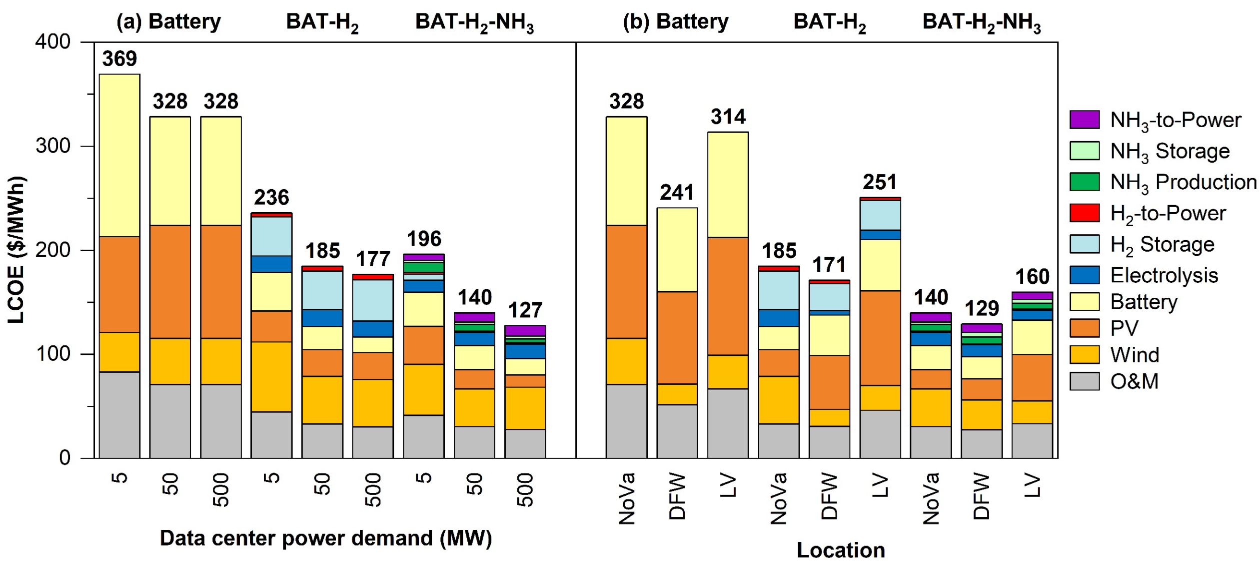

Figure 3: Breakdown of optimal LCOE for (a) 5 MW, 50 MW, and 500 MW data centers in Northern Virginia and (b) 50 MW data centers in Northern Virginia, Dallas-Fort Worth, and Las Vegas. Nitrogen production and storage as well as Haber-Bosch synthesis are included in "NH_3 Production".

shows the optimal ammonia energy storage schedule over for optimal operation from 2019 to 2024. It is evident that ammonia is accumulated through the first half of each year before being consumed to accommodate for seasonally low wind generation in second half of each year. From an interannual standpoint, the ammonia inventory is depleted by the end of 2021 to account for its lowest wind capacity factor while the highest net ammonia accumulation occurs in 2022 because its capacity factor is the highest.

Analysis of Power Demand Scale

Sustainable data center using 100% renewables and energy storage exhibit clear economies of scale (see Figure 3a). The LCOE for the 5 MW demand scale is considerably higher than for 50 MW and 500 MW demand scales regardless of the energy storage pathways under consideration. At this small scale, all technologies from wind and solar generation through to ammonia synthesis have higher capital intensity. The loss in economies of scale for nitrogen and ammonia production is particularly impactful. Data center energy systems at the 5 MW demand scale benefit least from the incorporation of ammonia relative to LCOE reductions at 50 MW and 500 MW demand scales. Additionally, the hybrid battery-hydrogen-ammonia storage system at the 5 MW demand scale uses both hydrogen- and ammonia-to-power combustion technologies, unlike the larger systems which only use ammonia for dispatchable power generation. This occurs to reduce the capacity and accompanied higher capital intensity of small-scale ammonia synthesis despite hydrogen having a higher storage cost.

The economic outlook of powering 50 MW and 500 MW data centers with renewables is similar. Renewable generation and batteries exhibit little to no cost savings with this scaleup while electrolysis does exhibit some economies of scale. This is evident in comparing the battery and battery-hydrogen LCOEs which are reduced by less than \$10/MWh with the 10x scaleup from 50 MW to 500 MW. Ammonia energy storage is well-suited for large centers on the order of 500 MW. Incorporating ammonia at this scale results in deeper cost reductions relative to smaller scales. Ammonia is also important for energy storage at hyperscale data centers from an optimal capacity standpoint. The optimal battery and hydrogen storage capacities are 21, 000 MWh and 3, 200 mtH_2 respectively when these are the standalone storage pathways for 500 MW NoVa data centers. These capacities are not realistic relative to current deployments, requiring 7x more battery capacity [26] and 10x more hydrogen storage capacity [27] than the largest facilities for each currently operational in the United States. Conversely, the hybrid battery-hydrogen-ammonia data center requires only 2, 800 MWh battery and 100 mtH_2 because long-duration, high-capacity storage can be facilitated by 105, 000 mtNH_3 ammonia storage.

Large-scale data centers are also best suited to ammonia energy storage from a safety standpoint. The ammonia synthesis and storage capacities these data centers would require are similar to those already used in the ammonia fertilizer supply chain. In contrast, using ammonia for energy storage across many small data centers would increase the number of facilities at which ammonia must be stored and handled and would thus increase the associated risk.

Analysis of Data Center Location

Hybrid battery-hydrogen and even more so hybrid battery-hydrogen-ammonia storage offers the same qualitative advantages across the three studied locations. Storage pathways with lower storage costs than batteries enable more complete utilization of lower optimal renewable generation capacities, which results in lower generation cost contributions to the LCOE, especially for solar (see Figure 3b). Battery storage cost contributions are also meaningfully less when storage can occur in the form of hydrogen and/or ammonia. When the ammonia storage pathway is considered, the optimal energy storage systems for 50 MW demand data centers in DFW and Las Vegas only use ammonia for dispatchable power generation as was previously discussed for the optimal hybrid battery-hydrogen-ammonia NoVa energy storage system.

The location of data centers does have a quantitative effect of the economics of sustainable data centers for each storage pathway (see Figure 3b). For battery-only storage systems, NoVa has the highest LCOE. Both DFW and Las Vegas have higher solar potential and less seasonal solar variation, making these locations better suited to batteries alone. Hydrogen and even more so ammonia energy storage enables better use of wind generation. This results in Las Vegas having the highest LCOE for these hybrid systems because its wind potential is lower than NoVa or DFW and must install considerably more solar generation as a result. Conversely, DFW has better wind and solar potential than NoVa and considerably better wind potential than Las Vegas. This results in the DFW system having the lowest LCOE regardless of the storage pathways under consideration because these systems have lower total renewable generation and total energy storage costs. Nonetheless, hybrid battery-hydrogen-ammonia energy storage results in a NoVa LCOE only 9% higher than the DFW LCOE. In comparison, the NoVa battery LCOE is 36% higher than the DFW battery LCOE. Overall, ammonia storage makes sustainable data centers more economically competitive in more locations.

CONCLUSIONS

In this work, we analyze the economics of using hydrogen and/or ammonia along with batteries in hybrid energy storage systems to meet data center power demands using 100% behind-the-meter renewable energy. We perform this analysis through the lens of an economic optimization model which minimizes the levelized cost of energy (LCOE) by simultaneously making technology selection, sizing, and operational scheduling decisions. Optimal scheduling occurs for a five-year operating horizon with hourly resolution based on time series data for historical renewable availability to ensure that optimal selection and sizing decisions account for hourly, seasonal, and interannual variability. We use this model to determine the optimal LCOE of using 100% renewable and hybrid energy storage systems for data centers with 5 MW, 50 MW, and 500 MW power demand in Northern Virginia (NoVa), Dallas-Fort Worth (DFW), and Las Vegas

We find that hybrid battery-hydrogen and battery-hydrogen-ammonia energy systems provide lower LCOE than using batteries alone for all scales and locations. These lower storage cost pathways enable larger storage capacity so that more energy can be economically stored and used rather than curtailed, resulting in less investment in renewable generation. Hybrid battery-hydrogen-ammonia systems provide the lowest LCOE and ammonia provides at least 95% of total energy storage capacity in these hybrid systems due to its low storage cost. Ammonia energy storage is best suited to large-scale data centers due to the economies of scale for nitrogen and ammonia production. It is also best suited to locations with high wind potential, the seasonal and interannual variability of which can be economically balanced with data center power demands via ammonia storage.

Future work will compare the viability of ammonia energy storage with conventional fossil fuel technologies as well as small modular nuclear reactors in the context of data centers across different U.S. locations. This future work will include techno-economic analysis of these energy storage pathways under a consistent set of assumptions. We will also compare the emissions and water intensity of these different energy storage pathways through a life cycle assessment framework.

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REFERENCES

1. Gorman W, Kemp JM, Rand J, Seel J, Wiser R, Manderlink N, Kahrl F, Porter K, Cotton W. Grid connection barriers to renewable energy deployment in the united states. Joule 9:101791 (2025). https://doi.org/10.1016/j.joule.2024.11.008
2. Rand J, Strauss R, Gorman W, Joachim S, Kemp J, Seongeun J, Robson D, & Wiser R. Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2022. Lawrence Berkeley National Laboratory (2023) https://doi.org/10.2172/1969977
3. Shehabi A, Smith SJ, Hubbard A, Newkirk A, Lei N, Siddik MAB, Holecek B, Koomey J, Masanet E, & Sartor D. 2024 United States Data Center Energy Usage Report. Lawrence Berkeley National Laboratory (2024) eta.lbl.gov/publications/2024-lbnl-data-center-energy-usage-report
4. Electric Power Research Institute. Powering Intelligence: Analyzing Artificial Intelligence and Data Center Energy Consumption (2024) epri.com/research/products/3002028905
5. He W, Xu Q, Liu S, Wang T, Wang F, Wu X, Wang Y, Li H. Analysis on data center power supply system based on multiple renewable power configurations and multi-objective optimization. Renewable Energy 222:119865 (2024). https://doi.org/10.1016/j.renene.2023.119865
6. Ren X, Wang J, Hu X, Sun Z, Zhao Q, Chong D, Xue K, Yan J. A novel demand response-based distributed multi-energy system optimal operation framework for data centers. Energy and Buildings 305:113886 (2024). https://doi.org/10.1016/j.enbuild.2024.113886
7. Long X, Li Y, Li Y, Ge L, Gooi HB, Chung C, Zeng Z. Collaborative response of data center coupled with hydrogen storage system for renewable energy absorption. IEEE Trans. Sustain. Energy 15:986-1000 (2024). https://doi.org/10.1109/tste.2023.3321591
8. Temiz M, Dincer I. A unique bifacial PV and hydrogen-based cleaner energy system with heat recovery for data centers. Applied Thermal Engineering 206:118102 (2022). https://doi.org/10.1016/j.applthermaleng.2022.118102
9. Sepulveda NA, Jenkins JD, Edington A, Mallapragada DS, Lester RK. The design space for long-duration energy storage in decarbonized power systems. Nat Energy 6:506-516 (2021). https://doi.org/10.1038/s41560-021-00796-8
10. Cesaro Z, Ives M, Nayak-Luke R, Mason M, Bañares-Alcántara R. Ammonia to power: forecasting the levelized cost of electricity from green ammonia in large-scale power plants. Applied Energy 282:116009 (2021). https://doi.org/10.1016/j.apenergy.2020.116009
11. Sánchez A, Castellano E, Martín M, Vega P. Evaluating ammonia as green fuel for power generation: a thermo-chemical perspective. Applied Energy 293:116956 (2021). https://doi.org/10.1016/j.apenergy.2021.116956
12. Palys MJ, Daoutidis P. Using hydrogen and ammonia for renewable energy storage: a geographically comprehensive techno-economic study. Computers & Chemical Engineering 136:106785 (2020). https://doi.org/10.1016/j.compchemeng.2020.106785
13. Palys MJ, Mitrai I, Daoutidis P. Renewable hydrogen and ammonia for combined heat and power systems in remote locations: optimal design and scheduling. Optim Control Appl Methods 44:719-738 (2021). https://doi.org/10.1002/oca.2793
14. Sánchez A, Zhang Q, Martín M, Vega P. Towards a new renewable power system using energy storage: an economic and social analysis. Energy Conversion and Management 252:115056 (2022). https://doi.org/10.1016/j.enconman.2021.115056
15. Veltroni V, Calabrese M, Carcasci C, Pagliai M. Techno-economic assessment of power-to-ammonia-to-power for long-term energy storage. Energy Conversion and Management 348:120621 (2026). https://doi.org/10.1016/j.enconman.2025.120621
16. Su K, Wang L, Jiang D, Lin J, Yang C, Wu F, Liu D, Wu F, Zheng C, Gao X. Towards zero-carbon

power supply: development of a multi-energy coupled offshore green energy production island. Sustainable Energy Technologies and Assessments 85:104791 (2026). https://doi.org/10.1016/j.seta.2025.104791
17. Schack D, Rihko-Struckmann L, Sundmacher K. Linear programming approach for structure optimization of renewable-to-chemicals (r2chem) production networks. Ind. Eng. Chem. Res. 57:9889-9902 (2018). https://doi.org/10.1021/acs.iecr.7b05305
18. Palys MJ, Daoutidis P. Renewable ammonia for islanded energy storage. Current Opinion in Green and Sustainable Chemistry 48:100946 (2024). https://doi.org/10.1016/j.cogsc.2024.100946
19. Javed MS, Jurasz J, Guezgouz M, Canales FA, Ruggles TH, Ma T. Impact of multi-annual renewable energy variability on the optimal sizing of off-grid systems. Renewable and Sustainable Energy Reviews 183:113514 (2023). https://doi.org/10.1016/j.rser.2023.113514
20. Salmon N & Bañares-Alcántara R (2022). Importance of interannual renewable energy variation in the design of green ammonia plants. In *Comput. Aided Chem. Eng.* 49: 757-762 (2022). https://doi.org/10.1016/B978-0-323-85159-6.50126-3
21. NREL. National solar radiation database (2024) https://nsrdb.nrel.gov/data-viewer
22. NREL. Annual Technology Baseline (2025) https://atb.nrel.gov/electricity/2024b/about
23. EPRI. Electrolysis techno-economic analysis – CapEx rate (2024) https://apps.epri.com/lcri-electrolysis-tea/en/capex-rates.html
24. Palys MJ, Moot T, Parvathikar S, Zhang K, Kavale CA, Gupta JK, Daoutidis P. Techno-economic optimization of flexible distributed green ammonia production. International Journal of Hydrogen Energy 206:153230 (2026). https://doi.org/10.1016/j.ijhydene.2025.153230
25. Damodaran A. Cost of Equity and Capital (US) (2026) https://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/wacc.html
26. Thomas M. Cleanview: Battery storage projects in the United States (2024) https://cleanview.co/battery-storage-projects/us
27. Swanger A. World's largest liquid hydrogen tank nearing completion. *Cold Facts* 38(2): 20220004276 (2022). https://ntrs.nasa.gov/citations/20220004276