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Research Brief

Properties of Deeply Decarbonized Electric Power Systems with Storage

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To illuminate the role of energy storage in future decarbonized electric power systems, we constructed detailed models of optimal assets and hourly operation of power systems in three US regions in 2050 under a range of assumptions about generation and storage technologies' availability and cost. We found that nearly complete decarbonization using only VRE generation and (very little) natural gas can be achieved without reduced reliability or large increases in system average electricity cost. In efficient decarbonized power systems, the distribution of the hourly marginal value of energy (MVE) will be drastically different from the distributions of spot prices in current systems: there will be more hours of high MVEs and many more hours of low MVEs. To encourage economy-wide decarbonization, wholesale markets and retail rate structures will need to be modified.

As policy makers across the world design and implement policies to achieve long-term deep decarbonization of the power sector, the share of variable renewable energy (VRE) generation (i.e., wind and solar) is expected to grow substantially in the next few decades. The large-scale integration of wind and solar generation is contingent on designing flexible power systems that can balance variations in wind and solar output to continuously meet electricity demand. In low-carbon systems dominated by VRE generation, the availability of dispatchable resources (e.g., natural gas, nuclear, coal, and reservoir hydropower) will be severely limited.

In such systems, power system flexibility can be enhanced by deploying energy storage along with other enhancements to legacy electric power systems: (1) transmission network expansion to increase the geographic footprint of balancing areas and better exploit spatiotemporal variations in demand and weather-driven VRE resource availability; (2) demand flexibility and demand response; and (3) deployment or retention of some dispatchable low-carbon generation. Here, we use systems optimization approaches to examine the value of energy storage for achieving the deep decarbonization of the electric sector and the implications for storage technology development and electricity market design under a wide range of technological and economic assumptions.

Specifically, we analyze power system evolution in three U.S. regions—the Northeast, Southeast and Texas, as well as, with less detail, at a national level. All these regions, and the United States as a whole, experienced significant reductions in carbon dioxide (CO_2) emissions from electricity generation between 2005 and 2018. These reductions reflect the combined effects of stagnant electricity demand; a large reduction in coal-fired generation in favor of natural gas generation, largely for economic reasons; and significant increases in VRE generation, importantly (but not exclusively) driven by public policy.

Given the central role for electrification in long-term U.S. decarbonization efforts, the model- based findings in this chapter primarily rely on electricity demand projections from a high- electrification scenario developed by the National Renewable Energy Laboratory (NREL) for its 2018 Electrification Futures (EFS) study. In NREL's high-electrification scenario, U.S. electricity consumption increases by a factor of 1.6 by 2050 relative to the 2018 level of roughly 4,000 terawatt-hours. Subject to these demand assumptions, we analyze power system evolution for different 2050 power system decarbonization targets, defined in terms of CO_2 emissions produced per kWh of electricity generated, for our three regions of the country in 2050.

In our study, we focus on four emissions constraints: 0 gCO_2/kWh, 5 gCO_2/kWh, 10 gCO_2/kWh, and 50 gCO_2/kWh. When contemplating the common goal of "net-zero" carbon energy systems, where the term "net-zero" is understood to allow for the inclusion of negative emissions technologies, the 5 gCO_2/kWh or even 10 gCO_2/kWh emissions constraint is likely more informative than the very strict 0 gCO_2/kWh constraint. While our analysis focused on grid decarbonization by 2050, achieving zero or net-zero carbon emissions from electricity generation sooner than 2050 would require more rapid shifts in the generation mix and possibly an expanded role for energy storage.

We found that the near-complete decarbonization of power systems can be achieved with VRE deployment, in conjunction with available Li-ion battery energy storage, along with infrequent use of dispatchable natural generation. At the same time, we find that full decarbonization based on deploying VRE and Li-ion storage technologies while ruling out any use of natural gas is significantly more expensive at the margin. It provides a compelling reason to focus public and private RD&D resources on further improving the cost and performance attributes of a range of technologies, including emerging long- duration energy storage (LDES) technologies, alternative low- or no-carbon generation technologies that are dispatchable, and negative emissions technologies that can remove CO_2 from the atmosphere.

While these broad observations apply across all regions studied here, our modeling reveals significant regional variation in system costs, optimal storage capacity deployment, and optimal generation mix under different emission constraints. The differences primarily reflect differences in the quality of wind and solar resources and thus in the cost of zero-carbon generating technologies in the three regions we examine. Therefore, the challenges of "getting to net zero" will vary across regions based on their resource endowments.

Due to data limitations, we did not model the demand-side impacts of very extreme weather events. Such events, which can affect both electricity demand and supply, are likely to become more important in the future owing to climate change. Due to computational tractability, we had to resort to approximating annual grid operations using representative weeks for two of the study regions using multi- zonal grid representation. Collectively, these factors, coupled with our assumption of perfect foresight, mean that our results likely underestimate the value of storage and the magnitude of storage deployment that would be cost-effective in low-carbon power systems.

At the same time, other assumptions in our modeling may contribute to results that overestimate the value of storage. First, we ignore use-based degradation of electrochemical storage. If degradation were included, it might limit the value of these storage resources. Second, our modeling does not consider the availability of bioenergy-based power generation with or without carbon capture or other dispatchable renewable generation sources such as geothermal. If such sources become available, their deployment could help minimize the cost impacts of going from near-complete decarbonization to full decarbonization and could significantly reduce the value of LDES. Finally, our analysis is based on least-cost investment planning for a future year (2050) with corresponding technology cost projections for that year. In reality, VRE and other resource investments will be added incrementally over time, likely leading to higher investment costs than were assumed here.

We conclude by highlighting the complexity of long-term investment planning aimed at efficiently achieving deeply decarbonized and reliable power systems and the importance of fundamental research to advance the state-of-the-art in models used for investment planning, as well as the need for system operators to continuously review and update their planning approaches to incorporate best available methodologies. System planning needs to account more effectively for variability in demand and supply, especially under extreme weather events, and for correlations between the supplies from individual generators in the portfolio and between total generator output and demand. This variability is likely to increase with climate change.

References

Junge, C., C. Wang, D. Mallapragada, H. Gruenspecht, J. Pfeifenberger, P. Joskow, and R. Schmalensee (2022), "Properties of Deeply Decarbonized Electric Power Systems with Storage," MIT CEEPR Working Paper 2022-003, February 2022.

About the Authors

Cristian Junge is a graduate research assistant at the MIT Energy Initiative. As part of the Future of Storage Economics Team, his research focuses on understanding the role of energy storage technologies in deeply decarbonized power systems.

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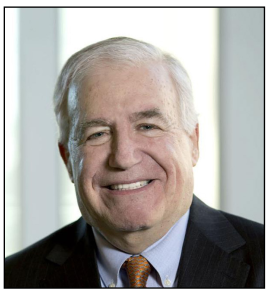
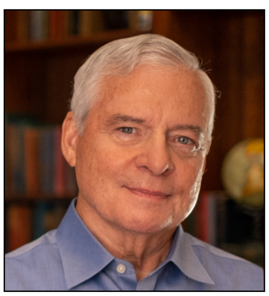
Dharik Mallapragada is a Principal Research Scientist at MIT and joined the MIT Energy Initiative in May 2018. Through his Ph.D. and nearly five years of research experience in the chemicals and energy industry, Dharik has worked on a range of sustainability-focused research topics such as designing light-weight composite materials and carbon-efficient biofuel pathways, as well as developing novel tools for energy systems analysis. His research interests include the design of novel energy conversion processes and their integration into the energy system. At MIT, Dharik is working on advancing power systems modeling tools to study questions around renewables integration and economy-wide electrification. Dharik holds a M.S. and Ph.D. in Chemical Engineering from Purdue University. He received a B.Sc. in Chemical Engineering from the Indian Institute of Technology, Madras.

Howard Gruenspecht recently joined Massachusetts Institute of Technology's (MIT) Energy Initiative as a senior energy economist. From 2003 through August 2017, he was deputy administrator of the U.S. Energy Information Administration, the statistical and analytical agency within the U.S. Department of Energy (DOE). As the agency's senior career official he was responsible for directing its energy data and analysis programs. From 1991 to 2000, Howard served DOE's Office of Policy in key leadership positions, including deputy assistant secretary for economic and environmental policy. His accomplishments at DOE were recognized with two Distinguished Presidential Rank Awards, the highest honor conferred on a career senior executive, first by President Bill Clinton and later by President George W. Bush. Howard received his B.A. from McGill University in 1975 and his Ph.D. in economics from Yale University in 1982.

Hannes Pfeifenberger is an economist with a background in electrical engineering and over 25 years of experience in the areas of electricity markets, regulation, and finance. Johannes specializes in electricity market design and energy policies, transmission pricing and cost-benefit analyses, analysis and mitigation of market power, strategy and planning, storage and generation asset valuation, ratemaking and incentive regulation, contract disputes and commercial damage. Mr. Pfeifenberger is a Senior Fellow at Boston University's Institute of Sustainable Energy (BU-ISE) and a Visiting Scholar at MIT's Center for Energy and Environmental Policy Research (CEEPR).



Paul Joskow is the Elizabeth and James Killian Professor of Economics at the Massachusetts Institute of Technology (MIT) and President emeritus of the Alfred P. Sloan Foundation. Joskow has been on the MIT faculty since 1972, where he was the head of the MIT Department of Economics from 1994 to 1998 and director of the MIT Center for Energy and Environmental Policy Research from 1999 to 2007. Joskow became president of the Sloan Foundation in 2008 and returned to MIT in 2018. At MIT his teaching and research areas include industrial organization, energy and environmental economics, competition policy, and government regulation of industry. He has served on the boards of the New England Electric System, National Grid PLC, TC Energy, State Farm Indemnity, Exelon Corporation (current), Putnam Mutual Funds (current), and the Whitehead Institute for Biomedical Research.



Richard Schmalensee served as the John C Head III Dean of the MIT Sloan School of Management from 1998 through 2007. He was a member of the President's Council of Economic Advisers from 1989 through 1991 and served for 12 years as Director of the MIT Center for Energy and Environmental Policy Research. Professor Schmalensee is the author or coauthor of 11 books and more than 120 published articles, and he is co-editor of volumes 1 and 2 of the Handbook of Industrial Organization. His research has centered on industrial organization economics and its application to managerial and public policy issues, with particular emphasis on antitrust, regulatory, energy, and environmental policies. He has served as a consultant to the U.S. Federal Trade Commission, the U.S. Department of Justice, and numerous private corporations.

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