Powering the energy transition with better storage

30 March 2021, by Leda Zimmerman

Exploring different scenarios and variables in the storage design space, researchers find the parameter combinations for innovative, low-cost long-duration energy storage to potentially make a large impact in a more affordable and reliable energy transition. Credit: Bumper DeJesus/Andlinger Center for Energy and the Environment

"The overall question for me is how to decarbonize society in the most affordable way," says Nestor Sepulveda SM '16, Ph.D. '20. As a postdoc at MIT and a researcher with the MIT Energy Initiative (MITEI), he worked with a team over several years to investigate what mix of energy sources might best accomplish this goal. The group's initial studies suggested the "need to develop energy storage technologies that can be cost-effectively deployed for much longer durations than lithium-ion batteries," says Dharik Mallapragada, a research scientist with MITEI.

In a new paper published in *Nature Energy*, Sepulveda, Mallapragada, and colleagues from MIT and Princeton University offer a comprehensive cost and performance evaluation of the role of long-duration energy storage (LDES) technologies in transforming energy systems. LDES, a term that covers a class of diverse, emerging technologies, can respond to the variable output of renewables, discharging electrons for days and even weeks, providing resilience to an electric grid poised to deploy solar and wind power on a large scale.

"If we want to rely overwhelmingly on wind and solar power for electricity—increasingly the most affordable way to decrease carbon emissions—we have to deal with their intermittency," says Jesse Jenkins, an assistant professor of mechanical and aerospace engineering and the Andlinger Center for Energy and the Environment at Princeton University and former researcher at MITEI.

In their paper, the researchers analyzed whether LDES paired with renewable energy sources and short-duration energy storage options like lithium-ion batteries could indeed power a massive and cost-effective transition to a decarbonized grid. They also investigated whether LDES might even eliminate the need for available-on-demand, or firm, low-carbon energy sources such as nuclear power and natural gas with carbon capture and sequestration.

"The message here is that innovative and low-cost LDES technologies could potentially have a big impact, making a deeply decarbonized electricity system more affordable and reliable," says lead author Sepulveda, who now works as a consultant with McKinsey and Company. But, he notes, "We will still be better off retaining firm low-carbon energy sources among our options."

In addition to Jenkins and Mallapragada, the paper's coauthors include Aurora Edington SM '19, a MITEI research assistant at the time of this research and now a consultant at The Cadmus Group; and Richard K. Lester, the Japan Steel Industry Professor and associate provost at MIT, and former head of the Department of Nuclear Science and Engineering.

"As the world begins to focus more seriously on how to achieve deep decarbonization goals in the coming decades, the insights from these system-level studies are essential," says Lester. "Researchers, innovators, investors, and policymakers will all benefit from knowledge of the cost and technical performance targets that are suggested by this work."

Performance and cost

The team set out to assess the impacts of LDES solutions in hypothetical electric systems that reflect real-world conditions, where technologies are scrutinized not merely by their standalone attributes, but by their relative value when matched against other energy sources.

"We need to decarbonize at an affordable cost to society, and we wanted to know if LDES can increase our probability of success while also reducing overall system cost, given the other technologies competing in the space," says Sepulveda.

In pursuit of this goal, the team deployed an electricity system capacity expansion model, GenX, earlier developed by Jenkins and Sepulveda while at MIT. This simulation tool made it possible to evaluate the potential system impact of utilizing LDES technologies, including technologies currently being developed and others that could potentially be developed, for different future low-carbon electric grid scenarios characterized by cost and performance attributes of renewable generation, different types of firm generation, as well as alternative electricity demand projections. The study, says Jenkins, was "the first extensive use of this sort of experimental method of applying wide-scale parametric uncertainty and long-term systems-level analysis to evaluate and identify target goals regarding cost and performance for emerging long-duration energy storage technologies."

For their study, the researchers surveyed a range of long-duration technologies—some backed by the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) program—to define the plausible cost and performance attributes of future LDES systems based on five key parameters that encompass a range of mechanical, chemical, electrochemical, and thermal approaches. These include pumped hydropower storage, vanadium redox flow batteries, aqueous sulfur flow batteries, and firebrick resistance-heated thermal storage, among others.

"Think of a bathtub, where the parameter of energy storage capacity is analogous to the volume of the tub," explains Jenkins. Continuing the analogy, another important parameter, charge power capacity, is the size of the faucet filling the tub, and discharge power capacity, the size of the drain. In the most generalized version of an LDES technology, each attribute of the system can be independently sized. In optimizing an energy system where LDES technology functions as "an economically attractive contributor to a lower-cost, carbon-free grid," says Jenkins, the researchers found that the parameter that matters the most is energy storage capacity cost.

"For a comprehensive assessment of LDES technology design and its economic value to decarbonized grids, we evaluated nearly 18,000 distinctive cases," Edington explains, "spanning variations in load and renewable resource availability, northern and southern latitude climates, different combinations of LDES technologies and LDES design parameters, and choice of competing firm low-carbon generation resources."

Some of the key takeaways from the researchers' rigorous analysis:

- LDES technologies can offer more than a 10 percent reduction in the costs of deeply decarbonized electricity systems if the storage energy capacity cost (the cost to increase the size of the bathtub) remains under the threshold of $20/kilowatt-hour. This value could increase to 40 percent if energy capacity cost of future technologies is reduced to $1/kWh and to as much as 50 percent for the best combinations of parameters modeled in the space. For purposes of comparison, the current storage energy capacity cost of batteries is around $200/kWh.
- Given today's prevailing electricity demand

patterns, the LDES energy capacity cost must fall below $10/kWh to replace nuclear power; for LDES to replace all firm power options entirely, the cost must fall below $1/kWh.
- In scenarios with extensive electrification of transportation and other end-uses to meet economy-wide deep decarbonization goals, it will be more challenging in northern latitudes to displace firm generation under any likely future combination of costs and efficiency performance range for known LDES technologies. This is primarily due to greater peak electricity demand resulting from heating needs in colder climates.

Actionable insights

While breakthroughs in fusion energy, next-generation nuclear power, or carbon capture could well shake up their models, the researchers believe that insights from their study can make an impact right now.

"People working with LDES can see where their technology fits in to the future electricity mix and ask: "Does it make economic sense from a system perspective?'" says Mallapragada. "And it's a call for action in policy and investment in innovation, because we show where the technology gaps lie and where we see the greatest value for research breakthroughs in LDES technology development."

Not all LDES technologies can clear the bar in this design space, nor can there be reliance on LDES as the exclusive means to expand wind and solar swiftly in the near term, or to enable a complete transition to a zero-carbon economy by 2050.

"We show how promising LDES technologies could be," says Sepulveda. "But we also show that these technologies are not the one solution, and that we are still better off with them complementing firm resources."

Jenkins spies niche market opportunities for LDES immediately, such as places with a lot of wind and solar deployed and limits on transmission to export that power. In such locations, storage could fill up when transmission is at its limit, and export power later while maximizing use of the power line capacity. But LDES technologies must be ready to make a major impact by the late 2030s and 2040s, he believes, by which time economies might need to be weaned completely off of natural gas dependency if decarbonization is to succeed.

"We must develop and deploy LDES and improve other low-carbon technologies this decade, so we can present real alternatives to policymakers and power system operators," he says.

In light of this urgent need, Jenkins at Princeton and Mallapragada at MIT are now working to evaluate and advance technologies with the greatest potential in the storage and energy fields to hasten the zero-carbon goal. With help from ARPA-E and MITEI, they are making the state-of-the-art GenX electricity system planning model an open-source tool for public use as well. If their research and modeling approach can show developers and policymakers what kind of designs are most impactful, says Sepulveda, "We could have a decarbonized system that's less expensive than today's system if we do things right."

More information: Nestor A. Sepulveda et al. The design space for long-duration energy storage in decarbonized power systems, *Nature Energy* (2021). DOI: 10.1038/s41560-021-00796-8

Provided by Massachusetts Institute of Technology