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EVOLVING COST AND PERFORMANCE DYNAMICS OF BATTERY STORAGE FOR FUTURE ENERGY SYSTEMS

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ABSTRACT

Battery storage is increasingly important for improving flexibility and supporting renewable integration in future energy systems, yet its deployment depends on evolving economic and technical characteristics. This study evaluated historical, contemporary, and projected cost and performance dynamics across six battery storage technologies using longitudinal techno-economic data spanning 2015–2050. Capital expenditure, efficiency, lifetime, and related operational indicators were assessed through descriptive statistics, temporal and cross-technology comparisons, cost–performance correlations, and technology-adjusted regression models. The results showed significant long-term reductions in capital costs, with adjusted annual declines of 4.94% for USD/kWh and 1.61% for USD/kW. Lithium-ion LFP and NMC exhibited comparatively favorable cost-efficiency characteristics and high efficiency, while vanadium redox-flow demonstrated lower efficiency but relatively long lifetime. Significant inverse associations were identified between USD/kW capital cost and efficiency and between USD/kWh capital cost and lifetime. Historical and projected models further demonstrated variation in the magnitude of cost reduction across periods. These findings indicate improving economic competitiveness of battery storage while highlighting removal.

Introduction

As electricity systems evolve towards a low-carbon mix, energy storage is becoming more relevant in the power network as the demand for variable renewable energy grows.As the electricity system moves towards a low carbon mix, energy storage is becoming more relevant as power networks have to accommodate increasing shares of variable renewable energy. There is substantial decarbonisation potential in solar and wind resources, but they are also intermittent which leads to mismatch between electricity generation and demand. Imbalances can be minimized by storing excess electricity to provide it when needed, reducing fluctuations, and contributing to system flexibility and reliability. Battery energy storage systems (BESS) are especially appealing due to their modularity, scalability, and ability to respond quickly, as well as their use across various scales of the grid (Sayed et al., 2023). Renewable penetration also alters the balancing requirements, as well as the interactions between electricity network, electricity storage, and generators (Laugs et al., 2020).

Battery storage offers several operational services other than energy shifting. These include frequency regulation, voltage support, peak-load management, smoothing of renewable energy, reserve provision and grid stabilization. These features are of great importance for renewable-integrated power systems (RIPS) making BESS more relevant (Datta et al., 2021). Furthermore, the battery systems can reduce the time-varying voltage and power oscillations from solar and wind generation (Alam et al., 2021). As storage technologies continue to develop, the spectrum of solutions becomes wider for such applications, and the efficiencies, lifetimes, costs and operational features of various storage technologies have an impact on their suitability for particular energy system requirements (Wei et al., 2023). New technologies also suggest ongoing advancements in storage technologies and applications (Liu et al., 2025).

Economic performance is an important factor in determining the scalability and competitiveness of battery storage. The technical characteristics determine the value that storage can provide over its operational life, and capital expenditure, fixed operation and maintenance costs influence investment decisions. There are significant differences in cost and performance across energy-storage technologies, so that a combination of economic and technical factors should be considered (Mongird et al., 2020). Technological competitiveness is also important and can be enhanced by developments in materials and fabrication, which are also improving storage efficiency and performance (Admase et al., 2025). Commercialization and diversification of stationary storage applications are also reflected in market experience, whereby storage applications are developing more rapidly than before (Figgener et al., 2020).

These developments have implications for future energy systems. For large-scale renewable integration, flexibility is needed in the aspect of addressing intermittency, balancing constraints and network stability, resulting in energy storage being an influential system resource (Ergun et al., 2025). The deployment of storage can play a role in decarbonization by enhancing the usage of renewables and reducing the reliance on traditional balancing resources (Karduri & Ananth, 2023). Comparisons of emerging renewable technologies using data, further underlines the importance of assessing and comparing technological pathways by measurable economic and performance metrics (Pavithra et al., 2025).

Although there has been an increasing number of studies on battery storage, the evolution of costs and technical performance are often examined independently, with little focus on understanding how they evolve over time. Comparisons that make a distinction between the present and the future, as well as among the various battery technologies, are still especially relevant. This paper helps fill this gap by performing a longitudinal analysis of battery-storage cost and performance trends. It is intended to numerically describe the historical and projected economic characteristics of the major battery-storage technologies, to numerically compare efficiency, lifetime and related performance characteristics of the various alternative battery-storage technologies, and to numerically assess cost-performance relationships and implications for future energy-system deployment. The resulting evidence can clarify how evolving storage technologies can aid increasingly renewable, flexible and economically viable electricity systems.

Research Objectives

- To quantify historical and projected trends in the capital and operational costs of major battery storage technologies.
- To compare the efficiency, lifetime, and energy-to-power characteristics of battery technologies across temporal and technological categories.
- To evaluate cost–performance relationships among battery storage technologies and determine their implications for future energy-system deployment.

2. Methodology

2.1 Research Design

The research design of the study was quantitative longitudinal research where the changes in cost and performance attributes of battery storage technologies were studied. Secondary techno-economic data was utilized to estimate changes over historical, contemporary and projected time periods. The analytical framework combined descriptive statistics, temporal trend analysis, technology-level comparison and cost–performance assessment. Analysis was carried out to distinguish historical observations from projections, so as to interpret the temporal patterns properly.

2.2 Data Source and Variable Selection

Secondary data was used from the Global and National Energy Systems Techno-Economic (GANET) database created by Hatton et al. (2024) which includes battery-storage data between 2015 and 2050. The technologies analyzed include lithium-ion, LFP, NMC, lead-acid, Vanadium Redox-flow and sodium-sulphur. Capital expenditure, fixed O&M and variable O&M costs were the economic variables. Technical indicators included efficiency, lifespan, energy to power ratio and construction times.

2.3 Data Preprocessing and Harmonization

Data was checked for missing data, duplicate records, misclassified technology, and inconsistent measurement units. Temporal fields and technology labels were standardized to help compare technologies and across years. The analysis of capital costs in USD/kW and USD/kWh was done separately, as it would not be appropriate to add these up. No artificial imputations were made in the case of missing values, and historical/current versus future projected observations were differentiated.

2.4 Descriptive, Temporal, and Comparative Analysis

The major cost and performance indicators were calculated using descriptive statistics such as mean, median, standard deviation, minimum and maximum. The cost and technical battery characteristics were quantified between 2015 and 2050 using a temporal analysis, including percentages where applicable. Since the economic and performance trajectories are considered different, an attempt was made to identify them by conducting technology-specific comparisons. Trends and projections were examined on their own prior to comparing the general trends.

2.5 Cost–Performance and Statistical Analysis

Comparable technology-year observations were used to explore cost–performance relationships, the focus being on associations between capital cost, efficiency and lifetime. Pearson or Spearman correlation analysis was performed depending on the distribution of the data and availability. The temporal increase in harmonized capital costs has been quantified, with regression analysis, considering differences between battery technologies. Data were analysed using Python and the results were compared statistically according to $p < 0.05$ and presented with tables and figures.

3. Results

3.1 Dataset Characteristics and Descriptive Statistics

There were 671 year-specific observations available in the analytical dataset, across 2015–2050 and six battery technology categories. The variety in the capital costs was significant within both reporting units. The medians of CAPE and CAE were 1768.46 USD/kW and 345.93 USD/kWh, respectively, while the medians of the corresponding mean values were 1967.52 USD/kW and 383.58 USD/kWh. The overall mean efficiency and mean lifetime were 83.99% and 16.71 years respectively based on the technical indicators. Most of the fixed O&M observations were in

USD/kW/yr and most of the variable O&M observations were comparatively low. The distribution and coverage of the key cost and performance indicators in the analysis are summarized in Table 1.

Table 1. Descriptive Statistics of Battery Storage Cost and Performance Indicators

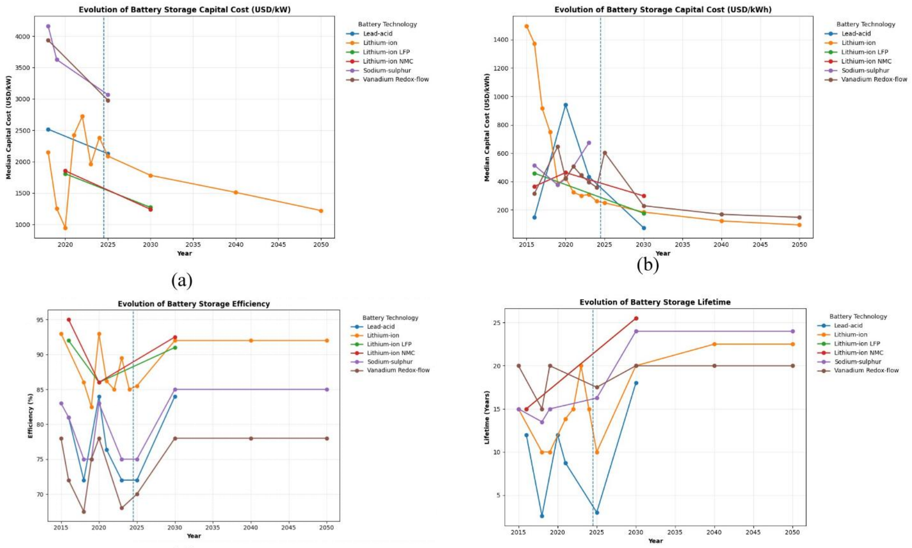
Indicator	Unit	N	Mean	Median	SD	Minimum	Maximum
Capital Cost	USD/kW	178	1967.52	1768.46	1011.77	41.00	4487.42
Capital Cost	USD/kWh	155	383.58	345.93	241.67	61.63	1494.68
Construction Time	Years	25	0.75	1.00	0.36	0.20	1.50
Efficiency	%	60	83.99	85.00	7.75	67.50	97.00
Fixed O&M	USD/kW/yr	170	34.94	28.78	31.41	0.00	111.89
Fixed O&M	USD/kWh/yr	12	7.21	5.60	3.09	3.54	12.99
Lifetime	Years	54	16.71	15.00	6.15	2.60	31.00
Variable O&M	USD/MWh	17	0.46	0.44	0.55	0.03	2.20

3.2 Historical and Projected Battery Storage Cost Dynamics

Overall, capital costs trended downward over time, with a more pronounced downward trend for energy-normalized CAPEX. Median USD/kWh CAPEX was 1494.68 in 2015, decreased to 268.51 by 2024, and was projected at 112.25 by 2050. Median USD/kW CAPEX declined from 3225.73 in 2018 to 2384.38 in 2024 and was projected to reach 1220.98 in 2050. The decrease was not strictly linear due to a changing number, type and providers of estimates over the years. Selected annual median CAPEX values are provided and the historical to projected cost transition is illustrated in Table 2.

Table 2. Temporal Changes in Median Battery Storage Capital Costs

Year	Period	Median CAPEX (USD/kW)	Median CAPEX (USD/kWh)
2015	Historical/Contemporary	—	1494.68
2018	Historical/Contemporary	3225.73	750.83
2020	Historical/Contemporary	1739.81	432.81
2022	Historical/Contemporary	2724.39	326.83
2024	Historical/Contemporary	2384.38	268.51
2025	Projected	2183.42	324.63
2030	Projected	1363.46	229.99
2040	Projected	1511.02	127.65
2050	Projected	1220.98	112.25



(a) (b)

(c) (d)

Figure 1: Temporal Evolution of Battery Storage Capital Costs

3.3 Evolution of Battery Storage Performance

The efficiency and expected operational lifetime of the battery technologies were clearly different. The efficiency of the lithium-ion NMC was the top with the mean value of 91.50%, followed by the lithium-ion LFP at 90.00%, and the conventional lithium-ion with 88.94%. The mean efficiency of vanadium redox-flow was the lowest at 74.25%. Lifetime for LFP was 20.25 years on average, NMC 20.25 years, and vanadium redox-flow 18.75 years. The mean lifetime of lead-acid was the lowest at 10.79 years. Table 3 shows efficiencies and lifetimes for all six technologies and illustrates differences in technical performance profiles.

Table 3. Efficiency and Lifetime Characteristics by Battery Technology

Technology	**N Efficiency**	**Mean Efficiency (%)**	**Median Efficiency (%)**	**N Lifetime**	**Mean Lifetime (years)**	**Median Lifetime (years)**
Lead-acid	7	77.34	76.36	8	10.79	10.50
Lithium-ion	26	88.94	88.44	23	16.53	15.00
Lithium-ion LFP	4	90.00	90.00	4	20.25	19.00
Lithium-ion NMC	4	91.50	91.50	4	20.25	19.00
Sodium-sulphur	9	79.67	81.00	7	17.71	15.00
Vanadium Redox-flow	10	74.25	76.50	8	18.75	20.00

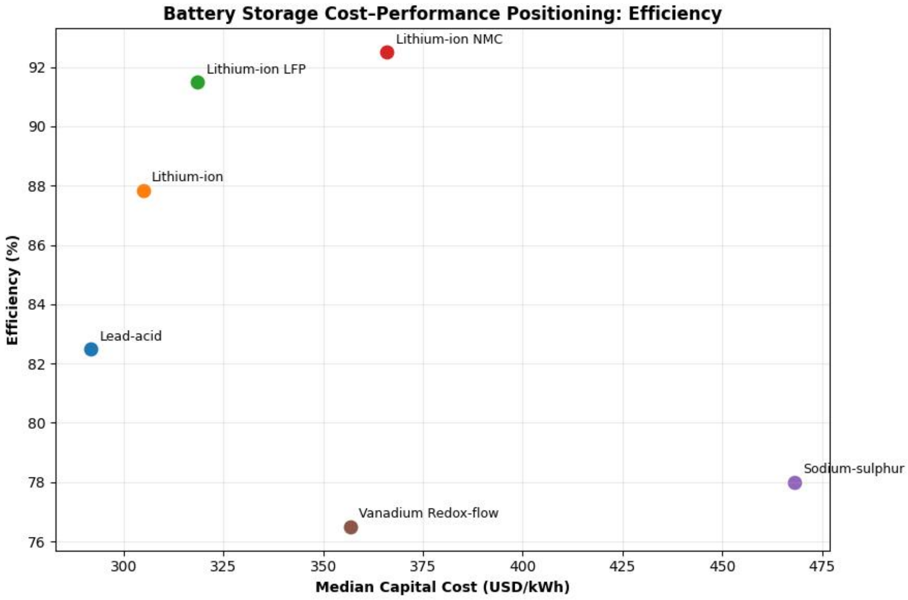


Figure 2: Temporal Evolution of Battery Storage Efficiency and Lifetime

3.4 Comparative Technology-Level Cost and Performance Dynamics

A cross-sectional analysis of CAPEX and performance showed different technology-level profiles. The median CAPEX for matched USD/kW-efficiency observations is lower for lithium-ion LFP and NMC than for all other battery options investigated, at 1540.08 USD/kW and 88.50% for LFP and 1547.78 USD/kW and 89.25% for NMC. The conventional lithium-ion recorded 1959.65 USD/kW and 86.18%. Sodium-Sulphur and Vanadium-Redox-Flow (VRF) had lower efficiency and higher costs. Table 4 shows a summary of these matched cost–efficiency characteristics, as well as the number of technology-year pairs that support each estimate.

Table 4. Technology-Level Cost–Efficiency Positioning

Technology	Median CAPEX (USD/kW)	Median Efficiency (%)	Matched N
Lead-acid	2321.79	72.00	2
Lithium-ion	1959.65	86.18	11
Lithium-ion LFP	1540.08	88.50	2
Lithium-ion NMC	1547.78	89.25	2
Sodium-sulphur	3626.00	75.00	3
Vanadium Redox-flow	3457.45	68.75	2

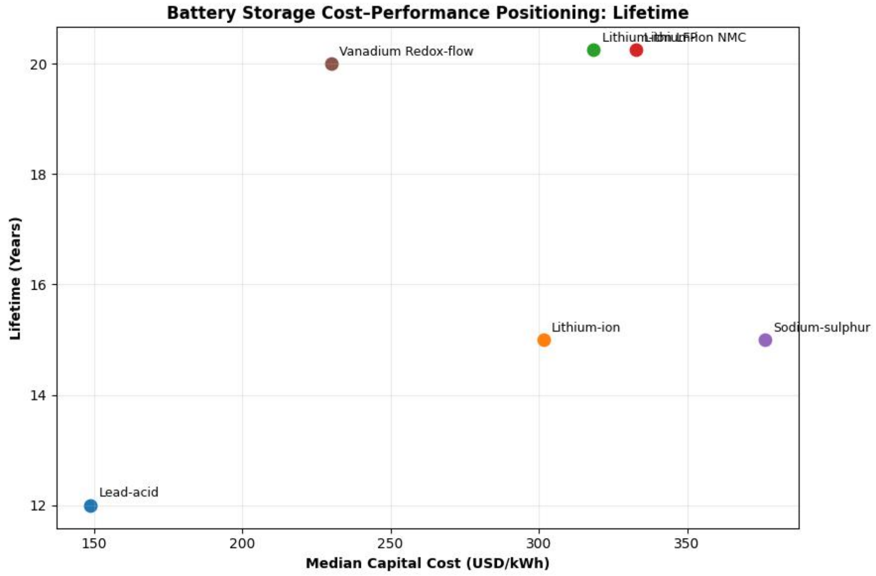


Figure 3: Cost–Efficiency Positioning of Battery Storage Technologies

The complementary cost–performance pattern was generated by Lifetime. The median CAPEX for Vanadium redox-flow was USD 229.99/kWh and the median lifetime was 20.00 years. LFP and NMC observed median lifetimes of 20.25 years while each estimate was based on only two matched technology-year observations. The median price of conventional lithium-ion was 301.52 USD/kWh with a median lifetime of 15.00 years. Table 5 shows the matched USD/kWh CAPEX – lifetime characteristics that were used in creating the corresponding cost – lifetime comparison.

Table 5. Technology-Level Cost–Lifetime Positioning

Technology	Median CAPEX (USD/kWh)	Median Lifetime (years)	Matched N
Lead-acid	148.76	12.00	3
Lithium-ion	301.52	15.00	11
Lithium-ion LFP	318.48	20.25	2
Lithium-ion NMC	332.66	20.25	2
Sodium-sulphur	376.30	15.00	1
Vanadium Redox-flow	229.99	20.00	5

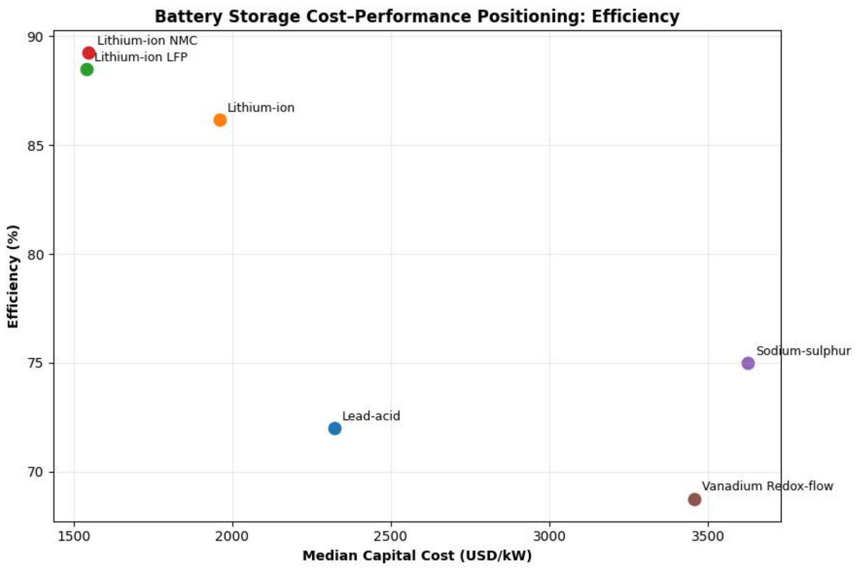


Figure 4: Cost–Lifetime Positioning of Battery Storage Technologies

3.5 Cost–Performance Relationships

Matched year of technology observations were used to perform a correlation analysis, not unmatched raw records. The highest correlation coefficient was found between the USD/kW CAPEX (Pearson r = −0.7923 and Spearman ρ = −0.8061 both statistically significant p < 0.001). USD/kWh CAPEX was moderately and negatively associated with lifetime according to Spearman correlation (ρ = −0.5050, p = 0.0118). However, the efficiency was not significantly associated with USD/kWh CAPEX, and the association between USD/kW CAPEX and the client's lifetime was not statistically significant. The full Pearson and Spearman correlation are shown in Table 6.

Table 6. Correlations Between Battery Capital Cost and Performance

CAPEX Unit	Performance Indicator	N	Pearson r	Pearson p	Spearman ρ	Spearman p
USD/kWh	Efficiency	33	−0.0213	0.9064	−0.1553	0.3881
USD/kWh	Lifetime	24	−0.3667	0.0780	−0.5050	0.0118
USD/kW	Efficiency	22	−0.7923	<0.001	−0.8061	<0.001
USD/kW	Lifetime	19	−0.3240	0.1759	−0.4092	0.0819

The cost–performance relationships were found to be different between historical and contemporary observations and projected observations for each period. The historical association between CAPEX and efficiency was negative and significant (ρ = −0.6898 at 0.0091 p value) and the projected association was strengthened (ρ = −0.8306 at 0.0056 p value). An important CAPEX–lifetime relationship was also found for a projected USD/kW (ρ = −0.7899, p = 0.0113). These period-specific relationships are summarized in Table 7, which shows that the relationships were not consistent across the periods.

Table 7. Period-Specific Spearman Cost–Performance Correlations

Period	CAPEX Unit	Performance Indicator	N	Spearman ρ	p
Historical/Contemporary	USD/kWh	Efficiency	22	0.0374	0.8689
Historical/Contemporary	USD/kWh	Lifetime	13	−0.1335	0.6636
Historical/Contemporary	USD/kW	Efficiency	13	−0.6898	0.0091
Historical/Contemporary	USD/kW	Lifetime	10	0.1066	0.7693
Projected	USD/kWh	Efficiency	11	−0.1389	0.6838
Projected	USD/kWh	Lifetime	11	−0.1823	0.5916
Projected	USD/kW	Efficiency	9	−0.8306	0.0056
Projected	USD/kW	Lifetime	9	−0.7899	0.0113

3.6 Statistical Analysis of Capital Cost Evolution

In the technology adjusted regression analysis, both CAPEX measures decreased over time, a finding that was significant. The year coefficient for USD/kWh was −0.0507 ($p < 0.001$), which equated to an estimated annual decrease of 4.94% when technology was accounted for. The interval for its 95% confidence was from −5.90% to −3.97% and the model had an adjusted R^2 of 0.4886. USD/kW CAPEX decreased by an estimated 1.61% annually ($p = 0.002$), with a 95% confidence interval from −2.62% to −0.59%. Table 8 shows the main technology adjusted regression estimates for both CAPEX measures.

Table 8. Technology-Adjusted Regression Models of Capital Cost Evolution

CAPEX Unit	N	Technologies	Adjusted R²	Year Coefficient	Robust SE	p	Annual Change (%)	95% CI
USD/kW	178	6	0.0562	−0.0162	0.0053	0.0020	−1.61	−2.62 to −0.59
USD/kWh	155	6	0.4886	−0.0507	0.0052	< 0.001	−4.94	−5.90 to −3.97

Another distinction was made between historical/contemporary and projected cost dynamics using separate temporal models. The historical and contemporary USD/kWh CAPEX growth rate was found to be estimated at -6.83% per year ($p = 0.0189$) while the projected USD/kWh CAPEX growth rate was found to be -3.62% ($p < 0.001$). A major annual drop in projected USD/kW CAPEX of 1.94% ($p = 0.0070$) was observed. The historical/contemporary USD/kW model had a positive annual estimate of +2.90% but was not statistically significant ($p = 0.6101$). The regression estimates and the fit statistics for each period are presented in Table 9.

Table 9. Historical/Contemporary and Projected CAPEX Regression Models

CAPEX Unit	Period	N	Years	Technologies	Annual Change (%)	p	Adjusted R^2
USD/kW	Historical/Contemporary	94	7	4	+2.90	0.6101	−0.0199
USD/kW	Projected	79	4	3	−1.94	0.0070	0.1060
USD/kWh	Historical/Contemporary	105	10	6	−6.83	0.0189	0.0845
USD/kWh	Projected	50	4	5	−3.62	< 0.001	0.4933

4. Discussion

The results show a clear downward trend in the capital cost of batteries over time, and different trends for different technologies. The technology adjusted models revealed annual CAPEX reductions of about 4.94% in USD/kWh and 1.61% in USD/kW, further attests to significant improvement in storage economics over time. This trend is significant for renewables-heavy power systems because energy shifting/balancing, voltage regulation, and grid flexibility are increasingly required as variable renewable energy grows, an increasing need for battery storage (Datta et al., 2021). The findings therefore indicate that the lower battery costs can improve the potential for broader deployment in future electricity systems.

An analysis of the difference between historical/contemporary and projected periods is also significant. Historical USD/kWh CAPEX reduced at an increased rate compared to projected CAPEX suggesting that further cost reduction is possible but at a lower rate. This pattern should be taken with a grain of salt as future values are projections and not actual results. In addition to technology costs, the introduction of energy-system transformation requires regulatory frameworks,

infrastructure coordination, and market design. Integrated energy systems need the right policy frameworks to ensure that technological advances can contribute to greater system benefits, as highlighted by Cambini et al. (2020).
The findings also revealed that lithium-ion, LFP and NMC systems held more cost-efficient positions than lead-acid, sodium-sulphur and vanadium redox-flow systems for technology level differences. Lithium-ion had a relatively strong efficiency throughout the time, and LFP and NMC are the ones with the highest mean efficiencies. Efficient and fast response storage that can help maintain system stability is especially important in renewable-dominated systems. Renewable generation with power-electronic converters can change the conventional stability characteristics of a system, which can lead to an increased need for flexible storage systems that can support system operation (Meegahapola et al., 2020).
Efficiency was not the only relevance for overall technology suitability; lifetime results proved that. The mean lifetimes of LFP and NMC were extremely long, and vanadium redox-flow had a good lifespan even if it was less efficient. This further emphasises the importance of making a multidimensional comparison as a storage technology may provide a range of cost, efficiency and service life combinations. A more comprehensive evaluation of renewable energy also calls for an integrated approach instead of a single focus on one of three aspects: economic, technical and environmental (Farghali et al., 2023).
The results of the cost performance analysis indicated a high level of negative correlation between USD/kW CAPEX and efficiency and a moderate negative correlation between USD/kWh CAPEX and lifetime. The results indicate that costs of capital did not necessarily correlate with performance. These correlations are associative, however, and not causal, as the data in the database comes from various sources, countries and time periods. Data-driven comparative analysis continues to be valuable for understanding the general patterns of technologies and providing evidence for energy system decision-making (Pavithra et al., 2025).
New sodium-based technology could also be part of the storage diversification efforts in the future. The research on sodium-ion electrolyte and solid-state architecture is still in progress, which continues to mitigate conductivity, safety, and materials issues (Liu et al., 2023; Lin et al., 2025). The use of sodium-ion systems has emerged as a promising option due to their cost benefits and availability of materials, but they still have performance challenges that need to be addressed (Deshmukh et al., 2025; Si et al., 2025).
Overall, the results are consistent with the increasing potential of battery storage integration into future electricity systems with a higher share of renewables. As more renewables are added to the grid, the need for flexibility, frequency control, and reliable grid integration will continue to grow (Iweh et al., 2021; Alqahtani et al., 2022). Long-term cost and performance assessment should be carried out with the integration of degradation, cycling behavior, levelized storage costs, and use of larger technology-specific datasets, which should enhance the robustness of the assessment.

5. Conclusion
This study has investigated the changing cost and performance characteristics of the leading battery storage technologies, to shed light on their future possible contribution to energy systems. The results show that the battery CAPEX can be clearly reduced in the long term, where the technology-adjusted models show that the annual reduction in CAPEX is around 4.94% for USD/kWh and around 1.61% for USD/kW, respectively. Different life times of competing technologies indicated other trade-offs, with lithium-ion technologies such as LFP and NMC coming out with positive cost-efficiency ratios. Although the efficiency of vanadium redox-flow was relatively low, its longevity was favourable, which shows that technology suitability has nothing to do with economic or technical indicators. The cost–performance analysis also revealed significant inverse relationships between selected CAPEX and performance measures, where the cost reduction does not always go hand in hand with the lower technical characteristics. The historical/contemporary and projected observations separation also revealed that the size of cost saving is different for different periods and cost measures. Together, these results show the growing economic and technical potentials of battery storage for renewable electricity systems and the need for technology-specific assessments.

Future studies should include degradation and cycling characteristics, levelized storage costs, technology-specific revenues from system services, and more extensive datasets to deliver more complete evidence for long-term planning and investment decisions in storage.

References

1. Admase, A. T., Asrade, E. D., & Fanta, S. W. (2025). A comprehensive review on energy storage materials & technologies: applications of nanofabrication techniques for enhanced performance and efficiency. Materials for Renewable and Sustainable Energy, 14(3), 56.
2. Alam, M. J. E., Muttaqi, K. M., & Sutanto, D. (2021). Battery energy storage to mitigate rapid voltage/power fluctuations in power grids due to fast variations of solar/wind outputs. Ieee Access, 9, 12191-12202.
3. Alqahtani, S., Shaher, A., Garada, A., & Cipcigan, L. (2022, August). Frequency Stability in Renewable-Rich Modern Power Systems, Saudi Grid Case Study. In 2022 57th International Universities Power Engineering Conference (UPEC) (pp. 1-6). IEEE.
4. Cambini, C., Congiu, R., Jamasb, T., Llorca, M., & Soroush, G. (2020). Energy systems integration: implications for public policy. Energy policy, 143, 111609.
5. Datta, U., Kalam, A., & Shi, J. (2021). A review of key functionalities of battery energy storage system in renewable energy integrated power systems. Energy Storage, 3(5), e224.
6. Deshmukh, K., Varade, K., Rajesh, S. M., Sharma, V., Kabudake, P., Nehe, S., & Lokawar, V. (2025). Sodium-ion batteries: state-of-the-art technologies and future prospects. Journal of Materials Science, 60(8), 3609-3633.
7. Ergun, S., Dik, A., Boukhanouf, R., & Omer, S. (2025). Large-scale renewable energy integration: Tackling technical obstacles and exploring energy storage innovations. Sustainability, 17(3), 1311.
8. Farghali, M., Osman, A. I., Chen, Z., Abdelhaleem, A., Ihara, I., Mohamed, I. M., ... & Rooney, D. W. (2023). Social, environmental, and economic consequences of integrating renewable energies in the electricity sector: a review. Environmental chemistry letters, 21(3), 1381-1418.
9. Figgener, J., Stenzel, P., Kairies, K. P., Linßen, J., Haberschusz, D., Wessels, O., ... & Sauer, D. U. (2020). The development of stationary battery storage systems in Germany–A market review. Journal of energy storage, 29, 101153.
10. Iweh, C. D., Gyamfi, S., Tanyi, E., & Effah-Donyina, E. (2021). Distributed generation and renewable energy integration into the grid: Prerequisites, push factors, practical options, issues and merits. Energies, 14(17), 5375.
11. Karduri, R. K. R., & Ananth, C. (2023). Decarbonizing the grid: Pathways to sustainable energy storage. This paper has been published in International Journal of Advanced Research In Basic Engineering Sciences and Technology (IJARBEST) DOI, 10.
12. Laugs, G. A., Benders, R. M., & Moll, H. C. (2020). Balancing responsibilities: Effects of growth of variable renewable energy, storage, and undue grid interaction. Energy Policy, 139, 111203.
13. Lin, X., Zhang, S., Yang, M., Xiao, B., Zhao, Y., Luo, J., ... & Sun, X. (2025). A family of dual-anion-based sodium superionic conductors for all-solid-state sodium-ion batteries. Nature Materials, 24(1), 83-91.
14. Liu, Q., Zhao, X., Yang, Q., Hou, L., Mu, D., Tan, G., ... & Wu, F. (2023). The progress in the electrolytes for solid state sodium-ion battery. Advanced Materials Technologies, 8(7), 2200822.
15. Liu, X., Li, W., Guo, X., Su, B., Guo, S., Jing, Y., & Zhang, X. (2025). Advancements in energy-storage technologies: A review of current developments and applications. Sustainability, 17(18), 8316.
16. Meegahapola, L., Sguarezi, A., Bryant, J. S., Gu, M., Conde D, E. R., & Cunha, R. B. (2020). Power system stability with power-electronic converter interfaced renewable power generation: Present issues and future trends. Energies, 13(13), 3441.
17. Mongird, K., Viswanathan, V., Balducci, P., Alam, J., Fotedar, V., Koritarov, V., &

Hadjerioua, B. (2020). An evaluation of energy storage cost and performance characteristics. Energies, 13(13), 3307.
18. Pavithra, C. V., AmalanJoseph, J., Enbharajan, M., & Savitha, S. (2025, October). Comparative Assessment of Emerging Subsea Renewable Energy Technologies: A Data-Driven Systems Analysis. In 2025 Second International Conference on Intelligent Technologies for Sustainable Electric and Communications Systems (iTech SECOM) (pp. 1-7). IEEE.
19. Sayed, E. T., Olabi, A. G., Alami, A. H., Radwan, A., Mdallal, A., Rezk, A., & Abdelkareem, M. A. (2023). Renewable energy and energy storage systems. Energies, 16(3), 1415.
20. Si, H., Ma, J., Xia, X., Wang, Q., Geng, S., & Fu, L. (2025). Solid-state sodium-ion batteries: theories, challenges and perspectives. Chemistry–A European Journal, 31(5), e202403247.
21. Wei, P., Abid, M., Adun, H., Kemena Awoh, D., Cai, D., Zaini, J. H., & Bamisile, O. (2023). Progress in energy storage technologies and methods for renewable energy systems application. Applied Sciences, 13(9), 5626.
22. Hatton, L., Staffell, I., & Johnson, N. (2024). The Global and National Energy Systems Techno-Economic (GNESTE) Database: Economic and performance data for battery storage in current and future electricity systems [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.10890349