Enhancing Renewable Energy Reliability in New England: The Potential of Pumped Hydroelectric Energy Storage

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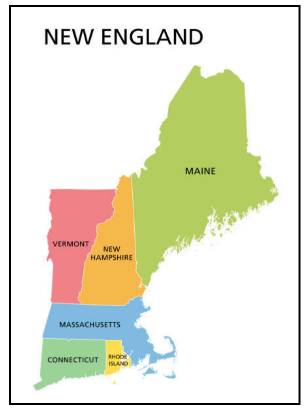
SIT Summer

As greenhouse gas emissions accelerate the rate of global warming, the United States must speed the transition from fossil fuel to renewable energy infrastructure. As a prominent leader in clean energy policy developments, New England has the opportunity to pave a clear path for other states to follow (Delaney, 2019). However, a clear obstacle for implementing renewable energy resources is the decrease in consistent power generation. Wind and solar both rely heavily on natural resources that are not always present, and even hydroelectric and geothermal power, which are relatively consistent, experience fluctuations in supply (Dhal, 2021). Therefore, implementing electricity storage solutions is crucial to maintain reliable power during peak hours and support clean, renewable energy sources.



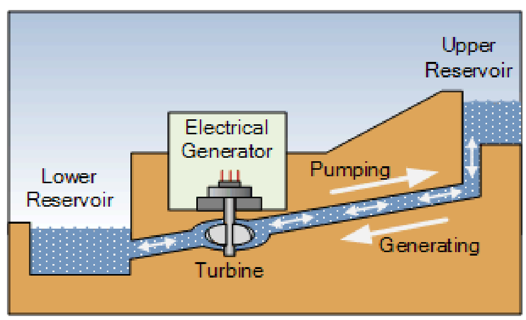
New England experiences intense precipitation compared to other regions of the U.S. and has a diverse watershed with opportunities for hydroelectric energy storage (Hydrosource). Pumped hydroelectric energy storage (PHES) has proved to be a mature solution to the reliability issues posed by solar and wind. PHES is estimated to be more efficient than most other energy storage options for long term generation at a high capacity, while also being comparatively non-resource intensive (Laporte, 2019). The implementation of PHES in New England would provide necessary grid stability, and auxiliary services such as flood control and groundwater recharge, in addition to delivering socio-economic benefits to the region. The maneuverability of PHES, which can shift from zero to full power within minutes, makes it an invaluable asset for managing unexpected fluctuations in power generation from wind and solar systems which can often stop at a moment's notice (Haas, Prieto-Miranda, Ghorbani, & Breyer, 2022). This essay will therefore examine New England's capacity for PHES as a means of providing consistent energy for the region, answering the following question: How can hydropower electric storage in New England be identified and utilized to increase renewable energy reliability, and what political, economic, and social obstacles need to be overcome to do so?

To answer this research question, the paper conducts a thorough analysis of the most effective implementations of PHES given the available technology and then uses a GIS software to identify optimal PHES locations in the region. GIS is also used to provide a general analysis of the effects of introducing the proposed PHES when compared to the increased solar and wind power in the region, to provide a picture of the technology's long term impact. With the PHES capacity and potential impact measured, the last section of the paper provides an overview of current policies affecting PHES and makes recommendations for new policies to encourage development alongside wind and solar. Using past literature, the paper provides information about regulatory challenges, public perception, and economic considerations to provide a strategic implementation plan with a reasonable timeline.

Background

Pumped hydroelectric energy storage facilities are large-scale, reversible energy storage technology that utilizes the potential energy of water to store and release electricity. By capitalizing on the simple principle of converting electrical energy into potential energy, and vice versa, PHES systems have proven to be a vital component in modern power grids (Ali, Stewart, Sahin, & Silva Vieira, 2023).

Figure 1: The following Image illustrates the system design of PHES (Tutorials 2023)



In recent years, PHES systems have represented 3% of the total installed electricity generation capacity in the world and around 95% of the electric grid storage capacity, making them the most extensively used storage systems (Papadakis, Fafalakis, & Katsaprakakis, 2023).

In New England, there are two active industrial PHES systems: the Northfield Mountain facility (built in 1964) and the Bear Swamp facility (built in 1968). Both facilities were originally constructed to balance supply from the now-decommissioned Yankee Rowe nuclear power station in Massachusetts during times of energy fluctuation. Despite the nuclear plant's closure in 2007, these PHES facilities, with capacities of 1,080 MW and 600 MW respectively, remain operational (Miller & Simonelli, 2022). They provide critical grid services by storing excess energy during off-peak times and releasing it during peak demand periods, which is increasingly valuable as the region incorporates more intermittent renewable energy sources . These facilities are integral to New England's energy infrastructure, ensuring grid stability and reliability.

Hybrid Systems

When evaluating the potential impact of PHES in New England, it's important to note that existing technologies already enable effective integration of energy storage with renewable sources. Hybrid energy systems combining solar, wind, and PHES offer significant improvements in energy reliability and efficiency by leveraging the complementary nature of these renewable sources. Solar-PHES systems store excess solar energy generated during the day which is then released to generate electricity during nighttime or cloudy periods. Solar-PHES systems are cost-effective, with costs ranging from $0.098 to $1.36 per kilowatt hour (kWh) and payback periods of 10 to 15 years, making them viable in regions with abundant solar resources (Javed, Ma, Jurasz, & Amin, 2020). Meanwhile Wind-PHES systems also have demonstrated technical and economic viability, particularly in regions with high wind variability. With payback periods ranging from 6 to 12 years, wind-PHES systems can significantly reduce operating and maintenance costs over time (Javed, Ma, Jurasz, & Amin, 2020). Wind-Solar-PHES systems integrate both wind and solar energy with PHES to create a balanced and reliable renewable energy system. Feasibility studies show that wind-solar-PHES systems are technically and economically viable in various locations, offering lower operational costs. Economic studies report costs ranging from $0.099 to $0.286 per kWh, with favorable payback periods due to the declining costs of renewable technologies (Javed, Ma, Jurasz, & Amin, 2020). These hybrid systems significantly lower environmental impacts and enhance the stability of renewable energy supplies.

Technological Considerations

Specific design considerations help narrow down the most suitable locations for the development of PHES systems in New England. For large-scale PHES systems, land constraints are a primary focus. Sites with a minimum elevation difference of 100 meters are prioritized to ensure sufficient gravitational potential energy for generating electricity (Ali, Stewart, & Sahin, 2021). Existing reservoirs must be within 20 km of each other to keep construction costs manageable and ensure feasibility (Ghorbani, Makian, & Breyer, 2019). Additionally, sites receiving at least 60 mm of annual rainfall are preferred to account for water loss due to evaporation and leakage, as adequate rainfall helps maintain reservoir water levels without relying excessively on external water sources, ensuring the sustainability of the PHES system (Ali, Stewart, & Sahin, 2021).

Additional factors include a slope constraint greater than 10%, proximity to water bodies, and infrastructure such as roads and power lines within 10 km. A 10% slope constraint ensures that the land is neither too steep nor too flat, making construction feasible and cost-effective. Proximity to water bodies provides an additional water source to fill the reservoirs, which compensates for evaporation losses and can help maintain the water levels in the reservoirs (Soha et al., 2017). Access to existing infrastructure such as roads and power lines is crucial for reducing construction and operational costs, facilitating the transportation of construction materials and equipment and simplifying the integration of the PHES system into the existing power grid (Rogeau, Girard, & Kariniotakis, 2017).

These design considerations are crucial for optimizing efficiency, minimizing environmental impact, and ensuring economic viability in PHES system development. Evaluating these criteria helps identify locations that balance technical, environmental, and economic factors, making PHES systems a viable solution for energy storage and grid stability.

GIS Analysis

Data & Methods

In order to answer the original research question the GIS analysis for this study was broken down into different sections. The results of each section were then compared to provide information on the capabilities of PHES to aid wind and solar power development.

First, the geographic potential for PHES facilities in New England was identified and the capacity of each upper reservoir was measured. For PHES suitability, a dataset of current reservoirs (Ruddy & Hitt, 1990) in the region was paired with elevation data(USGS, 2021). Large reservoirs (larger than $1*10^9$ m^3) were identified and selected under the conditions of being within 20 km of a different large reservoir with a head height differential of over 100 meters. Then, Using annual rainfall raster data, along with powerline and road vector data, the list of potential reservoirs was cut down to those within range of existing power lines and roads and those that receive proper rainfall to mitigate evaporation rates.

Next, the energy storage capacity and the power generation capacity of the suitable sites were calculated. After all possible conventional PHES were identified, the energy capacity(E) and power generation(Pg) was identified using the following respective formulas:

$$E = \rho * g * h * V * \mu \qquad\qquad Pg = \rho * g * h * Q * \eta$$

Here's a quick breakdown of what was used for the calculations:

ρ (Density)	Water's density is 997 kg/m³ at 25°C.
g (Gravity)	The standard gravity on Earth at sea level is 9.81 m/s².
h (Elevation Head)	This is the height difference between the pairs of reservoirs.
V (Volume)	This is the total capacity of the reservoir.
μ (Storage Efficiency)	We assumed 90% efficiency to account for evaporation and leakage losses.
Q (Flow Rate)	Measured in m³/s
η (Generation Efficiency)	We assumed 79% efficiency, considering the losses

Most of the data constants came from literature, while the GIS provided the Volume (V), Flow (Q), and height (h). Volume was the total capacity, and height was the head elevation difference. Flow was difficult to define due to its variability, so the values used were estimated from historical data trends of similar reservoirs. Because of these methods, the results might vary slightly upon implementation (Ghorbani, Makian, & Breyer, 2019).

Lastly an analysis of potential locations for solar and wind farms was conducted to identify where PHES could aid the transition to renewable energy. For the suitability of wind and solar in the region, raster image data for wind speeds and solar irradiation were utilized in addition to the previous powerline and roads data to create a suitability map (WorldClim, 2020). Elevation rasters were also utilized to find large, flat areas of land for solar panel installation and elevated locations for wind turbines (as they have better performance along ridges and mountain tops).

Results

When observing the storage capacities of all of the reservoirs in New England, 78 locations were deemed viable. Notably, a sizable number of potential locations were found in western Massachusetts and Connecticut. However, in measuring reservoir capacity alone, the most expansive locations were in Maine.

Reservoir and Dam Capacity in New England

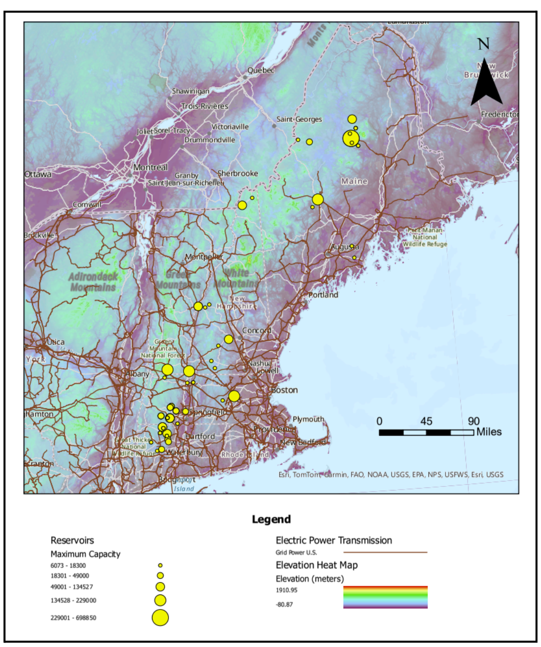
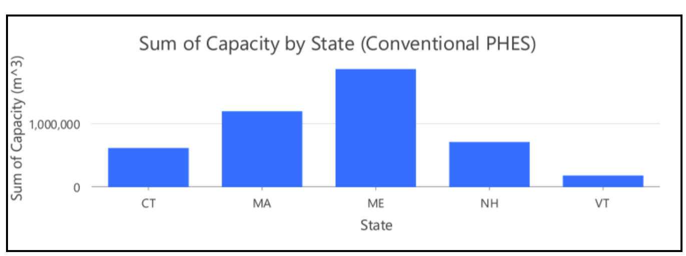


Figure 2: This Map highlights the key reservoirs and dams for conventional pumped hydroelectric storage in New England overlaid with the elevation map and powerline data. All data points exist within 20 km of another data point and have a head elevation difference of over 100 meters.

Figure 3: The following chart obtained from the same data as Figure 1 shows the relative storage capacity of all dams and reservoirs in New England.



Energy capacity was measured for each reservoir due to its impact on energy storage. However, the initial GIS analysis may not holistically represent complete PHES systems, as these facilities can only store and generate power based on their smallest reservoir. When expanding the analysis to identify PHES systems as pairs of reservoirs and measuring the combined energy storage capacity and power generation, reservoirs in Connecticut and Massachusetts appear more advantageous. Based on the GIS estimates, Massachusetts, with 32 total locations, has the potential to store over 80 GWh, with a power generation capacity of 31 MW. Connecticut, with 18 locations, has potential for 28 GWh and a power generation of 25 MW. And Maine, with 15 locations, has a potential for 17 GWh, and a generation of 21 MW. The decrease in power and capacity is due to the fact that Maine's systems link large reservoirs with much smaller ones, resulting in limited storage and generation capacity. In contrast, Massachusetts and Connecticut feature more prevalent and evenly distributed reservoir pairs, enhancing their overall performance.

Energy Capacity and Power Generation Distribution in New England

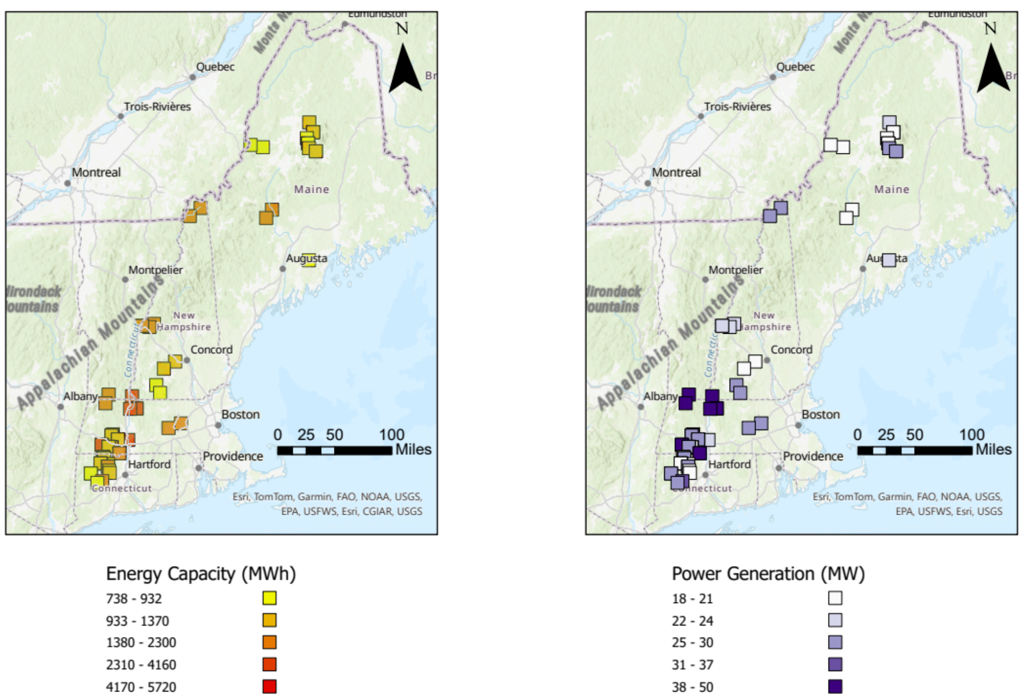


Figure 4: The Energy Capacity (left) and Power Generation (right) of New England PHES systems based on the calculations described in the paper's methods.

In addition to the hydroelectric power potential in more southern states of New England, a suitability analysis of both wind turbine potential and solar energy potential shows that the majority of the region's renewable energy may be in the same locations. The suitability analysis excludes current land-use regulations and socioeconomic factors, except for the distance to power lines which mitigates infrastructure cost. The analysis solely concentrates on environmental efficiencies, such as slope, wind speed, and irradiance data to maximize development and energy generation potential. Based on the results shown below, Massachusetts, Connecticut, and Vermont have the highest wind turbine potentials. And near PHES, there is a strong possibility of hybrid wind-PHES systems in western Massachusetts specifically. For solar panels, the potential lies mostly on the southern coast of Massachusetts and Connecticut, with some potential in western Massachusetts as well leading to similar possibilities for hybrid solar-PHES.

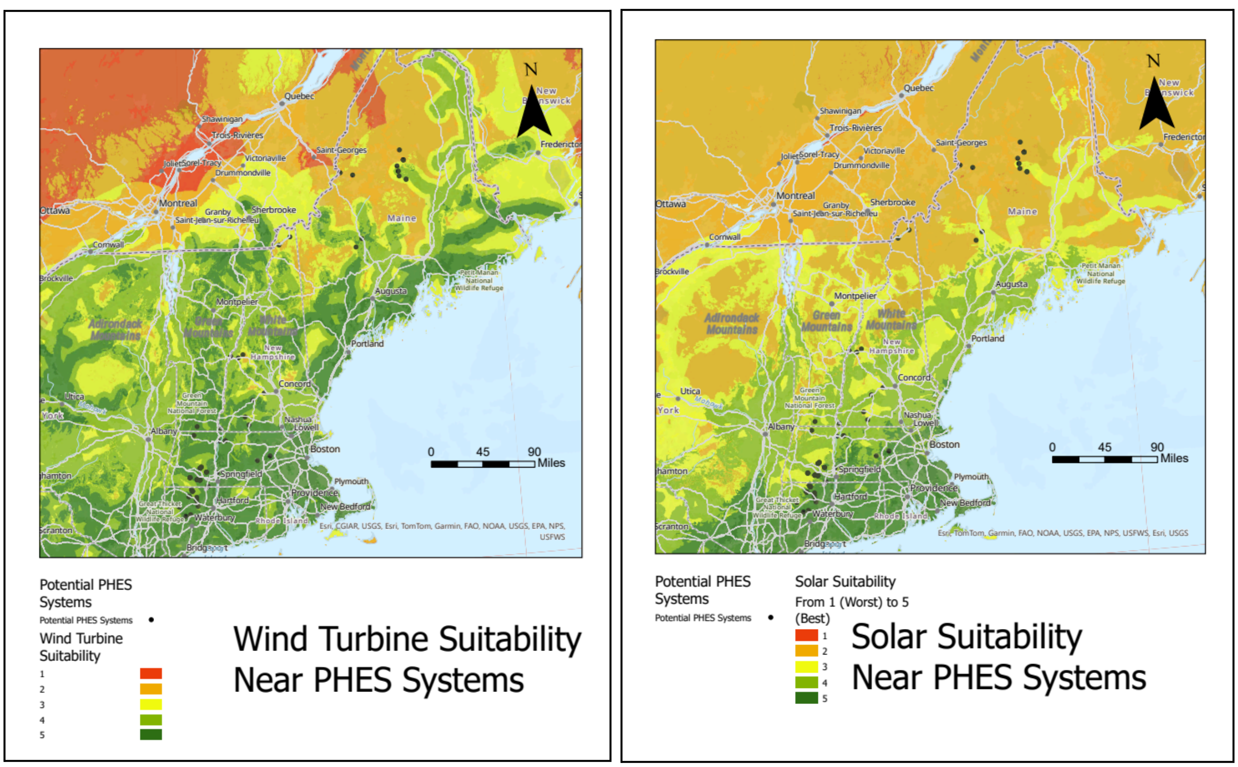


Figure 5: Identifications of land optimal for Wind Turbines (left), and Solar panels (right) combining wind speed, irradiation, power grid locations, and slope/elevation data.

Discussion

Based on the results of the GIS analysis, conventional PHES systems are clearly suitable within the region and can be implemented alongside solar and wind facilities. However, from the figures and maps alone, it is not completely clear whether the estimated capacity of PHES from this survey will be able to accommodate a complete transition to renewable energy sources. Specifically, it is uncertain if the energy provided by PHES could effectively compensate for periods of low energy generation from wind and solar power. According to the Energy Information Association, New England consumes on average 20,000 MWh per day (EIA, 2024). With a combined maximum estimated PHES capacity of approximately 125,000 MWh (in Maine, Massachusetts, and Connecticut), that means that, in theory, large scale PHES could support the energy grid system for almost a week. Of course, the storage capacity of PHES is not always completely full, and generation would vary, but so long as enough wind and solar power is available to properly store energy for the PHES facilities, the grid system would experience minimal risks to energy reliability. Therefore, PHES could likely mitigate the intermittency issues associated with wind and solar power and ensure that renewable energy can be harnessed effectively, even during periods of low generation.

It is important to note that this analysis does not take into account all factors for the implementation of PHES. Due to scope limitations of this paper, only conventional PHES systems –built between two existing reservoirs– were evaluated, but other technologies exist. Greenfield and Bluefield PHES systems utilize artificial reservoirs from land formations, including valleys, old mining quarries, or even the ocean. These technologies could enhance the variability and capacity of PHES in New England. In the future, more research must be conducted to determine the suitability of each design and its impact throughout the region (Papadakis, Fafalakis, & Katsaprakakis, 2023).

Additionally, while the potential for PHES in New England is substantial, the GIS analysis does not take into account various techno-environmental and socio-economic barriers that may hinder development. For example, the construction of PHES requires substantial investments in infrastructure which necessitates geological stability. While the rugged and varied terrain of New England makes PHES feasible, creating viable PHES sites would require significant and costly modifications to the natural landscape. With these modifications, a host of environmental concerns arise, including harm to local ecosystems, lower water oxygen concentrations, disrupted reservoirs and riverbeds, and limited water supply for downstream users. Additionally, the high capital costs associated with PHES projects are a significant barrier. Initial investment requirements are substantial, covering the cost of land acquisition, construction, and technology implementation. These costs can deter investors and slow down project development, especially in places where economic returns are uncertain (Ali, Stewart, & Sahin, 2021).

Policy Implementation

In order to mitigate obstacles to PHES and maximize the benefits of hybrid wind-solar-PHES, policy decisions for the region can be made to incentivize development and generate market support. In the United States, federal and state-level policies have already played a role in promoting energy storage. At the federal level, the Federal Energy Regulatory Commission (FERC) has issued several orders to facilitate the integration of energy storage into wholesale electricity markets. They are responsible for regulatory support and licensing of PHES projects – Northfield Mountain and Bear Swamp facilities operate under these licenses (Tabari & Shaffer, 2020).

At the state level, several states have adopted energy storage mandates and targets, as well as policies, to encourage the deployment of storage systems in general. Massachusetts has policies that promote energy for PHES by providing financial incentives, simplifying permitting processes, ensuring market reforms to properly value grid services, and integrating PHES with renewable energy sources to enhance grid reliability and support the region's decarbonization goals (Commonwealth of Massachusetts, 2024). Additionally, Connecticut's Energy Storage

Solutions program, incentivizes a range of electric storage technologies, including hydrogen, mechanical, thermal, and pumped hydropower, to enhance grid resilience and support peak shaving – storing energy during off-peak times when electricity rates are lower and discharging that energy during peak demand periods. Managed by Eversource and United Illuminating, the program offers upfront financial incentives and performance-based payments to residential, commercial, and industrial customers, aiming to deploy 580 MW of energy storage by 2030, with a focus on benefiting low-income and vulnerable communities (CT, 2024).

Recommendations

To integrate more pumped hydroelectric storage (PHES) into the development of new renewable wind and solar projects in New England, creating more financial incentives is essential, including offering higher tax credits, providing larger grants, and implementing increased feed-in tariff rates specifically for projects that combine wind, solar, and PHES. These financial incentives would help offset the substantial initial investments required for such projects, making them more attractive to investors. Additionally, Streamlining regulatory frameworks, and ensuring that hybrid systems can participate in capacity markets could directly incentivize development.

To eliminate bureaucratic obstacles there should be one centralized permitting process, in which a single regulatory body coordinates and oversees all necessary approvals, reducing permitting approval duplications. This body could provide a clear timeline and guidelines for developers, ensuring a more predictable and efficient process. Additionally, implementing standardized environmental assessment procedures and pre-approving certain project types or locations based on predefined criteria could further simplify the regulatory landscape. These measures would reduce the administrative burden on developers, lower the costs associated with lengthy permitting processes, and make New England a more attractive region for investment in renewable energy projects that include PHES.

To incentivize development economically, capacity markets can be utilized. In a capacity market, power plants and other resources PHES bid into the market, offering their capacity to be available during peak periods. Then grid operators, such as Independent System Operators (ISO) New England, assess the total capacity needed and select the bids from different energy sources to meet this requirement, typically at the lowest cost. The selected resources are then paid a capacity payment, which serves as a steady revenue stream in addition to any payments they receive for the electricity they generate. For example, if a PHES facility agrees to provide 100 MW of capacity, it will receive capacity payments for ensuring that 100 MW is available during peak times. This system ensures grid reliability by guaranteeing that there is enough capacity to meet demand spikes, thereby preventing blackouts and maintaining grid stability. For hybrid systems incorporating PHES with wind and solar, participation in capacity markets can significantly enhance financial viability by providing predictable income (Sayed et al., 2023).

Integrating more PHES with renewable wind and solar projects in New England requires financial incentives and streamlined regulatory frameworks. Centralizing the permitting process and leveraging capacity markets will make these hybrid systems financially viable and attractive to investors. These measures will ensure grid reliability, support the transition to renewable energy, and position New England as a leader in sustainable energy development.

Conclusion

The integration of Pumped Hydroelectric Energy Storage with renewable energy sources such as wind and solar is crucial for ensuring a stable and reliable energy supply in New England. As the region continues to lead in clean energy initiatives, addressing the intermittency of renewable sources through advanced storage solutions like PHES will be essential. The GIS analysis conducted in this study has identified viable locations for PHES, demonstrating the region's substantial potential for energy storage and grid stability. By leveraging New England's natural advantages, such as abundant rainfall and diverse watersheds, PHES can provide critical grid services and enhance the overall efficiency of the energy system.

However, the successful implementation of PHES faces several challenges, including high initial capital costs, regulatory hurdles, environmental impacts, and social acceptance. To overcome these obstacles, a comprehensive policy framework is required. This framework should include financial incentives, such as expanded tax credits and grants, streamlined regulatory processes, and market reforms that properly value the contributions of PHES. By adopting these strategic policy measures and leveraging its inherent geographical advantages, New England can serve as a model for other regions, demonstrating how to effectively integrate renewable energy and storage solutions to achieve a sustainable and resilient energy system.

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