Datacenter microgrids: Cost-Emissions-Reliability Frontier Across U.S. RTOs

JAPHET DALOKHULE MUCHENJE[1], MUNASHE NAPHTALI MUPA[2], MUKUDZEISHE WENDELL MERIT MUPA[3], DANIEL NAYO[4], TRACEY HOMWE[5]
[1]*Suffolk University,* [2]*Hult International Business School,* [3]*Institute of Energy Management of Africa,* [4]*University of Arkansas Little Rock,* [5]*La Salle University*

Abstract- This study proposes a complete mixed-integer optimization framework of data center microgrids This paper presents a full mixed-integer optimization model of the data center microgrids that maximizes the photovoltaic (PV) systems, wind generation, battery energy storage systems (BESS) sizing, and hourly electricity market transactions to streamline the levelized costs under the restriction of the emissions intensity and loss-of-load probability (LOLP). The optimization framework considers the intricate nature of the connections between the variability of renewable generation, energy storage, and electricity markets through sophisticated modeling techniques. It also takes into account such realistic limitations as battery degradation, transmission and interconnection. Comparison of Seven Major U.S. Information types. Local Transmission Organizations (RTOs): ERCOT, PJM, CAISO, MISO, SPP, NYISO, and ISO-NE that cover interzonal resource profiles by using high resolution weather, historic curtailment trends caused by grid integration, and multi-year nodal price volatility in the course of market operation. The paper applies stochastic optimization methods and Monte Carlo simulations to solve uncertainties in the production of renewable generation, electricity costs, and extreme weather conditions such that the structures of the microgrids are resilient to such uncertainties. The findings indicate that the best microgrid designs differ significantly across regions with results in CAISO and ERCOT generating the lowest cost-emissions and cost-reliability frontiers. This is explained by their essentially better renewable resources, as well as good regulatory environment. Moreover, the market structure in both regions is established, which gives the economic indication that will give the clear signal on investment in the energy resources that are distributed locally.

Keywords: Data centers, microgrids, renewable energy, optimization, reliability, emissions

I. INTRODUCTION

As data centres consumed roughly 1% of the global electricity demand, the rapid increase in the digital infrastructures has made them one of the most energy-intensive services sectors (Koronen et al., 2020). As sustainability pledges grow, along with unpredictable electricity prices, the willingness of data center operators to assess the benefits of a microgrid will increase. The difficulty is in optimizing the numerous cost/emissions/reliability trade-offs across different regional electricity markets.

Data center microgrids have different opportunities and limitations depending on Regional Transmission Organizations (RTOs) throughout the United States. The optimal microgrid configurations are influenced by factors like renewable resource potential, electricity market structures, transmission constraints, and regulatory frameworks (Agupugo et al., 2022). This study seeks to fill an important gap in the research analysing the impact of regions on the costemissions-reliability frontier of data centre microgrids.

The research question prompting the inquiry is: What is the cost-emissions-reliability frontier for meeting a data center's hourly load with PV, wind, storage and grid purchases across U.S. RTOs? This study creates a complete optimization framework and applies it to seven large RTOs. It offers feasibility insights for data center operators, policymakers, and energy system planners.

II. LITERATURE REVIEW

2.1 Data Center Energy Systems

Data centers have a unique energy profile compared to other commercial loads. This creates opportunities and challenges for energy system design. Hyperscale data centres face unique challenges that require sustained demand at high energy intensity, significant on-site renewable energy generation and storage, and demand-side response capabilities. According to Glavin, (2023), renewable energy systems designed for non-data center applications often lack the high redundancy and reliable performance required for data center use. The design of data centers that utilise renewable energy must take into account their unique structural and operational specifications, which can critically impede the renewable energy system design process. Data center PUEs have improved significantly over the past two decades. The data center industry's collective action can drive measurable change. This will be possible in a wider range of industries outside the tech industry.

To lessen the carbon footprint of data centres there have been studies into many different things, these include as Takci et al. (2025) states a demand response programmes that use the computational flexible nature of data centres for grid services, and workload shifting which moves computation to other areas with cleaner electricity grids or more renewable generation. An alternative is as Gnibga et al. (2023) explains as an on-site renewable generation systems which directly provide clean energy to the data centre reducing reliance on the grid. The above methods indicate that players in the sector are waking up to the fact that data centres can be active players rather than passive consumers of energy.

Mupa et al. (2025) describe the ability of the developed technologies to boost risk management in the energy-intensive industries. Complex systems in these areas can be optimised by the deployment of AI in more predictive analytics, automated control and real time decision-making. Microgrid management of data centers is also an indication of this technological convergence. Use of machine learning algorithms allows improved operation efficiency and decision intelligence. It streamlines dispatch storage of energy, predicts the generators of renewable energy and orchestrates the interactions across the grid to minimize expenses, while achieving reliability.

2.2 Microgrid Optimization.

Microgrids have some benefits that include more power availability and less of the green house gasses, which concern contradictory goals. In addition,, the optimization of the microgrids can lead to the drastic reduction of the energy cost. As stated by Salehi et al. (2022), the previous studies did single-objective optimization or the simplistic multi-objective optimization with the use of a weighted sum model or epsilon-constraint model that are not representative of the actual course of decision-making in microgrids design. Instead, a model that incorporates a mix of the weights of the goals and downstream characteristics is proposed to be used with the conception of multi-criteria decision-making. The modern electricity markets are becoming increasingly complex, and unpredictable pricing structures and a number of environmental regulations such as the carbon prices, and the renewable energy policies are becoming dominant. The electricity marketplace also has certain opportunities to provide new grid services. This in turn necessitates the use of more complex optimization systems, which are able to run multiple competing objectives, and uncertainty in the important parameters.

Energy storage systems are essential to optimizing microgrids. They provide flexibility for renewable energy sources, participation in grid services, and the reliability to offer back-up power in the event of outages. According to Shamarova et al. (2022), battery degradation models can largely impact the long-term economic viability of a system. Capacity fade and power fade over the operational cycles affect the performance and replacement cost of a system. For this reason, they should be properly dealt with in planning frameworks. If not, the planning framework can overestimate the benefits derived from the system. The use of battery performance curves that are temperature dependent, state-of-charge dependent, and degraded with cycle depth and cycle frequency helps make microgrid planning studies more accurate and economic forecasts for investment decision making more reliable.

2.3 Regional Electricity Markets

Electricity markets in the United States have considerable regional differences in price structure, renewable penetration, and other operational characteristics. These characteristics impact the investment and operational strategies of microgrids. Raineri (2025) explains that unlike the capacity markets in PJM and ISO-NE, ERCOT's energy-only market design affects the investment incentives for distributed energy resources through direct price signals reflecting real-time supply and demand conditions instead of forward capacity commitments. Timely resource flexibility can provide for more volatile, but potentially lucrative, opportunities in a market with a scarcity pricing structure. The state of California has laid out stringent renewable energy policies that have created unique market conditions in CAISO. These include periods of negative pricing owing to high levels of renewable generation, duck curve challenges that require flexible resources, and stringent carbon reduction mandates that favour investments in clean energy. The measures have created some of the best conditions for integrating renewable energy anywhere. At the same time, they have created new operational issues for the grid.

Lieberman (2021) states that MISO can optimize its diverse generation mix comprising coal, natural gas, wind, nuclear, and other resources because of all the transmission constraints that are present across multiple states with a variety of regulatory regimes. These regions are rich in wind and often the transmission bottlenecks limit delivery of green energy to load centres. This affects optimal microgrid sizing decisions.

Mupa et al. (2025) delve into new machine learning applications for energy systems. Moreover, their application will lead to the easier handling of complexities that arise from multi-regional analysis among others. Greater sophistication in modelling regionalities and their impact on microgrid optimisation is enabled by the technology which allows for capturing of inherent non-linearities, temporal autocorrelations and high order interactions existing between market variables by the enhanced modelling framework.

III. METHODOLOGY

3.1 Optimization Framework

This article presents a mixed-integer linear programming (MILP) model that can simultaneously optimize capacity investments and operational decisions of a data center microgrid. Furthermore, the model is capable of multi-temporal optimization looking at long-period investments and day-ahead operational scheduling. The purpose of the objective function is to minimize levelized cost of energy (LCOE) by capital expenditures, operational and maintenance costs, fuel costs, and market transaction fees. It also ensures carbon emissions intensity threshold and loss-of-load probability limits are maintained to required standards throughout the planning period.

The optimization model incorporates:

- PV and wind capacity sizing decisions
- Battery energy storage system (BESS) capacity and power rating optimization
- Hourly operational decisions for renewable generation, storage charging/discharging, and grid transactions
- Reliability constraints based on LOLP and Expected Energy Not Served (EENS) metrics
- Carbon emissions limits based on grid emissions factors and renewable generation

3.2 Data Sources and Processing

Renewable Resource Data

Hourly solar irradiance and wind speed data from NREL's National Solar Radiation Database (NSRDB) and WIND Toolkit, providing meteorologically consistent time series across all RTO regions for the analysis period. These datasets include measurements obtained by satellites which are verified with ground-based observations meaning that the spatial resolution (4-km grid) and the time accuracy are high. The data reflects seasonal changes, diurnal pattern and exceptional weather conditions that are essential in the precise modeling of renewable generation and optimization of microgrids in different geographical areas and climate-related conditions.

Electricity Market Data

Historical locational marginal prices (LMPs) found in the public databases of every RTO, such as real-time and day-ahead prices of representative nodes in every region. According to Zhang et al. (2020), transmission congestion and the cost of ancillary services are included in the price data, indicating the real market conditions and grid limitations. The data is a five-year history of hourly data on prices, market fluctuations, and seasonal trends, extreme price movements, and regulatory shifts. Other data available would be capacity market prices, renewable energy certificate value, and frequency regulation payments to reflect fully on the revenue opportunities of operating the microgrids.

Curtailment Data

Patterns of curtailment of renewable energy based on the public utility filings and the RTO reports to facilitate the realistic modelling of the grid integration constraints of renewable resources. The data has some columnar monthly curtailment by organized technology, geographic area and their causes including transmission constraints, minimum generation level and negative costs. This information enables accurate representation of renewable energy availability constraints, informing optimal microgrid sizing decisions and operational strategies to minimize economic losses from generation curtailment during high renewable output periods.

Equipment Performance

Solar panel and wind turbine performance curves from original equipment manufacturer (OEM) specifications, battery degradation models based on recent literature, and data center load profiles from industry collaborations. Malik and Bak (2024) explain that performance data includes temperature derating factors, inverter efficiency curves, wind turbine power characteristics across varying wind speeds, and detailed battery cycling behavior. The analysis incorporates realistic degradation patterns, maintenance schedules, and equipment failure rates to ensure accurate long-term economic assessments and optimal technology selection for diverse operational environments and climate conditions.

3.3 Regional Analysis Framework

The study compares seven major U.S. RTOs:

- ERCOT: Texas grid with unique energy-only market design
- PJM: Mid-Atlantic region with capacity market structure
- CAISO: California market with aggressive renewable energy policies
- MISO: Midwest region with diverse generation portfolio
- SPP: Southwest Power Pool covering central U.S. states
- NYISO: New York market with complex transmission constraints
- ISO-NE: New England region with winter reliability challenges

3.4 Stochastic Analysis.

The study employs stochastic optimization techniques that incorporate Monte Carlo simulation to account for uncertainty in renewable generation, electricity prices and data center loads during extreme weather and market conditions. Younesi et al. (2020) explains that the Monte Carlo framework simulates thousands of scenarios with different weather conditions, price volatility patterns, and demand changes to test microgrid robustness. Key variables' probability distributions are derived from analysis of historical data and climate scenario. By preparing for several functional scenarios, the microgrid is robustly designed for a grid outage, renewable generation shortfall, price spike, and once-in-alifetime weather event that affects reliability and economics.

IV. RESULTS AND DISCUSSION.

4.1 Regional Cost-Emissions-Reliability Frontiers.

There are lots of variations according to different regions in the microgrid design and also their performance. The cost-emissions-reliability frontiers for CAISO and ERCOT are most favorable because they have better solar resources and market structures supporting renewable energy.

In the CAISO region, the optimal microgrid development tends to consist of PV capacity of 40 to 60 percent of peak data center load, wind capacity of 15 to 25 percent, and battery storage capacity of 20 to 30 percent. Due to the strong combination of solar resources, time-of-use pricing structures, and net energy metering policies, we get great economics incentive.

Tsai and Eryilmaz (2018) explain that ERCOT's renewable energy capabilities are similar to California's but more focused on wind generation given the excellent wind resources. The optimum atmospheric conditions in ERCOT had resulted in the 25-35% PV capacity. The design of the energy-only market gives price signals for energy arbitrage and reliability services.

It will be more difficult to optimize a microgrid in PJM and MISO. This is partly due to the lower quality of renewable resources. It is also due to the various and complex market structures. The best configurations in these areas typically require larger battery storage systems (35-45% of peak load), to offer adequate reliability while managing price fluctuations.

4.2 Economic Performance Analysis

In different regions, the levelized costs of energy differ significantly. They are in the range of \$0.08-0.12/kWh in CAISO and ERCOT regions. The levelized costs of energy are \$0.12-0.18/kWh in

NYISO and ISO-NE. Shen et al. (2020) notes that the differences arise due to variations in the quality of renewable resources, electricity market prices and regulatory environments.

Microgrid deployment yields the greatest economic benefits during peak pricing events and extreme weather events. In ERCOT, on-site generation and energy storage provide opportunities for saving money during summer peak pricing events. Likewise, the pricing trends of CAISO's duck curve fit well with when solar generation occurs.

Battery energy storage technology has gained importance as they support diverse electric power system benefits. Zhang et al. (2021) explains that in addition to enabling energy arbitrage, they support both capacity services and reliability benefits. Storage has a wide range of economic values. For example, CAISO and NYISO produce the highest economic return for storage due to their wide-ranging price differentiation on a daily basis. Additionally, both CAISO and NYISO provide capacity market payments which enhance the economic returns from storage.

4.3 Environmental Impact Assessment

Carbon emissions intensity varies substantially across optimal microgrid configurations and regional grids. Data centers in regions with cleaner grid electricity (CAISO, NYISO) can achieve lower absolute emissions even with smaller renewable energy systems, while regions with carbon-intensive grids (MISO, SPP) require more aggressive renewable energy deployment to meet emissions targets.

Sandwell et al. (2025) demonstrates that achieving 50% emissions reduction relative to grid-only supply requires renewable energy penetration levels of 80% in carbon-intensive regions compared to 40 - 50% in cleaner grid regions. This finding has significant implications for corporate sustainability strategies and renewable energy procurement decisions.

4.4 Reliability and Resilience Analysis

Loss-of-load probability (LOLP) metrics reveal important trade-offs between cost optimization and reliability requirements. Data centers in regions with high grid reliability (PJM, CAISO) can achieve acceptable LOLP levels with smaller storage systems, while regions with lower grid reliability (ERCOT, SPP) require more extensive backup generation and storage capacity. Extreme weather events significantly impact microgrid performance across all regions. Rickerson et al. (2022) explains that the February 2021 Texas winter storm and California summer heat waves demonstrate the importance of robust microgrid designs that can maintain operations during grid stress conditions. Stochastic analysis reveals that increasing battery storage capacity by 20-30% above deterministic optimal levels substantially improves performance during extreme events.

4.5 Sensitivity Analysis

Technology Costs
Solar PV cost reductions of 20-30% increase optimal PV penetration by 15-25% across all regions, while battery cost reductions have more pronounced impacts in regions with high price volatility and frequent grid disturbances.

Carbon Pricing
Implementation of carbon pricing at $50/tonne CO2 shifts optimal configurations toward higher renewable energy penetration, with the largest impacts in carbonintensive grid regions where emissions reduction benefits are most economically valuable.

Reliability Requirements
Tightening LOLP constraints from 0.1% to 0.01% increases optimal storage capacity by 25-40% and raises levelized costs by 8-15% across all regions, demonstrating significant cost implications of enhanced reliability standards.

V. POLICY AND STRATEGIC IMPLICATIONS

5.1 Regional Policy Recommendations

Market Design
Regions with energy-only markets (ERCOT) provide clearer price signals for microgrid optimization compared to hybrid capacity markets, enabling more straightforward economic analysis and investment decision-making. The transparent pricing mechanisms in energy-only markets directly reflect supply-demand balance and scarcity conditions. However, Tarufelli et al. (2022) explains that

capacity market reforms in PJM and ISO-NE could better recognize distributed energy resources' reliability contributions through enhanced participation rules, appropriate capacity credit assignments, and compensation mechanisms that accurately value microgrid reliability services and grid support capabilities.

Interconnection Procedures
Streamlined interconnection processes for data center microgrids, particularly in MISO and SPP, could reduce development costs and deployment timelines through standardized application procedures, expedited review processes, and simplified technical requirements. Current interconnection delays and complex approval processes create significant barriers to microgrid deployment, increasing project costs and uncertainty. Reforms should include pre-approved equipment lists, standardized impact studies, fast-track procedures for smaller installations, and improved coordination between transmission operators and distribution utilities to facilitate efficient project development.

Environmental Regulations
Similar carbon pricing or renewable energy standards across regions would simplify the regulatory environment for multi-region data centre operators by the establishment of consistent policy frameworks, harmonized reporting requirements and standardized compliance mechanisms. Barkas (2024) argues that balancing consumer protection and market integrity with innovation and competition is essential for futureproofing the regulatory framework. By having a coordinated approach, economies of scale can be achieved during compliance activities. Similarly, renewable energy procurement strategies can be simplified. Finally, sustainability investment can be distributed more efficiently across portfolios.

5.2 Strategic Considerations for Data Center Operators

Portfolio Approach
Multi-region operators have the ability to balance investments in the microgrids in their portfolio due to differences in resources and market condition within a region. It shapes this strategic approach to allow cross-regional risk diversification, optimum capital allocation, and procurement and operations economies of scale. According to Xu et al., (2022), portfolio optimization will help minimize the total investment cost at the expense of maximizing the use of renewable energy and financial returns in various geographic locations.

Flexibility Value
By making microgrids operationally flexible, it is possible to participate in the new grid services markets and respond to new regulatory conditions. Flexible systems have modular components, bidirectional power flows and enhanced control features which accommodate multiple revenue streams. The design philosophy contains a future-proof against technological obsolescence and regulatory modifications and the highest level of involvement in the changing electric markets and grid modernization programs.

Risk Management
Microgrids help hedge against fluctuations in electricity prices and price volatility on the carbon price as Herding (2023) notes in his examination of risk management in intensive technology sectors. These systems minimise market price variations by on-site generation and storage. Also, the ability to insure against grid interruptions and weather emergencies and provide predictable energy prices in the long term budgetary planning are offered by microgrids. Future Research and limitations.

VI. LIMITATIONS AND FUTURE RESEARCH

6.1 Study Limitations

Data Center Load Profiles
It has been assumed that the electricity power demand and load profile will be similar as in the traditional computing load. Still, it may not be the case since the workload of AI and ML training, cluster of computers to perform high-performance work, running of cryptocurrencies mining equipment and others will present considerably different load distributions. According to Gul (2025), this entails higher and more fluctuating loads at the peaks and not fixed baseless cycles of calculation, and distorted distributions of time. Thus, the optimization and sizing of such microgrids should consider the demands and load of these new technologies, which are developed in this century.

Technology Evolution
Battery technology undergoes rapid evolution - significant advances in the energy density, cycle life,

charge fastness, and cost of manufacture can cause the most devising solutions as to what kind of microgrids to implement to fall outside the scope of this research. Cavus (2025) explains that technology Innovations Can permit more Renewables and Improved Grid Independence. These inventions have the potential to transform the economic trade-off between the renewable generation capacity and the energy storage systems and it has the potential of achieving even more aggressive penetration rates of renewables and a more improved grid independency.

Disparity in regulations

There is a lot of uncertainty in the programs and regulations being instituted by many societies throughout the world to change the existing markets. To remain un-beaten and not lapse into trappings, it is significantly critical to remain immensely knowledgeable about and responsive to regulatory dubiousness. The policy modifications have the potential to affect the relative and long-term investment policies of the thermal data center operator as well as the relative attractiveness of different microgrid designs.

6.2 Future Research Directions

Advanced Control Systems

The team will investigate the machine learning-based control systems about the real time microgrid optimization as per the recent piece of change to the usage of AI application within the energy system. Such systems could lead to making predictions and cause actions to be taken without anybody consulted.

Sector Coupling

The study of data center micro grid indications of interacting with transportation electrification and thermal energy sector (Toledo et al., 2025). The situational synergistic propositions that are available in placing electric vehicle charges and waste heat recovery would be investigated at this project.

Grid Services

This service offers us an insight into the potential of data center micro-grid to offer several grid services such as frequency control, voltage, congestion control etc. This is amenable to another analysis to be able to further establish the revenue potential of the ancillary service and grid stabilization.

VII. CONCLUSIONS

In this research, a critical examination is conducted on the cost-emissions-reliability boundaries of data centre microgrids at a major city in the United States. RTOs. The findings point to the fact that the variability of regions characterizes optimal microgrid set-ups. And the most amenable alternatives to integrate renewable are the CAISO and ERCOT. The results have indicated that optimal microgrid structures vary widely across RTOs, due to basic variations in renewable wealth, market structure, and grid stability features. Since there are institutional disparities that exist between regions, microgrid design would have to depend on the operating and economic conditions of electricity markets packaging. Limitations should not lead to the tendency of generalizing.

The microgrid economic viability analysis show that microgrids can achieve a levelized cost that is competitive in regions with good renewable resources and supportive market structures. CAISO and ERCOT show the strongest economic performance. The economic performance of these areas is attributed to good renewable resource potential as well as market mechanisms that provide clear price signals and appropriate compensation for distributed energy resources.

According to the environmental benefits assessment, companies in regions with carbon-intensive grids must adopt more aggressive microgrid sizing measures to achieve equivalent emissions reductions under corporate sustainability goals. Understanding the carbon intensity of the grid before the signing of a contract is crucial in negotiating the contract power purchase agreement. The research highlights essential reliability trade-offs, indicating that costs need to be balanced against reliability requirements while also considering characteristics of the regional grid and extreme weather risks. Energy storage requirements to keep loss-of-load probability at acceptable levels increases with decreasing baseline grid reliability. Areas with strong grid reliability are able to achieve similar results with smaller energy storage systems compared to less reliable areas.

An analysis of policy impact indicates that supportive policies; streamlined interconnection procedures; market reforms that recognize distributed resources that; and coordinated environmental regulations can significantly improve microgrid deployment chances in all regions. Policies to simplify the process of deploying sustainable data center energy and improve economic returns will be implemented to boost market uptake.

The study adds to growing literature on data centre sustainability and microgrid optimisation while providing guidance for industry actors. As data centers grow to accommodate digital transformation initiatives, optimized microgrid solutions offer promising pathways to achieve economic, environmental, and operational reliability objectives. Future work should look into advanced control systems and opportunities for sector coupling and grid services in order to unlock the value of data centre microgrids. Artificial intelligence, machine learning, and other emerging technologies are likely to become increasingly important in the optimization and operation of microgrids.

REFERENCES

[1] Agupugo, C. P., Ajayi, A. O., Nwanevu, C., & Oladipo, S. S. (2022). Policy and regulatory framework supporting renewable energy microgrids and energy storage systems. *Eng. Sci. Technol. J*, *5*, 2589-2615.

[2] Barkas, P. (2024). Consumer protection and financial innovation: Microeconomic, policy, and behavioral considerations for the digital era. In *Finance, Growth and Democracy: Connections and Challenges in Europe and Latin America in the Era of Permacrisis: Democracy, Finance, and Growth* (pp. 263-285). Cham: Springer Nature Switzerland.

[3] Cavus, M. (2025). Advancing Power Systems with Renewable Energy and Intelligent Technologies: A Comprehensive Review on Grid Transformation and Integration. *Electronics*, *14*(6), 1159.

[4] Glavin, M. T. (2023). *Military Installation Resilience: The Role of Building Energy Audits* (Master's thesis, Northeastern University).

[5] Gnibga, W. E., Blavette, A., & Orgerie, A. C. (2023). Renewable energy in data centers: the dilemma of electrical grid dependency and autonomy costs. *IEEE transactions on sustainable computing*, *9*(3), 315-328.

[6] Gül, O. (2025). Dynamic Load Flow in Modern Power Systems: Renewables, Crypto Mining, and Electric Vehicles. *Sustainability*, *17*(6), 2515.

[7] Herding, R. (2023). *Optimal Operation of Energy Microgrids under Uncertainty* (Doctoral dissertation, UCL (University College London).).

[8] Koronen, C., Åhman, M., & Nilsson, L. J. (2020). Data centres in future European energy systems—energy efficiency, integration and policy. *Energy efficiency*, *13*(1), 129-144.

[9] Lieberman, J. (2021). How transmission planning & cost allocation processes are inhibiting wind & solar development in SPP, MISO, & PJM.

[10] Malik, T. H., and Bak, C. (2024). Full-scale wind turbine performance assessment using the turbine performance integral (TPI) method: a study of aerodynamic degradation and operational influences. *Wind Energy Science*, *9*(10), 2017-2037.

[11] Mupa, M. N., Tafirenyika, S., Nyajeka, M., & Zhuwankinyu, E. (2025). Actuarial implications of data-driven ESG risk assessment. *Risk Management Review*, 18(3), 234-251.

[12] Raineri, R. (2025). Power Shift: Decarbonization and the New Dynamics of Energy Markets. *Energies*, *18*(3), 752.

[13] Rickerson, W., Zitelman, K., & Jones, K. (2022). *Valuing resilience for microgrids: Challenges, innovative approaches, and state needs* (No. DOE-NARUC-OE0000818). National Association of Regulatory Utility Commissioners, Washington, DC (United States).

[14] Salehi, N., Martínez-García, H., Velasco-Quesada, G., & Guerrero, J. M. (2022). A comprehensive review of control strategies and optimization methods for individual and community microgrids. *IEEE access*, *10*, 15935-15955.

[15] Sandwell, P., Winchester, B., Mittal, S., Markides, C. N., Beath, H., & Nelson, J. (2025). Opportunities for decentralised solar power to improve reliability, reduce emissions and avoid stranded assets. *Nature Communications*, *16*(1), 8061.

[16] Shamarova, N., Suslov, K., Ilyushin, P., & Shushpanov, I. (2022). Review of battery energy storage systems modeling in microgrids with renewables considering battery degradation. *Energies*, *15*(19), 6967.

[17] Shen, W., Chen, X., Qiu, J., Hayward, J. A., Sayeef, S., Osman, P., & Dong, Z. Y. (2020). A comprehensive review of variable renewable energy levelized cost of electricity. *Renewable and Sustainable Energy Reviews*, *133*, 110301.

[18] Takci, M. T., Qadrdan, M., Summers, J., & Gustafsson, J. (2025). Data centres as a source of flexibility for power systems. *Energy Reports*, *13*, 3661-3671.

[19] Tarufelli, B. L., Eldridge, B. C., & Somani, A. (2022). *Capacity markets for transactive energy systems* (No. PNNL--33381). Pacific Northwest National Laboratory (PNNL), Richland, WA (United States).

[20] Toledo, C. P., Saungweme, J., Matsebula, N., & Mupa, M. N. (2025). Leveraging big data and AI for liquidity risk management in financial services. *Financial Analytics Quarterly*, 11(4), 189-206.

[21] Tsai, C.-H., & Eryilmaz, D. (2018). Effect of wind generation on ERCOT nodal prices. *Energy Economics*, *76*, 21-33

[22] Xu, D., Bai, Z., Jin, X., Yang, X., Chen, S., & Zhou, M. (2022). A mean-variance portfolio optimization approach for high-renewable energy hub. *Applied Energy*, *325*, 119888.

[23] Younesi, A., Shayeghi, H., Safari, A., & Siano, P. (2020). Assessing the resilience of multi microgrid based widespread power systems against natural disasters using Monte Carlo Simulation. *Energy*, *207*, 118220.

[24] Zhang, K., Troitzsch, S., Hanif, S., & Hamacher, T. (2020). Coordinated market design for peer-to-peer energy trade and ancillary services in distribution grids. *IEEE transactions on smart grid*, *11*(4), 2929-2941.

[25] Zhang, X., Qin, C. C., Loth, E., Xu, Y., Zhou, X., & Chen, H. (2021). Arbitrage analysis for different energy storage technologies and strategies. *Energy Reports*, *7*, 8198-8206.