

Pump Storage in The Energy Mix: Building Resilience in an Intermittent Renewable Landscape

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Abstract

This study addresses wind energy intermittency with pumped water storage integration for power grid services in the City of Chicago. Our model utilizes an exogenous autoregressive wind forecasting model in conjunction with Model Predictive Control to analyze and understand energy supply and demand in the city of Chicago. When optimal pumping rate, release rate, and storage capacity are derived, simulation results indicate that up to a 51% reduction in unmet energy demand is expected compared to the case of using wind-driven energy exclusively. Increases in the frequency of optimization parameter calculations, along with the development of novel pumping and release infrastructure, yield further increases in model efficiency. The economic analysis of the proposed system reveals a Levelized Cost of Storage (LCOS) of \$498.87 per MWh, which, while higher than typical values for pumped storage systems, underscores the significant benefits in terms of large-scale energy storage and grid stability.

Introduction

The city of Chicago and the greater Chicago area experience high peak demand periods, with millions of people paying top dollar for reliable energy access. Our project focuses on the Chicago region for several reasons. First, as a major metropolitan area, energy needs and reliability are critical. Second, its terrain makes it highly suitable for both wind and water energy production. Finally, with its nickname as the “Windy City,” Chicago has decades of specific weather data available for forecasting purposes. The primary goal of our project is to evaluate the proposed pumped water storage system compared to the current business-as-usual scenario, ultimately determining whether the societal benefits, such as reduced carbon emissions and increased energy stability, outweigh the construction and operational costs.

The main challenge for renewable energy sources like wind and solar is intermittency — natural resources are not constant and fluctuate in their availability. Wind and solar energy generation depend on environmental factors outside human control, causing fluctuations that can disrupt grid stability and reduce resilience. Although our report focuses on wind energy, the same challenges apply to other renewable energy sources. Addressing this key issue is of utmost importance to ensure a stable and reliable power supply.

Common strategies of our modern day to address intermittency include battery storage, demand response programs, and grid interconnections. Though these solutions are common they do have their shortcomings. Lithium-ion batteries, while effective for short-term energy storage, have a high cost of production, limited resources for supply, and have limited lifespans. Demand response programs depend on user participation, which can be unpredictable, especially in densely populated areas. Grid interconnections require extensive infrastructure, making them challenging to scale quickly. For this reason we chose to explore another option, pumped water systems.

Pumped water storage for energy production involves pumping water from a lower reservoir to a higher one when excess energy is available and releasing it through turbines to generate electricity when demand is high and the renewables are not meeting said demand. Pumped storage provides a reliable, cheap, and on demand power source to alleviate intermittency concerns. In preliminary research water storage shined as the obvious option. Compared to other energy storage technologies, it stands out for its cost-effectiveness, scalability, and ability to store energy for extended periods. Other options like batteries and flywheels are suitable for short-duration storage but become economically impractical for long-term applications, especially in large cities with high energy needs. Hydrogen storage, while capable of long-term energy retention, faces challenges related to efficiency, infrastructure, and energy losses during conversion processes. With all this considered water pumped storage is a clear favorite for our implementation.

Our selection of pumped water storage is driven by its environmental, economic, and technical advantages. It offers a sustainable way to balance energy supply and demand while supporting the integration of renewable energy sources like wind. By reducing reliance on fossil fuels and enhancing grid stability, pumped storage can play a vital role in Chicago's transition to a cleaner, more resilient energy future.

Literature Review

The integration of pumped storage with wind energy has been extensively studied as a means to address the intermittency of renewable energy sources and enhance grid stability. This literature review explores various aspects of this integration, including technical feasibility, economic viability, and optimization strategies.

Pumped storage hydropower (PSH) is a well-established technology that has been used for decades to provide grid stability and energy storage. The combination of PSH with wind energy can significantly

improve the flexibility and reliability of power systems. Studies have shown that hybrid systems combining wind, solar, and pumped storage can achieve high levels of energy autonomy and sustainability. For instance, Simão and Ramos (2020) demonstrated that a hybrid system with integrated pumped storage and a reservoir volume of 378,000 m³ could ensure 72% annual consumption satisfaction, offering a technically feasible and cost-effective solution (1).

The economic feasibility of integrating wind energy with pumped storage has been a focal point of research. Wild (2011) conducted a techno-economic analysis of a wind farm coupled with a pumped storage facility, highlighting the potential for economic competitiveness. The study found that with pumped storage capital costs below \$1.53 million per MW and a firm energy price of \$130 per MWh, such systems can be economically viable (2). Additionally, optimization strategies can further enhance the economic returns of these systems. For example, a study on the optimization operation strategy of wind-pumped storage systems reported an internal rate of return of 9.8% and a net present value of 872 million Chinese Yuan, outperforming other energy storage configurations (3).

Optimization of the operation of wind-pumped storage systems is crucial for maximizing their efficiency and economic benefits. Various methods, including stochastic optimization and model predictive control, have been employed to address the uncertainties in wind energy production and optimize the scheduling of energy storage and release. Wild (2011) explored several optimization techniques, concluding that reliability-based design optimization is particularly effective in managing wind forecast errors and ensuring a reliable energy supply (2). These optimization strategies are essential for enhancing the performance and economic viability of integrated wind-pumped storage systems.

Methods

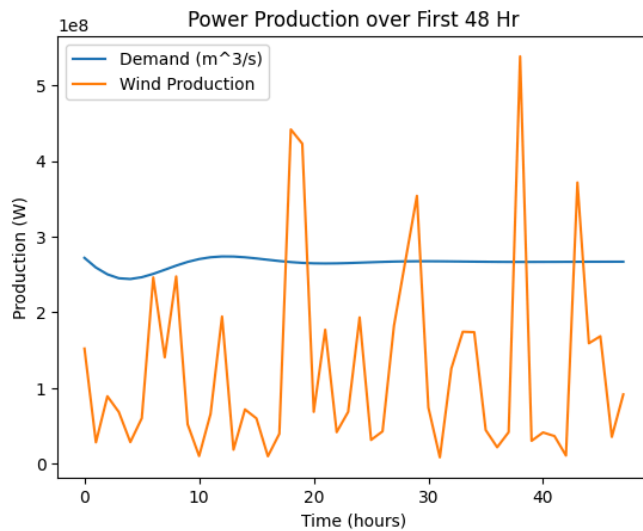
To support our proposed system, we developed a wind speed forecasting model to give us mock data of wind speed for the next year. This data was aimed to help reservoir operators prepare to drain and fill the reservoir in anticipation of low or high wind energy levels. The forecast was created using an exogenous autoregressive (AR) approach. The type of model predicts future wind speeds based on historical wind and air temperature change data. This data was gathered from the Great Lakes Environmental Research Laboratory. In addition we implemented noise in our forecast to create a buffer that lessened our reliance on a perfectly accurate projection. Noise gave us uncertainty that would allow us to prepare for the random weather events that happen throughout the year. That is an important part of our model because it provides resilience, which is the most important component of an energy system. At the conclusion of running these forecasts we had projected hourly wind data for the next year. We then used the resulting forecast applying Model Predictive Control (MPC) by integrating the wind data with energy demand projections to optimize water storage actions.

To model pumped storage, our approach centers on comparing energy demand and generated windpower for each timestep. If the demand exceeds windpower generation and the reservoir is not empty, the project will release at a spill rate s and the storage decreases by $s * \Delta t$ where Δt is the timestep, one hour (3600 s). If this decrease is more than the available storage, then all of the available storage is instead released, leaving the reservoir empty. On the other hand, if demand does not exceed windpower and the reservoir storage is not at full capacity, the project will pump at store rate p . We assume for this model that pumping and spilling are mutually exclusive such that, for example, no energy is produced when demand is not greater than windpower (i.e., when pumping). For the instances where energy is produced, it follows the following formula:

$$Power = Q * \rho * h * g * \eta$$

where Q is the release rate in m/s, ρ is the density of water, 1000 kg/m³, g is acceleration due to gravity, and η is efficiency, which we here set to 90%.

The parameters p and s and ideal storage volume were found using the genetic algorithm NSGA-II with 1000 generations. The program implements a black-box approach analogous to biological evolution, implementing a lost load-minimizing objective function as its fitness criteria.

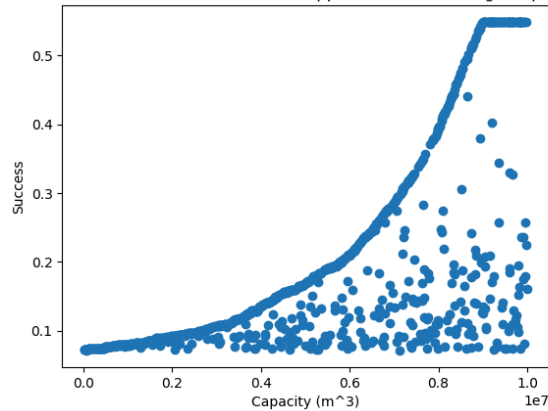


Results & Discussion

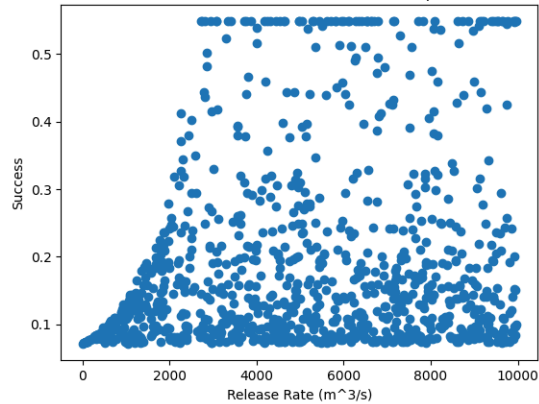
Ultimately, our study uncovered two primary approaches to pumped storage MPC: 1) Long-Term Rate Selection and 2) Real-Time Evaluation. That is, engineers and energy systems managers, or their digital counterparts, can either apply an optimized pumping and releasing program or manage pumped storage on a day-to-day basis.

For the first approach, our model revealed an upper limit on the efficiency of the pumped storage system, demonstrated by a Monte Carlo simulation (1000 parameter combinations). The test revealed that, although there is not much clear correlation between the parameters and success (frequency of exceeded demand), there exist firm boundaries, most notably capping success at approximately 55%. For reference, the do-nothing case yields a success of about 7%.

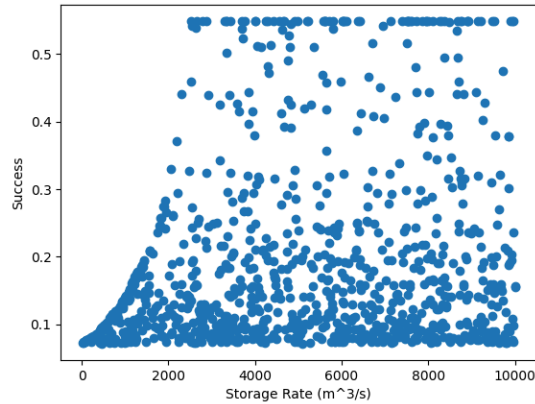
MONTE CARLO TEST: Success vs. Upper Reservoir Storage Capacity



MONTE CARLO TEST: Success vs. Pump Rate

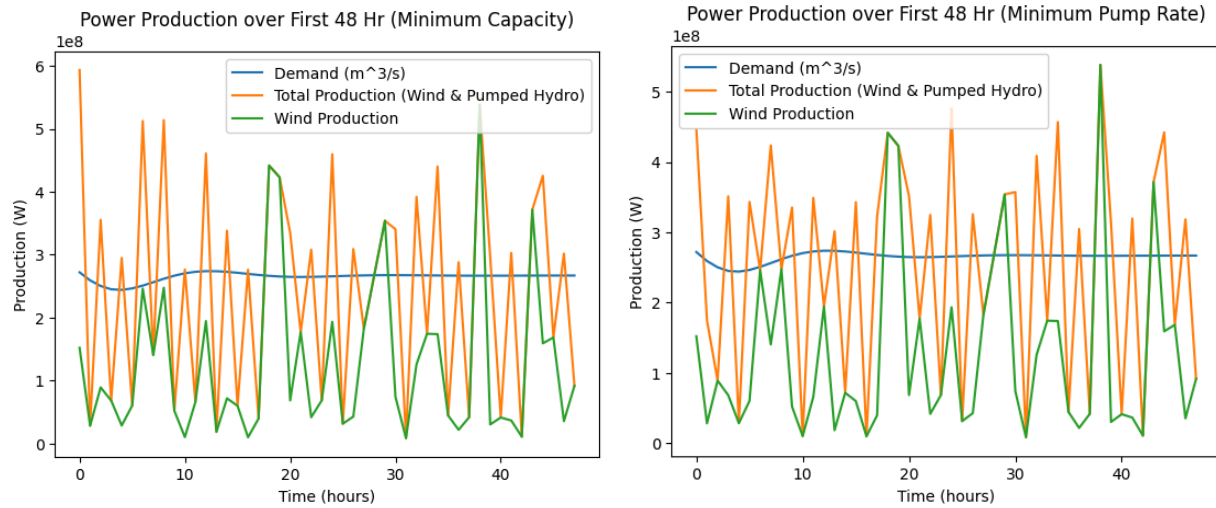


MONTE CARLO TEST: Success vs. Release Rate



The results of the evolutionary algorithm approach reach the maximum model efficiency, albeit with varying relationships between parameters. Storage capacity and pump rate are of most interest because they pose the most obvious technical barriers. However, we found no obvious tradeoffs or correlations between parameters in the final population returned by the program. The lowest storage capacity in the

population is 9,053,445.1 m³, corresponding to a pump rate of 7,560.8 m³. The lowest pump rate is 2,784.6 m³, corresponding to a storage capacity of 9,822,333.6 m³. The low-capacity solution yields 163,310,673 kWh of lost load over the period studied and the low-pump solution yields 162,781,744 kWh, both corresponding to a 51% decrease from the windpower-only case (333,129,584 kWh). Lost load here corresponds to the sum of the difference between demand and power supply, counting only when demand exceeds supply. Note that the total energy produced for the low-pump and low-capacity solutions are approximately 423 GWh and 403 GWh, respectively. All numbers presented are subject to some discrepancy as the genetic algorithm, run with minimal generations, contains inherent variability.



The second approach involves real-time decision-making. For the time series we observed, we found that the maximum disparity between demand and supply (current windpower) is 265,254,923.6 W, corresponding to a minimum storage of 9,022,276.3 m³ to dispatch over an hour. With this approach, optimal release would be calculated at each timestep, depending on the demand-supply difference. Note, however, that this does not consider the need to re-stock the reservoir and the corresponding time lost in doing this. Such an issue could be resolved if infrastructure exists to pump and release water

simultaneously. Therefore, with an increase in accuracy and demand exceedance comes added computational and infrastructure requirements.

Economic Analysis

The proposed pumped storage system near Chicago, Illinois, aims to enhance energy storage capabilities and grid stability. This system is designed to dispatch up to 9,924,503.93 m³ of water at peak demand, providing a robust solution for energy storage and distribution. This takes into account a 10% capacity buffer to control against natural events. The following sections detail the economic analysis of this project, including capital and operational expenditures, and the calculation of the Levelized Cost of Storage (LCOS).

The system has a capacity of 2,454 MW and an annual energy throughput of 430 GWh. These specifications are critical for meeting the energy demands of the region, particularly during peak hours. The expected lifetime of the system is 40 years, and a discount rate of 5% is applied to account for the time value of money in the economic analysis (4).

The CapEx for the pumped storage system encompasses various costs, including civil works, electromechanical equipment, land acquisition, engineering and design, environmental compliance, construction, and a contingency allowance. Based on industry standards and recent data, the CapEx is estimated at \$3.68 billion (5)(4). This estimate aligns with typical costs for large-scale pumped storage projects, which can range from \$1.5 million to \$4 million per MW (4).

The annual OpEx includes both fixed and variable costs associated with the operation and maintenance of the system. Fixed O&M costs are calculated as a percentage of the nameplate capacity, amounting to \$49.08 million per year. Variable O&M costs, based on the annual energy throughput, are estimated at

\$1.505 million per year. These costs reflect the ongoing expenses required to maintain and operate the system efficiently.

To determine the total annual costs, the CapEx is annualized using the annuity formula. This formula accounts for the discount rate and the expected lifetime of the system, resulting in an annualized CapEx of \$217.12 million per year. Adding the annual O&M costs, the total annual costs amount to approximately \$267.705 million. This comprehensive cost assessment ensures that all financial aspects of the project are considered.

The LCOS is a crucial metric for evaluating the economic feasibility of energy storage projects. It is calculated by dividing the total annual costs by the annual energy throughput. For this project, the LCOS is determined to be \$498.87 per MWh. This value is higher than typical LCOS values for pumped storage systems, which generally range from \$150 to \$200 per MWh (6). In comparison, lithium-ion batteries typically have an LCOS ranging from \$131 to \$232 per MWh, and flow batteries range from \$187 to \$367 per MWh (7).

Despite the higher LCOS, the proposed pumped storage system offers significant benefits in terms of large-scale energy storage and grid stability. These advantages are crucial for integrating renewable energy sources and ensuring a reliable energy supply. The detailed economic analysis presented here provides a comprehensive understanding of the financial aspects of the project, supporting its feasibility and potential impact on the energy market.

Conclusion

The proposed pumped storage system represents a significant advancement in renewable energy integration, addressing both the technical and economic challenges associated with energy storage. The

research presented in this paper highlights several key findings and considerations that underscore the potential impact and feasibility of this system.

The optimal release strategy, calculated at each timestep based on the demand-supply differential, ensures efficient energy management. However, the structuring of pumping and releasing will be largely up to the operators of this system. This leaves large margins for human error in the efficiency of energy used. Nonetheless, this dual capability will be crucial for maintaining reservoir levels and operational cohesion throughout the lifespan of this project, especially during hours of peak demand.

The economic feasibility of the pumped storage system is governed by a comprehensive LCOS analysis. The resulting \$498.87 per MWh LCOS is slightly outside the competitive range compared to its counterparts in the long term energy storage sector. Moreover, Preliminary sizing of the reservoir, including a 10% safety margin, ensures that the system itself will be resilient in the face of unforeseen natural circumstances.

The use of an autoregressive model for wind speed prediction is a robust approach, but the addition of variables such as temperature and atmospheric pressure would work to enhance forecast accuracy. Demand modeling must also account for expected changes in demand patterns, including population growth trends and shifts in large sector activity. These factors are critical for ensuring the long term viability and responsiveness to changing energy needs.

Integrating the pumped storage system with the existing grid infrastructure in Chicago presents both regulatory and technical challenges. Addressing these challenges will require close collaboration with regulatory bodies and stakeholders to ensure compliance and seamless operation. Technical considerations include grid compatibility, system reliability, and the inevitable need for infrastructure upgrades.

Implementing a pumped storage system in the Chicago region necessitates a thorough assessment of environmental impacts. Potential concerns include land use, water resource management, and effects on local ecosystems. Mitigation strategies must be developed to minimize adverse impacts and ensure sustainable operation.

The successful implementation of this pumped storage system would significantly enhance integration of renewable energy sources, contributing to an overall sustainable and resilient energy grid. The insights gained from this paper will inform future projects and innovations in energy storage technology. As seen above, this system is on the cusp of being competitive. With some technological reworking to reduce costs and improve energy throughput efficiencies, this technology will be at the forefront of grid resilience in a green future. This comprehensive evaluation provides a solid foundation for decision-making and strategic planning in the renewable energy sector.

Thus, the proposed pumped storage system offers a promising solution to the challenges of renewable energy integration. By addressing technical, economic, and environmental considerations, this project has the potential to make a substantial impact on the future of energy storage and grid stability.

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