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Modeling Multi-Day Energy Storage in New York

Storage Portfolios that Can Enable a Reliable, Zero Carbon Grid

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EXECUTIVE SUMMARY

New York is racing to achieve its goals to supply at least 70% of electricity demand from renewable energy resources by 2030 and to achieve a zero emissions electric grid by 2040, some of the most ambitious electricity decarbonization goals in the country.[1] This is a substantial undertaking that has produced various modeling studies evaluating the resource pathways that will allow New York to meet its targets at the least cost. Each of these studies identified 20 to 45 gigawatts of resources that will be needed by the future system to meet electric demand and maintain reliability, but cannot be provided by technologies that are currently available at commercial scale.

The New York Independent System Operator (NYISO) suggests that this technology gap be filled with a new class of "dispatchable emissions-free resources" (DEFRs) that will provide "sustained on-demand power and system stability"[2] when renewable energy supplies are insufficient to meet energy demand. Previous studies substituted proxy resources to act as DEFRs while noting that a number of different technologies might emerge to meet zero-carbon firm capacity needs. The challenge New York faces next is to determine which portfolio of emerging technologies can fill this resource gap at least cost.

This analysis supplements prior studies and evaluates the extent to which diverse types of emerging long-duration energy storage (LDES) and multi-day energy storage (MDS) technologies could serve as DEFRs and help New York achieve a reliable, affordable, zero-carbon grid. LDES is defined as storage with durations between 10 and 24 hours.[3] The U.S. Department of Energy's Pathways to Commercial Liftoff: Long Duration Energy Storage report describes these technologies as serving "a diurnal market need by shifting excess power produced at one point in a day to another point within the same or next day."[4] MDS resources have durations of greater than 24 hours, meeting "a market and end-use customer need where there may be an extended shortfall of power (e.g., multiple days of low wind and solar or resiliency applications) several times per year."[5] There is substantial evidence from New York's prior studies that these resources can deliver dispatchable emissions-free capacity to support reliability over multi-day periods of grid stress.

This study uses investment and dispatch modeling to: 1) identify the least-cost portfolio of diverse emerging LDES and MDS energy storage technologies to meet New York's 2030 and 2040 clean energy goals; 2) evaluate changes in system cost that occur when adding LDES and MDS technologies to the optimized resource portfolio; and 3) determine the ways in which LDES and MDS operate in New York's electric grid to support overall system reliability.

1 Climate Leadership and Community Protection Act (CLCPA): Chapter 106 of the Laws of 2019 (codified, in part, in Public Service Law (PSL) §66-p). The CLCPA became effective on January 1, 2020.
2 NYISO, 2021-2040 System & Resource Outlook, pp. 13-14.
3 Different jurisdictions may define the durations of LDES and MDS technologies differently.
4 US Department of Energy, 2023, Pathways to Commercial Liftoff: Long Duration Energy Storage, pp. 2.
5 Id.

Key Findings: 35 GW of multi-day energy storage are needed by 2040 to meet New York's dispatchable emissions-free resource needs and reduce overall resource needs and total system costs

New York needs 4.8 GW of multi-day storage by 2030 and 35 GW by 2040 to reliably integrate renewables and achieve decarbonization goals.

This study identified a 4.8 GW need for multi-day energy storage in the least-cost 2030 portfolio, which grows to 35 GW by 2040. This long-term need aligns with the need for DEFRs identified in prior studies and demonstrates that multi-day energy storage can provide flexible, dispatchable capacity over the hourly, daily, and multi-day time-scales necessary to balance renewables over a season, managing renewable energy lulls and periods of extreme weather. The availability of MDS has the added benefit of avoiding both land-use impacts and transmission investments, as it avoids the overbuild of renewable and energy storage resources that otherwise are required. In 2030, the addition of MDS avoids 5 GW of <10-hour lithium-ion storage and 5 GW of solar resources.

In 2040, modeling results demonstrate that a portfolio of different storage technologies work together to maintain reliability in a zero carbon grid. The least cost resource portfolio includes 35 GW of MDS – 19 GW of iron-air batteries and 16 GW of hydrogen storage - for inter-week and seasonal energy shifting. It also includes 3.2 GW of LDES and 2.8 GW of lithium-ion for intra-day energy shifting. This storage portfolio avoids 64 GW of <10-hour lithium-ion storage and 1.5 GW of new nuclear resources that otherwise would have been built.

The inclusion of LDES and MDS technologies can reduce the cost of achieving New York's decarbonization targets by 6% in 2030 and 29% in 2040 compared to scenarios with only lithium-ion energy storage.

Emerging long-duration and multi-day energy storage technologies can lower the annualized system costs of achieving New York's 2030 climate goals by 6 percent ($0.4 billion/year) compared to scenarios in which lithium-ion batteries are the only available storage technology. Those cost savings increase to almost 30 percent by 2040 ($8.7 billion/year). LDES and MDS save customer costs by shifting large volumes of clean energy from periods of excess to periods of undersupply, thereby reducing the total amount of new resources required to meet the state's energy demands.

Multi-day storage resources maintain system reliability in a zero carbon grid due to their ability to discharge continuously during multi-day periods of grid stress.

Least-cost portfolios for New York in both 2030 and 2040 have an order of magnitude more energy storage capacity (GWh) when LDES and MDS are included in resource planning, allowing them to support the grid during energy-limited conditions that may last for many days. In 2040, for example, including diverse storage technologies reduces total storage power capacity needs by 26 GW, but increases total storage energy capacity from 538 GWh to 5,334 GWh. This stored energy capacity is a critical resource during renewable generation lulls. During one modeled 2040 offshore wind lull, weekly wind generation was only 32.7% of its average output, which resulted in an energy shortfall of 1,168 GWh. During this lull, the portfolio of storage technologies served 23.8% of net load, with MDS alone serving 16.1% of net load during that week. Short-duration storage and LDES provide intra- and inter-day shifting consistently throughout the year, while MDS provides critical inter-week flexibility and firming of bulk energy across weeks, weather systems, and seasons, and it steps in to meet demand during multi-day renewable lulls. A portfolio of storage technologies, both existing and emerging, work together to demonstrate how storage acts as a dispatchable, emissions-free resource in support of a reliable, zero carbon grid.

INTRODUCTION

Existing studies of pathways to achieve New York's ambitious climate goals have identified a substantial need for dispatchable, emissions-free resources, but have not investigated which technologies can meet that need. This study assesses a range of specific technologies that can fill the gap for dispatchable emissions-free resources (DEFR) and allow New York to integrate increased volumes of renewable energy onto the electric grid.

Three separate studies of New York's decarbonization targets have identified a long-term need for 20 GW to 45 GW of dispatchable, emissions-free resources to support the state's climate goals.

In 2020, the New York Independent System Operator (NYISO) retained The Brattle Group to examine the resources that are needed to reliably meet New York's decarbonization objectives. Brattle identified that New York's future resource portfolio requires resources that can operate flexibly across days, weeks, and seasons to balance supply and demand. Brattle calls for new technologies that can provide either seasonal storage or zero-emission, dispatchable supply.[6] The study results demonstrate a need for 18 GW of storage and flexible load by 2040 for short-term balancing and 35 GW of DEFRs for long-term balancing. Study authors noted a need to "develop a more robust understanding of the role of long duration storage."[7]

New York's Climate Action Council Draft Scoping Plan, authored by E3 and Abt Associates, came to similar conclusions, finding that wind, solar, and hydro energy power most of the state's economy in 2050. Study authors identified that 21-27 GW of new firm, zero-carbon capacity resources would be part of a least-cost system in 2040 to support grid reliability.[8]

NYISO's 2021-2040 System & Resource Outlook identified needs for 27-45 GW of DEFRs by 2040 to replace the electrical attributes provided today by fossil fueled generation.[9] NYISO stated that: "Long-duration, dispatchable, and emission-free resources will be necessary to maintain reliability and meet the objectives of the CLCPA. Resources with this combination of attributes … will be critical to future grid reliability."[10]

Staff of the New York State Department of Public Service (DPS) and the New York State Energy Research and Development Authority (NYSERDA) issued "New York's 6 GW Energy Storage Roadmap: Policy Options for Continued Growth in Energy Storage" at the end of 2022. The Storage Roadmap describes the state's procurement plan for 6 GW of battery storage resources with durations of less than 8 hours by 2030. New York's current Storage Roadmap was based on the Climate Action Council Draft Scoping Plan, and neither evaluate storage resources with durations above 8 hours nor quantify the benefits these technologies might provide to the electric grid.

This study examines the role of various energy storage technologies in decarbonizing New York's electric grid.

This study supplements prior analysis and examines the least-cost portfolio of resources to meet New York's 2030 and 2040 decarbonization targets when a diverse set of specific technologies are represented, including long-duration and multi-day storage technologies and other emerging DEFR options. This analysis was conducted using

6 The Brattle Group, New York's Evolution to a Zero Emission Power System, June 2020.
7 Id.
8 E3, Draft Scoping Plan Appendix G: Integration Analysis Technical Supplement, December 2021.
9 NYISO, 2021-2040 System & Resource Outlook, August 2022.
10 Id at 33.

Formware, a least-cost capacity optimization and production cost tool designed to capture the chronology and multi-scenario optimization needed to accurately model grids with substantial renewables and long-duration storage. Formware simulates the least-cost build and operation of generation and storage resources. It considers growth in electricity demand due to electrification, policy goals around decarbonization, reliability targets and reserve margins, and annual variability in renewable production and demand driven by weather. A description of Formware and its use in peer validated studies is provided in Appendix B.[11]

Input data and assumptions for this study are drawn from the New York Draft Climate Scoping Plan Analysis to the extent possible. The key differences are associated with our inclusion of more storage and DEFR resources, our modeling of hydrogen, and finally time series and ELCC data that was not included in the NY CLCPA report. Detailed input assumptions and methodology are contained in Appendix B.

This analysis improves upon prior studies in three important ways:

1. **Includes a diverse set of long-duration and multi-day energy storage and DEFR candidate technologies:** Candidate resources for capacity expansion include a diverse set of storage technologies ranging in duration from 4 hours to 100+ hours, in addition to the geothermal and small modular reactors. This report also has an accurate model of hydrogen - including realistic storage capacity needs and renewable generation needed to support hydrogen creation - improving upon the simpler representations in prior studies. (See Appendix B for further details).
2. **Models a full-year chronology for representing long duration storage:** We perform the capacity planning optimization over all 8,760 hours in a year. Formware's ability to optimize resource dispatch with hourly resolution across the full year allows us to capture the value of long-duration and multi-day storage, as well as more accurately characterizing the need for DEFRs.
3. **Examines 2030 as well as 2040:** We model resource portfolios to support New York's renewable energy and zero carbon targets in 2030 and 2040, respectively. In particular, we capture the effect emerging technologies could have on 2030 costs and goals, a year that was omitted from optimizations in prior New York studies but is the focus of ongoing policy development.

These refinements to input assumptions and methodology allows us to answer questions about the future resource mix that best meets New York's future energy needs while supporting its ambitious decarbonization goals. By expanding on previous studies methodologically as well as in scope, this study answers a key question raised by many prior studies: Which resources can supply least-cost dispatchable, emission-free capacity in New York in 2030 and beyond?

To answer this question, we model least-cost resource portfolios that meet New York's 2040 goal of achieving a zero emissions electric grid, as well as the interim 2030 target of 70 percent renewable energy. For both 2030 and 2040, we examine how the presence of long-duration and multi-day storage changes the least-cost resource portfolio, using the following scenarios:

Technology Scenarios:

- **Short-Duration Only:** Limits storage availability to lithium-ion batteries with durations <10 hours
- **No MDS:** In addition to lithium-ion batteries, this scenario adds storage technologies with durations of 10-24 hours. No multi day storage technologies - including iron-air batteries and hydrogen-based storage - are available in this scenario.
- **All Storage:** Adds multi-day storage technologies with durations >24 hours to the mix of assets available to the model for selection as part of the optimal resource portfolio.

In addition to these base scenarios, we also model a number of different sensitivity cases. A description of these sensitivity cases, along with the results of the analysis, are found in Appendix A.

11 This tool and the methods are the same used in a California Energy Commission-funded study that Form Energy and E3 are jointly conducting of emerging long-duration energy storage needs in California. See: California Energy Commission, Staff Workshop on Long Duration Energy Storage Analysis, May 2023.

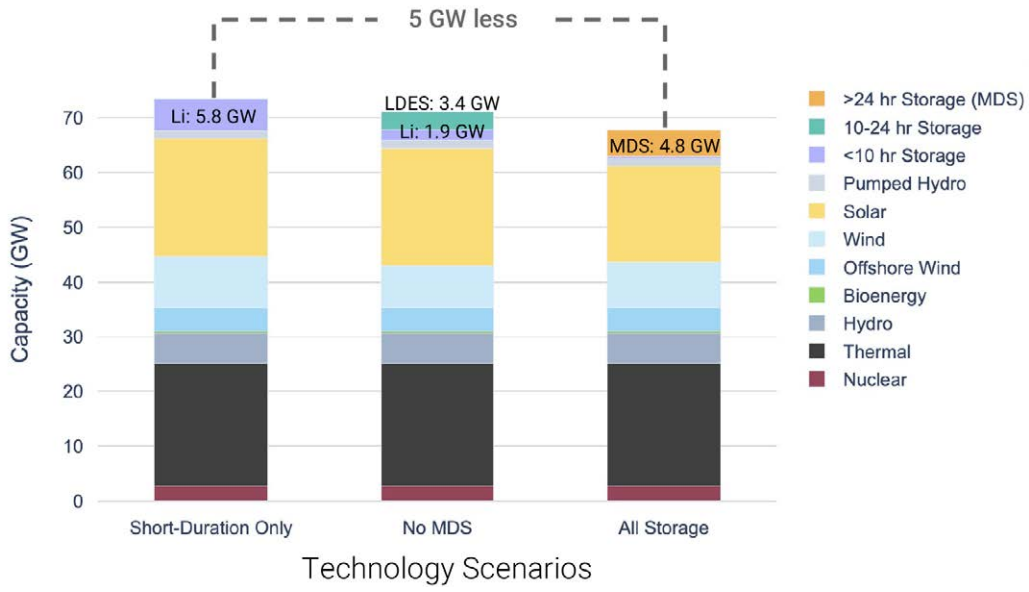
RESULTS

This section reviews the results of our main scenarios for 2030 and 2040. We first investigate the effects of LDES and MDS availability on the total resource build needed to meet New York's goals, followed by an exploration of the cost implications of those shifts in resource capacity. Finally, we explore how LDES and MDS can support the overall reliability of the New York grid. Please see Appendix A for results from our sensitivity analyses, including technology price sensitivities, weather sensitivities, and an investigation into the uses of LDES and MDS for supporting the retirement of fossil-fired peaking plants in New York City.

LDES and MDS technologies are part of New York's least-cost resource portfolio in 2030 and lower the total resource build required to meet decarbonization targets.

Consistent with New York's storage mandate, we find that 4.8 to 5.8 GW of storage capacity is part of the least-cost resource portfolio in 2030, with availability of longer duration storage resources supporting lower storage capacity build, as illustrated in Figure 1. In the Short-Duration Only scenario the model adds 5.8 GW of lithium-ion batteries with durations of <10 hours. When LDES is included in the No MDS scenario, total storage capacity drops to 5.3 GW. Finally, in the All Storage scenario, total storage capacity falls again, to 4.8 GW.

Figure 1. Total installed capacity by technology scenario, 2030 (2014 weather year)

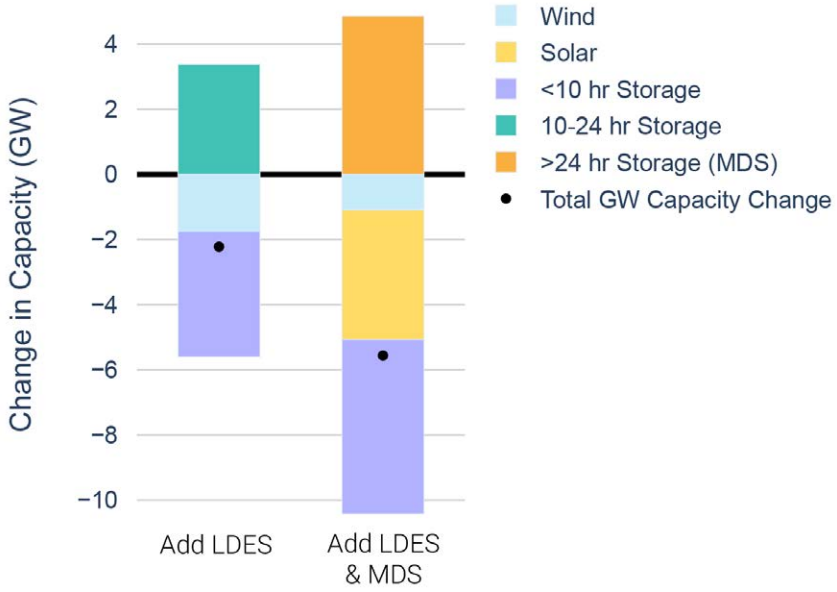


The availability of longer-duration storage reduces the total installed capacity of both storage and renewables in 2030, as shown in Figure 2. In 2030, building 3.4 GW of 10-24 hour LDES technologies eliminates the need for 1.7 GW of wind as well as 3.8 GW of lithium-ion storage, compared to the *Short-Duration Only* scenario. Adding multi-day storage as an option allows 4.8 GW of multi-day storage capacity to displace 5.3 GW of lithium-ion storage and 5 GW of solar and wind. These capacity shifts occur under a variety of assumptions about the underlying weather, which affects load and renewable availability (See Appendix A). They also provide a much greater total capacity to store energy, with 499.4 GWh of total capacity in the *All Storage* scenario compared to only 47.8 GWh in the *Short-*

Duration Only scenario.[12] In the absence of LDES and MDS technologies, the resource portfolio is substantially overbuilt in order to meet demand during peak periods, often leading to sizable renewable energy curtailment during lower demand periods. The larger volumes of energy storage offered by LDES and MDS technologies thus drive the displacement of a portion of these renewable and storage resources selected in the Short-Duration Only scenario, resulting in lower overall costs as well as fewer land use impacts and lower transmission investment costs.

Figure 2. Change in capacity from Short Duration Only to other scenarios, 2030 (2014 weather year).

'Add LDES' shows avoided resources in GW by technology type, when going from the Short-Duration Only scenario to the No MDS scenario. "Add LDES & MDS" shows avoided resources when going from Short-Duration Only to the All Storage scenario. Positive values indicate resources added to the portfolio built in the Short Duration Only scenario, negative values indicate resources removed.



In 2040, long-duration and multi-day storage can meet the identified need for DEFRs in New York while avoiding 26 GW of total new capacity to achieve New York's decarbonization goals (shown in Figure 3). The *All Storage* scenario builds 26 GW less total resource capacity than the *Short-Duration Only* scenario, and builds almost 35 GW of multi-day storage to meet the need for DEFRs.[13] The magnitude of multi-day storage capacity selected in the least-cost optimization is consistent with the 20 - 45 GW need for DEFRs identified in New York's previous studies. The *All Storage* scenario also provides 5,334 GWh of storage capacity, an order of magnitude greater than the 538 GWh of energy storage capacity in the *Short-Duration Only* scenario. In the *Short-Duration Only* scenario, our least-cost modeling builds a portfolio with 36% more nuclear power capacity, 22 times more MW of lithium-ion storage and 6% more solar capacity than in the All Storage scenario to make up for the low volumes of energy storage capacity. Multi-day storage allows shifting wind investments towards cheaper on-shore capacity from off-shore capacity, as the precise timing of generation is less critical. A reduction in overall resource build translates to lower land usage, lower transmission needs, and fewer projects to shepherd through permitting and interconnection.

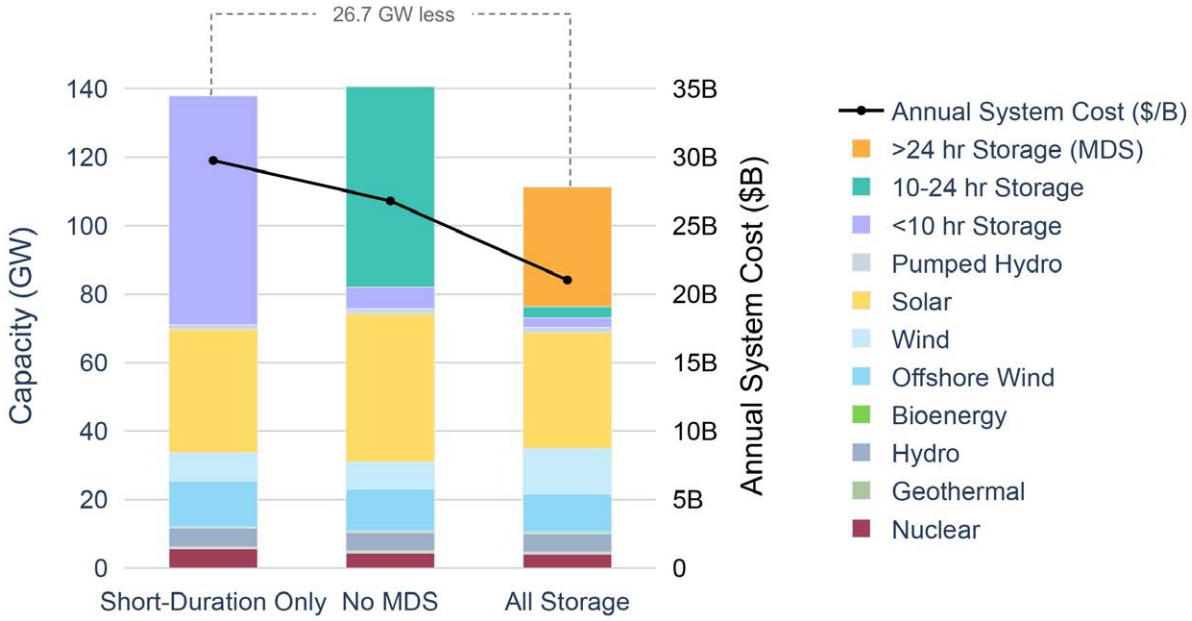
12 Energy storage amounts can be measured by their power capacity, typically denoted in kW, MW, and GW; this is the unit in which other electric grid resources are also typically designated. They can also be measured by their energy capacity, typically denoted in kWh, MWh and GWh. The ratio of the energy capacity to power capacity of a storage resource indicates how long that resource can discharge continuously at maximum power, often referred to as the duration of the storage resource.

13 The All Storage scenario has 42 GW of total storage capacity, while the Short-Duration Only scenario has 68 GW. These figures include 1.4 GW of existing pumped hydro storage.

In the *All Storage* scenario in 2040, over 19 GW of iron-air storage and 16 GW of hydrogen-based storage provide the flexibility needed to meet reliability goals. While previous studies have assumed hydrogen fuel is always available when needed, this may not be the case if hydrogen creation is powered by variable renewables. This analysis more accurately represents the costs of installed hydrogen capacity, taking into account the full life cycle - including generation capacity, and temporally-resolved hydrogen creation, storage, and utilization (see Appendix B for more details).

Figure 3. Total installed capacity, 2040 (2014 weather year)

In the All Storage scenario, MDS resources are composed of approximately 19 GW of iron-air based storage and 16 GW of hydrogen-based storage. Annualized system costs are shown overlaid in blue.

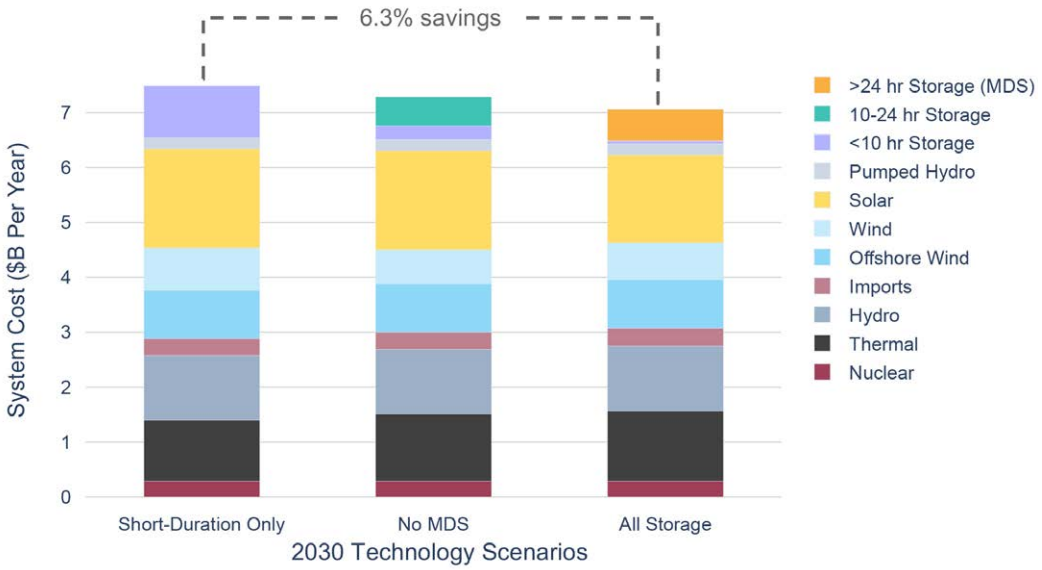


MDS and LDES could also help New York achieve its goal of retiring fossil-fired peaker plants located in New York City by 2030. Modeling results shown in Appendix A suggest that MDS and LDES can significantly reduce the total capacity of offshore wind and storage needed to replace those peaker plants with zero-carbon alternatives and to maintain reliability in 2040. This opportunity for LDES and MDS will grow as New York moves towards its 2040 decarbonization goals. Offshore wind, which NYC has significant access to, pairs effectively with longer-duration storage, since wind is likely to have multi-day peaks and lulls that require a complementary resource to provide a firming function. Additional analysis should incorporate more detailed network and land availability information to provide more specific estimates of possible benefits.

The inclusion of LDES and MDS technologies in optimal resource plans reduces the cost of New York's decarbonization targets by 6% in 2030 and 29% 2040.

Adding LDES and MDS as options in resource portfolios results in substantial cost savings through lower overall required investments in storage as well as renewables, shown in Figures 4 and 5. LDES and MDS result in the more efficient use of renewables, by shifting energy from seasons of excess energy to periods with insufficient energy. In 2030, including storage durations of 10-24 hours reduces costs by $260 million per year relative to a *Short-Duration Only* portfolio, and adding multi-day storage further reduces costs by an additional $258 million per year. **The total annualized system cost savings between the *Short-Duration Only* and the *All Storage* scenario are over 6% in 2030.**

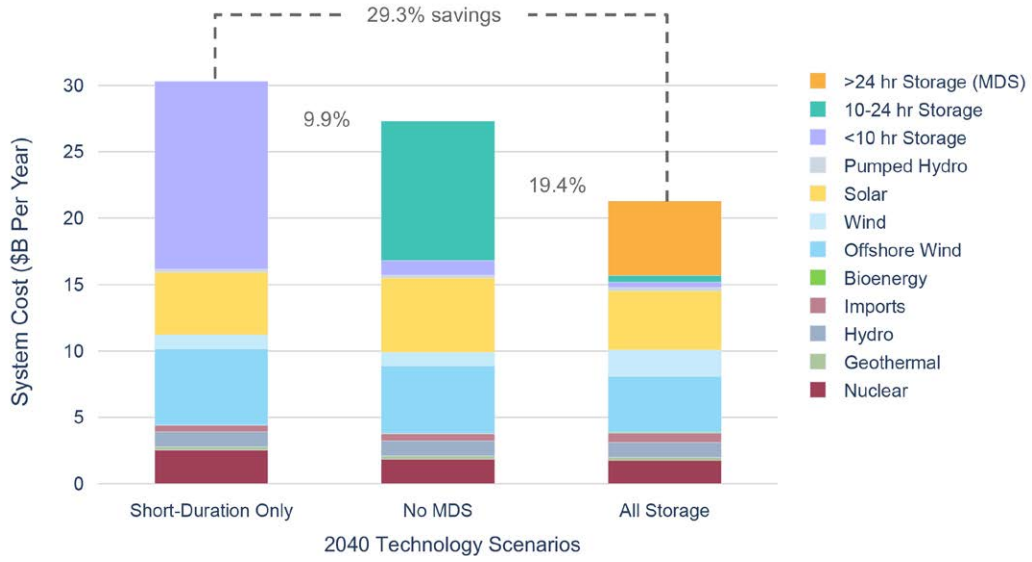
Figure 4. Annualized system cost, 2030 (2014 weather year)



In 2040, the All Storage scenario saves almost 30 percent in annualized system costs relative to the Short-Duration Only scenario, shown in Figure 5. To maintain reliability in a high renewables grid, New York needs firm, dispatchable resources that can provide power over multiple days. LDES and MDS technologies provide that service at a lower cost than lithium-ion batteries.

The magnitude of the cost saving potential shown here remains across a wide variety of assumptions about the cost of various storage technologies. Appendix A goes into more detail on our price sensitivity analysis, which examines how our 2030 and 2040 results change in the face of high or low projections for storage prices.

Figure 5. Annualized system cost, 2040 (2014 weather year)



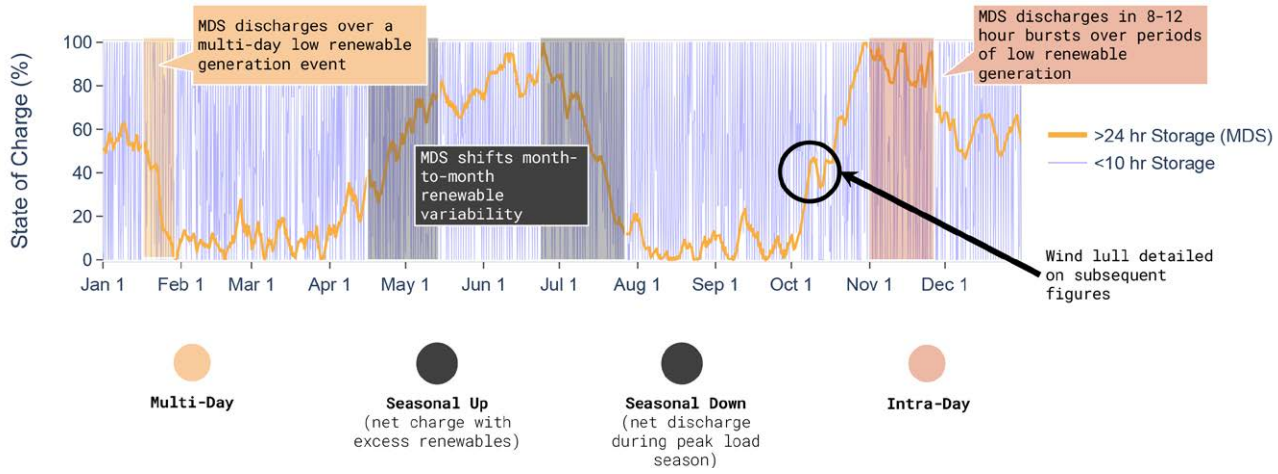
Multi-day storage acts as a dispatchable, emissions-free resource and maintains reliability under variable weather conditions.

MDS acts as a dispatchable, emissions-free resource by consistently providing energy during demand spikes and renewable lulls, and balancing the multi-day and seasonal variability in renewable energy availability. It complements lithium-ion storage, which provides shorter-term, intra-day energy shifting. These dynamics are evident as soon as 2030, as shown in Figure 6, which shows the state of charge for <10 hour Li-ion storage and MDS over the course of a full year. Storage technologies with durations of <10 hours experience near-daily full depth cycling. Multi-day storage assists with daily peaks and renewable energy ramps where needed, while using its large energy reserves to support seasonal shifting and to meet high net demand during peak seasons. Figure 6 reflects two distinct seasonal charging periods: once during the spring to meet summer peaking needs, and once during the fall to meet winter demand.

In 2040, short-duration, LDES and MDS technologies work together to provide energy shifting on the many scales needed to manage a decarbonized grid. Short-duration storage and LDES both provide intra-day shifting consistently throughout the year, with LDES also providing some inter-day shifting when needed. MDS provides critical inter-week flexibility and firming of bulk energy across weeks, weather systems, and seasons, and steps in to meet demand during multi-day renewable lulls. A portfolio of storage technologies, both existing and emerging, work together to demonstrate how storage acts as a dispatchable, emissions-free resource in support of a reliable, zero carbon grid.

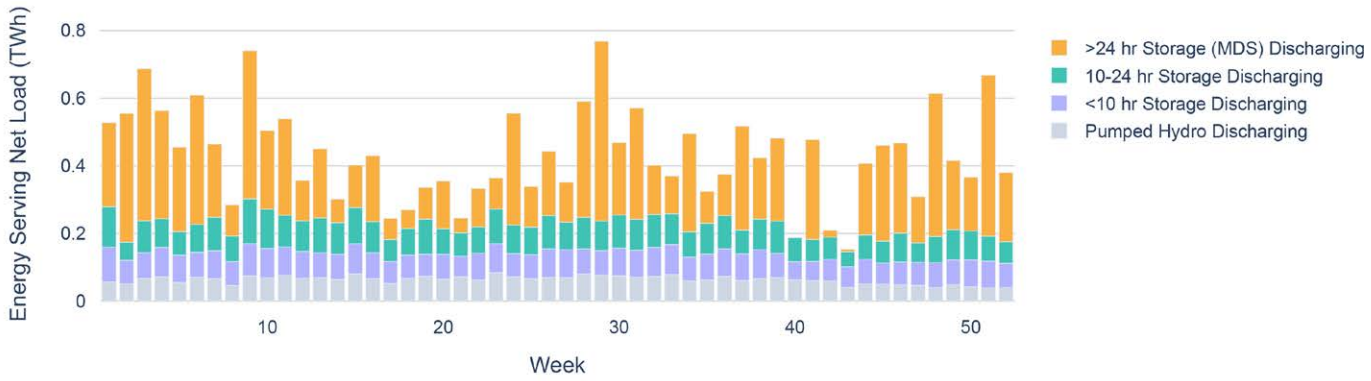
Figure 6. Annual state of charge, 2030 All Storage scenario (2014 weather year).

<10h Li-Ion storage cycles to full depth on a near-daily basis, creating the near blur shown in purple.



MDS provides critical flexibility and bulk energy to the grid on a weekly, monthly, and seasonal timescale, discharging anywhere from 1.1 GWh to 530 GWh per week as energy is shifted across weather patterns and seasons. MDS works in concert with storage of shorter durations, which provide intra-week and inter-day energy shifting consistently throughout the year. MDS provides the bulk of the inter-week and seasonal flexibility from dispatchable resources. These dynamics are illustrated in Figure 7, which shows total energy discharged by storage to serve load over all the weeks in 2040 in the *All Storage* scenario. The resource portfolio relies on MDS's duration and its unique ability to fill in during renewable lull periods that last for anywhere from a few hours to several days by drawing on its significant energy storage reserves.

Figure 7: Weekly sum of energy discharged from storage, All Storage scenario, 2040 (2014 weather year)

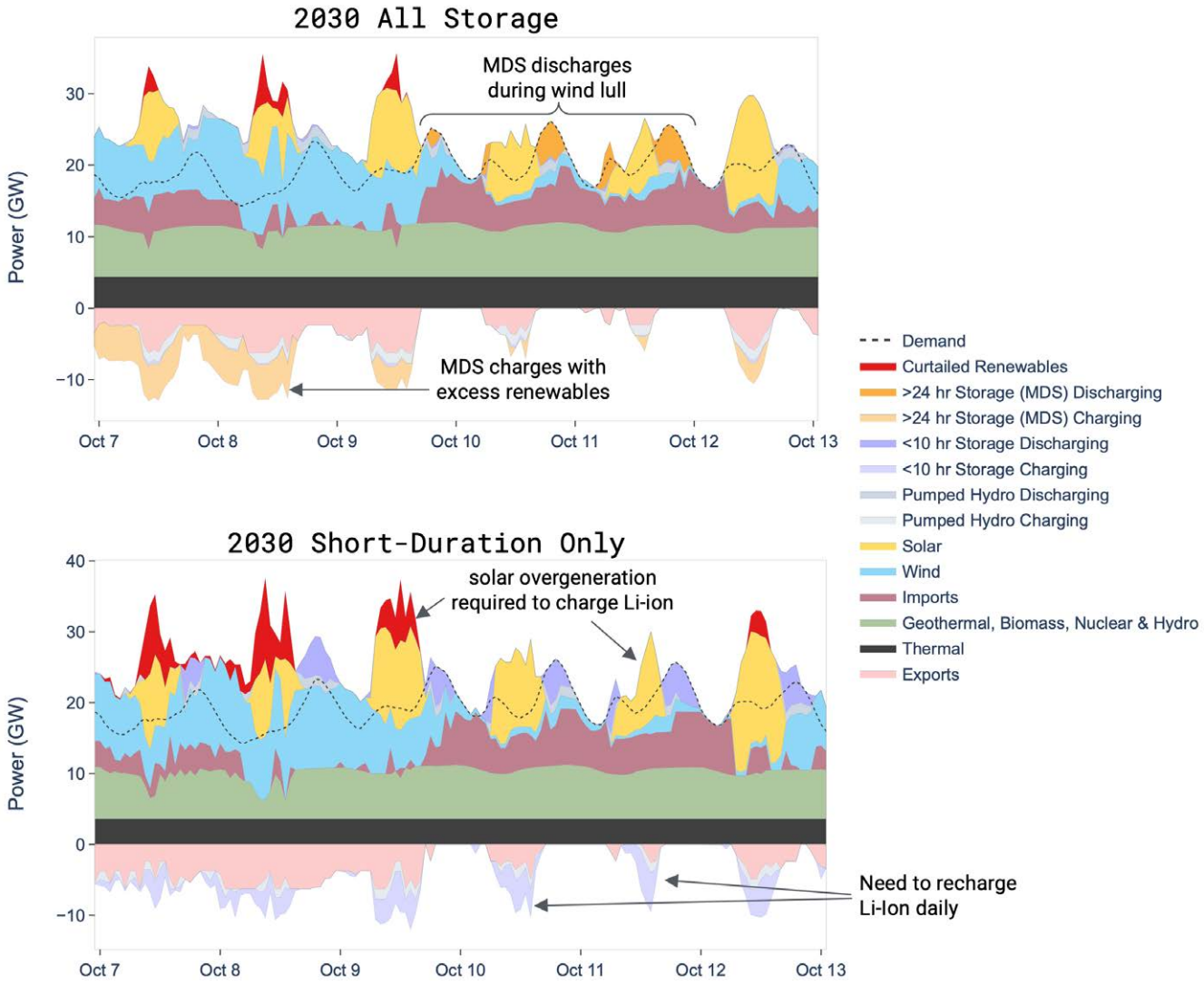


MDS is able to deliver flexible, firm energy in large quantities during multi-day renewable energy lulls. For example, during the week-long lull in wind generation during week 29 in Figure 7, weekly wind generation is only 32.7% of the weekly average, a shortfall of 1,168 GW. During that week, MDS provides 530 GWh of energy - 45% of the wind-driven renewable lull and 16.1% of the total net energy[14] needed in that week. Shorter duration storage helps provide the net energy needed as well, but in smaller quantities that are more consistent with typical weekly dispatch: <10 hour Li-Ion provides 2.6%, 10-24 hour LDES provides 2.7%, and pumped hydro storage provides 2.4% of the net energy needed. In total, storage technologies serve 23.8% of net load, demonstrating how a diverse suite of storage technologies can support a reliable, zero carbon grid.

The large energy reserves provided by MDS allow it to meet peak demand for several days in a row without recharging, and shift excess renewable generation to times when the grid is energy-limited. Figure 8 demonstrates how this ability can come into use as early as 2030. It compares dispatch in the *All Storage* scenario to the dispatch in the *Short-Duration Only* scenario during an October wind lull. During this lull, the system is energy-limited: it has enough installed power capacity (GW) to meet peak demand, but getting enough energy (GWh) at the right time is a challenge. In the *All Storage* scenario, multi-day storage solves this challenge by using its long duration and large energy capacity to meet peak demand for several days in a row, with limited recharging; it also is able to reduce curtailment in the prior days through long-duration charging. However in the *Short Duration Only* scenario, the energy limitations during that wind lull must be met through additional solar resources, which provide sufficient energy to recharge short-duration storage; the excess solar capacity, and limited charging capacity of shorter-duration shortage, result in additional curtailment earlier in the week.

14 Net energy is load that is not met via variable renewable energy (solar and wind generation). During week 29 the grid experiences a major lull in wind generation, receiving only 32.7% of mean annual wind generation. Remaining net load not served by storage is met with a combination of bioenergy, hydro, nuclear, and geothermal generation, which operate at levels only slightly higher than typical weekly dispatch, as well as imports from neighboring regions.

Figure 8. Comparison of system dispatch during a wind lull, 2030 (2014 weather year)

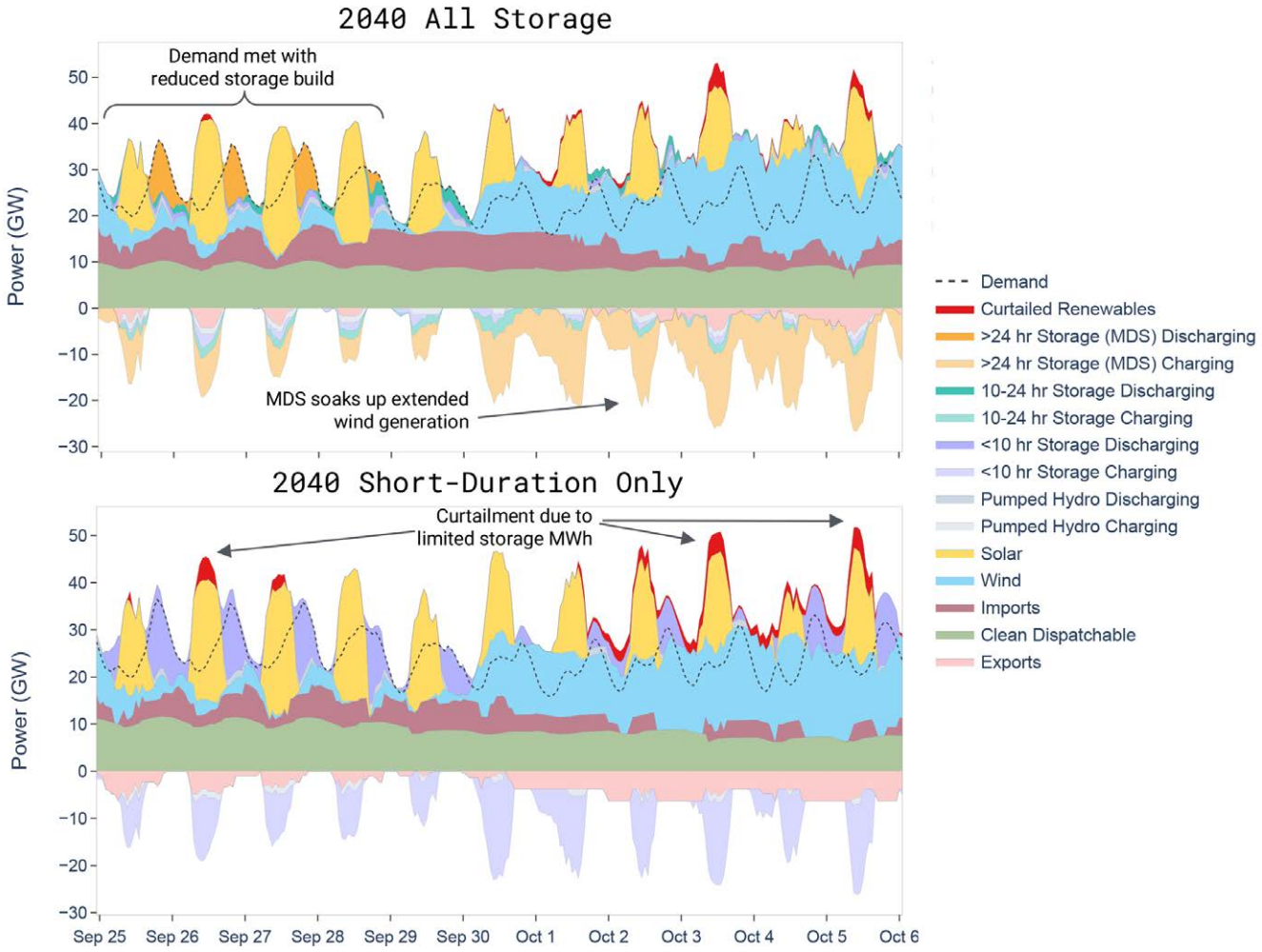


Relying on shorter-duration storage during renewable energy lulls requires a greater capacity of both storage and solar to address energy limitations and support off-peak recharge. In the *Short Duration Only* scenario, shown in the bottom half of Figure 8, there is 0.5 GW more storage power capacity than the *All Storage* scenario, but only 47.8 GWh of capacity to store energy, an order of magnitude less than the 499 GWh in the *All Storage* scenario. Without the additional energy in reserve and ability to charge and discharge for longer periods, the system requires both more short-duration storage as well as more solar. In the *Short-Duration Only* scenario, shown in the bottom half of Figure 8, there is 5.3 GW of lithium-ion storage on the system, compared to 4.8 GW of multi-day storage in the *All Storage* scenario. That extra storage capacity is needed for long duration net peaks, and to help compensate for the limited capacity to store energy. There is also 21.5 GW of solar capacity in the *Short-Duration Only* scenario, 3.9 GW more than in the *All Storage* scenario. This solar overbuild is necessary so that there is sufficient generation available to recharge short-duration storage between daily peaks during energy-limited periods like renewable lulls. This overbuild, however, also results in increased land use, greater curtailment of renewables, and higher system costs.

In 2040, similar dynamics are even more pronounced. Figure 9 illustrates how a suite of diverse storage technologies can meet net demand peaks during renewable generation lulls, and reduce curtailment during periods of excess generation. Meanwhile, in the Short-Duration Only scenario, significant energy must be curtailed or exported due to a lack of sufficient storage energy capacity, despite having 60 GW more storage power capacity than the All Storage scenario.[15]

Figure 9. Comparison of system dispatch during a wind lull followed by wind excess, 2040 (2014 weather year).

The All Storage scenario has 60 GW less storage than the Short-Duration Only scenario, and uses a diverse suite of short-duration storage, MDS and LDES to meet net demand peaks and limit curtailment during periods of excess generation.



LDES and MDS can improve the reliability of the New York grid in the face of varying weather patterns. Appendix A examines our weather sensitivities, which show that LDES and MDS dramatically reduce changes in resource requirements between weather years. In the absence of LDES and MDS, resource portfolios vary widely depending on weather-driven variations in load and renewables generation.

15 In the Short-Duration Only scenario, li-ion sometimes discharges when load is already met because New York has some surplus energy, and there is demand in external regions that will pay for that surplus energy.

CONCLUSIONS

A diverse portfolio of energy storage resources, including long-duration energy storage (LDES) and multi-day storage (MDS), is the least cost approach to meeting New York's needs for dispatchable, emissions-free resources (DEFRs) to enable a reliable zero carbon electric grid. This study shows that if LDES and MDS are included in least-cost resource planning, they can reduce the total costs of achieving New York's electric grid decarbonization goals by 6% in 2030 and almost 30% in 2040, and likely also reduce total land-use impacts and transmission needs by avoiding 26 GW of total resource capacity by 2040. These conclusions are the result of state-of-the-art least-cost capacity expansion modeling that optimizes resource needs over 8,760-hour grid operations and introduces emerging energy storage technologies among future resource options to build on previous investigations of the resources New York needs to achieve its deep decarbonization goals.

4.8 GW of MDS technologies are part of New York's least-cost resource portfolio in 2030 and 35 GW by 2040, which lowers the total resources required to meet decarbonization targets.

This study identified a need for 4.8 GW of multi-day storage by 2030 and up to 35 GW by 2040 to meet New York's renewable and zero carbon electricity goals. In a scenario that includes LDES but excludes MDS, total LDES needs are 3.4 GW by 2030 and 58.5 GW by 2040, showing that both MDS and LDES technologies can provide significant benefits relative to a portfolio with only <10 hour storage. The inclusion of both LDES and MDS energy storage resources lowers total energy resource needs by 5.5 GW in 2030 and more than 26 GW by 2040 (approximately 19 percent fewer resources). This reduction in overall resource build translates to lower land usage, lower transmission needs, and fewer projects to shepherd through permitting and interconnection. This long-term need for LDES and MDS resources aligns with the 20 GW to 45 GW need for DEFRs identified in prior studies and demonstrates that multi-day energy storage can provide flexible, dispatchable capacity over the hourly, daily, and multi-day time-scales necessary to balance renewables over a season, managing renewable energy lulls and periods of extreme weather.

The inclusion of LDES and MDS technologies in optimal resource plans reduces the cost of New York's decarbonization targets by 6% in 2030 and 29% 2040.

Emerging long-duration and multi-day energy storage technologies can lower the annualized system costs of achieving New York's 2030 climate goals by 6 percent ($0.4 billion/year) compared to scenarios in which lithium-ion batteries are the only available storage technology. Those cost savings increase to almost 30 percent by 2040 ($8.7 billion/year). LDES and MDS save customer costs by shifting large volumes of clean energy from periods of excess to periods of undersupply, thereby reducing the total amount of new resources required to meet the state's energy demands.

Multi-day storage acts as a dispatchable, emissions-free resource and maintains reliability under variable weather conditions.

Multi-day storage supports system reliability by balancing the multi-day and seasonal variability in renewable energy generation, while also helping manage daily net peaks and ramps. Least-cost portfolios for New York in both 2030 and 2040 have an order of magnitude more capacity to store energy (GWh) when LDES and MDS are included in resource planning, thanks to the higher energy:power ratio from storage with longer durations. This large energy reserve capacity gives the grid the resources to reliably ride out multi-day lulls in renewable generation and to soak up long periods of excess generation. Variable weather conditions will have an increasing effect on electric grids with high penetrations of renewable electricity and building electrification, creating more periods when the system is likely to be limited not by the total power capacity of installed resources, but instead by the amount of energy available to the grid at the right times. Multi-day storage provides the ability to smooth and firm energy availability at a large scale, creating a reliable, resilient grid that supports New York's decarbonization goals.

Near term policy support is needed to build a market for emerging MDS and LDES technologies and realize the future cost savings and reliability improvements these resources can enable

Between 2030 and 2040 New York will need to deploy on average at least 3 GW per year of new LDES and MDS technologies to realize the opportunity to significantly reduce the costs of decarbonizing the electric grid. None of these technologies have yet been deployed at scale in the state, yet by 2030 the deployment of 3.4 GW to 4.8 GW of these technologies could save the state $0.4 billion per year in electric system costs. These needs and opportunities point to the urgency of policy makers taking action in the coming years to rapidly develop a multi-GW scale market for these resources by 2030 to ensure that these resources are available when needed. The early creation of a market for these emerging technologies, and the development of market mechanisms and policies needed to integrate them effectively, will support even larger cost reductions from these technologies in 2040 and beyond and accelerate the timeline for New York to gain valuable policy, wholesale market design, and technology learnings. Policy action now will give the private sector the stable market signals needed to invest in manufacturing capacity, supply chains, and project development pipelines needed to deploy these emerging resources at GW-scale before 2030.

APPENDIX A: SENSITIVITY ANALYSIS AND RESULTS

Three sets of sensitivities are presented here. The first set examines the retirement of fossil fuel-fired peaking units located in New York City by 2030, and the least-cost investment needed to replace them. We apply the previously-presented technology availability scenarios after removing all fossil-fuel-fired plants in New York City. Our modeling suggests that introducing multi-day storage reduces the storage capacity needed to meet this 2030 policy objective.

The second set of sensitivities examine how our core results might change if our modeled storage technologies cost more or less than expected. Future prices for storage technologies are uncertain, due to supply constraints, uncertainty in technological development, and many other factors. We model a high and low cost sensitivity for each of the following four technology classes:

- All lithium-ion durations (<10 hours)
- 10 to 24-hour storage (Flow batteries & CAES)
- Hydrogen storage of all durations (100 to 1000 hours)
- Iron-air storage (100 hours)

Finally, the third set of sensitivity cases analyzes the impact of weather on our optimized resource portfolios. These weather-related sensitivities examine the effect of weather-driven variation in demand, renewable output, and prices in external markets. Base scenarios use weather data from 2014; however, we also investigate the impact of using weather data taken from the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM)[16] for the years 2007 through 2013.

Multi-day storage can reduce investment required to replace peaker plants in NYC by 2030.

There has been substantial discussion around the retirement of fossil-fired peaker power plants in New York City by 2030, prompted by both the decarbonization goals set in the Climate Leadership & Community Protection Act as well as the desire to reduce the air quality and health impacts to a large number of people who live nearby one of these plants. Research suggests that there are elevated rates of asthma and other pollution-related health conditions in adjacent communities, which tend to largely be low-income and people of color.[17]

New York City (NYC) is transmission constrained, meaning it lacks the necessary transmission to be able to import the energy it consumes during periods of high demand. NYC requires sufficient generation and storage capacity within the city limits in order to maintain system reliability in the area. Currently, in-region fossil-fired peaking units serve load when demand is high. This sensitivity case evaluated the role of storage to maintain reliability within NYC if these peaking units were to be retired.

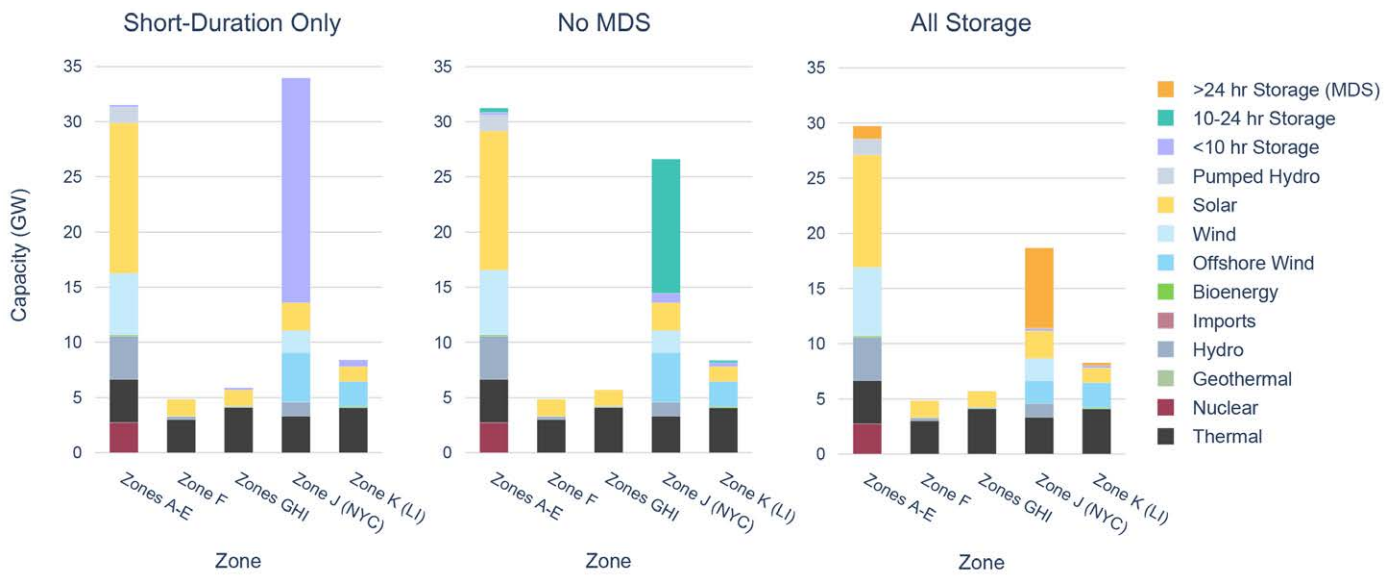
To capture the retirement of NYC's peaker plants, we removed all fuel-oil-fired and gas-fired peaking units in Zone J, which represents New York City, and allowed Formware to select the least-cost resource replacement that maintains local reliability standards (see Appendix B for additional modeling details).

Our modeling demonstrates that introducing multi-day storage could significantly reduce the overbuild of storage and renewables required to meet this policy objective in 2030. Multi-day storage enables the replacement of peaker plants with fewer GW of replacement renewable and storage capacity, as shown in Figure A1.

16 Available at: https://sam.nrel.gov/download.html
17 See: https://www.utilitydive.com/news/campaign-to-shut-down-new-york-citys-peaker-plants-gains-congressional-all/605670/

Figure A1. Installed capacity by node, NYC peaker retirement sensitivity analysis, 2030

Solar and onshore wind displayed in Zone J is delivered via the CleanPath transmission line.



New York City has access to large volumes of offshore wind generation, but needs sufficient storage to effectively "firm" the resource and make it a dispatchable replacement for fossil-fired peaking units. Wind is prone to multi-day lulls in availability, and when only storage with <24 hours in duration is available, it takes both more storage and more wind to provide sufficient local reliability resources than if multi-day storage were available.

When MDS is introduced, the total amount of offshore wind needed in Zone J decreases by 53.8 percent, and the total amount of storage capacity required decreases by 63 percent compared to the *Short-Duration Only* scenario. Multi-day storage both absorbs excess wind generation, reducing curtailment of the resource, and has enough energy capacity to discharge for several days continuously without needing to recharge, providing a reliable source of power during these lull periods.

The challenge of maintaining reliability in NYC despite transmission constraints will only grow as New York moves to increase its offshore wind power capacity and meet its 2040 decarbonization goals. Results from the *Short-Duration Only* base case scenario in 2040 show that to balance wind, contend with transmission constraints and maintain reliability in NYC, as much as 49.5 GW of lithium-ion storage capacity would be needed in Zone J. In the *All Storage* scenario, however, only 13.88 GW of total storage capacity is required within the NYC zone: 11.68 GW of MDS, 1.2 GW of LDES and 1 GW of <10hr lithium-ion.

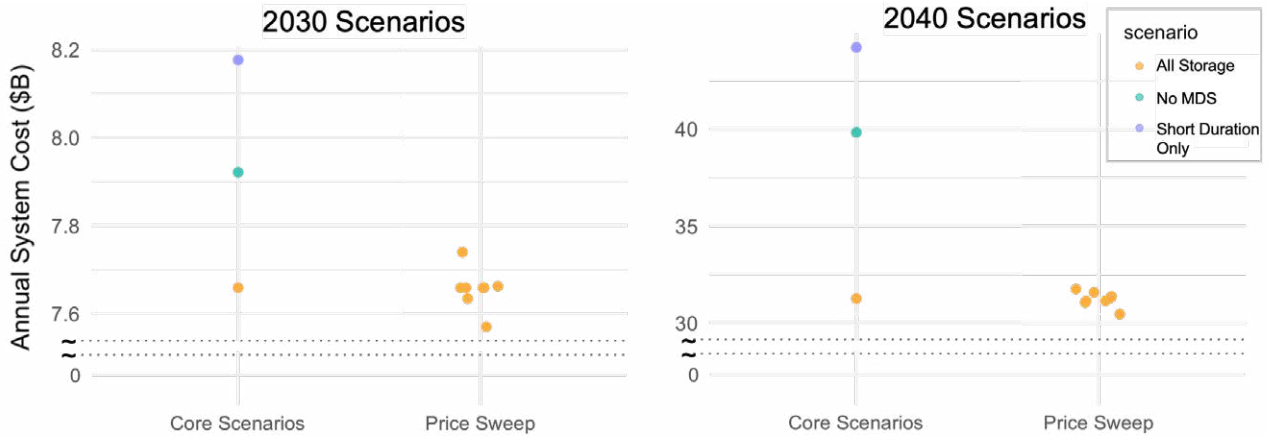
LDES and MDS provide lower and more predictable system costs despite uncertainty in future weather and technology prices.

The second set of sensitivities tests the variance in identified cost savings relative to changes in prices of storage technologies. Each price-based sensitivity changes the price of one class of storage technology to a high or low forecast, leaving everything else the same, to isolate the importance of the price of that particular technology class. See Appendix B for more detail.

Annual system savings resulting from the addition of LDES and MDS remain under different future storage technology price assumptions.

The bulk of cost savings that result from the inclusion of LDES and MDS in New York's resource mix persist across all price assumptions we examined, as illustrated in Figure A2. Our base case scenarios, using mid-level cost projections for all storage technologies, found that introducing LDES and MDS could result in annualized price savings of 6.3 percent in 2030 and 29.3 percent in 2040. Even in the most unfavorable price sweep results, cost savings compared to the Short-Duration Only scenario are still 5.3 percent in 2030 and 28.2 percent in 2040, illustrating the robustness of these results to changes in forecasted technology costs.

Figure A2: Sensitivity of annual system cost to changes in technology cost

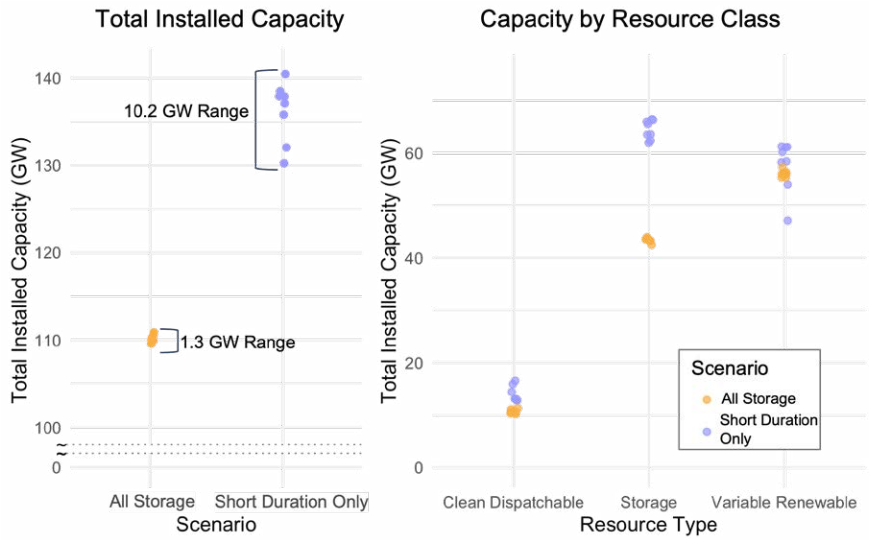


Inclusion of LDES and MDS provide more predictable annualized costs that are less sensitive to variations in weather.

The third set of sensitivities examine the impacts of weather – which affects demand for electricity, renewable availability, and import/export prices – on resource optimization and resulting system costs in 2040. Weather data from the years 2007-2013 augments our base runs, which use the weather year 2014, resulting in seven additional sensitivities to the base case. (See Appendix B for more detail on methodology.) These results demonstrate how weather drives capacity selection and resource dispatch, increasing resource need under more extreme weather and decreasing the need in a more mild year, and the resulting annualized system cost.

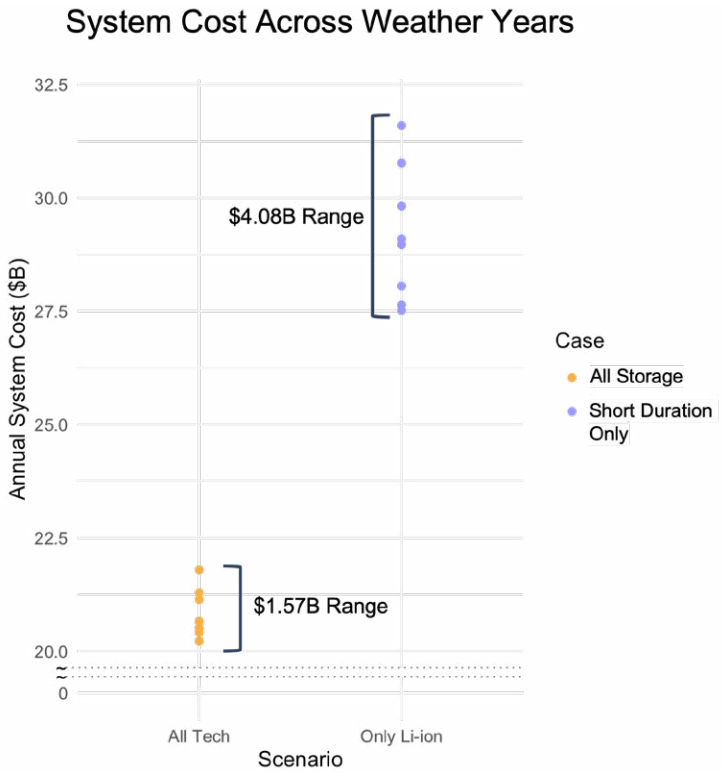
Figure A3 shows the optimized, least-cost capacity additions in 2040 under all modeled weather years in both the *All Storage* and *Short-Duration Only* scenarios. Total capacity additions are both lower and less variable across weather years in the *All Storage* scenario when LDS and MDS are available for selection in the model. There is an almost-ten-fold reduction in variation, from a 10.2 GW range in total capacity in the *Short-Duration Only* scenario to a 1.3 GW in the *All Storage* scenario. Longer-duration storage makes the system more robust to variable weather conditions, reducing the risk of over- or under-building capacity due to unexpected weather conditions. The right side of Figure A3 breaks down capacity additions into three categories: Clean Dispatchable (hydro, nuclear, geothermal, and bioenergy), Storage, and Variable Renewable (solar and wind). In that figure, the *All Storage* scenario (in orange) shows reductions in the volumes of both Clean Dispatchable and Storage capacity required to meet demand across all weather years. Although there is not always a reduction in installed capacity of variable renewable energy, there is a shift towards cheaper options, e.g. shifting from off-shore to on-shore wind, since the timing of production is less relevant when there is ample storage capacity.

Figure A3: Optimized capacity additions under 2007-2013 weather years, 2040



When LDS and MDS technologies are available, we find that annualized costs are both lower across all weather years than in the *Short-Duration Only* scenario, and that there is less variability between individual weather years, as shown in Figure A4. LDS and MDS create a system that is more robust to variable weather conditions, avoiding a need for excess capacity or other expenses in years with increased amounts of grid stress compared to the *Short-Duration Only* scenario.

Figure A4: Annualized system cost across weather years for 2040, in the All Storage and Short-Duration Only scenarios.



APPENDIX B: INPUT ASSUMPTIONS AND METHODOLOGY

NYISO System-Wide Portfolio Optimization

This study provides a detailed analysis on the value of multi-day storage by modeling a wide variety of storage technologies, each with technology-specific operational characteristics and costs. The complete list of modeled storage technologies, along with cost and performance characteristics, is provided in Table B1. These include long-duration and multi-day storage technologies with durations of 10-24 hours and >24 hours. In contrast, the New York Storage Roadmap and related Scoping Plan analysis focus only on short-duration lithium-ion storage technologies of 4 to 8 hours, and represent all other energy storage and zero-carbon technologies as a hypothetical hydrogen-based firm capacity resource. This aggregated resource class does not capture the interactive effects and tradeoffs associated with different types of energy storage and does not account for the chronological restrictions of needing to produce hydrogen before it can be used as a fuel.

This study methodology uses an 8,760 hour optimization for improved representation of renewable and storage behavior. In previous analyses of New York's decarbonization targets, grid planning tools model a representative set of individual days to determine the optimal resource portfolio required to meet system demand. This time sampling methodology can capture dispatch of thermals, renewables, and storage during single day periods of grid stress. However, Formware's 8,760 hour optimization more accurately represents resource dynamics that occur on multi-day time scales, which are particularly important when evaluating the role of LDES and MDS in a highly decarbonized system. These include charge and discharge of storage over multi-day periods, energy arbitrage by LDES and MDS over monthly and seasonal horizons, and dispatch of renewables and storage during multi-day reliability events.

Lastly, this system optimization modeling utilizes weather-correlated load and utilized renewable generation data. Historically, simulation tools have not utilized renewable generation profiles and load profiles that are derived from the same historical time period. E3's CLCPA and Storage Roadmap studies do not clarify what renewable generation and load profiles they use; however similar reports done for other areas of the United States neglect to use the same weather conditions for renewable generation and load, and thus do not capture correlated impacts of weather on load and renewable generation. As described in the following section, the capacity expansion and production cost modeling in this study utilizes renewable generation and load time series that are shaped according to historical weather data in order to capture the impacts of correlated weather-driven events on system reliability.

Input data and assumptions for this study are drawn from the *New York Draft Climate Scoping Plan Analysis* to the extent possible. Detailed input assumptions and methodology are described below.

Formware

Formware, the model used in this study, is Form Energy's in-house capacity expansion, dispatch, and production cost model. It finds the least-cost mix of assets, and the operational strategies of those assets, necessary to meet system requirements during all 8,760 hours in a year across diverse weather, load, and contingency scenarios. The model is highly customizable, allowing Form Energy to create bespoke analyses of utility systems and integrated markets. In this study, it was used as a linear model capturing dispatch, investment, and transmission flows.

Formware differs from other industry models in its ability to perform multi-scenario resource optimization over 8,760 hours per year. This enables improved capture of long-duration energy storage operations and weather variability on high renewable grids. Formware has been used in studies such as the 2023 California Energy Commission report on the Value of Long Duration Storage in California, in which it was successfully benchmarked against the RESOLVE model developed by the consulting firm E3.

Modeling Hydrogen

Green hydrogen is an emerging technology that is a candidate to meet the need for DEFRs; hydrogen can be used store excess energy and be used to generate electricity during periods of shortage. It can be more complicated to model than a typical battery because the generation, storage, and usage steps can happen more independently than they would in a battery, where all three steps happen within the same facility.

When modeling hydrogen as a possible DEFR, it is important to capture many of the same things that are important for a typical battery; the amount of hydrogen fuel that is stored on hand, and the chronological restrictions of needing to produce hydrogen before it can be used as a fuel. It is also important to capture the extra generation that must be built to create hydrogen.

This study uses a sophisticated model of hydrogen to capture these dynamics that is much more accurate that that used in previous studies. Hydrogen is represented similarly to a battery, in that its 'state of charge' (i.e. amount of stored hydrogen) is tracked in each hour. Investments in electrolyzer capacity, storage capacity, and h2-compatible combustion turbine capacity can be made separately, and the model can choose between aboveground tank-based storage, or underground geological storage in regions of New York with suitable geology (ie in northwestern NY). Electricity needed to produce hydrogen can come from in-state investment in renewable generation, or from electricity imports that are subject to existing transmission constraints.

This representation of hydrogen ensures that the hydrogen-creation infrastructure needed to support critical grid reliability needs is available locally, without assuming that multi-state hydrogen transportation infrastructure will be robust by 2030 or 2040. It also ensures that the timing of hydrogen creation, storage, and usage is realistic, and that sufficient storage capacity must be created to support expected dynamics. This representation ensures that hydrogen selected by the model is sufficiently reliable to meet the need for DEFRs.

Unfortunately, some studies have represented hydrogen in an overly-simple manner that may leave the resulting systems vulnerable to reliability problems. The modeling for the *New York Climate Action Council Draft Scoping Plan* took one such approach, in which the amount of hydrogen fuel and timing of its creation was not accounted for. That study assumes that hydrogen fuel is always available when needed, and that half of the state's hydrogen needs can be easily imported from other states via an existing, sufficiently-reliable multi-state hydrogen transportation infrastructure. The in-state generation that must be built to meet the other half does not have any temporal constraints placed on it. There is no assessment of the volume of local storage capacity that would be required in each node.

NYISO System Input Data

Input data was drawn from E3's analysis for the New York Climate Action Council Draft Scoping Plan[18] (CLCPA) where possible to ensure consistency with existing studies. That includes the following data:

- System layout, including zonal aggregation, transmission constraints between represented zones, and transmission constraints with other balancing areas.
- Existing and planned capacity of generation and storage resources in 2030 and 2040, including planned additions to the grid as well as planned retirements.
- Planned additional transmission capacity, including the Clean Path and Champlain Hudson Power Express lines.
- Fuel costs for natural gas, distillate fuel oil, coal, and uranium.
- The planning reserve margin.[19]
- Policy goals: 70 percent clean energy by 2030 and 100 percent clean energy with all fossil assets retired by 2040.
- Cost adder of 25 percent for resources in Zones J and K (New York and Long Island).
- Investment and operational costs for solar, onshore wind, and offshore wind.

18 Available at https://climate.ny.gov/resources/draft-scoping-plan/. Specific data is available in Appendix G: Annex 1, which is available for download at the provided link.
19 E3 did not provide the ELCCs used to determine how different resources would contribute to the planning reserve margin.

Where data from E3 was not available, data were taken from other public sources. Below are key high-level assumptions, followed by tables of specific data used with sources.

- Operational parameters for thermal plants are taken from NREL's Advanced Technology Baseline (2022).
- ELCCs were based on those from GE Energy Consulting for the NYISO Capacity Accreditation Project where available. Where unavailable, we applied an extrapolation from existing resources. ELCCs are assumed to decline with additional capacity additions for storage and renewable assets.[20]
- Storage technology cost sources are detailed in Table B1.
- Inflation Reduction Act Tax Credits (2030 only):
  - We assume a 30 percent ITC credit is applied to capex costs for all storage investments; other tax credits are assumed to be retained by the developer or manufacturer.
    - Flow batteries are exempted from the ITC discount, due to their early development stage that may lead to their developers needing to retain the credit to produce a viable project.
  - For wind and solar, we assume that the full PTC is passed through to reduce the marginal cost per kWh.
  - We assume that no other credits are passed through from the manufacturer/developer.

Candidate Resource Parameters

Table B1. Modeled energy storage technologies and specifications[21]

			2030			2040			
Reference Technology	**Duration (hrs)**	**RTE (%)**	**Energy Capex ($/kWh)**	**Power Capex ($/kW)**	**Fixed O&M**	**Energy Capex ($/kWh)**	**Power Capex ($/kW)**	**Fixed O&M**	**In NYSERDA Storage Roadmap?**
Li-ion Battery [a]	4	85%	158	264	17	138	232	17	Yes
Li-ion Battery [a]	8	85%	158	264	29	138	232	29	Yes
Flow Battery [b]	12	68%	66	1092	23.2	61	829	18.6	No
A-CAES [c]	24	60%	32	1725	10	32	1725	10	No
Iron-air Battery [d]	100	42.5%	0	2150	17.5	0	2150	17.5	No
H2 Electrolyzer + Turbine, aboveground storage [e]	24 - 100	22%	45	Discharge: 856 (CT)	30	45	Discharge: 825 (CT)	28.75	No. Zero Carbon Firm Resource modeled a gas turbine
H2 Electrolyzer + Turbine, belowground storage [e]	100 - 1000	22%	6	Charge: 490	30	2.38	Charge: 403	28.75	

[a] 2022 NREL Advanced Technology Baseline, Moderate Case. Prices given in 2020 dollars.

[b] McKinsey LDES Council Benchmarking Study, 2022 (**http://www.ldescouncil.com/**)

[c] Synthesized from publicly available information on the costs of A-CAES. Prices given in 2020 dollars.

[d] Form Energy. A cost decline would be expected between 2030 and 2040; constant costs were assumed to be conservative. Capex is inclusive of the NPV of repowering costs at a discount rate of 8%.

[e] Discharge power capex ($/kW): NREL ATB 2022 costs for Combustion Turbine. Charge power capex ($/kW): Hunter et al. 2021 Joule (**link**). Belowground Storage Capex($/kWh): 2022 PNNL ESGC (**link**), Aboveground Storage Capex($/kWh): Ahluwalia et. al. 2019 (**link**). RTE: Hydrogen.energy.gov assumptions for electrolyzer & compression (**link**, **link**). CT RTE: NREL ATB 2022. Fixed O&M: 2022 PNNL ESGC (**link**) plus CT fixed O&M from NREL ATB 2022. Prices given in 2020 dollars.

20 ELCCs are used here to determine resource adequacy contributions in an effort to mirror existing modeling studies, including E3's. However, ELCCs are not accurate when used for investment planning far into the future, so the reliability of planned portfolios may be different than expected. This is because ELCCs for any given resource are determined in the context of a specific portfolio of resources and depend on the amounts of other resources present; in long term planning, this portfolio of resources is highly uncertain. Capturing these portfolio interdependencies is beyond the computational and practical capabilities of any existing resource planning model. Future research should examine the reliability needs of New York's grid in more detail.

21 All prices given in 2022 dollars except where otherwise noted. Values given are for the median price case. Power-based capex and Energy-based capex are added together. 2030 capex numbers are given without the 30 percent ITC discount, which is applied before modeling.

To provide an easier comparison of the costs assumed for hydrogen in this report and the Draft Scoping Plan for the CLCPA, prepared by E3, we provide the levelized cost of energy (LCOS) of hydrogen at a 10 percent capacity factor in Table B2. These LCOSs give a broad sense of the total cost, illustrating that despite differences in assumptions and modeling approaches between the two reports, overall costs are comparable. E3's provided LCOSs are based on a combination of out-of-state and in-state hydrogen generation. These LCOSs also illustrate the impact of choices like the use of conversion technology on discharge (fuel cell vs combustion turbine) and storage technology (aboveground tanks vs belowground caverns).

Table B2. LCOS of hydrogen at 10 percent capacity factor[22]

E3 CLCPA: H2 LCOS, Mid-Case at 10%CF ($2020)		
Technology	**2030**	**2040**
H2 with Fuel Cell	478 $/MWh	392 $/MWh
H2 with CT	370 $/MWh	325 $/MWh

This study: H2 LCOS, Mid-Case at 10% CF ($2020)		
Technology	**2030**	**2040**
H2 CT, Aboveground tank storage	468 $/MWh	458 $/MWh
H2 CT, underground storage (Available Zone A-E only)	545 $/MWh	301 $/MWh

Fossil fired technologies (natural gas and coal) take their operational characteristics from NREL's Advanced Technology Baseline (2022), except for startup cost, which is derived from Kumar et al. (2012).[23] We add enhanced geothermal and small modular reactors to the suite of generation technologies available for investment in New York by the year 2040; they are not modeled for the year 2030 due to the early stage of development of these technologies. The costs and operating characteristics of these technologies are given in Table B3.

Table B3. Characteristics of zero-carbon generation technologies (2020$)

	2040			
	Capex ($/kW)	**Variable O&M ($/MWh)**	**Fixed O&M ($/yr)**	**Heat Rate(BTU/kWh)**
Enhanced Geothermal [A]	4852.94	14.71	12.75	-
Small Modular Reactor [B]	4117.65	4.16	128.19	10450

[A] Enhanced geothermal estimates taken from Lazard's LCOE Analysis (**link**)

[B] SMR sources: Capital costs based on those used in peer-reviewed study Sepulveda et al (2018) (**link**) and supported by range found in Vibrant Clean Energy study (**link**). Operating costs taken from Lazard's LCOE Analysis v15 (**link**); costs are for traditional nuclear design so they are likely conservative.

22 Sources for hydrogen costs in this study are given in Table A1; E3's numbers are derived from the Appendix G of the Draft Scoping Report for the New York CLCPA.

23 N. Kumar, P. Besuner, S. Lefton, D. Agan, D. Hilleman, "Power Plant Cycling Costs" National Renewable Energy Laboratory. April 2012 https://www.nrel.gov/docs/fy12osti/55433.pdf

Deriving weather-correlated renewable, load, and imports price data

Renewable Generation Data

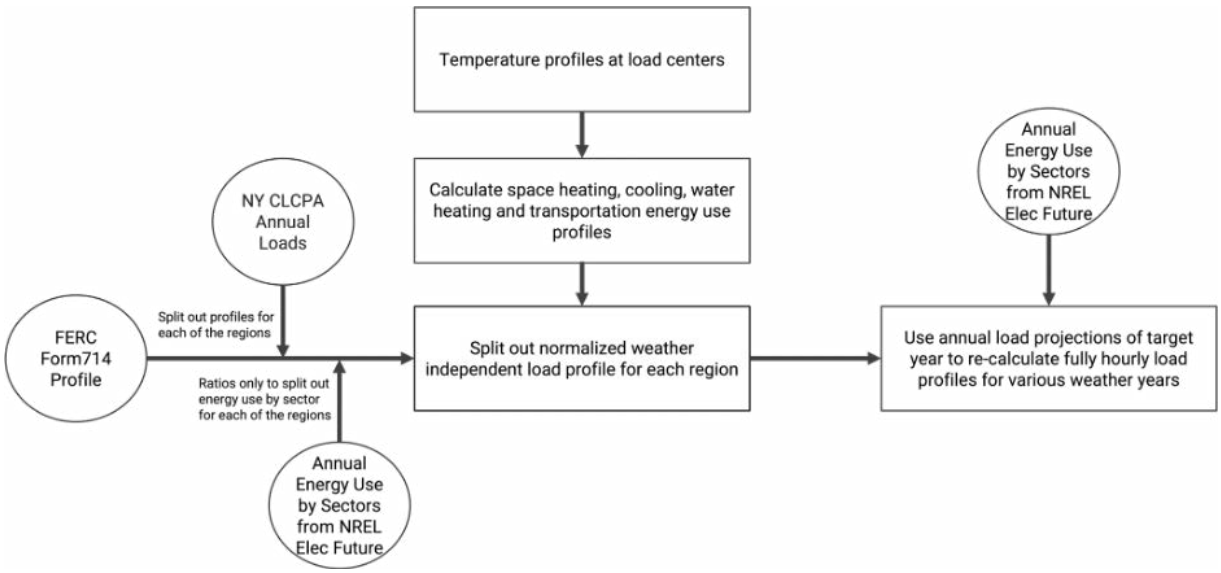
The renewable generation profiles used in this study are obtained from the National Renewable Energy Laboratory's (NREL) System Advisory Model (SAM)[24] for the 2007 to 2014 weather years. Renewable generation profiles from SAM are produced from high quality weather datasets using the National Solar Radiation Database (NSRDB)[25] for solar generation and the Wind Integration National Dataset (WIND) Toolkit[26] for wind generation. The renewable generation data from these sources capture the influence of the full range of weather variability on renewable generation.

Hourly Load Profiles

To model the impact of weather on load with high degree of fidelity, the load is split into two categories: (1) weather dependent loads and (2) weather independent loads. The weather dependent loads include space and water heating, space cooling and electric transport. Weather independent loads include industrial processes, military use, cooking, washing, lighting among others. The profiles of weather dependent loads change with the weather year used in the modeling, while the weather independent loads are assumed to remain unchanged.

Figure B1 shows the process diagram to create the load profiles used in this study. The 2017 load profile for NYISO from FERC Form 714 was used as a starting point. Load shapes for the individual regions modeled were split out using the annual load numbers obtained from the NY CLCPA draft scoping plan. The NREL electrification futures study[27] was used to determine the ratio of annual energy consumption that came from weather dependent loads and weather independent loads. The normalized hourly profiles for weather dependent loads were created using temperature profiles from 2017 (to match the FERC load data) at the load centers for the regions modeled. The method used to calculate the normalized load shapes for the weather driven loads is very similar to the one described in Section 2.5 of Vibrant Clean Energy's WIS:dom-P model[28].

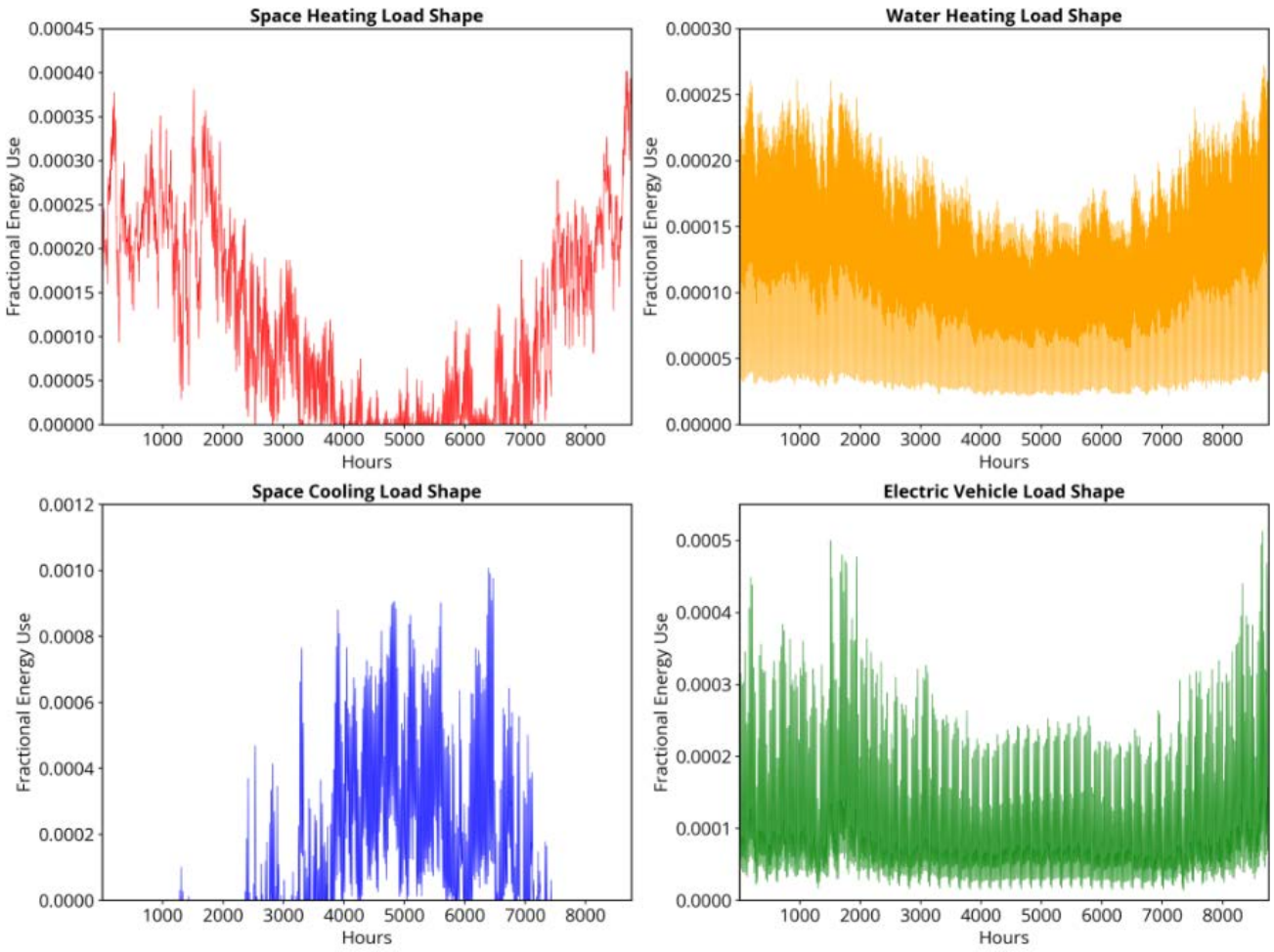
Figure B1. Process diagram for creation of weather correlated load profiles



24 https://sam.nrel.gov
25 Sengupta, M.; Habte, A.; Gotseff, P.; Weekley, A.; Lopez, A.; Molling, C.; Heidinger, A. (2014). "Physics-Based GOES Satellite Product for Use in NREL's National Solar Radiation Database: Preprint." 9 pp.NREL/CP-5D00-62237
26 Draxl, C., B.M. Hodge, A. Clifton, and J. McCaa. 2015. "The Wind Integration National Dataset (WIND) Toolkit." Applied Energy 151: 355366.
27 https://www.nrel.gov/analysis/electrification-futures.html
28 https://vibrantcleanenergy.com/wp-content/uploads/2020/08/WISdomP-Model_Description(August2020).pdf

The normalized hourly load shapes for the weather driven loads are shown in Figure B2. Formware was run using load profiles calculated using historical weather years.

Figure B2. Normalized hourly load shapes for weather driven loads in New York



Once the hourly profiles for weather dependent loads are created, the normalized weather independent load profile can be calculated by subtracting the weather dependent load profile from the FERC Form 714 load profile. Load profiles for future years were calculated by using the load projections for each of the sectors from the NREL Electrification Futures Study (using the "High Electrification" scenario) and multiplying with their respective normalized load profiles. To create load profiles for the various weather years, the respective normalized weather dependent load profiles are used for the weather dependent loads, while the weather independent load is assumed to remain unaffected.

Weather-correlated import and export prices volatility

In order to design a reliable system, we need to represent the idea that neighboring balancing areas may be experiencing stress at the same time as NYISO, so NYISO cannot rely on cheap imports for reliability support. We use import and export prices to represent the value of electricity in neighboring balancing areas; those prices are drawn from S&P Market Intelligence forecasts, and we adjust these to capture periods of weather-correlated grid stress using historical data.

Hours of historical peak grid stress are identified as the top 100 hours for hourly price in historical data. We then quantify how stressed the grid is in those hours as the ratio of the price in the stressed hour to the average price across the whole historical year of prices. That ratio is referred to as the 'peak to average' ratio. For each of the 100 hours of historical peak grid stress, we adjust the forecasted price to have the same peak-to-average ratio as the historical prices, using the equation given below.

$$\text{Forecast Adjusted Price} = \text{Forecast Annual Average Price} * \frac{\text{(Historical Price)}}{\text{(Historical Annual Average Price)}}$$

This process gives us forecasted prices with more realistic price volatility that is correlated with historical weather conditions.

In order to capture transaction costs associated with selling across balancing areas, we apply a 'hurdle rate' of 5 percent to these forecasted prices in adjoining balancing areas. For electricity imports, we increase prices by 5 percent, and for exports, we decrease prices by 5 percent.

Evaluation of Peaker Replacement Needs in New York City

To examine the cost of replacing peaker plants in New York City by 2030, we assume the retirement of gas- and oil-fired peaking units in Zone J, totaling 3,950 MW of capacity. Combined-cycle units totalling 3,334 MW capacity remain in Zone J. For these scenarios, we enforce a 19% local planning reserve margin (PRM) in Zones J and K, in line with the system-wide PRM but significantly below today's local PRM; as a result, results can be considered conservative, indicating directionally what might be required. Greater precision can be supported by more detailed study of the level of local capacity requirement needed in the future.

Price and Weather Sensitivities

Price Sensitivities

Price sensitivities explore how much the optimal capacity and system cost change if storage technologies cost more or less than forecast. Each separate sensitivity run explores changing the prices for one group of technologies while holding prices for all other technology prices at the base-case price level. The groups used for price sensitivities are as follows:

- All lithium-ion durations (<10 hours)
- 10 to 24-hour storage (flow batteries & CAES)
- Hydrogen storage of all durations (100 to 1000 hours)
- Iron-air storage (100 hours)

Testing a high and low price forecast for each group resulted in eight total price sensitivities. High and low price forecast levels were taken from the same sources as given in Table B1.

Weather Sensitivities

Weather sensitivities explore how much the optimal investments and system cost change if different weather years are used for determining load, renewable availability, and import/export prices. (Methods for creating those weather-driven datasets are described above.)

We have weather data for the years 2007-2014, resulting in 7 additional sensitivities to the base case (which uses weather year 2014). We compare annualized system costs from simulations using weather year 2008-2014 to the base weather year of 2007. All simulations have the same planning reserve margin requirements.

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