IESO Resource & Plan Assessments Technical Paper: Effective Load Carrying Capacity of Energy Storage

Evaluation on the Effective Load Carrying Capacity (ELCC) of energy storage to enhance system reliability and support Ontario's evolving electricity needs

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1. Executive Summary

With electricity demand in Ontario forecast to increase by 75 per cent by 2050, the IESO anticipates growth at great speed and scale, driven in large part by electrification, as well as specific commercial and industrial sector development. To help meet this anticipated demand, the IESO has begun procuring the energy storage resources needed to help displace fossil fuel use and electrify the system, with nearly 3,000 megawatts of installed storage capacity expected by 2028.

However, the value that energy storage provides to the system is dynamic, meaning its capacity value can change over time as system conditions evolve. This technical paper investigates the role of energy storage, particularly in terms of its ability to store excess power and inject that power back into the grid during times of system need. This ability can be quantified as its Effective Load Carrying Capacity (ELCC), also referred to as its capacity value, and is the main topic of this paper. While the trends and insights in this technical paper are relevant, the exact capacity values should not be taken as absolute as they are highly situational and depend on the specific system conditions at the time. Determining the capacity value is necessary to ensure procurements and energy policy are aligned with system needs. This paper evaluates how the capacity value of storage varies according to factors like storage penetration, duration, system supply mix, and demand profiles.

1.1 Key Findings and Implications

1.1.1 Declining Capacity Value with Increased Storage Penetration

Adding additional storage to the system without increasing duration results in diminishing reliability benefits, as fixed-duration storage units are unable to sustain output during extended peak demand periods. Furthermore, as storage penetration rises, competition for limited surplus capacity intensifies, reducing the ability of each unit to fully charge.

Implications: A well-balanced strategy that integrates storage with other energy-producing resources is critical to optimizing reliability and avoiding system oversaturation. Aligning storage deployment with surplus capacity and peak demand characteristics can ensure that reliability benefits are maximized. Capacity qualification frameworks should account for these dynamics by progressively adjusting capacity credits downward as storage penetration increases, reflecting its diminishing marginal contributions. Additionally, fostering a diverse portfolio of storage resources—including varied durations and complementary technologies—can address the declining incremental value of storage at higher penetration levels while supporting the system’s evolving needs.

1.1.2 Longer Duration Needed for Larger Storage Units

As storage penetration increases, increasing the duration of storage is essential to sustain its capacity value. Short-duration storage is well-suited for addressing brief demand peaks, while longer durations are necessary to support sustained reliability during extended high-demand periods.

Implications: Storage size and duration should be carefully aligned with demand patterns to maximize cost-effectiveness and operational value. For systems experiencing prolonged high-demand periods, long-duration storage may be required, whereas shorter-duration solutions are ideal for handling brief, intense peaks. Capacity qualification frameworks should appropriately credit longer-duration storage for its ability to provide extended reliability. Additionally, maintaining a diverse mix of storage configurations with varying durations and characteristics can effectively address a wide range of reliability needs, enhancing overall system flexibility and resilience.

1.1.3 Impact of System Composition on Capacity Value

The capacity value of storage is influenced by the mix of baseload and renewable generation within the system. Increasing levels of baseload generation enhance capacity value by providing consistent power for charging and stabilizing the grid during peak periods. However, excessive baseload can limit the need for storage to contribute during peak-shaving periods, reducing its effectiveness. Similarly, renewable generation increases storage's capacity value up to a saturation point. Beyond this, over-generation during low-demand periods can limit charging opportunities and reduce the incremental value of storage. Seasonal variations also play a role; "peakier" demand profiles in summer enhance capacity value, while flatter winter profiles reduce storage's ability to effectively support peak demand.

Implications: Capacity qualification frameworks must reflect the dynamic relationship between storage and the system's generation mix. Strategically integrating storage with additional energy-producing resources, such as renewables and baseload, can enhance its capacity value. A balanced mix of resources ensures that storage remains an effective tool for optimizing system reliability. Furthermore, as demand grows within a balanced system, new opportunities for storage to discharge during high-demand periods emerge, reinforcing its role as a valuable and adaptable resource in Ontario's energy landscape.

1.2 Next Steps

To maximize the role of storage in enhancing system reliability and supporting decarbonization efforts, the Independent Electricity System Operator (IESO) will explore the following focus areas across planning, procurement, and operational strategies:

- **Refine Capacity Qualification Frameworks**
  The IESO should adapt its capacity qualification methodologies to address the diminishing reliability contributions of storage at higher penetration levels. This involves appropriately recognizing the role of longer-duration storage in sustaining reliability during extended peak periods and adjusting for the dynamic effects of changes in system composition. These frameworks should evolve in tandem with system requirements to account for the complex interactions between storage, baseload, and renewable resources.

- **Promote Diversity in Storage Configurations**
  The IESO should prioritize establishing a diverse portfolio of storage configurations, incorporating a variety of durations, sizes, and technologies. Such diversity enables the system to effectively address a broad spectrum of reliability challenges, ranging from brief, intense peak demands to extended periods of high demand, while enhancing overall cost-effectiveness and operational flexibility.

- **Incorporate System Growth and Demand Evolution**
  The IESO should actively evaluate and integrate emerging opportunities for storage to discharge during high-demand periods as the energy system grows and demand increases. This includes

assessing the role of storage in addressing future reliability needs, particularly in light of increased electrification, industrial growth, and renewable energy integration.

- **Align Procurement Processes with System Needs**
  The IESO should structure procurement strategies to address evolving system requirements, prioritizing the integration of storage alongside baseload and renewable generation. By aligning storage deployment with these resources, the grid can effectively manage variability, meet peak demands, and optimize clean energy utilization, thereby advancing Ontario's decarbonization and reliability objectives.

- **Conduct Ongoing Assessments of Storage Value**
  Recognizing the dynamic nature of storage's capacity contributions, the IESO should implement regular evaluations of the capacity value of storage resources. These assessments should guide procurement strategies and ensure that storage resources are effectively aligned with the system's evolving reliability and decarbonization objectives.

- **Prepare for Seasonal Variability**
  The IESO should establish strategies to manage seasonal variations in storage performance. For example, ensuring sufficient capacity during winter months, when flatter load profiles provide fewer opportunities for storage to discharge, can help maintain system reliability year-round.

In summary, Ontario's evolving energy landscape will benefit from storage, but its full potential can only be achieved through strategic integration with energy-producing resources. This technical paper highlights the importance of designing procurements that recognize the value of diversity in capacity, such as incorporating longer-duration storage options to complement shorter-duration systems, especially as storage penetration increases. A diverse portfolio of capacity resources, including longer-duration storage and other complementary technologies, helps address the declining value of incremental storage as penetration grows, ensuring continued reliability and flexibility. Furthermore, as the system grows and demand increases, new opportunities emerge for deploying storage to meet evolving reliability needs. By tailoring procurement designs to address system needs and leveraging the opportunities created by rising demand, Ontario can maximize the contribution of storage to system reliability. Continual assessment of the capacity value of storage and its alignment with Ontario's system needs will remain crucial to optimizing reliability, sustainability, and cost-effectiveness.

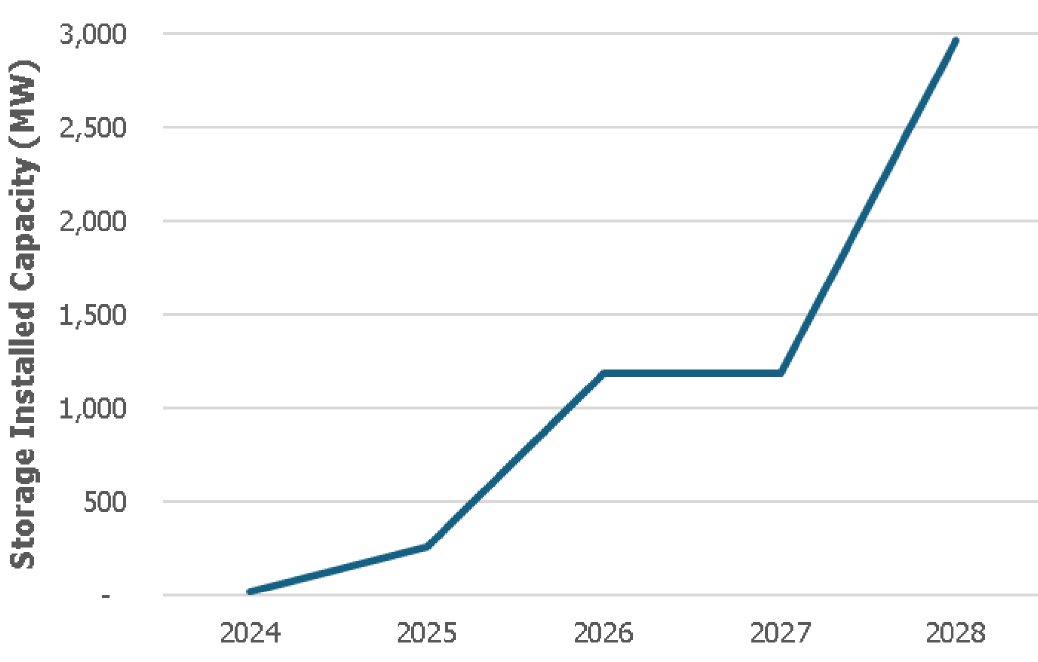
2. Introduction

While the trends and insights in this technical paper are relevant, the exact capacity values of storage should not be taken as absolute, as they are highly situational and depend on the specific system conditions at the time.

Ontario is undergoing a significant energy transition, driven by electrification, renewable integration, and decarbonization efforts. This shift requires reliable, flexible, and low-carbon resources to support a growing system. In the 2025 Annual Planning Outlook (APO), Ontario's electricity demand is projected to increase by 75% by 2050[1], amplifying the need for solutions that can balance supply with demand. While renewable resources like wind and solar can play key roles in building out Ontario's clean energy system, their intermittent nature presents challenges for consistent power delivery.

Energy storage offers a pathway to overcoming these challenges by providing dispatchable power that reduces dependency on fossil fuel peaking plants that emit greenhouse gases. As per Figure 1, the amount of storage capacity on Ontario's system, including both existing and committed projects, is set to grow from approximately 25[2] MW in 2024 to an estimated 3,000[2] MW by 2028. This increase stresses the importance of understanding the behaviour of energy storage to maximize the benefit that it can provide for system stability and decarbonization.

Figure 1 | Existing and Committed Storage Installed Capacity



[1] Electricity Demand in Ontario to Grow by 75 per cent by 2050

[2] These capacities do not include the existing pumped hydro storage at Beck PGS

Storage can extract value from intermittent renewable resources by shifting power from times of capacity surplus to periods of capacity deficit. For instance, wind power generation is often strongest during overnight hours, while Ontario's electricity demand typically increases in the afternoon/evening. Storage can address this mismatch by storing excess renewable capacity generated during off-peak hours and discharging it when demand is high. This function not only supports system stability but also reduces usage of fossil-fuelled peaking plants during high-demand periods. By maximizing the utilization of renewables, storage can amplify their contribution to Ontario's energy mix and enhance the province's ability to meet decarbonization targets.

The value of storage is a complex and dynamic function dependent on several key parameters: storage penetration, duration, the system's resource mix, and the demand profile. Smaller, short-duration storage systems may excel at frequency regulation and short-term balancing but may fall short during prolonged high-demand periods. In contrast, larger, long-duration systems offer sustained dispatchability but may require more significant investments. The system's resource mix further influences value, as a high renewable mix may benefit more from storage than a dispatchable-resource-heavy system. Additionally, Ontario's demand profile—characterized by seasonal peaks and valleys—affects how storage should be sized and deployed. These multifaceted interactions mean that storage value is not "one-size-fits-all" but rather varies according to specific system needs and operational goals.

This paper aims to explore the ELCC of storage in Ontario's power system by analyzing the impact of various parameters:

- Storage penetration and duration
- Demand forecast variations
- System resource mix changes

The analysis does not include certain storage parameters (e.g., technology type, charge/discharge rate, round-trip efficiency, response time, cycle life, operational profiles, transmission congestion etc.), allowing for a focused analysis of ELCC alone. Additionally, hybrid configurations, where storage is co-located with energy-producing resources like solar or wind, were not studied. The added generation scenarios considered in this analysis reflect standalone additions to the system and do not represent hybrid configurations.

3. Methodology and Assumptions

3.1 Methodology

The primary metric used to determine the value of storage in this paper is Effective Load Carrying Capacity (ELCC), which quantifies the reliability benefit provided by adding a new resource (energy storage in this assessment) to an existing resource portfolio. ELCC was assessed in relation to the Loss of Load Expectation (LOLE) and other relevant metrics (see Appendix 1 for definitions), capturing how storage would reduce the likelihood of a capacity shortfall. The analysis was conducted across all hours of the study years to ensure comprehensive results aligned with reliability targets.

The General Electric Multi-Area Reliability Simulation (MARS) software was used for this probabilistic ELCC analysis. The key steps in the methodology were as follows:

1. **Baseline Capacity Deficit**: Determine the system's perfect capacity[3] requirements to meet a specific reliability target without added storage, establishing baseline metrics for reliability. For example, if the baseline capacity need is 1,000 MW, this value represents the capacity required to maintain reliability in the absence of storage.
2. **Storage Simulation**: Integrate storage into the system and assess its impact on perfect capacity requirements at the established reliability level. In this example, we add 250 MW of 4-hour storage to the baseline system.

Calculation of ELCC: Calculate the ELCC as the reduction in perfect capacity need due to added storage, expressed as a percentage of the storage penetration. For instance, in Figure 2, if the system's capacity need with storage decreases to 800 MW to achieve the same reliability target, the reduction in capacity need is 200 MW. Therefore, the ELCC of the 250 MW storage addition is calculated as:

$$Storage\ ELCC = \frac{Reduction\ in\ Perfect\ Capacity\ Need\ with\ Addition\ of\ Storage}{Storage\ Penetration}$$

$$Storage\ ELCC = \frac{1000\ MW - 800\ MW}{250\ MW} = 80\%$$

This result demonstrates the effectiveness of storage in reducing the need for perfect capacity to achieve the reliability target.

This step-by-step approach, facilitated by the MARS software, enables a robust analysis of contribution of storage to system reliability, providing valuable insights into its role in meeting Ontario's capacity requirement.

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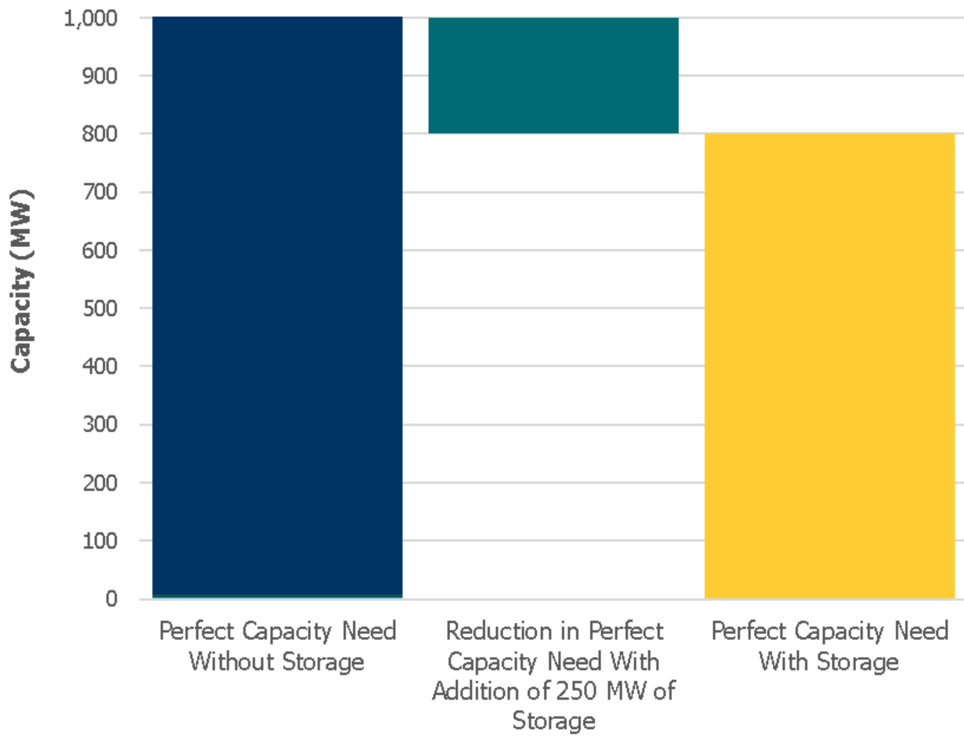
[3] Perfect Capacity refers to the idealized capacity required to meet demand at a specified reliability level without accounting for the operational characteristics, variability, or potential shortfalls of actual resources. It assumes fully dependable resources with zero variability or risk of failure, serving as a benchmark for assessing the reliability contribution of new resources, such as energy storage.

Figure 2 | Impact of Storage on Perfect Capacity Need



3.2 Assumptions

Table 1 outlines key assumptions categorized by demand, supply, study years, and the storage penetrations and durations studied. These assumptions were used to define the boundary conditions and scenarios under which the ELCC of storage was evaluated.

Table 1 | Study Assumptions

Assumption	Description
Base Case	2022[4] Annual Planning Outlook, Case 1 (Expiring resource contracts not renewed) 2022 Annual Planning Outlook - 2035 Summer - Case 2 (Expiring resource contracts renewed)
Year/Season	2027 Summer – 2036 Summer 2029/2030 Winter, 2035/36 Winter
Sensitivity Cases	2029 Summer with Pathways to Decarbonization (P2D - 2022) Demand 2035 Summer with Pathways to Decarbonization (P2D - 2022) Demand 2035 Summer - Case 2 + Additional Baseload (400 MW, 900 MW, 2000 MW) 2035 Summer - Case 2 with Additional VG (Variable generation) - Wind (x2, x5) 2035 Summer - Case 2 with Additional VG - Solar (x2, x4, x5)
Storage Duration (Hours)	4, 8, 12, 24
Storage Penetration/ Capacity (MW)	250, 500, 1000, 2000, 4000

For each case and sensitivity, there were four durations and five penetrations, resulting in a total of twenty storage duration/penetration combinations studied. These combinations included scenarios such as 250 MW with 4-hour duration, 250 MW with 8-hour duration, and up to 4000 MW with 24-hour duration.

Additionally, the following specific assumptions were applied to create a controlled environment for the study:

- **System Placement**: Storage resources were assumed to be added as a single unit located in the Toronto zone, reflecting the load centre of Ontario. This placement was intentional, as it helped simulate the impact of storage on areas with concentrated demand.

[4] The 2022 Annual Planning Outlook case was used because this study was initiated in late 2022, and it was the latest available case at the time.

- **Renewable Generation Scaling**: In scenarios with high renewable generation, existing resources were scaled proportionally to simulate increased penetration of renewable energy sources, enabling the observation of interactions between storage and a renewable-heavy resource mix.
- **Perfect Arbitrage**: The study assumed perfect arbitrage, where storage would charge during system capacity surplus[5] hours and discharge during system capacity deficit[6] hours. This assumption idealizes storage behavior to maximize its contribution to system reliability and capacity needs.

[5] Capacity surplus hours are defined as the hours during which the effective supply capacity of the generation fleet exceeds system demand.

[6] Capacity deficit hours are defined as the hours during which system demand exceeds the effective supply capacity of the generation fleet.

4. Findings

4.1 ELCC declines as more storage is added to the system

Keeping demand, supply, and storage duration constant within a year, as more energy storage is added to the system, the storage ELCC begins to decline. This phenomenon, as depicted in Figure 3, occurs because the reliability benefits of additional storage diminish with each new unit added, especially at higher levels of penetration.

Figure 3 | Change in storage ELCC with Increasing Storage Penetration (at 4-hour Duration)

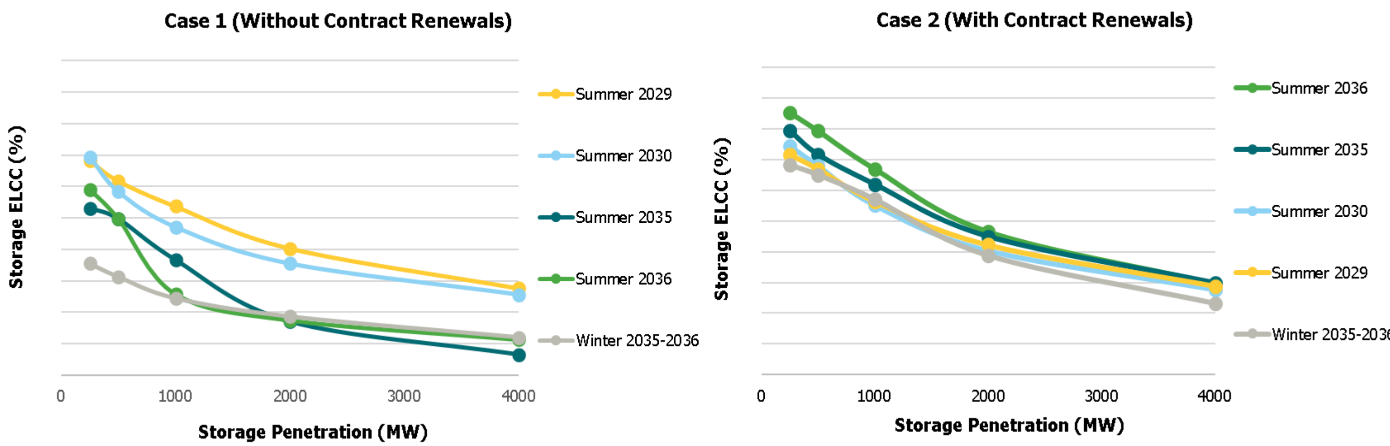


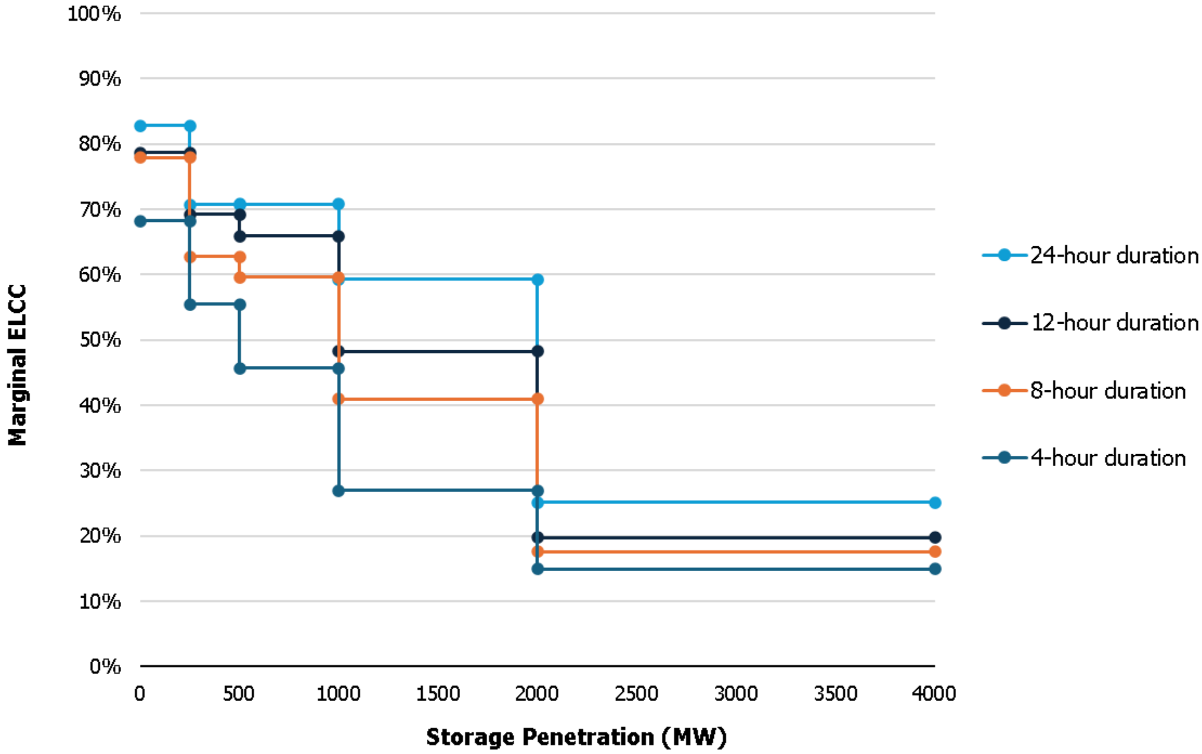
Figure 3 further demonstrates that the ELCC of storage varies over time depending on the underlying system assumptions. In the 2022 Annual Planning Outlook Case 1, where expiring generation contracts are not renewed, the ELCC of storage decreases from 2029 onward, as illustrated by the vertical downward shift of each subsequent year's plot. This decline occurs because the generation fleet decreases over time while demand is forecasted to grow, creating a significant imbalance between supply and demand. This imbalance leads to fewer surplus capacity hours available for charging storage, resulting in a decline in the ELCC of the same storage penetration each year.

In contrast, under Case 2, where expiring generation contracts are renewed, the imbalance between supply and demand is smaller. While supply remains steady, the growth in demand provides more opportunities for storage to contribute to system reliability. Storage can discharge more effectively during high-demand periods, allowing it to play a greater role in addressing system needs and enhancing reliability over time.

These contrasting outcomes highlight the importance of achieving a balanced system that optimizes the interplay between supply and demand. Such a balance ensures that storage has sufficient opportunities to contribute effectively to reliability and maximizes its overall system value. Additionally, the difference in seasonal ELCC is discussed as part of finding 3.

Figure 4 illustrates how, with all other factors held constant, the average marginal ELCC of added storage blocks decreases as storage penetration increases. For instance, in this scenario, the first 250 MW block of 8-hour duration storage provided nearly 80% average ELCC. In contrast, the final 2000 MW block of storage added to a system already equipped with 2000 MW (for a total of 4000 MW) delivered an average ELCC of less than 20%.

Figure 4 | Average Marginal ELCC of Added Storage Blocks (2029 Summer Case 1)



These diminishing marginal returns arise due to two primary factors:

- **Limited Duration to Address Extended Peak Demand**: When storage resources have a fixed duration (e.g., 4-hour or 8-hour storage), they can only supply power for a limited period. As additional storage units are added, the system's capacity to manage short, isolated demand peaks initially improves. However, as storage penetration continues to rise, the collective storage fleet becomes less effective in addressing prolonged periods of peak demand, such as consecutive high-demand days. In these situations, the limited duration of each storage unit means it may be fully discharged before the peak demand period ends, thereby reducing its overall contribution to system reliability.
- **Reduced Availability of Surplus Capacity for Charging**: Keeping all else constant, high storage penetration also affects the availability of surplus capacity during off-peak hours. With more storage units in the system, they begin to compete for the same surplus generation (typically from renewable sources like wind and solar). In a system with a fixed amount of renewable generation, this surplus capacity becomes increasingly scarce relative to the growing charging needs of the expanded storage fleet. As a result, not all storage units can fully charge during off-peak hours, limiting their ability to discharge during peak demand periods and, consequently, lowering their overall ELCC.

Implications of this finding: This finding highlights the importance of recognizing diminishing marginal returns when evaluating the ELCC of storage, keeping all else constant. While initial additions of storage significantly enhance reliability by shifting capacity from low-demand to high-demand periods, additional storage becomes less effective as penetration increases. This decline in marginal ELCC is driven by limited duration to address prolonged peak demand and reduced availability of surplus capacity for charging.

In the context of storage procurement, capacity qualification frameworks must account for these diminishing returns to ensure that storage is accurately valued and not over-procured relative to demand. Keeping all else constant, as storage penetration increases, the marginal ELCC for subsequent additions declines, meaning that later increments of storage contribute less to reliability than earlier ones. Capacity qualification processes should incorporate scenario-based modeling that reflects this dynamic, assigning progressively lower capacity credits to incremental storage resources as penetration rises. Additionally, storage procurement strategies should encourage diversity in storage characteristics, such as duration and location, to better align with system needs and mitigate the limitations of oversaturating the grid with uniform storage assets.

Summary: Keeping all else constant, while the first increments of storage can provide substantial reliability benefits, the value of additional storage diminishes as penetration levels increase. This reduced effectiveness is due to the storage fleet's limited duration for addressing extended peaks and increased competition for surplus capacity during off-peak periods. This finding highlights the importance of securing a more diverse portfolio of capacity resources, including longer-duration storage and other complementary technologies, to account for the declining value of incremental storage as penetration grows.

Additionally, as the system grows and demand increases, new opportunities emerge for deploying storage to address evolving reliability needs. Capacity qualification frameworks should reflect these dynamics by adjusting the capacity credits for storage resources based on their penetration, duration, and system needs. By carefully managing storage deployment and coordinating it with a balanced mix of energy-producing resources, system planners can maximize storage's contribution to reliability. This balanced and diverse approach ensures that procurement strategies align with the system's evolving reliability needs and leverage the opportunities created by a growing energy system.

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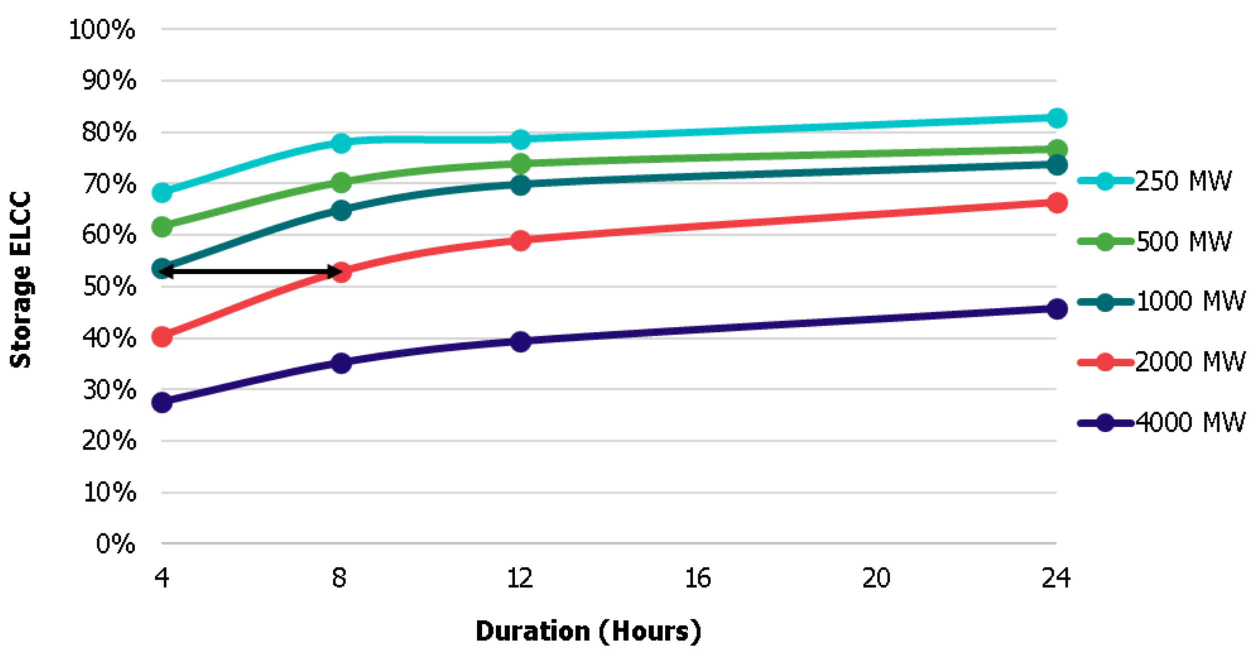
4.2 The larger the storage penetration, the longer the duration needed to sustain its ELCC

The ELCC of energy storage is influenced by both the penetration and duration of the storage connected. This finding reveals that keeping all else constant, including storage parameters such as round-trip efficiency (RTE), as the storage penetration increases, a longer duration is required to sustain its ELCC. Storage duration—the length of time the unit can discharge at full capacity—is a critical factor because it determines how well storage can meet demand over extended periods, particularly during high-demand peaks. For example, in Figure 5, doubling the storage penetration from 1,000 MW to 2,000 MW necessitates doubling the duration from 4 to 8 hours to maintain a ~50% ELCC in this particular case, as indicated by the arrow. It is also important to note that longer-duration storage technologies, such as Compressed Air Energy Storage (CAES), typically have lower RTE compared to batteries. This lower efficiency means that a larger portion of input energy is lost during storage and retrieval, which can impact the ELCC and must be accounted for when assessing the reliability contributions of different storage technologies.

Figure 5 | Impact of Duration on ELCC of Different Storage Penetrations (2029 Summer Case 1)



Key observations from this finding:

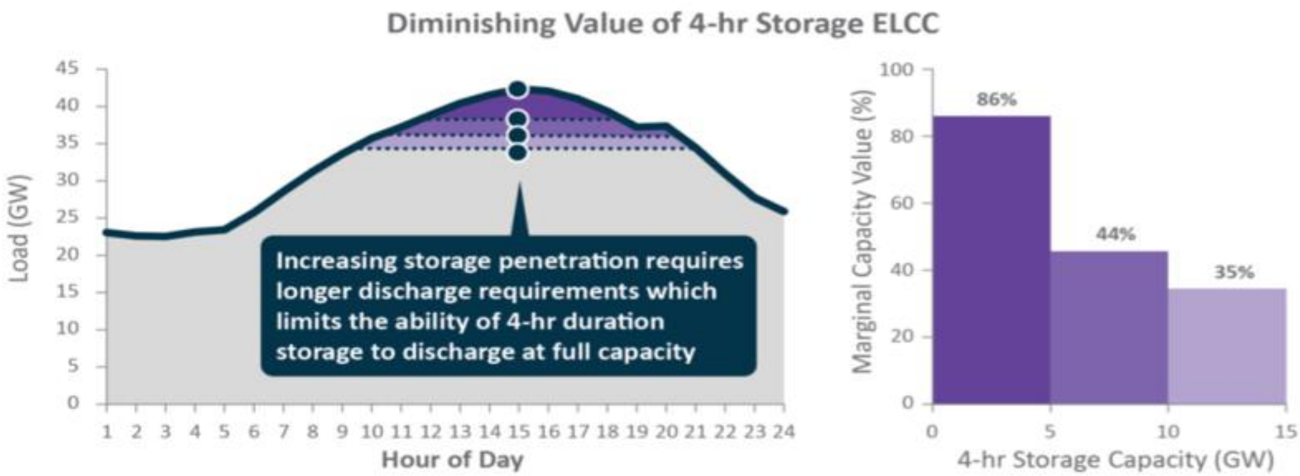
- **Larger Storage Penetration Requires Longer Duration**: For larger storage penetrations, longer durations are essential to ensure to maximize ELCC of storage as it ensures that storage can be effectively utilized during peak demand periods. For example, a 250 MW storage unit with a 4-hour duration can contribute a maximum of 1,000 MWh, while a 500 MW unit with the same 4-hour duration has twice the discharge capability (2,000 MWh). However, if peak demand stretches over extended periods, even the 500 MW unit may be insufficient unless its duration is extended. Consequently, as storage penetration increases, the duration must also be scaled up to maintain reliability and optimize the storage's ELCC.

- **Increasing Duration Yields Diminishing Returns**: Although increasing storage duration generally enhances ELCC, the rate of improvement begins to diminish beyond a certain point. Initially, extending duration from 4 hours to 8 hours boosts the storage's ability to reliably supply capacity during peak times, covering a greater portion of high-demand periods. However, as the duration increases further—from 12 to 24 hours—the additional benefit to ELCC becomes less pronounced. This diminishing return occurs because, beyond a specific duration, the storage unit can already cover most peak periods, and further increases contribute less to overall reliability. Moreover, the relationship between ELCC and duration is not linear; doubling the duration of storage does not result in a doubling of its ELCC. Instead, the improvement in ELCC grows at a slower rate as duration increases, highlighting the importance of carefully balancing duration with system needs to optimize the value of storage.

- **Optimal Duration Range**: The ELCC value of storage increases notably when duration extends from 4 to 12 hours, with most of the reliability benefits realized within this range. Beyond 12 hours, the ELCC benefit plateaus, generally reaching peak effectiveness between 12 and 24 hours. In this range, the storage is capable of addressing extended demand peaks occurring over consecutive high-demand hours, making it particularly valuable in systems with variable renewable energy sources that may experience prolonged low-generation periods (e.g., during cloudy or low-wind days). However, smaller storage penetrations reach this plateau much sooner, as their limited size allows them to meet demand only for shorter periods. In contrast, larger storage penetrations continue to see incremental ELCC benefits even at the longest studied duration of 24 hours, as their increased capacity enables them to sustain reliability over extended demand peaks.

Figure 6[7] further demonstrates the reasoning behind the need for increased duration. As the storage penetration at 4-hour duration is increased, the net peak load profile, depicted by the dotted lines, flattens significantly compared to the peaky load profile at the smallest storage penetration. Therefore, to increase the impact of the larger storage penetrations, a longer duration would be needed to impact the flat peak load hours.

Figure 6 | Impact of Increasing Storage Penetration at Constant Duration on Net Load



Implications of this finding: This finding suggests that to optimize the cost-effectiveness of storage investments, system planners should carefully consider both storage penetration and duration based on expected demand profiles and peak patterns. Systems with frequent short-duration peaks may benefit more from smaller, shorter-duration storage units, which can reliably meet short but intense demand periods. Conversely, systems with longer, sustained peak demand periods may require larger storage units with extended durations to fully support reliability needs.

From a capacity qualification perspective, this finding underlines the importance of tailoring qualification metrics to reflect the interaction between storage penetration and duration. For larger storage penetrations, capacity qualification processes must adjust ELCC estimates to account for the diminishing returns associated with shorter-duration storage at higher penetrations. Furthermore, procurement frameworks should incentivize configurations that align storage duration with system needs, ensuring that units with longer durations are appropriately credited in scenarios with extended demand peaks. To prevent overvaluation of extremely long-duration storage, capacity qualification should incorporate diminishing marginal ELCC gains beyond 12 to 24 hours, where incremental reliability contributions taper off.

Summary: while increasing storage duration does enhance ELCC, the most significant gains are realized up to approximately 12 hours, with a plateau effect between 12 and 24 hours. This insight emphasizes the importance of strategically selecting storage configurations that align with specific system demands. By incorporating these dynamics into capacity qualification frameworks, system planners can ensure storage procurement reflects the optimal trade-off between penetration, duration, and reliability contributions. This approach would maximize reliability while avoiding over-

[7] Image source: https://www.ethree.com/wp-content/uploads/2020/08/E3-Practical-Application-of-ELCC.pdf

investment in capacity that yields minimal additional benefits, thereby achieving both operational efficiency and economic value.

4.3 Changes to the base system can affect the ELCC of storage

The ELCC of storage is influenced not only by its penetration and duration but also by the composition of the underlying system. Changes in the base system, particularly through the addition of baseload or variable renewable generation, significantly affect the ELCC of storage. This finding highlights how interactions between storage and other generation resources can either enhance or limit the value of storage within a system context. Figure 7 and Figure 8 below show how changing system conditions affect storage ELCC.

In Figure 7, the increased storage ELCC is observed due to contract renewals in Case 2, which enhance supply and reduce capacity deficits. This creates a more balanced system with additional surplus hours available for storage to charge, ultimately increasing storage's ability to meet demand.

Figure 7 | Storage ELCC – 2035 Case (without and with contract renewals)

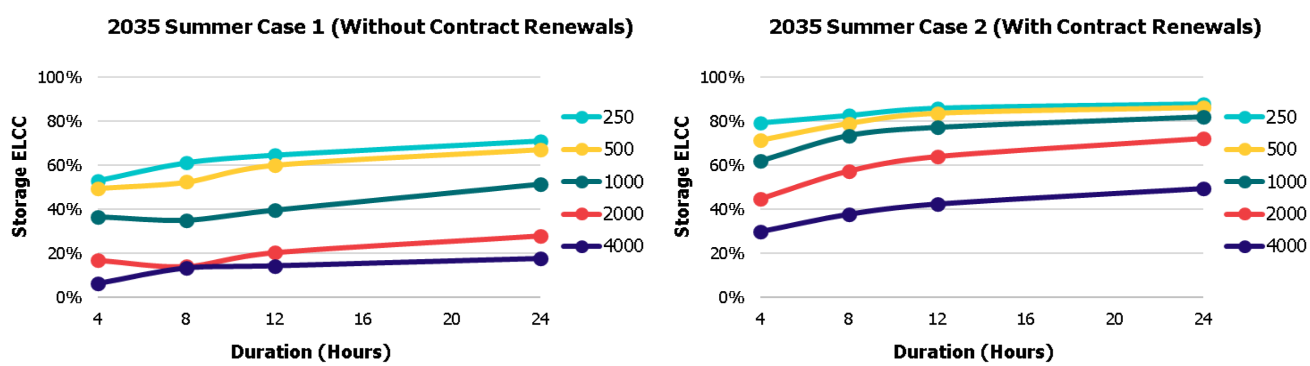
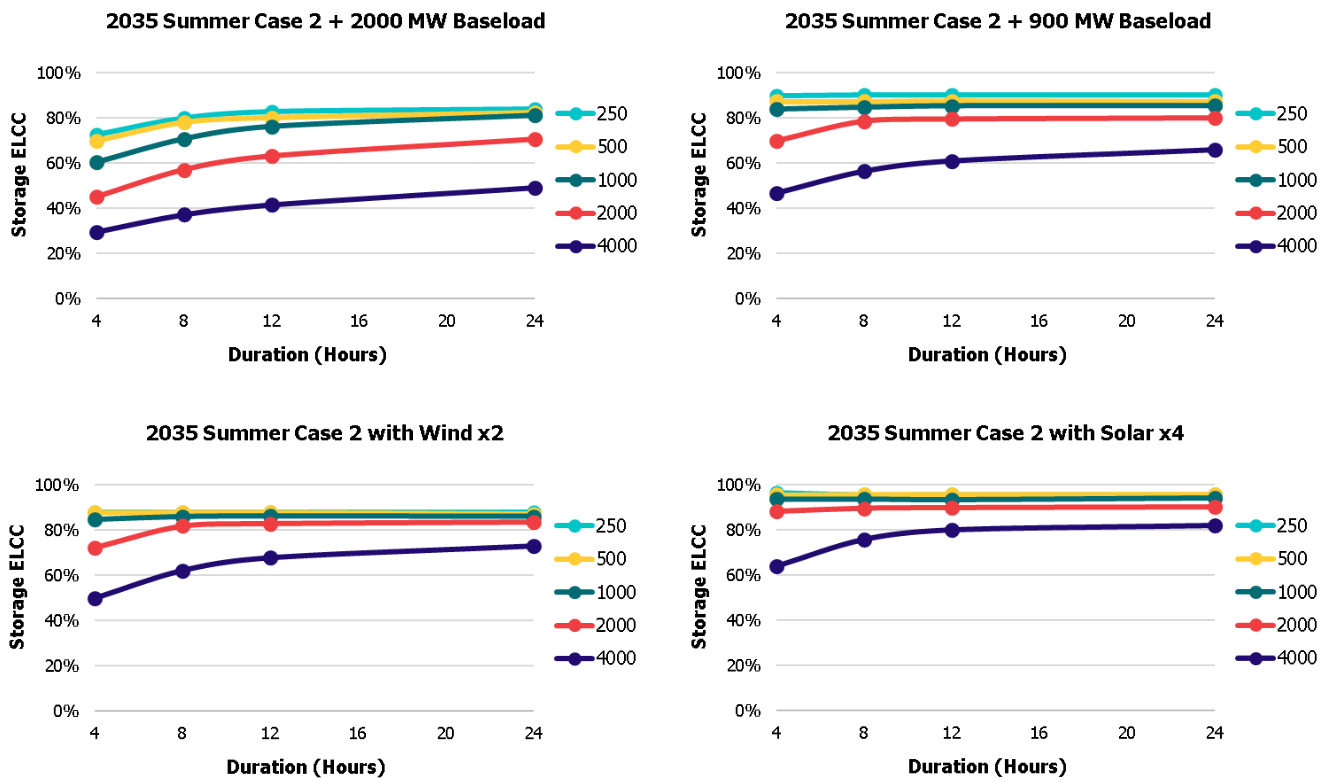


Figure 8 illustrates the impact of adding additional baseload and variable generation to Case 2. With these enhancements, the system generally becomes more balanced, leading to an overall increase in the ELCC of storage across most storage penetrations and durations. However, the 2000 MW added baseload plots highlight that when excessive baseload is added, the ELCC of storage begins to decrease. These results are discussed further later in this section.

Figure 8 | ELCC Impact of Added Generation on Storage ELCC in Case 2



Key Observations from this finding:

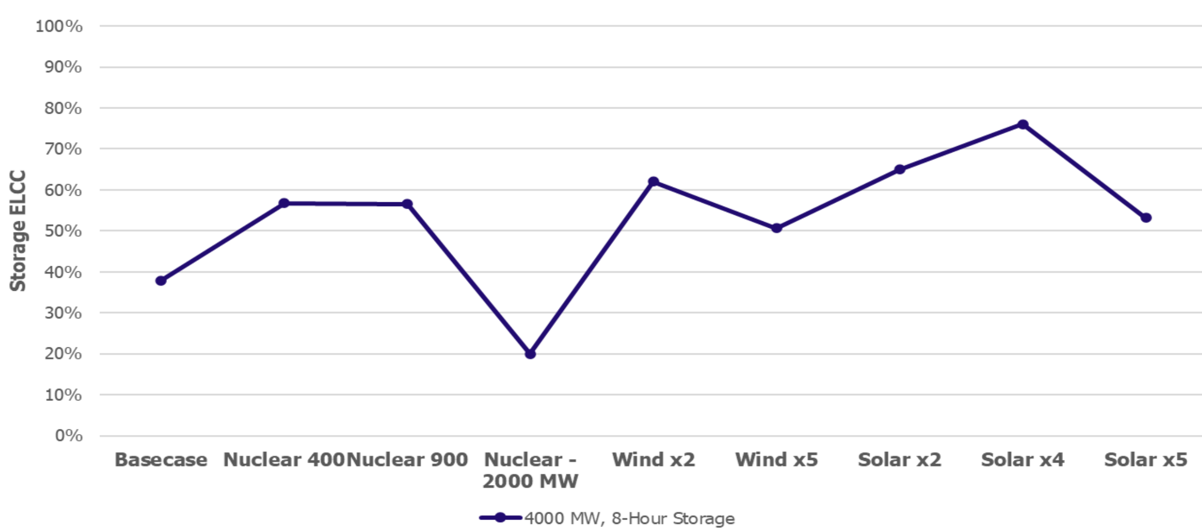
- **Effect of Added Baseload Generation on ELCC:** Keeping system conditions and storage penetration constant, adding baseload generation, such as nuclear, can initially enhance the ELCC of storage. Baseload resources provide consistent, reliable power, which helps stabilize the system. This reliability allows storage to operate more strategically, focusing on shaving high-demand peaks rather than compensating for variability or gaps in supply. Additionally, baseload generation ensures a steady supply of power during times when variable resources, like wind and solar, may not be generating, thereby increasing opportunities for storage to charge efficiently. As a result, the interaction between baseload and storage enhances the reliability benefits of storage, leading to an increase in its ELCC during the initial phases of baseload addition.

  However, this benefit does not continue indefinitely. Beyond a certain point, the addition of more baseload generation relative to demand can begin to decrease the ELCC of storage. As baseload generation increases beyond an optimal point, the need for storage to contribute during periods of high demand decreases, thus limiting its opportunities to discharge effectively. In such scenarios, storage becomes less critical for addressing reliability needs, and its marginal contribution to system stability diminishes. In these extreme cases, the combination of abundant baseload generation can "crowd out" the flexibility role that storage typically provides, leaving storage less valuable to the system's overall reliability framework. While overall system reliability may not decrease, this results in a suboptimal outcome, as the contribution of storage to meeting system needs is reduced despite its presence in the resource mix. However, an increase in demand can offset this decline in storage value by creating new opportunities for storage to charge and discharge effectively, restoring its contribution to system reliability

Thus, while baseload generation initially complements storage by providing a reliable and affordable foundation for charging and peak-shaving, its continued addition beyond an optimal level can undermine the system's reliance on storage and reduce its ELCC. This underscores the importance of finding a balanced mix of baseload, variable renewables, and storage to maximize reliability and system efficiency.

- **Effect of Variable Renewable Generation on ELCC**: Keeping system conditions and storage penetration constant, adding renewable generation, such as wind and solar, also impacts the ELCC of storage in a complex way. Increasing variable renewable generation improves the ELCC of storage by providing surplus capacity for charging during low-demand periods, which storage can then discharge during peak times. However, this benefit only holds up to a certain level of renewable penetration. Beyond this saturation point, excessive additional variable generation can reduce the incremental ELCC of storage due to over-generation during off-peak periods, where the electricity generated exceeds demand and storage cannot absorb more capacity because it is already charged or there are limited opportunities for subsequent discharge during peak hours. This phenomenon is illustrated in Figure 9, where increasing solar and wind generation up to 4 times in the year 2035 leads to a rise in storage ELCC. However, in this case, when variable generation exceeds this 4x increase, the ELCC of storage begins to decrease. Figure 9 further highlights this saturation effect with smaller increments, showing a decline in ELCC as solar generation increases from four times to five times. This saturation effect can also be influenced by factors such as the system's resource mix and net demand profile. Nonetheless, an increase in demand can mitigate this saturation effect by increasing the overall need for capacity, thus providing additional opportunities for storage to charge and discharge efficiently, which can sustain or even enhance its value in the system.

Figure 9 | Impact of Various Baseload and Variable Generation Additions on Storage ELCC (2035 Summer Case 2)



- **Impact of "Peaky" versus Flat Demand Profiles**: The shape of the daily load profile, whether "peaky" or flat, affects the ELCC of storage. Systems with "peakier" profiles—

characterized by shorter, sharper demand peaks—tend to extract more value from storage, as storage can be discharged precisely during these high-demand hours. In contrast, flatter profiles, where demand is relatively constant throughout the day, reduce the effectiveness of storage for peak shaving, thereby lowering ELCC. As per Figure 3, in Ontario, storage ELCC was observed to be lower in winter because daily load profiles are typically flatter compared to summer. This is attributed to several factors:

- Adoption of electric vehicles (EVs): Managed EV charging practices encourage charging during non-peak periods, flattening the daily system demand profile across all seasons. However, in winter, higher EV charging demand further amplifies this flattening effect.
- Incremental electrification of building heating and cooling: Electrification of residential and commercial space heating and cooling, driven by policies like the Toronto Green Standard Version 6, contributes to higher off-peak energy consumption. This further flattens winter demand, as heating demand is more evenly distributed throughout the day and night.
- Distinct summer cooling demand: Summer load profiles continue to be shaped by significant cooling loads, which operate primarily during daylight hours and contribute to identifiable and pronounced daily peaks in the afternoon and evening. This contrasts with winter heating demands, which are steadier across a 24-hour period.
- Less solar generation in winter: Compared to summer, there is significantly less solar generation output in winter. This reduces the availability of solar capacity during daylight hours, which affects both the timing and magnitude of surplus capacity available for storage charging, further flattening the demand profile.
- Greenhouse sector activity: The lighting demands in this sector primarily occur during nighttime, which contributes to a flatter winter demand profile, reflecting flatter winter profiles compared to summer.

Together, these factors highlight why winter load profiles are flatter than summer, limiting opportunities for storage to discharge during distinct peak periods and reducing its overall ELCC.

- **Optimal Integration of Renewables and Storage**: The synergy between solar/wind and storage creates an optimal hybrid configuration, where the combined impact on reducing peak needs is more effective than the individual contributions of each resource. For example, solar generation peaks during the day, creating a surplus that can be stored and dispatched later, when net demand peaks in the evening. This combined solar-storage approach smooths out fluctuations in both supply and demand, optimizing the ELCC of storage. However, as the levels of variable generation and storage both increase, careful management is required to prevent diminishing returns in ELCC due to excessive periods of surplus power with limited opportunities to discharge.

Implications of this Finding: These observations demonstrate the importance of considering the underlying system composition when evaluating the ELCC of storage. Systems with moderate levels of baseload generation can initially support higher ELCC values for storage, as the stability provided by baseload allows storage to focus on peak shaving and reliability enhancement. However, adding excessive baseload generation relative to demand can reduce storage ELCC, as it limits the opportunities for storage to discharge effectively during distinct peak periods. Similarly, in systems with elevated levels of renewable penetration, there is an optimal point where storage complements renewables most effectively. Beyond this point, the ELCC of storage declines due to over-generation during low-demand periods and reduced discharge opportunities during peak periods. As system conditions evolve, the ELCC of storage remains dynamic; the same storage unit may exhibit different ELCC values depending on factors such as demand growth, resource mix, and seasonal load profiles. Importantly, storage cannot function optimally as a standalone resource; it must be balanced with energy-producing resources that provide a stable supply, enabling storage to operate effectively during peak periods and maximize its contribution to system reliability. System planners and stakeholders should carefully balance the integration of baseload, renewable generation, and storage to maximize the reliability benefits of each resource.

To reflect these dynamics, capacity qualification frameworks, as part of the broader procurement process, should evolve alongside changes in both the system mix and demand forecast. Procurement designs should reflect technical considerations, such as storage duration, efficiency, and its role in complementing new energy-producing resources, to ensure storage is appropriately credited for its growing role in addressing emerging reliability needs. By tailoring capacity qualification methodologies within procurement processes to align with the evolving energy landscape, storage can be optimized to support system reliability.

Summary: the ELCC of storage is extremely sensitive to the underlying generation mix, demand profile, and changing system conditions. While moderate levels of additional baseload generation can improve ELCC through a stable supply, excessive baseload may reduce the effectiveness of storage. Similarly, renewable generation can initially enhance ELCC by providing surplus capacity for charging, but at high penetration levels, it can limit ELCC due to saturation effects. Additionally, "peakier" load profiles, such as those observed in summer, allow for higher ELCC values, while flatter profiles, like those in winter, reduce storage's peak-shaving effectiveness. As the system evolves, the ELCC of the same storage unit can vary significantly, reflecting the dynamic nature of storage ELCC in response to shifting demand and resource conditions. Ultimately, storage alone cannot meet all capacity needs; it must be deployed in conjunction with a balanced mix of baseload and renewables relative to demand to fully leverage its potential. This integrated approach to system composition optimizes the reliability contribution of each resource within Ontario's evolving energy landscape. By allowing capacity qualification frameworks to adapt in response to these changes, system planners can maximize the reliability contribution of storage and align its valuation with the evolving grid. This would ensure that storage continues to play an integral role in meeting Ontario's future energy and reliability needs.

5. Conclusion and Key Findings

The study concludes that energy storage can play a significant role in Ontario's growing low-carbon system. However, the Effective Load Carrying Capacity (ELCC) of storage can be influenced by a complex interplay of factors that require strategic deployment and balancing with other resources. Moreover, the ELCC of storage is dynamic, meaning that its reliability value can vary significantly over time due to changing system conditions such as demand growth, generation mix evolution, and fluctuations in surplus capacity availability. This dynamic nature highlights the need for continual evaluation to align storage deployments with Ontario's system requirements.

5.1 Key Findings and Implications:

5.1.1 Decline in ELCC with Increased Storage Penetration

Adding more storage to the system while holding the duration constant yields diminishing reliability benefits, primarily because fixed-duration storage units cannot sustain output across extended peak periods. Moreover, higher storage penetration leads to increased competition for surplus capacity, limiting the ability of each storage unit to fully charge.

Implications: A balanced deployment strategy that integrates storage with energy-producing resources is essential. By aligning storage deployment with available surplus capacity and peak demand characteristics, system planners can avoid oversaturation and optimize system reliability. Keeping all else constant, capacity qualification frameworks should assign progressively lower capacity credits to storage as penetration rises, reflecting diminishing marginal contributions. Additionally, securing a diverse portfolio of capacity resources, including longer-duration storage and other complementary technologies, can help address the declining value of incremental storage as penetration grows. This diversity ensures that the system can reliably meet evolving needs while maximizing the value of all resources.

5.1.2 Longer Duration Needed for Larger Storage Units

As storage penetration increases, the duration must also extend to maintain ELCC effectively. While short-duration storage is suitable for brief demand peaks, larger units require longer durations to support sustained reliability.

Implications: Stakeholders should carefully consider both storage size and duration based on demand patterns. For systems with extended high-demand periods, investing in long-duration storage may be necessary, while shorter durations are optimal for systems with brief, intense peaks. This strategic selection of duration can improve cost-effectiveness and operational value. Capacity qualification should credit longer-duration storage appropriately in scenarios where extended reliability contributions are needed. Furthermore, a diverse mix of storage configurations, with varying durations and characteristics, ensures that the system can address a range of reliability needs effectively, enhancing overall resilience and flexibility.

5.1.3 Impact of System Composition on ELCC

The ELCC of storage is sensitive to the mix of baseload and renewable generation in the system. Increasing levels of baseload enhance ELCC by providing consistent power for charging and stability during peak periods up to a point. However, excessive baseload can reduce storage ELCC by limiting opportunities for peak-shaving. Similarly, renewables enhance ELCC up to a saturation point, beyond which over-generation during low-demand periods reduces the incremental value of storage. In such cases, storage may not have room to charge further from the excessive capacity or may have fewer opportunities to discharge during the subsequent high-demand periods. Additionally, a "peaky" demand profile (common in summer) allows for higher ELCC values, while flatter winter profiles reduce storage's effectiveness in peak shaving.

Implications: Capacity qualification processes should account for the interplay between storage and system composition, as well as evolving demand forecasts. Additional energy-producing resources, including renewables and baseload, can enhance storage's qualification value when integrated strategically. Storage must be deployed alongside a balanced resource mix to optimize system reliability. Moreover, as load grows in a balanced system, it provides new opportunities for storage to discharge during high-demand periods, effectively contributing to system reliability. This ensures that storage remains a valuable and adaptable resource in Ontario's evolving energy landscape.

5.2 Next Steps

To optimize the contribution of storage to system reliability and decarbonization, the Independent Electricity System Operator (IESO) will consider the following next steps in planning, procurement, and operational approaches:

- **Refine Capacity Qualification Frameworks**:
  The IESO should ensure that capacity qualification methodologies account for diminishing marginal capacity contributions at higher storage penetration levels, appropriately credit longer-duration storage for its ability to sustain reliability during extended peak periods and adjust for the dynamic impacts of changing system composition. These frameworks should evolve alongside system needs to reflect the interaction between storage, baseload, and renewable resources.
- **Promote Diversity in Storage Configurations**:
  Recognizing that storage systems with varied durations, sizes, and technologies provide distinct reliability benefits, the IESO should encourage a diverse portfolio of storage configurations. This approach ensures that the system can address a wide range of reliability challenges, from short-term peak demands to prolonged periods of high demand, while maximizing cost-effectiveness and flexibility.
- **Incorporate System Growth and Demand Evolution**:
  As the energy system grows and demand increases, the IESO should identify emerging opportunities for storage to discharge during high-demand periods. This involves assessing the potential of storage to meet future reliability needs in the context of increased electrification, industrial demand, and renewable integration.
- **Align Procurement Processes with System Needs**:
  Procurement strategies should be designed to address evolving system requirements, emphasizing the value of storage in complementing baseload and renewable generation. Integrating storage into the system with these resources ensures that the grid can manage variability, meet peak demands effectively, and optimize the use of clean energy, supporting Ontario's decarbonization and reliability goals.

- **Conduct Ongoing Assessments of Storage Value**:
  Given the dynamic nature of storage's capacity contributions, the IESO should regularly assess the ELCC of storage resources. These assessments should inform procurement design and ensure that storage resources are aligned with the system's evolving reliability and decarbonization goals.
- **Prepare for Seasonal Variability**:
  The IESO should develop strategies to address seasonal differences in storage performance, such as ensuring adequate capacity during winter months, when load profiles are flatter.

By adopting these steps, the IESO can ensure that energy storage resources are deployed strategically, reflecting their dynamic role in enhancing reliability, supporting decarbonization, and meeting the province's growing energy needs. These actions will also position Ontario as a leader in leveraging energy storage to build a more resilient, sustainable, and cost-effective energy system.

Appendix 1 – Metrics Used

Metric	**Unit**	**Definition**
Loss of Load Expectation (LOLE)	Days/Year	The expected number of days per year for which the available resource capacity is insufficient to serve demand
Hourly Loss of Load Expectation (LOLH)	Hours/Year	The expected number of hours per year for which the available resource capacity is insufficient to serve demand
Loss of Energy Expectation (LOEE)	MWh/Year	The yearly summation of all hourly deficits in MWh
Effective Load Carrying Capacity (ELCC)	%	Reduction in perfect capacity need with the addition of storage as a percentage of storage penetration

Appendix 2 – Frequently Asked Questions

What is the ELCC of storage?

The ELCC of storage depends on multiple factors, including the system's resource mix, load profiles, and the size and duration of the storage. There is no one-size-fits-all answer, as the ELCC is influenced by the specific characteristics and needs of the electricity system in which the storage operates. Moreover, the ELCC of a storage unit is dynamic and can vary depending on changing system conditions, such as shifts in demand patterns, generation mix, and the availability of other resources. The same storage unit may exhibit different ELCC values in different scenarios, reflecting the adaptability of storage to evolving system requirements.

Is there a level of storage penetration where the ELCC drops off?

Yes, holding all else constant, the marginal ELCC of storage diminishes as storage penetration increases, as shown in Figure 4. This is due to diminishing marginal returns, as more storage saturates the system's ability to utilize surplus energy efficiently. Over time, the incremental reliability benefit of adding more storage declines. Additionally, prolonged periods of high demand further challenge storage's effectiveness because energy-limited resources may exhaust their capacity before the demand subsides. Without sufficient duration or complementary resources to recharge during these periods, storage struggles to maintain its contribution to reliability, amplifying the diminishing returns at higher penetration levels.

Does the ELCC increase as duration increases?

Yes, as depicted in Figure 5, for a given storage size, the ELCC increases as duration increases because longer-duration storage can cover more extended periods of peak demand. However, if storage size increases, the duration also needs to increase to maintain the same ELCC. This reflects the balance required between storage capacity and the duration it can discharge effectively. It is important to note that the increase in ELCC is not linear; doubling the storage duration does not result in a doubling of ELCC. Instead, the ELCC gain diminishes with increasing duration as the storage system begins to saturate its ability to meet the reliability needs of the grid. This diminishing return highlights the importance of optimizing both the size and duration of storage investments.

Does ELCC increase if more variable generation is added to the system?

Yes, adding wind or solar generation can initially increase storage's ELCC by creating surplus energy for charging. However, as variable generation levels rise, the system can reach a point of saturation, reducing the incremental value of storage. This phenomenon is show in Figure 9. This effect depends on the resource mix and the net demand profile, with peakier profiles yielding better storage value than flatter ones.

What factors impact the ELCC of storage?

Several system-level and storage-specific factors affect the ELCC of storage:

System-level factors:

- **Load Magnitude and Shape**: The size and variability of electricity demand over time. Systems with "peakier" load profiles (sharp, short demand peaks) allow storage to discharge effectively during high-demand periods, increasing ELCC. Flatter profiles reduce opportunities for peak shaving, lowering ELCC.
- **Resource Mix** (Renewables vs. Baseload): The types of energy generation resources in the system. Variable renewables like wind and solar enhance ELCC by providing surplus energy for charging, but excessive penetration can lead to over-generation during low-demand periods. In such cases, storage may not be able to absorb more energy because it is already fully charged, and fewer opportunities for subsequent discharge during peak periods further reduce its incremental value. Baseload generation initially complements storage by stabilizing the system but may reduce ELCC if excessive, as it flattens residual demand profiles.
- **Transmission Congestion**: Bottlenecks in the grid can limit storage's ability to charge efficiently or deliver energy where it is needed most, reducing its reliability contribution and ELCC.

Storage-specific factors:

- **Penetration**: The total amount of storage capacity connected to the system. Higher storage penetration can lead to diminishing marginal ELCC as additional units compete for the same surplus energy and discharge opportunities.
- **Duration**: The length of time a storage unit can discharge at full capacity. Longer-duration storage can sustain output during extended demand peaks, increasing ELCC. However, the benefits diminish beyond a certain point as most reliability needs are already met.
- **Technology**: The type of storage system, such as lithium-ion batteries or CAES (Compressed Air Energy Storage). High-efficiency technologies like lithium-ion batteries provide faster response and higher ELCC, whereas lower-efficiency technologies like CAES may offer reduced ELCC due to greater energy losses.
- **Charge/Discharge Rates**: The speed at which storage absorbs or delivers energy. Higher charge and discharge rates improve ELCC by enabling storage to respond quickly to system needs during periods of surplus energy or peak demand.
- **Round-Trip Efficiency (RTE)**: The percentage of energy retrieved compared to energy stored. Higher RTE means less energy is lost during charging and discharging, improving ELCC. Lower RTE reduces the storage system's overall contribution to reliability.
- **Response Time**: The speed at which storage reacts to changes in demand or supply. Faster response times enhance ELCC by allowing storage to address sudden changes in demand or supply, particularly for short-term reliability needs.
- **Cycle Life**: The number of charge/discharge cycles a storage system can complete before degradation. Storage technologies with longer cycle lives can operate more frequently without degradation, sustaining high ELCC over time.
- **Operational Profile**: How and when storage charges and discharges. Flexible operational strategies, such as charging during surplus renewable periods and discharging during demand peaks, maximize ELCC.

Can the ELCC of storage be increased? How would additional baseload generation affect it?

The ELCC of storage can increase with longer duration or changes to system conditions, such as adding more baseload/variable generation up to a point of saturation beyond which the ELCC decreases, as demonstrated in Figure 9. However, the diminishing returns from storage penetration persist regardless of these improvements.

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