

Evaluating the Benefits of Long Duration Storage: Modeling and Analysis of a Seasonal Energy Storage System against a Decarbonizing Power System

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Abstract

Long Duration Energy Storage (LDES) will play a critical role in successful decarbonization of the electric sector. LDES is needed to manage weather-driven energy needs and resources across time and will significantly reduce the required investment in energy production and transmission.

LDES benefits accrue at multiple time scales ranging from days to seasons to years. An adequate evaluation of these benefits is a challenging analytical task as it requires the use of multiple modeling techniques: (1) Capacity Expansion Modeling to size and site LDES based on its impact on future generation and transmission; (2) Operational Scheduling to ration use of storage inventory across time; and (3) Energy and Ancillary Services Modeling to emulate storage operations at daily and intra-day timescales.

In this paper, we discuss the coordination of these three models to assess LDES within a large regional electricity market. Our methodology uses sequentially optimized and coordinated decision cycles. From this, we provide a range of simulated metrics assessing benefits of a large-scale LDES at various time scales.

Keywords: Long Duration Storage Modeling, Grid Decarbonization, Market Operation.

1. Introduction

1.1. Background

Long Duration Energy Storage (LDES) is broadly defined as any technology that can be deployed competitively to store energy for prolonged periods and that can be scaled up economically to sustain electricity provision, for multiple hours, days, or even weeks, and has the potential to significantly contribute to the decarbonization of the economy [1]. In the United States, the Department of Energy has identified LDES as one of the key focus areas in meeting the current administration’s targets for carbon free electricity and net zero emissions [2]. Storage duration

is commonly used to categorize the class of commercial storage with the Department of Energy categorizing them as short duration (0-4 hours), Inter-day (10-36 hours), Multi-day (36-160 hours) and seasonal (160+ hours), noting that these definitions remain subject to discussion [3].

This paper discusses a methodology to model a fully integrated seasonal LDES into the power system based on a series of specifically designed, co-dependent power systems simulation models. It presents the outcomes of an economic benefit analysis and addresses some of the key policy and operational considerations that help ensure the successful deployment and integration of such a resource.

1.2. Measuring Benefits of Storage

An LDES can be considered successfully integrated if it is able to reliably demonstrate benefits at different levels.

1.2.1. Societal Benefits. Societal benefits typically reflect reductions in systemic costs associated with overall energy supply. These include changes to costs associated with capital investments, operation & maintenance (O&M) as well as costs associated with energy production. The production cost includes the cost to serve load from supply within the footprint, adjusted for sales revenues and costs for off-system purchases.

Societal benefits require a counterfactual “but for” case against which the changes are measured.

1.2.2 Storage Owners Benefits. The benefits to storage owners are the net revenues accrued in the markets for capacity, energy, and ancillary services.

Evaluation of benefits requires coherent modeling of storage participation in all markets and of price formation mechanisms.

1.2.3. Challenges. Benefits accrue at different time scales that are not properly captured within a single modeling framework and require the use of several models. That is because no single model today is

capable of accurately capturing all benefits accrued at all times.

The use of these models should be coordinated. That coordination should be conducted consistently with the market design framework. However, that framework is absent from today's markets not yet designed for LDES integration.

In this paper, we review several coordination mechanisms and compare the impact of such mechanisms on both metrics.

The critical objective of this paper is to explore and identify market design challenges.

1.3. Analysis Overview

The impacts of integrating an LDES begin by studying the impacts on long-term investment decisions through a **capacity expansion model**. This model captures the impacts to the changes in long term capacity mix affected by the addition of the LDES resource, such as the ability to provide firm capacity toward resource adequacy needs enabling the retirement of old fossil generators, as well as the ability of a system to better absorb renewable resources by reducing curtailments in low-load periods and the ability to provide dispatchable energy during peak periods. Something that is of growing importance in systems that are driven by decarbonization goals.

The next step is to schedule the operation of the LDES through a specially designed **storage rationing model (SRM)**, which enables the economic and optimal management of storage inventory over longer periods of time while remaining sensitive to systemic changes that drive the price signals for the storage operator. The key output of this model is a trajectory for the operation of the LDES resource that would advise its scheduling in the economic dispatch modeling.

Finally, the economic benefits of fully integrating this resource are studied by measuring various parameters coming out of a traditional **energy and ancillary services model (E&AS)** which captures its interaction with hourly nodal spot prices based on security constrained unit commitment and economic dispatch [4].

The analysis conducted by the authors is based on integrating an LDES resource into the Independent System Operator, New England (ISO-NE) power system, and utilizing the Hydro Quebec (HQ) system as a reservoir for storage of the long-term energy. The analysis utilizes the ENELYTIX[®] modeling system which provides highly robust yet flexible analytical tools to simulate power system operations, applying parallel processing on the cloud.

3. Modeling Environment

3.1. Power Market

The analysis for LDES integration was carried out based on the Independent System Operator New England (ISO-NE) footprint with the Hydro Quebec (HQ) system serving as a long duration storage element, connecting to ISO-NE through a high voltage direct current (HVDC) intertie. It is noted that the methodology applied here was developed for the specific market regions and technologies as a case study but provides a broader framework that could be applied to any power market or long duration technology that possesses comparable operational characteristics.

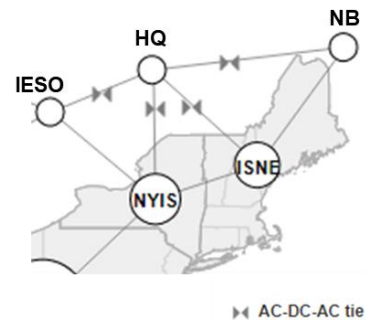


Figure 1. Illustration of the ISO-NE (ISNE) system and its interconnections with the neighboring regions including HQ.

ISO-NE consists of six US states comprising a population of roughly 15.1 million and an annual load of 114 TWh in 2023 [5]. The system generation mix is relatively balanced with fossil-based generation making up half of the total generation mix with the balance served through nuclear and renewables. The six states forming ISO-NE have aggressive policy goals for decarbonization reflected in the renewable portfolio standards and decarbonization goals through 2050 [6]. The New England States plan to achieve these goals through procurement of renewables supported by storage with targeted procurements for offshore wind being set at 11 GW by 2040 [6]. The impact of decarbonization is also reflected in the states' projected load growth as electrification of heating and transportation increases, motivating needs for increased transmission to prevent bottlenecks caused by the siting of future clean energy resources against the location of load centers [7]. The growth in electrification is expected to reflect on the system peak with ISO-NE expected to transition from a summer peaking system to a dual peaking system [8]. The combination of cyclic seasonal variation in demand

and a high degree of renewable penetration creates favorable conditions for the integration of a seasonal LDES [9].

The HQ system consists of a generation mix that is 99% renewable [10], relying on its vast network of interconnected hydro-generation facilities, HQ is able to supply zero-emission dispatchable energy to serve its local demand alongside significant exports to neighboring regions through various AC and DC interties. It is noted that the HQ system is connected to system operators that form part of the eastern interconnection, but HQ is not synchronized with them. Figure 1 provides an overview of these ties.

Hydropower is an energy limited resource with the operators having the ability to regulate flows against both need and price signals by holding predictable flows of water behind large reservoirs or series of reservoirs. To that end, electricity generated via hydropower may, within limits, be substituted by an alternative source, such as imports from ISO-NE, at any point in time, resulting in the withholding of quantities of water that would have otherwise been used for power generation. This withheld water can then be released back at a later point in time, with the overall process representing a large virtual battery or LDES. Such an application of hydropower for seasonal use presents a unique use case compared to conventional pumped storage hydro that is considered more as a short-to-medium duration storage system and exists in New England.

3.2. Market Models and Scenarios

The analysis looks at two key metrics – the revenues from the operation of the LDES, and the systemic benefits to society through the integration of the resource in the system. The study of the latter metric involves the establishment of a counterfactual scenario where the storage system is absent. For the purposes of this analysis, the counterfactual scenario is called the “Base Case” and the scenario with the LDES is integrated is called the “Proposal Case.”

The modeling carried out uses a forward-looking projection of the ISO-NE system developed by the authors which represents a future with significant achievements of the states’ policy targets. The projection is based on numerous assumptions that align with similar policy modeling exercises being undertaken by ISO-NE [11]. The model includes the nodal representation of the power system including all front-of-the-meter generation obtained from the ISO-NE CELT Report [12], transmission topology obtained from FERC form 715 filings, and projections for commodities from S&P Global [13] and WoodMackenzie [14]. New York is represented as an

external area modeled as a balanced market with dynamic interchanges with ISO-NE, while existing ties to other external regions including New Brunswick and HQ are based on historic interchanges.

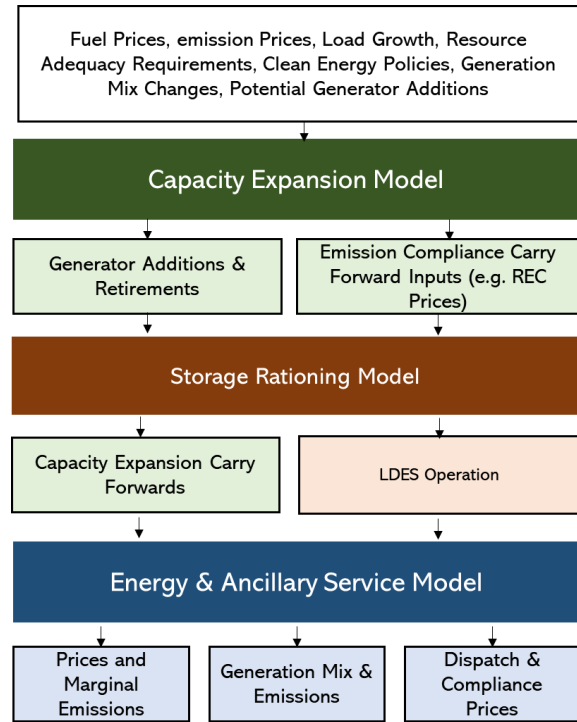


Figure 2. ENELYTIX Model Components

The analysis process required the development and running of three models – the capacity expansion, SRM, and the E&AS in a sequential manner where the outputs of one model would inform the inputs to the next as illustrated in Figure 2. Two parallel sets of models were set up for the Base Case and Proposal Case scenarios with the SRM being run only for the Proposal Case. Details of the SRM are covered in Section 3.

3.3. Overview of ENELYTIX® Simulation Software

The authors used the ENELYTIX® computer simulation software platform to simulate the operation of the New England and New York wholesale electricity markets for energy and ancillary services, forward capacity, and Renewable Energy Credits. ENELYTIX® develops internally consistent, detailed projections of prices in each of the above markets as well as the key physical parameters underlying those market prices such as capacity additions and retirements, energy generation by source, carbon

emissions, and natural gas burn. The two key modules are:

The Capacity Expansion model determines an optimal electric system expansion over a long-term planning horizon. In the study, the capacity expansion simulation was limited to ISO-NE. The module's function is to minimize the net present value of the total cost, i.e., capital, fuel, and operating, of the generation fleet serving the wholesale market within the ISO-NE electrical footprint subject to resource adequacy, operational, and environmental constraints. Resource adequacy constraints are specified in terms of installed capacity requirements ("ICR") for the ISO-NE system as a whole and for reliability zones within ISO-NE. Environmental constraints include requirements for state-by-state procurement of electric energy generated by renewable resources, as well as emissions requirements.

The Energy and Ancillary Services (E&AS) model simulates the Day-Ahead and Real-Time market operations within the footprint of the ISO-NE and New York Independent System Operator (NYISO) power systems and markets. The module implements chronological simulations of the Security Constrained Unit Commitment (SCUC) and Economic Dispatch (SCED) processes, as well as the structure of the ancillary services in ISO-NE and NYISO markets.

Both models use the common database structure of Power System Optimizer (PSO) market simulator developed by Polaris Systems Optimization, Inc.

4. Modeling Long Duration Storage

4.1. The Storage Rationing Model

To facilitate the modeling of the LDES, the authors configured ENELYTIX® as a Storage Rationing Model (SRM). The primary objective of this model was to establish an intermediate step uniquely suited to solve for optimal LDES dispatch in a manner that is not achievable by either the capacity expansion module or the E&AS module.

The capacity expansion model is a cost minimization optimization equipped to make optimal economic decisions over multiple decades but relies on temporal simplifications resulting in a non-chronological representation that is vital to energy storage optimization. The E&AS model on the other hand offers detailed chronological unit commitment and economic dispatch, but is limited in its lookahead, which is typically limited to 24-72 hours. Attempting to optimize LDES by either augmenting the temporal resolution of the capacity expansion or extending the lookahead for the energy and ancillary services model proves to be computationally demanding.

The SRM is configured as a simplified version of the E&AS model, retaining the core algorithms that simulate nodal least cost optimization of the power system within the ISO-NE and NYISO footprint. It computes the chronological hourly dispatch with select simplifications, namely the relaxation of integer constraints such as unit commitment constraints and multi-cycle dependency reflecting distinct operational rules within ISO-NE and NYISO systems. This simplification is necessary to optimally ration the use of the LDES over a long optimization horizon.

The SRM is a rolling horizon optimization. Each step of that optimization evaluates the period of 1 year, or 8760 hours and is repeated periodically over the solve, or delta-time period. Figure 3 illustrates the cycle setup for a 1-year period that is solved in succession of 1-year horizons. The resulting solution is constructed as a concatenation of solution segments over solve periods of each rolling horizon step.

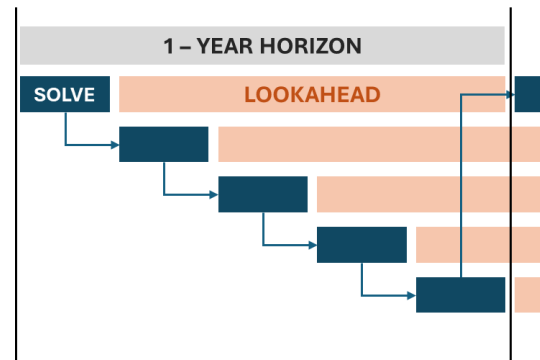


Figure 3. Annual Solve Cycles in the SRM

4.2. Representation of the LDES in Power Market Models

The HQ virtual LDES is represented as a point injector with a nameplate capacity representative of the size of the transmission line, interconnecting at a specific interconnection point within the ISO-NE transmission system. For purposes of this analysis, the authors did not iterate the point of interconnection but instead used an existing intertie location to model the injection and extraction of energy with appropriate transmission upgrades that would be capable of handling the additional flows.

Line losses associated with HVDC converter station and HQ system losses were used to determine cycling losses for the LDES, i.e., the reduction in energy from storage discharge relative to the energy used to charge. The analysis assumed an infinite volume of storage is available and that the storage would return to the same charge state over a 1-year period.

The capacity expansion model uses a simplified representation of the LDES due to limitations on representation of chronological modeling. The models ensure that any use of energy from storage is compensated by corresponding quantities of charge and storage cycling losses. For purposes of this analysis, the capacity contribution of the storage was assumed to be zero.

The SRM and the EAS model utilize traditional representation of storage resources whose basic governing equations are listed below.

State of Charge (SOC) Equation – Monitors and limits the amount of energy held in storage in each hour.

$$s_t = s_{t-1} + \varepsilon u_t \tau - q_t \tau; t = 1, \dots, T \quad (1)$$

Discharge MW Limit – Limits the maximum discharge from the storage each hour to the unit size.

$$0 \leq q_t \leq Q^{max} t = 1, \dots, T \quad (2)$$

Charge MW Limit – Limits the maximum charging of the storage to the unit size.

$$0 \leq u_t \leq U^{max} t = 1, \dots, T \quad (3)$$

Storage Capacity Limit – Limits the maximum possible storage capacity at any given point in time.

$$0 \leq s_t \leq S^{max} t = 1, \dots, T \quad (4)$$

Gross price (storage acquisition costs) – market price spent per incremental unit of stored energy

$$\gamma_t^{gross} = \frac{1}{\varepsilon} \lambda_t \quad (5)$$

Net price (storage discharge revenue) – net price received per incremental unit of discharged energy

$$\gamma_t^{net} = (\lambda_t - c_t^q) \quad (6)$$

Marginal Value of Energy in Storage (VEIS) – shadow price for the state of charge equation (1), represented as ψ_t

Where,

s = Stored Energy

ε = Storage Efficiency

u = Charge

q = Discharge

ψ_t = VEIS/ShadowPrice

γ_t^{gross} = Gross Price

γ_t^{net} = Net Price

ε = Storage Efficiency

λ = LMP

c = Cost of Storage

VEIS at a specific time interval equals the reduction/increase of the value of the objective function due to the infinitesimal reduction/increase of stored energy that occurs at that time interval.

In effect, the storage compares the VEIS to the Gross and Net prices which are reflective of storage parameters and market prices, triggering it to charge, discharge, or do nothing. These governing equations for storage capture the duality principle of linear programming where minimizing the system cost of operating the storage can also be viewed as maximizing the revenues of the storage unit.

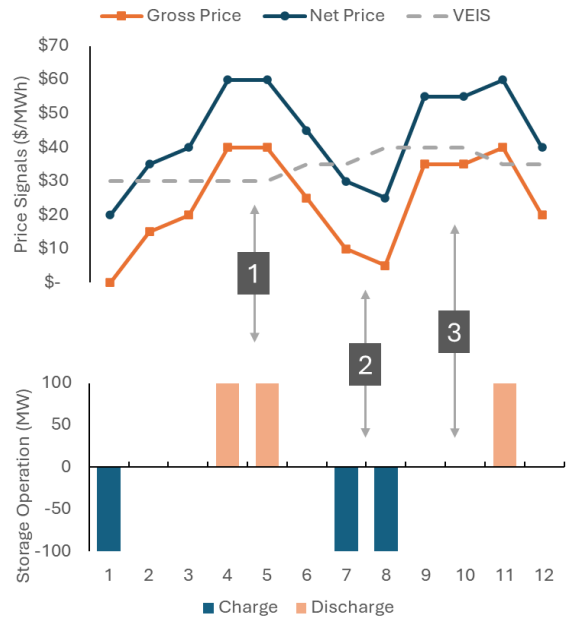


Figure 4. Illustrative operation of Storage against VEIS price signals.

Figure 4 illustrates the storage operation for a sample set of hours against the price signals when (1) discharge when VEIS is below net price, (2) charge when VEIS is above Gross Price, and (3) do nothing with VEIS is between Gross and Net Price.

5. Modeling Process Discussion

5.1. The Capacity Expansion Process

The capacity expansion process across the Base Case and Proposal Case establishes two future mixes of resources with and without the integration of LDES. This allows an assessment of the impact of the LDES over the longest time period, i.e., over decades.

Figure 5 illustrates the transitioning in capacity mix in ISO-NE at 5-year intervals, highlighting the

significant growth in renewables and storage requirements to meet the constraints and requirements of a decarbonized system. Both capacity expansion models enforce the decarbonization goal as a carbon cap which produces an implied carbon cost that is applied to carbon producing units in subsequent models. This carbon price drives the seasonal variation in energy prices over the study period.

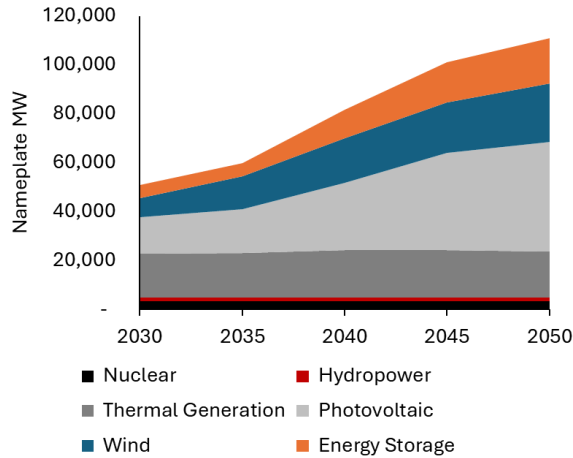


Figure 5. Projected Mix of Resources in the Base Case Model.

The contribution of LDES toward resource adequacy for purposes of this study is assumed to be zero although studies suggest the capacity credits can be as high as 100% [3].

Resource adequacy constraints in both the models binds similarly with no notable differences in retirements, however the Proposal Case model adds greater renewable resources to supply energy consumed by cycling losses of the LDES which aligns with the expectation of the system being able to better absorb otherwise curtailed renewables.

5.2. The Storage Rationing Model Process

The Storage Rationing model enables the assessment of benefits of the LDES over moderately long periods, i.e., seasons.

Having established the structure of the SRM that ensured reasonable results and runtimes, the modeling process focused on establishing physical parameters of the long duration storage to assure a consistent and quantifiable operation year-on-year. This meant assuming a finite maximum storage capacity as well as an initial storage charge state relative to the storage maximum capacity. This storage state would be the point at which the state of charge (SOC) of the LDES would be at the beginning and the end of the annual analysis.

Numerous iterative simulations of the SRM were conducted varying storage sizes, cycle start seasons, as well as simulations years at storage parameters that would result in annual cyclic operation. The values resulting from this process set the storage capacity to be equivalent to approximately 1,250 hours of storage with an initial charge state to be at 60% of the maximum storage capacity.

Figure 6 provides a trajectory of the storage SOC over a sample winter peaking year as a percentage of its max value. The chart also provides monthly average prices as a point of reference to understand the seasonality in prices which drive the storage scheduling.

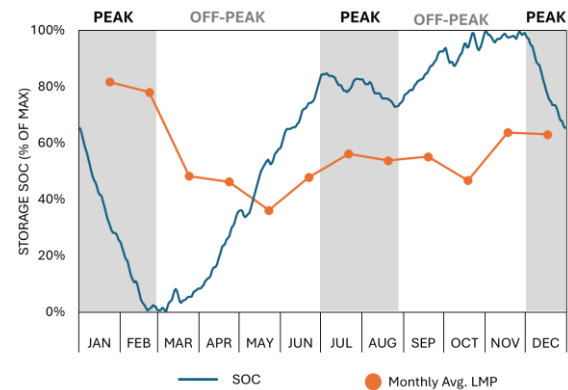


Figure 6. Seasonal Operation of the LDES

The SRM-optimized operation of the LDES demonstrates remarkable responsiveness to seasonal price variations, in alignment with the expected behavior.

- Beginning at a charged state, the system dispatches to reduce high winter prices through February.
- Following that, the LDES stays at a relatively consistent SOC demonstrating intra-day and intra week interactions after which it charges aggressively over the shoulder period where prices are at their lowest in the year.
- The LDES remains at its highest SOC during the summer peak where it only partially discharges. This partial discharge is informed by the second shoulder period that has slightly higher prices than the first, but also ensures storage levels remain high for the upcoming winter peak.
- The LDES charges over the shoulder period and starts discharging over the winter.

This cycle repeats each year. The key drivers to such behavior are the underlying energy prices which depress over the shoulder periods against a dual peaking system. In time, the load growth and high

penetration of renewables increase the seasonal price separation, further incentivizing the price arbitrage seen by the LDES operation.

While not precise, the SRM also provides an estimate of the expected revenues for the operation of the LDES. From the standpoint of the storage operator, it is imperative that the cyclic operation of storage result in net positive revenue, i.e. the total revenues generated from sale of stored energy, equal to the hourly discharge MWh multiplied by the nodal price in that hour, be greater than the cost of charging the storage unit, equal to the hourly charge MWh multiplied by the nodal price in that hour. This is especially relevant when considering the cycling losses of storage that need to be compensated by the price arbitrage.

Figure 7 charts the state of charge of the LDES (shaded area) against the calculated cumulative revenues from annual operation (black line) as a percentage of their respective maximum values. The overall movements in the trajectory of revenues is an inverse of the SOC as can be expected. It is noted that while the SOC starts and ends at the same point, the revenues grow from zero in the beginning to maximum at the end of the winter peak, cycle through the remaining of the seasons and ending with a net positive revenue close to 80% of the maximum value, demonstrating effective price arbitrage.

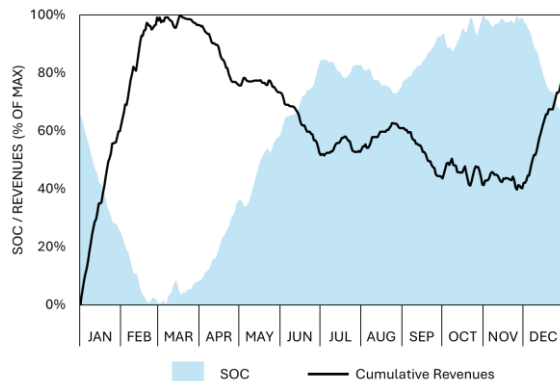


Figure 7. Operation & Revenues of the LDES

Thus, the resultant rationing profile obtained from the SRM not only reflects the expected seasonal behavior but also demonstrates positive net revenues that can be expected to reduce system supply costs by supplying energy during stress periods and charging during slack periods.

Individual SRM were run for each year in the analysis period that would be reflective of charge profiles suited to the system mix and prices associated with that year.

5.3. The Energy & Ancillary Services Modeling Process

The E&AS models serve to simulate the granular, nodal hourly simulations of the energy market to fully assess the impacts of integrating the LDES at the shortest possible time horizon. The annual storage rationing profiles obtained from the SRM are fed into the E&AS model as an operating guideline to overcome the myopic lookaheads that are embedded in the formulation of a traditional production cost model.

The E&AS models should theoretically demonstrate similar or higher level of benefits than those reported out of the SRM because of additional price fluctuations caused by adding back constraints associated with unit commitment and transmission, as well as further intra-day hourly optimizations due to the more granular hourly timesteps. To facilitate such intra-day optimizations, an additional constraint was imposed on the LDES that would ensure that the end of day (EOD) SOC in the E&AS would exactly match the EOD SOC in the SRM. This achieves two objectives:

1. It ensures that the broader trajectory of the LDES aligns with the optimal seasonal behavior developed in the SRM model that is otherwise not visible to the E&AS model.
2. It provides room for the E&AS model to utilize the LDES as short-term storage in the 24-hour periods within EOD constraints.

During the implementation of the SRM profiles in the E&AS model, the authors observed notable variations in the estimates storage revenues resulting from varying the structure and data flows between the decision cycles of the E&AS model and tested different configurations that would represent a range of real-world operating scenarios, or cycle configurations.

6. Market Design considerations of Storage Scheduling in the E&AS Model

Before discussing the configurations in detail, it is important to establish the three key decision cycles implemented within the E&AS model run sequentially within the ENELYTIX® simulation model:

1. A System Cycle (SC) which is a simplified optimization cycle primarily used to establish interchange schedules between NYISO and ISO-NE systems.
2. Two Day Ahead (DA) scheduling cycles emulating Day-ahead markets in NYISO and

ISO-NE, subject to interchange schedules determined in the SC cycle

3. An Economic Dispatch (ED) cycle that uses commitment schedules from the prior DA cycles for system dispatch, interchange re-optimization, and price formation.

This paper will discuss five configurations of storage operation that reflect different perspectives and degrees of operational flexibility that could be applied to storage scheduling. These five configurations are summarized in Figure 8.

6.1. Cost Minimization [CM] Configurations.

The SRM and E&AS models are both cost minimization models whose objective is to minimize system costs. The trajectory of storage operation obtained from the SRM is based on that minimized cost and is expected to achieve comparable levels of cost minimization in the E&AS models.

However, each step of cost minimization in the SRM model is performed over a year-long optimization horizon whereas, the optimization in the E&AS model is performed over a 72-hours horizon covering a 24-hour day and a 48-hour look-ahead period.

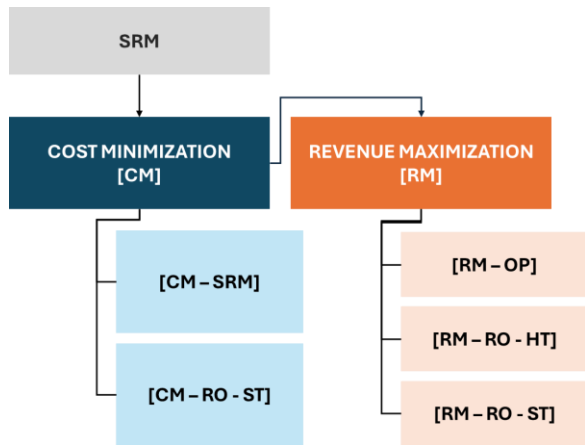


Figure 8. Configurations of the E&AS Cycle

The cost minimization configurations can be considered representative of scenarios where the system operator might schedule storage, in view of broader system economics.

6.1.1. SRM based EOD SOC Targets [CM-SRM]. This market design option assumes that the system operator would impose storage targets on the LDES derived from the SRM as hard constraints, forcing it to operate within the confines of the EOD schedules.

As the results of this configuration discussed in Section 7 indicate, both the storage revenues and adjusted production cost savings under these configurations were consistently lower than similar metrics observed in the SRM optimization. These observations suggest that the operational details reflected in E&AS model with unit commitment representation and differences in the duration of the optimization horizon could lead to significant degradation of storage profitability and in the reduction of adjusted production costs.

These gaps occur due to systemic differences in the model configurations where prices deviate significantly between the SRM and E&AS models due to differences in granularity and constraints, resulting in sub-optimal operation of the LDES in the E&AS model.

6.1.2. SRM EOD Targets Re-optimized Daily. Targets are Soft Constraints [CM-RO-ST] –

In the CM-RO-ST configuration, EOD schedules are used as hard constraints only in the SC cycle. As noted earlier, the optimization problem of that cycle is structurally identical to the SRM formulation except for the horizon length. From that cycle, the model now takes not only the interchange schedule, but also daily VEIS which are passed to the DA subsequent cycles. It is important to note that due to the difference in the optimization duration between SRM and the SC cycle, storage VEIS obtained from these two are different with the SC cycle VEIS much better reflecting the short-term market economics.

In the DA cycles, the EOD targets are set as soft constraints using daily VEIS as target violation penalties.

6.2. Revenue Maximization [RM] Configurations.

To provide yet another perspective on scheduling of storage, an alternative design was tested that assumes that the LDES scheduling is handled by the storage operator/owner thus pursuing the revenue maximization objective. To emulate this scenario, we assume that the operator forecasts LMPs at the storage node using the most advanced CM-RO-ST simulation and uses these LMPs to come with the profit maximizing schedule corresponding EOD targets. We further assume that those targets are communicated to the system operator. The system operator then uses these targets according to one of the three following alternatives.

6.2.1. Operate on Revenue Maximized hourly Schedule [RM-OP]. This configuration operates the

LDES based on the hourly schedule as determined by the revenue maximized optimization with no deviations permitted.

6.2.2. RM EOD Targets Re-optimized Daily. Targets are Hard Constraints [RM-RO-HT]. This configuration enforced EOD targets as hard constraints but permits deviations from the hourly schedules as long as the EOD targets are met.

6.2.3. RM EOD Targets Re-optimized Daily. Targets are Soft Constraints [RM-RO-ST]. In this case, similarly to the CM-RO-ST case, EOD hard targets are enforced only at the SC cycle whereas in the DA cycle targets are treated as soft constraints with penalties set by the SC cycle as daily VEIS value.

7. Results

Two key metrics are used to assess the performance of the LDES across the SRM and the six configurations tested as part of the E&AS cases. The first metric reviewed is the storage revenues which are summarized in Figure 9 and Figure 10 for an early year and a late year respectively. The revenues are indexed to the run reporting the highest value.

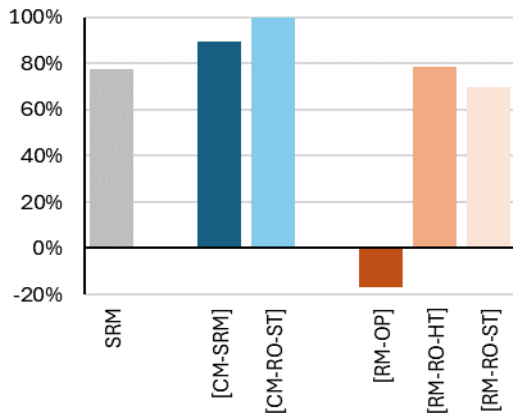


Figure 9. LDES Net Revenues (Early Year)

Both years follow a common narrative in terms of results – the cost minimized approach that has the greatest flexibility offers the highest operating revenues while the revenue maximized default run offers the lowest to the extent that it is a net cost in the early year. Adding more flexibility tends to produce better results overall, and the revenues in the best E&AS model outperform the SRM by about 20%.

The second metric calculates the reduction in adjusted production costs for the ISO-NE system, which calculates the total cost including variable O&M, fuel costs, emission costs and costs for imports

and calculates the net reductions relative to the Base Case E&AS model.

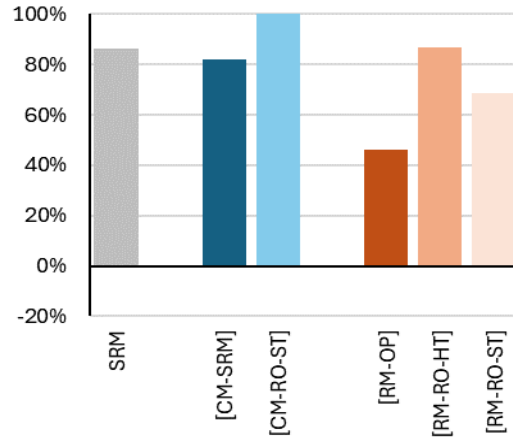


Figure 10. LDES Net Revenues (Late Year)

Figure 11 present comparable metrics comparing the adjusted production costs across the configurations.

The configuration that yields the highest and lowest net revenues show comparable ranking based on the adjusted production cost metric, indicating that incentives for a storage operator are expected to align with those of a system operator.

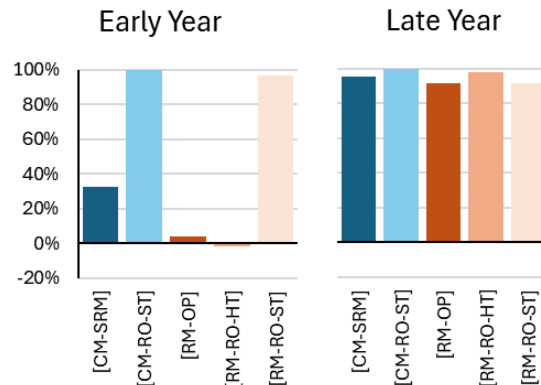


Figure 11. Adjusted Production Cost Savings

8. Conclusions

The paper and underlying analysis provide a pathway to modeling and assessing the benefits of integrating an LDES in a real-world system that is both robust and comprehensive albeit specific and stylized with numerous region and study driven simplifying assumptions.

More important than the numbers coming out of the analysis is the dependency of successful

integration of the LDES on the market design and operating regime of storage. This raises many critical questions that are to be addressed to ensure expected benefits are actually realized, such as who operates and schedules the storage, what data and tools need to be used to analyze the benefits, how does the scheduling impact the various stakeholders involved in the process.

The testing of cycle setups during the E&AS modeling process presents several takeaways.

1. The benefits of the LDES to the owners and to the society are heavily dependent on market design.
2. The actions of the system operator are crucial to the success of the use of LDES.
3. Developers and owners of the LDES need to be actively involved in the market process to ensure a mutually beneficial outcome.
4. The comprehensive evaluation of LDES is a complex problem that requires modeling of the system at multiple timescales, requiring consistent models and data.
5. It is important to represent operational details of the LDES adequately and accurately and their impact on price formation mechanisms.

A substantial further research and design efforts are needed to establish robust market participation rules for LDES.

The reals storage rationing process should be designed as a stochastic optimization problem that develops long-term rationing schedules based on the probabilistic forecasting of system conditions such as demand, output of weather dependent variable resources and other factors. The rationing could be re-evaluated on a daily basis as the new forecasts become available.

The coordination rule between storage operators and the system operator should be further explored and the right balance should be found between assuring alignment of benefits and operational efficiencies of the rationing process and daily and intra-day scheduling efforts. Co-optimization of numerous storage resources with the security constrained unit commitment and economic dispatch are becoming increasingly challenging from the computation perspective.

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