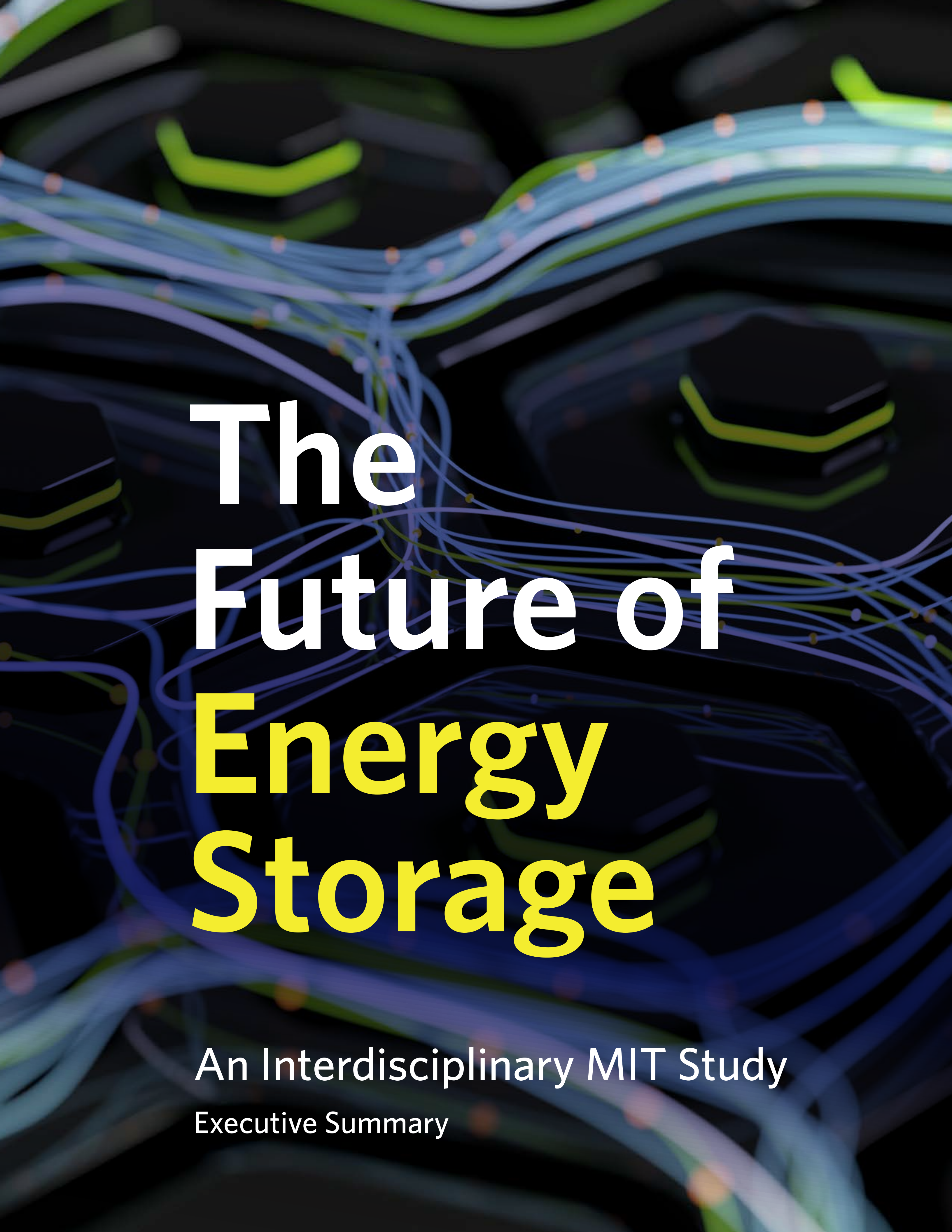

The Future of Energy Storage

An Interdisciplinary MIT Study

Executive Summary

The Future of Energy Storage

AN INTERDISCIPLINARY MIT STUDY

Other reports in the MIT *Future of* series:

- The Future of Nuclear Power (2003)
- The Future of Geothermal Energy (2006)
- The Future of Coal (2007)
- Update to the Future of Nuclear Power (2009)
- The Future of Natural Gas (2011)
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Incorporated in the cover art is a 3D concept illustration of battery cells, a form of electrochemical energy storage. © Getty Images

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While the members of the advisory committee provided invaluable perspective and advice to the study group, individual members may have different views on one or more matters addressed in the report. They are not asked to individually or collectively endorse the report findings and recommendations.

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Foreword and acknowledgments

The Future of Energy Storage study is the ninth in the MIT Energy Initiative's *Future of* series, which aims to shed light on a range of complex and vital issues involving energy and the environment. Previous studies have focused on the role of technologies such as nuclear power, solar energy, natural gas, geothermal, and coal (with capture and sequestration of carbon dioxide emissions), as well as systems such as the U.S. electric power grid. Central to all these studies is understanding the role these particular technologies can play in both decarbonizing global energy systems and meeting future energy needs. Energy storage will play an important role in achieving both goals by complementing variable renewable energy (VRE) sources such as solar and wind, which are central in the decarbonization of the power sector.

The study will prove beneficial for a wide array of global stakeholders in government, industry, and academia as they develop the emerging energy storage industry and consider changes in planning, oversight, and regulation of the electricity industry that will be needed to enable greatly increased reliance on VRE generation together with storage. The report is the culmination of more than three years of research into electricity energy storage technologies—including opportunities for the development of low-cost, long-duration storage; system modeling studies to assess the types and roles of storage in future, deeply-decarbonized, high-VRE grids in both U.S. regions and emerging market, developing economy countries; and implications for electricity system planning and regulation.

The study was guided by a distinguished external Advisory Committee whose members dedicated a significant amount of their time to participate in multiple meetings; to comment on our preliminary analysis, findings, and recommendations; and to make available experts from their own organizations to answer questions and contribute to the content of the report. We would especially like to acknowledge the wise and able leadership of the Committee's Chair, Linda Stuntz. The study is certainly better as a result of this thoughtful, expert input. However, the study is the responsibility of the MIT study group; the Advisory Committee members do not necessarily endorse all of its findings and recommendations, either individually or collectively.

The Future of Energy Storage study gratefully acknowledges our sponsors: Core funding was provided by The Alfred P. Sloan Foundation and The Heising-Simons Foundation. Additional support was provided by MIT Energy Initiative members Shell and Equinor. As with the Advisory Committee, the sponsors are not responsible for and do not necessarily endorse the findings and recommendations. That responsibility lies solely with the MIT study group.

This study was initiated and performed within the MIT Energy Initiative. Alexandra Goodwin, Senior Administrative Assistant at MITEI, provided support to both the study team and the Advisory Committee. Special thanks are due to the MITEI events team, specifically to Carolyn Sinnes, Administrative Assistant; Debi Kedian, Events Manager; and

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Executive summary

This interdisciplinary MIT study examines the important role of energy storage in future decarbonized electricity systems that will be central to the fight against climate change. Deep decarbonization of electricity generation together with electrification of many end-use activities is necessary to limit climate change and its damages. Wind and solar generation—which have no operating carbon dioxide emissions, have experienced major cost reductions, and are being deployed at scale globally—are likely to provide a large share of future total generation. Unlike traditional generators, the output from these variable renewable energy (VRE) resources depends on weather conditions, which sometimes change rapidly; thus, VRE generators cannot be dispatched to follow variations in electricity demand. Electricity storage, the focus of this report, can play a critical role in balancing electricity supply and demand and can provide other services needed to keep decarbonized electricity systems reliable and cost-effective. As we discuss in this report, energy storage encompasses a spectrum of technologies that are differentiated in their material requirements and their value in low-carbon electricity systems. As electricity grids evolve to include large-scale deployment of storage technologies, policies must be adjusted to avoid excess and inequitable burdens on consumers, to encourage electrification for economy-wide decarbonization, and to enable robust economic growth, particularly in emerging market developing economy countries. Social justice and equity must be included in system design. The time horizon for this study is 2050, consistent with previous *Future of* studies in this series, though we are also interested in technologies that can be deployed at scale in the nearer timeframe of 2030.

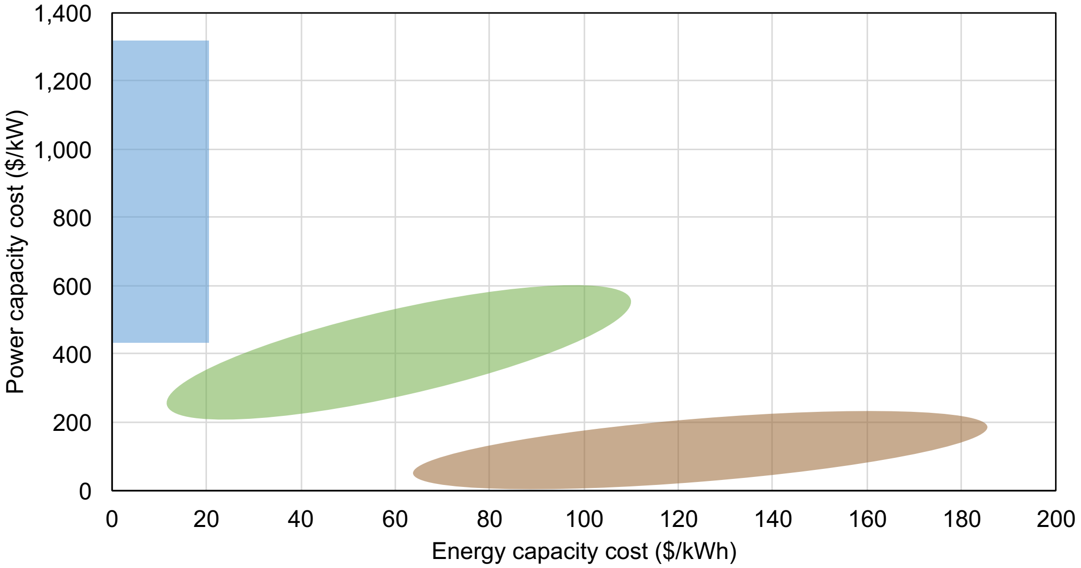
Energy storage enables cost-effective deep decarbonization of electric power systems that rely heavily on wind and solar generation without sacrificing system reliability. Assuming favorable cost reduction trends for VRE technologies continue, the modeling analysis conducted for this study identifies cost-effective pathways for decarbonizing electricity systems—reducing emissions by 97%–99% relative to 2005 levels in the United States, for example—while maintaining grid reliability. Efficient decarbonization will require substantial investments in multiple energy storage technologies, as well as in transmission, clean generation, and demand flexibility. If "negative emissions" technologies—that is, technologies for removing carbon dioxide from the atmosphere—become available, they can provide emissions offsets that enable small amounts of natural gas generation to be part of a cost-effective net-zero electricity system.

Energy storage basics

Four basic types of energy storage (electrochemical, chemical, thermal, and mechanical) are currently available at various levels of technological readiness. All perform the core function of making electric energy generated during times when VRE output is abundant and wholesale prices are relatively low available at times when VRE output is scarce and wholesale prices are relatively high. This flexibility provides a range of benefits to power systems.

An energy storage facility can be characterized by its maximum instantaneous *power*, measured in megawatts (MW); its *energy* storage capacity, measured in megawatt-hours (MWh); and its round-trip *efficiency* (RTE), measured as the fraction of energy used for charging storage

Figure ES.1: Three groups of storage technologies based on power- and energy-capacity costs



The blue region, with high power and low energy capacity costs, includes thermal, chemical (e.g., hydrogen), metal-air battery, and pumped hydro storage technologies. Lithium-ion batteries fall in the brown area, with low power, but high energy-capacity costs; flow batteries fall in the intermediate, green region. In addition to the two parameters displayed in this figure, other cost and performance attributes, e.g., charge and discharge efficiencies, are also important when comparing storage technologies within and across each class. The full set of characteristics used in system modeling are discussed in Chapter 6.

that is returned upon discharge. The ratio of energy storage capacity to maximum power yields a facility's storage *duration*, measured in hours—this is the length of time over which the facility can deliver maximum power when starting from a full charge. Most currently deployed battery storage facilities have storage durations of four hours or less; most existing pumped storage hydro (PSH) facilities have durations of eight to twelve hours or more. Storage technologies also differ in energy density, which is the maximum amount of energy that can be stored per unit volume. Battery technologies with high energy density are particularly well-suited for use in electric vehicles (EVs) and mobile electronics; technologies with lower energy density can nonetheless be used for storage in electricity system applications where the efficient use of space is generally less important. Energy storage technologies also differ in other attributes, including the extent of facility-specific scale economies (geographical footprint, modularity) and the extent to which their performance degrades with use.

The technologies considered in this report fall into three main groups based on their power and energy capacity costs (Figure ES.1). Generally, technologies with low energy-capacity costs and high power-capacity costs (the blue area in the figure) are most suitable for longer duration storage applications (up to multiple days) and less frequent charge-discharge cycles; these include thermal, chemical, metal-air battery, and pumped hydro storage options. Technologies in the brown area, including lithium-ion batteries, are better suited to shorter duration applications (a few hours) and more frequent cycling. Technologies with intermediate capabilities, including flow batteries, are in the green area.

Electricity system storage technologies

The study examines electricity-to-electricity storage technologies in four categories: electrochemical, thermal, chemical, and mechanical. We do not catalog, let alone evaluate, all options within each of these categories; rather, we focus on examples of storage technologies in each category and seek to highlight issues that apply across a broad set of technologies within these categories. Some of the technologies we consider, such as lithium-ion batteries, pumped storage hydro, and some thermal storage options, are proven and available for commercial deployment. Others would require further research, development, and demonstration, and may not be commercially available at scale until the 2030s or 2040s. Table ES.1 summarizes our assessment of the availability of various storage technologies and storage-supporting technologies and practices in the near term (by 2030). All the technologies we consider in this report could be commercially available by 2050.

Successful innovation for energy and many other manufacturing-related technologies typically passes through five stages: idea creation ➛ R&D ➛ engineering at pilot scale ➛ technology demonstration ➛ deployment. Table ES.1 indicates the current stage of innovation for various storage technologies. The private sector has provided significant venture capital for storage technologies generally, and for lithium-ion batteries used in vehicles in particular. As discussed in this study, EV battery development has significantly improved prospects for short-duration electricity system storage. So far, long-duration storage technologies have not experienced similar help from other market drivers. While the value of long-duration storage (>12 hours) is low when VRE penetration is low, long-duration storage technologies clearly become more valuable as decarbonization requirements become more stringent and reliance on VRE generation grows. This is especially true if grid operators are precluded from using natural-gas-fueled generation, with or without carbon capture and storage, to provide balancing capacity during extended supply troughs for VRE generation or during unusually high levels of demand due to extended extreme weather events. The value that long-duration storage could provide in a highly decarbonized electricity system argues for increased federal support of various kinds of long-duration storage options, depending on the stage of innovation different technologies have reached.

The current policy focus on relatively near-term decarbonization goals pushes both public and private attention toward downstream technology demonstration and deployment involving relatively mature technologies. The U.S. Department of Energy (DOE) can play a helpful role in this area, but its involvement should reflect two important lessons learned from past demonstration and deployment efforts. First, Congress should enable more joint technology demonstration projects with industry, unfettered by the Federal Acquisition Regulation and other rules that constrain technology development and demonstration on commercial terms. The purpose of public investment in technology demonstration and early deployment activity is to disseminate knowledge, which is inconsistent with policies such as requiring cost sharing in exchange for intellectual property rights.

Second, efforts to accelerate the deployment of any commercial technology should rely on incentives and mechanisms that reward success but do not interfere in project management. The Biden administration has proposed tax credits for a wide range of storage technologies, in addition to tax credits for transmission and various clean generation technologies, including wind and solar. In contrast to electricity generation technologies, where performance-based payments such as production tax credits can be directly linked to output measures,

Table ES.1: Summary of findings on the current innovation status of selected energy storage technologies

Technology	Current innovation status					Chapter
Electrochemical storage						**2**
Li-ion batteries		②		④	⑤	**2**
Flow batteries (aqueous inorganic)		②		④	⑤	**2**
Flow batteries (aqueous organic)	①	②	③			**2**
NaS batteries				④	⑤	**2**
Metal-air batteries		②	③			**2**
Critical materials supply (metals and rare earths)	①	②	③			**2**
Battery re-cycling	①	②	③	④		**2**
Battery second use	①	②				**2**
Advanced power electronics		②	③	④		
Pumped hydro storage				④	⑤	**3**
Thermal storage		②	③	④		**4**
Hydrogen						**5**
Production, transport, storage	①	②		④		**5**
H_2 generation—photoelectric, very high temperature gas reformation, advanced electrolysis		②				**5**

① Idea creation, study, and analysis—public and private sponsors
② R&D—university, national laboratory, and private sector performers
③ Pilot scale engineering
④ Demonstration & testing
⑤ Deployment—depends upon progress and market conditions.
Further discussion is found in the chapters listed in the right column.

performance-based support for non-generation energy technologies such as storage must be based on preset development and operational testing measures.

Electrochemical storage

Electrochemical storage systems, which include well-known types of batteries as well as new battery variants discussed in this study, generally have higher energy density than mechanical and thermal storage systems, but lower energy density than chemical systems. Round-trip efficiency for battery storage ranges widely, from as much as 95% for lithium-ion (Li-ion) chemistries to as little as 40% for metal-air chemistries. A compact footprint and independence from hydrological and geological resources make batteries a versatile and highly scalable technology that can be sized for a range of applications, from power plants down to residential uses. Our study yields several key takeaways.

Lithium-ion batteries possess high energy density, high power density, and high roundtrip efficiency, facilitating their near-ubiquitous use in electric vehicles and their widespread use in short-duration (typically 4 hours or less) electricity system storage applications. The dominant role of Li-ion batteries in the rapidly growing EV market has attracted significant investment from the private sector and is supporting rapid expansion of battery manufacturing capacity in the United States (currently most of this investment is coming from foreign firms). Cost and limits on the availability of key materials currently used in battery manufacture have set a floor on

Li-ion battery costs and may constrain future deployment, inspiring a shift toward chemistries that use more earth-abundant elements. Other advances being vigorously pursued for Li-ion battery components will also support cost and performance improvements. With these trends, Li-ion batteries will continue to be a leading technology for EVs and for short-duration storage, but their storage capacity costs are unlikely to fall low enough to enable widespread adoption for long-duration (> 12 hours) electricity system applications.

To enable economical long-duration energy storage (> 12 hours), the DOE should support research, development, and demonstration to advance alternative electrochemical storage technologies that rely on earth-abundant materials. Cost, lifetime, and manufacturing scale requirements for long-duration energy storage favor the exploration of novel electrochemical technologies, such as redox-flow and metal-air batteries that use inexpensive charge-storage materials and battery designs that are better suited for long-duration applications. While several novel electrochemical technologies have shown promise, remaining knowledge gaps with respect to key scientific, engineering, and manufacturing challenges suggest high value for concerted government support. Innovation in these technologies is being actively pursued in other countries, notably China.

Thermal energy storage

Thermal energy storage (TES) has attributes suitable for long-duration storage including the ability to store heat effectively in low-cost materials. This report discusses several generic TES strategies that reflect varying degrees of technology readiness.

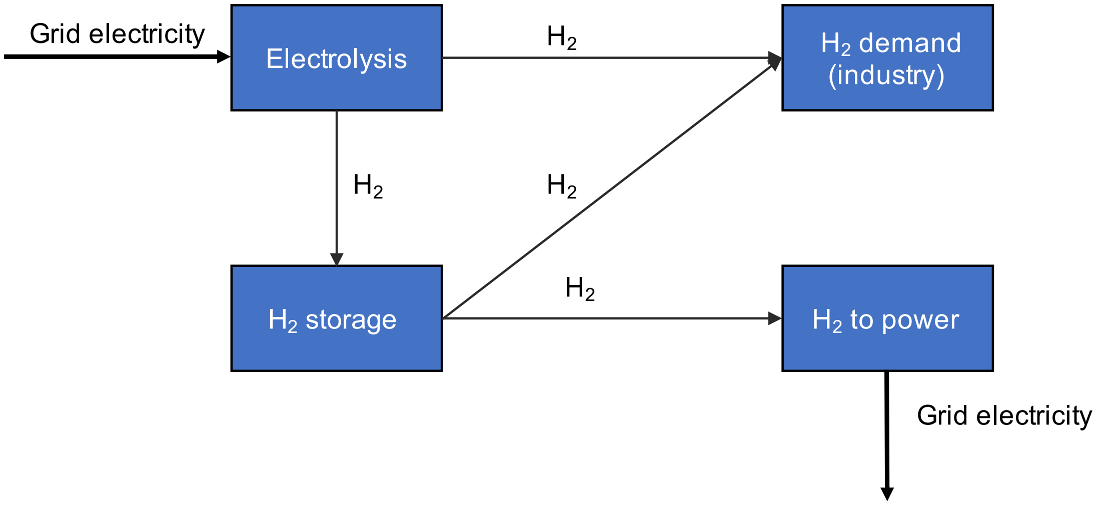
One possible near-term TES approach focuses on reducing the cost of converting heat to electric power, the main component of overall TES system cost, by reusing steam turbines at existing power plants and adding thermal storage and new steam generators in place of existing fossil-fuel boilers. This retrofit can be done today using commercially available technologies, and it may be attractive to plant owners and local communities as a way to use assets that would otherwise be abandoned as electricity systems decarbonize.

Chemical energy storage: Hydrogen

Hydrogen is widely considered a leading chemical energy storage medium because it can be directly produced from electricity in a single step and consumed either as a fuel to produce power or as a feedstock or heat source for other industrial processes. We focus on hydrogen in this chemical storage section.

Hydrogen's role as a form of energy storage for the electricity sector will likely depend on the extent to which hydrogen is used in the overall economy, which in turn will be driven by the future costs of hydrogen production, transportation, and storage, and by the pace of innovation in hydrogen end-use applications. Hydrogen is currently produced, transported, and sold as a feedstock for numerous industrial processes. Today, the dominant technology for hydrogen production relies on fossil fuels and produces carbon emissions. The ability to produce low-carbon hydrogen by splitting water (also known as electrolysis) using low-carbon grid electricity can support decarbonization in end-use sectors such as industry and transportation, as well as in the power sector. Figure ES.2 shows how hydrogen produced via electrolysis can serve as a low-carbon fuel for industry as well as for electricity generation during periods when VRE generation is low. Use of electrolyzers as a dispatchable load for the power system could also reduce the costs of power system decarbonization by increasing capacity utilization of VRE resources.

Figure ES.2: Illustration of cross-sector (power-industry) coupling of hydrogen



Coupling leads to cost reductions through increased utilization of variable renewable energy assets and operation of electrolyzers as dispatchable loads.

We support the effort that the DOE is leading to create a national strategy that addresses hydrogen production, transportation, and storage. In particular, the ability of existing natural gas transmission pipelines to carry hydrogen without suffering embrittlement, either at reduced pressures or if hydrogen is blended with natural gas or other compounds, remains an open question that deserves government-supported study by the DOE and the U.S. Department of Transportation. An important step in this direction is the call in recent legislation for the creation of at least four hydrogen hubs.

Mechanical storage

Electrical energy can be converted into various forms of mechanical energy such as gravitational potential energy and kinetic energy; electrical energy can also be used to compress a gas such as air. Some of these forms of mechanical energy are suitable for large-scale and long-duration energy storage. As a category, mechanical energy storage includes a wide variety of technologies. A common feature of all these technologies, however, is that their energy density is much lower than the energy density of chemical or electrochemical storage technologies. Consequently, mechanical energy storage systems tend to have large footprints and require geologically favorable locations—thus, they are not well suited for use in small-scale facilities.

Pumped storage hydropower (PSH) stores energy in the potential energy of water pumped uphill. PSH is a mature, widely deployed technology that accounts for well over 90% of the functional grid-scale energy storage capacity that currently exists, both globally and in the United States. Yet, PSH deployment has significantly slowed in the United States and in many other countries since the 1990s (the notable exception is China). This trend reflects, among other factors, the reduced value of intraday energy arbitrage as a result of the increased use of flexible gas-fired generation. In addition, PSH projects have high initial costs and inflexible sizing and siting requirements; historically, these projects have also experienced long construction periods and major cost overruns.

While not strictly an electricity-to-electricity storage technology, existing conventional hydropower systems with storage reservoirs could play a larger role in balancing supply and demand in electricity systems that rely heavily on VRE generation. Where there is significant potential to play this role, system planners should consider options for increasing the amount of water that is held behind dams for use in balancing electricity systems.

Compressed air energy storage (CAES) systems store pressurized air in underground cavities or above-ground tanks; some CAES systems also store the heat that is generated when the air is compressed. This technology has been widely discussed as a potential grid-scale energy storage option, but it faces significant hurdles to deployment at scale. Although cost estimates for CAES are subject to multiple uncertainties, estimates of energy cost for this technology are generally higher than estimates for other energy storage technologies that are expected to be available in the future.

Co-locating energy storage systems with existing power plants that are being retired could reduce storage costs by enabling the reuse of existing grid interconnections and, in some cases, other power plant components. Using existing interconnections would save time as well as cost. In addition, as noted above, existing turbines can be reused in thermal storage systems that repower existing turbines using zero-emissions heat or fuel. The DOE should investigate the cost and system impacts of thermal storage technologies and other options that offer promise for reusing existing assets, as well as the social acceptance of such reuse strategies by neighboring communities, and should sponsor demonstration projects where appropriate.

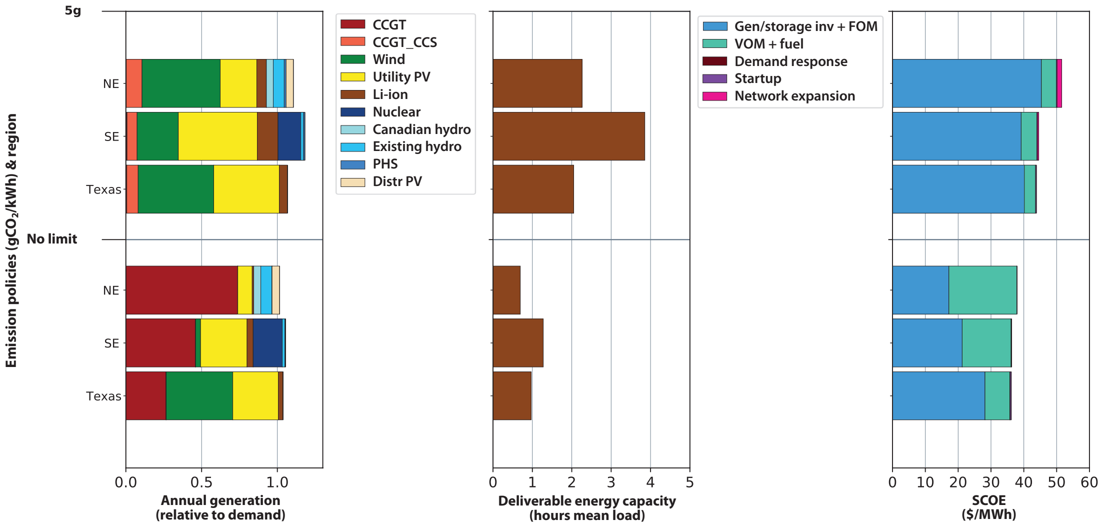
Efficient high-VRE electricity systems with storage: Modeling results and implications for governance and policy

This section examines potential roles for storage in a developed country context and in an emerging market developing economy country context. These two country contexts are illustrated by results for three different regions in the U.S. and for India, respectively.

Modeling results for a developed country: Three U.S. regions

Our modeling for the U.S. power sector focused on three regions: the Northeast (New York and New England), the Southeast, and Texas for largely "greenfield" systems in 2050. These regions differ significantly in their electricity demand profiles, wind and solar resources, and availability of hydropower and existing nuclear resources. These differences affect both the least-cost generation mix in the absence of emissions constraints and the cost of achieving different degrees of decarbonization**.** Figure ES.3 shows modeled projections for annual generation, deliverable energy capacity, and system cost of electricity for each region in 2050 under two policy scenarios: no carbon constraint and emissions constrained to 5 grams of carbon dioxide per kilowatt-hour (gCO_2/kWh). If 2050 electricity demand remains the same as the 2018 level, then reducing the average carbon intensity of the U.S. power sector to 5 gCO_2/kWh would lower 2050 emissions by 99.2% relative to 2005. On the other hand, if electricity use grows such that demand in 2050 is greater than in 2018, as projected in the electricity demand scenario used to model energy storage impacts for this study (Mai et al. 2018), a U.S. sector-wide average carbon intensity of 5 gCO_2/kWh would deliver a 98.7% reduction in power sector emissions relative to 2005. The illustrative results in Figure ES.3 are from scenarios that assume only Li-ion battery and pumped hydro storage

Figure ES.3: Annual generation relative to demand



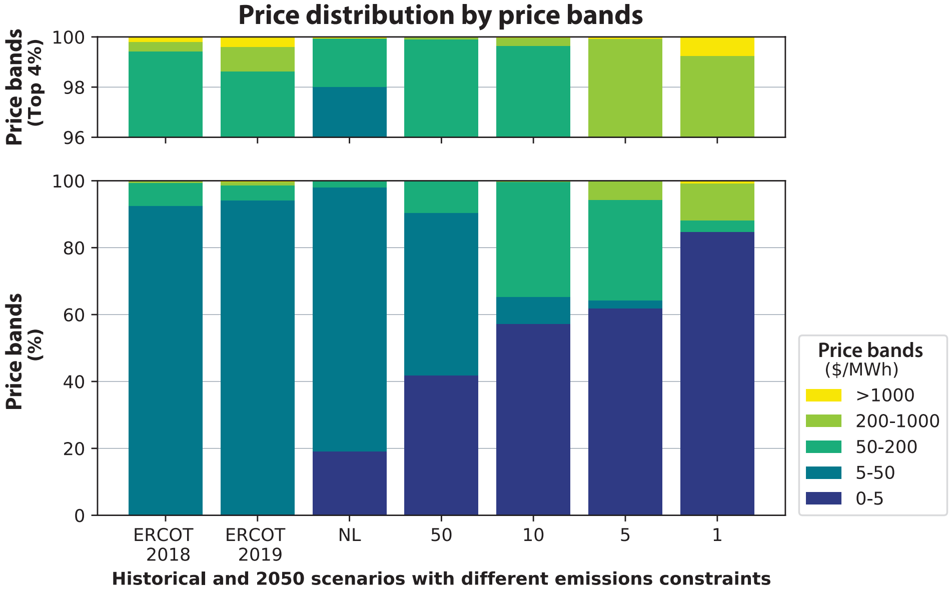
Annual generation relative to demand, deliverable energy capacity from storage (measured in hours of discharge at mean load), and system average cost of electricity (SCOE) in the Northeast (NE), Southeast (SE), and Texas in 2050. Modeling results are shown for a scenario with no limit on emissions (bottom half of each chart) and for a policy scenario with an emissions intensity limit of 5 gCO_2/kWh (top half of each chart) (note that the policy scenario assumes decarbonization to a level that reduces U.S. power sector emissions by approximately 99% relative to 2005). SCOE includes total annualized investment; fixed O&M; operational costs of generation, storage, and transmission; and any non-served energy penalty. Emissions intensity under the "No Limit" policy case for each region is as follows: NE: 253 gCO_2/kWh, SE: 158 gCO_2/kWh, Texas: 92 gCO_2/kWh. For the Northeast region, "Wind" represents the sum of onshore and offshore generation. In this illustration, Li-ion batteries are the sole new technology deployed for energy storage purposes in the power sector. The full report discusses modeling results for a wide range of storage technologies, of which Li-ion batteries are only one example. PHS = Pumped Hydro Storage. VOM = Variable O&M cost.

are available; our modeling of U.S. regions (discussed in Chapter 6) examines a wide range of other storage technologies.

The ability of storage technologies to substitute for, or complement, essentially all other elements of a power system (including generation, transmission, and demand response), coupled with uncertain climate change impacts on electricity demand and supply, means that more sophisticated analytical tools are needed to plan, operate, and regulate the power systems of the future and to ensure that these systems are reliable and efficient. Important focus areas include system stability and dispatch (including enabling the participation and compensation of distributed storage and generation (PV) assets in system dispatch and wholesale markets), resource adequacy, and retail rate design. The development of new analytical tools must be accompanied by additional support for complementary staffing and upskilling programs at regulatory agencies. This effort should be led by the DOE in cooperation with independent system operators and regional transmission organizations (ISOs/RTOs).

The distribution of hourly wholesale prices or marginal value of energy will change in deeply decarbonized bulk power systems, with many more hours of zero or very low prices and more hours of high prices compared to today's wholesale markets.

Figure ES.4: Hourly marginal wholesale price of energy for Texas

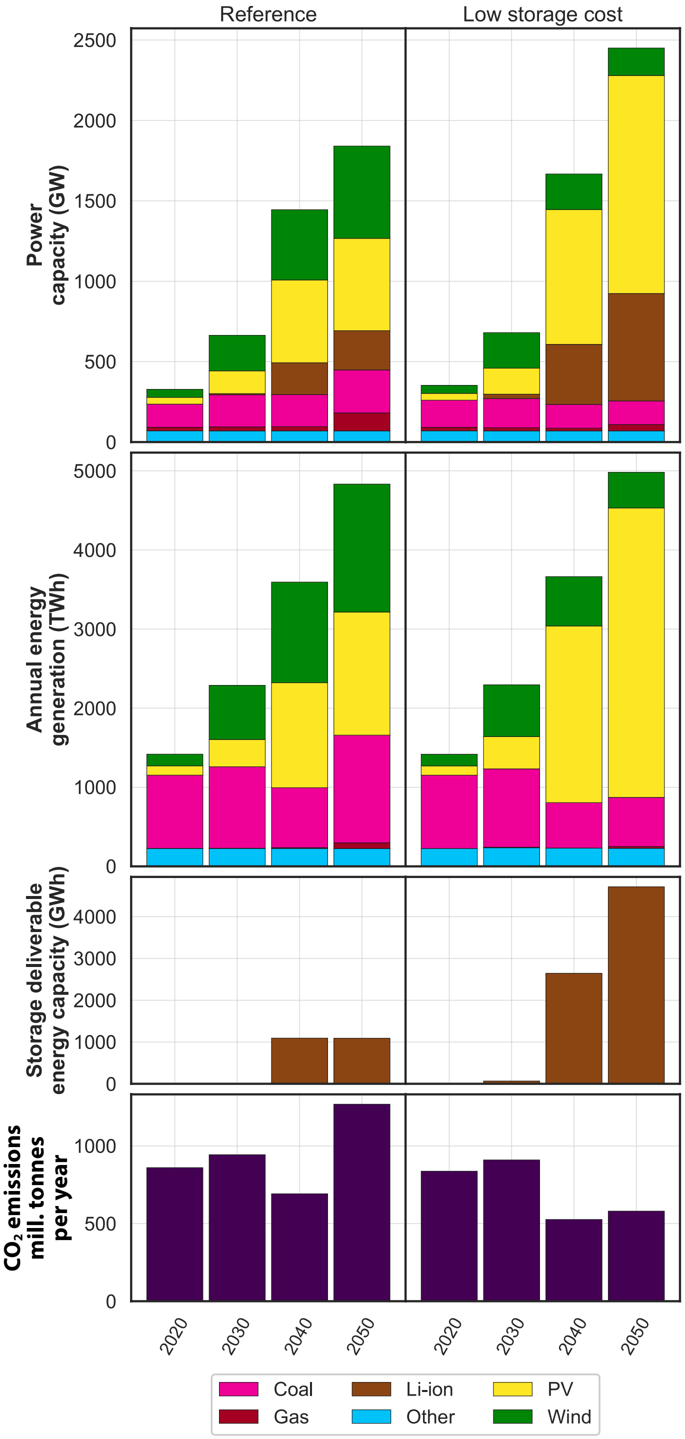


Hourly marginal wholesale price of energy for Texas under various emissions scenarios ranging from no limit (NL, 3rd bar from left) to 1 gCO_2/kWh (right-most bar). The price bands are based on the known marginal cost of various generation technologies; we zoom in on the top 4% of the price bands to show the price distributions at that extreme. Historical price distributions in ERCOT are shown for reference. For the purposes of this figure, we assume Li-ion battery storage only. The effect of including other storage technologies on these results is discussed in Section 6.3.4.

This is because VRE-dominant bulk power systems with storage will have relatively high fixed (capital) costs and relatively low marginal operating costs compared to today's bulk power systems, which largely rely on thermal generators. Figure ES.4 compares the distribution of historical hourly wholesale electricity prices for 2018 and 2019 in the ERCOT system, which covers nearly all of the state of Texas, with 2050 scenarios. Bars represent the distributions of prices for the no-limit and carbon-constrained Texas modeling cases. Increased reliance on VRE generation, with zero marginal cost, greatly increases the percentage of hours when prices, represented by marginal system costs in our modeling, are under $5 per MWh. This effect increases as the carbon constraint becomes more stringent (i.e., allowable emissions are ratcheted down). During the highest-price hours, shown at the top of the bars and in the exploded section of the figure, modeled prices are significantly above those in the present ERCOT market.

The combination of relatively high capital costs and many more hours when prices are very low will create financing challenges for both VRE generation and storage, particularly since regulators will likely continue to cap (as they do at present) extremely high prices that could otherwise support cost recovery. Future patterns of wholesale electricity prices and the goal of decarbonizing other sectors through electrification with decarbonized electricity also reinforces the benefit of adopting retail pricing and retail load management options that reward all consumers for shifting electricity uses away from times when high wholesale prices indicate scarcity to times when low wholesale prices signal abundance.

Figure ES.5: Impact of Li-ion storage cost projections on cost-optimal bulk power system evolution in India



Installed capacity (1st row), annual energy generation (2nd row), storage energy capacity (3rd row), and annual CO_2 emissions (4th row). Results in the left column are for a reference case, which uses a mean estimate for future Li-ion battery capital costs. The right column assumes a low-cost trajectory for future Li-ion battery capital costs.

Transmission expansion, which allows for increased VRE deployment in locations with higher-quality VRE resources and improves VRE integration by balancing resource intermittency across connected areas and smoothing the effects of geographical differences in VRE supply and demand, is also important for cost-effective decarbonization. The current likelihood that cost-effective transmission projects to bring generation from areas with high-quality VRE resources to major load centers will face extended delays or possible rejection suggests the need for statutory and regulatory changes to reduce barriers to transmission expansion. A shortfall in new transmission capacity may lead to a larger role for storage as well as higher costs in future decarbonized electricity systems.

Modeling results for an emerging market, developing economy country: India

Coal-dependent emerging market and developing economy countries that lack access to abundant low-cost gas or gas infrastructure, such as India, represent a very large and important future market for electricity-system applications of energy storage technologies. Modeling for this study suggests that energy storage will be deployed predominantly at the transmission level, with important additional applications within urban distribution networks. Overall economic growth and, notably, the rapid adoption of air conditioning will be the chief drivers of energy storage deployment. Assuming continued technology cost declines, we find that VRE generation and storage compete favorably with new coal from a cost standpoint in India over the medium and long term, but existing coal plants linger absent carbon pricing, as shown on the left panel of Figure ES.5.

Modeling results for a scenario that assumes the availability of low-cost storage and VRE generation technology in India are shown in the right panel of Figure ES.5. These results point to significant reductions in both system cost[1] and modeled carbon dioxide emissions from India's electricity system relative to baseline projections (captured in the left panel). Reductions in system cost and CO_2 emissions occur whether or not there are caps or taxes on carbon emissions. This result highlights the global environmental benefit of lower costs for electricity storage.

Additional study

Several storage-related topics beyond those addressed in this study deserve attention. These include: (1) manufacturing and supply chain trends, and their impacts in terms of the availability and cost of energy storage technologies and U.S. competitiveness; (2) the relationship between the stability of an economic and regulatory policy framework for economy-wide decarbonization and the time required to achieve a net-zero-carbon electricity sector; (3) the establishment of expectations for recycling and reuse for end of life batteries; (4) identification of environmental, health, and safety aspects of specific electricity storage systems; and (5) the practically available scope for load flexibility and demand response to reduce grid storage needs and associated costs.

References

Mai, T., P. Jadun, J. Logan, C. McMillan, M. Muratori, D. Steinberg, L. Vimmerstedt, R. Jones, B. Haley, B. Nelson. (2018). *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States.* Golden, CO: National Renewable Energy Laboratory.

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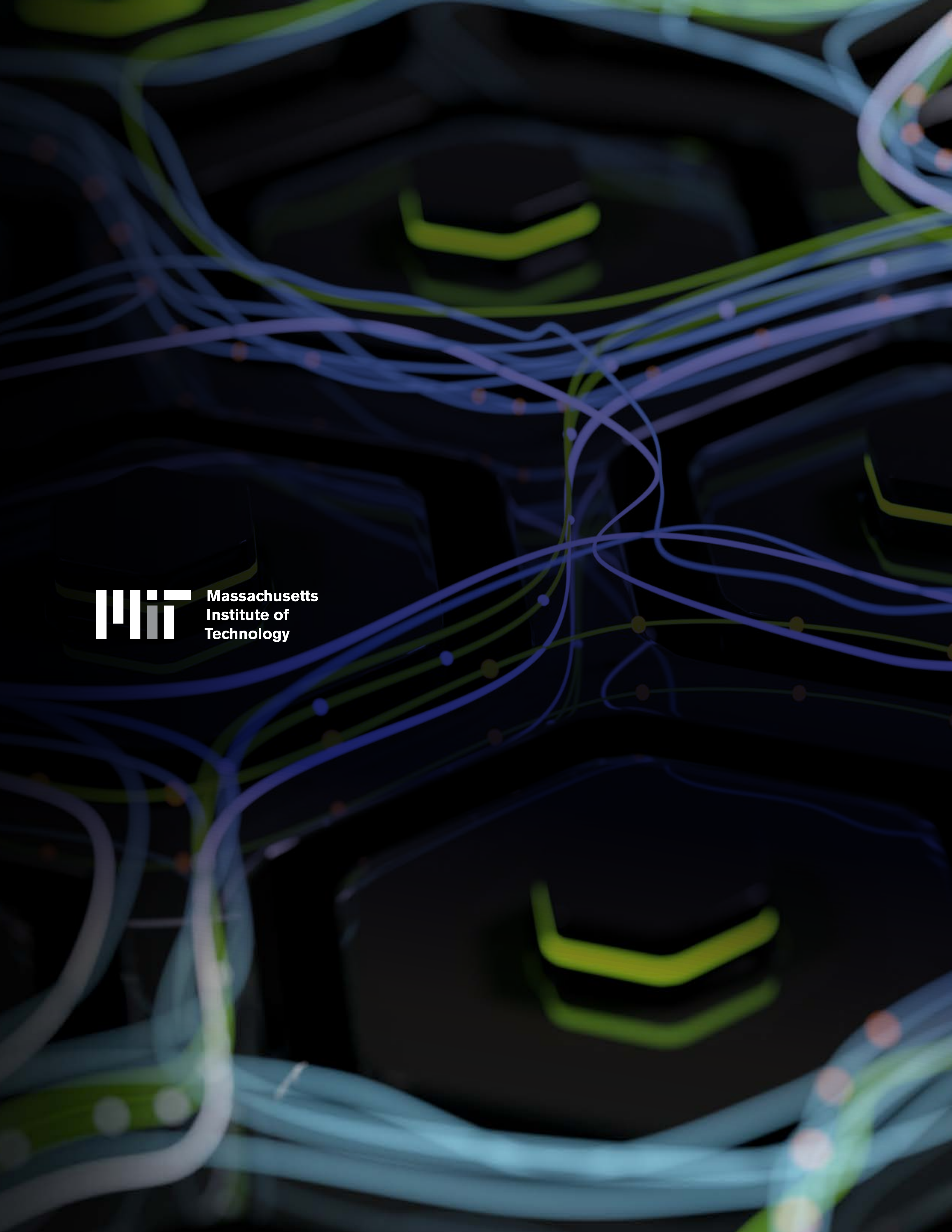
[1] The resulting average system costs of electricity in 2040 and 2050 are reduced by 22% and 39%, respectively.



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