Review on Economic Analysis of Grid-tied Battery Storage Systems and Optimization Strategies

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***Abstract*— This comprehensive review paper provides an in-depth exploration of the landscape of energy management strategies within the context of emerging energy markets. It underscores the significance of effective energy management and optimization, particularly in light of the surging integration of renewable energy sources, growing sustainability concerns, and the dynamic shifts within the energy sector. This review extensively analyses three fundamental domains: electricity demand estimation, battery storage systems, and energy arbitrage methodologies placing a significant emphasis on the body of the research related to electricity storage optimization. Furthermore, it delves into the widespread strategies that are adopted in battery storage systems, which have assumed a pivotal role in energy storage and the equilibrium of supply and demand in the modern energy landscape. Nevertheless, amidst this extensive examination, a considerable research gap arises, specifically highlighting the lack of dedicated studies addressing energy arbitrage methods tailored to the unique attributes of emerging energy markets. This gap is particularly prominent in the context of Sri Lanka's growing energy market, where the prominence of renewable energy sources is on the rise. The review underscores that in order to fully harness the vast potential of renewable resources and optimize energy supply within this distinctive setting, it is crucial to develop and implement customized energy arbitrage strategies. These strategies should be designed to accommodate the evolving energy dynamics and the integration of renewable energy, that would thus enable energy markets to function effectively while maximizing economic benefits. Therefore, as the global energy landscape continues to transform, with a growing focus on sustainability and renewable energy, this paper sheds light on the need for innovative and tailored energy solutions in emerging markets.**

Keywords—battery energy storage systems, renewable energy integration, energy management, energy arbitrage

I. Introduction

Sri Lanka's economic growth in recent years, spanning industries like manufacturing and tourism, has been remarkable. However, the economic crisis of 2022, characterized by fiscal constraints, foreign exchange shortages, and economic uncertainties, has created significant challenges for the nation. This crisis, impacting the energy sector, particularly the availability of fuel for thermal power plants, has raised questions about the sustainability of Sri Lanka's energy infrastructure [1]. The dependence on hydrocarbon fuels during peak demand periods has substantially driven up electricity costs and exerted pressure on foreign exchange reserves. As a result, the need for efficient energy storage solutions has become more pressing.

Battery storage technology has emerged as a crucial component to ensure a resilient and cost-effective electricity infrastructure in Sri Lanka. These systems have the capacity to store excess electricity generated during low-demand periods and release it when demand peaks, optimizing resource utilization [2]. Nevertheless, the substantial upfront capital costs associated with battery storage systems have been a significant barrier to widespread adoption. To make battery storage more accessible and economically feasible, it is crucial to explore the broader economic opportunities they present, including their potential role in providing lucrative ancillary services to the grid

In undertaking this review on the economic analysis of grid-tied battery storage systems and optimization strategies, a methodical approach was adopted. The chosen keywords—were carefully selected to align with the core components of the topic. The systematic literature search, inclusive criteria, and critical review process were tailored to extract insights into the economic considerations and optimization strategies associated with integrating battery storage into the grid, particularly within the context of Sri Lanka's energy infrastructure challenges.

II. Literature Review

A. *Electricity Demand Estimation*

Accurate electricity demand forecasting in Sri Lanka is a critical facet of effective energy management. Using co-integration and error-correction models household electricity demand in Sri Lanka has been forecasted and it found that increasing electricity prices is not an effective means of reducing consumption, indicating price inelasticity in demand [4]. Also, the "energy ladder" hypothesis, which sees a shift to modern fuels with rising incomes has been confirmed to the context of Sri Lanka [5]. Engle functions, an economic tool, reveal that firewood and kerosene are considered inferior goods in urban and estate sectors, while LPG and electricity are normal goods and that income has less impact on the estate sector's fuel choices [6]. A study has been done to assess the correlation of electricity demand for several factors [7]. Accordingly, electricity demand is positively correlated with factors like GDP, population, GDPPC, average annual temperature, the number of consumer accounts, and previous year demand. Conversely, it's negatively correlated with the average electricity price and relative humidity. Additionally, there's a moderate positive correlation with energy intensity, but no significant correlation with average rainfall. The transition from a predominantly hydro-based power system to one primarily coal-based in Sri Lanka during the early 21st century has been outlined as a response to growing demand and the necessity for diversified energy sources [8].

A comprehensive analysis of energy consumption forecasting in Sri Lanka, employing various parametric and nonparametric techniques [9]. It introduces the Seasonal Subseries Aggregation (SSA) method as a novel forecasting tool for Sri Lanka. The study's findings suggest that nonparametric models generally outperform their parametric counterparts due to the non-stationary nature of energy consumption time series data and the non-normal distribution of energy sources like petroleum and coal in Sri Lanka. Specifically, the SSA model emerges as the most effective for energy consumption forecasting in Sri Lanka, followed by the Neural Network (NN) model. A wind power forecasting model for a significant Sri Lankan wind farm, Pawan Danavi, has been created using gene expression programming (GEP) [10]. The results demonstrate the model's robustness and high accuracy allowing for future projections of wind power generation based on anticipated weather conditions.

A study has been conducted employing six econometric techniques to estimate electricity demand functions varying specifications and elasticities, shedding light on the complexity of demand forecasting [30]. A study has also delved into Artificial Neural Networks (ANNs) and Multiple Regression models, with the ANN model as a superior performer highlighting the promise of machine learning techniques in achieving more accurate electricity demand predictions [31].

In the realm of short-term electricity demand forecasting (STLF), the need for accurate short-term load forecasting by employing two methodologies based on Artificial Neural Networks (ANN) and Autoregressive Integrated Moving Average (ARIMA) has been applied to a dataset comprising six years of half-hourly load demand data from the Ceylon Electricity Board in Sri Lanka [11]. Furthermore, integrating weather elements, especially rainfall, into ANN models can significantly improve prediction accuracy, given the strong correlation between rainfall and electricity demand.

A study based on Econometric models, such as linear regression, to forecast electricity consumption of Italy based on economic and demographic factors has been conducted incorporating variables like GDP, GDP per capita, and population to make these forecasts [6]. The income and price elasticity of electricity demand in Turkey employing a time-varying parameters model based on the Kalman filter has been done and the results reveal that both industrial and residential electricity demand have income and price elasticities lower than one [7].

B. *Battery Storage Systems*

The integration of Renewable Energy Sources (RESs) such as wind turbines and photovoltaic units into Micro-Grids (MGs) has given rise to a rapid increase of demand for Battery Energy Storage (BES) systems and by substantial wind and solar energy generation, the energy supply often exhibits considerable fluctuations, leading to instances where periods of abundant supply do not coincide with times of peak demand [32]. This variance in supply can result in more significant and rapid power surpluses and shortages. Batteries present an effective solution in this scenario, capable of storing excess energy during surplus periods and smoothly discharging it to balance sudden shifts and imbalances in the grid.

This perspective is reflected in Tesla's virtual power plant initiative. A study about efficient strategy for managing storage systems involved in energy arbitrage markets has also been conducted [33]. The strategy utilizes a computationally streamlined approach based on mixed-integer linear programming. It considers various factors, including variable-energy conversion losses and battery capacity wear due to cycling, within its cost function. Therefore, it emphasizes the vital role that economics play when considering strategies for energy storage management. Meanwhile, a study has also introduced a cost-based approach for determining optimal BES sizes in MGs taking into account various constraints, including the power capacity of Distributed Generators (DGs), power and energy capacity of BES, charge/discharge efficiency, operating reserve, and the imperative of meeting load demand [34]. Also, another study has acknowledged the inherent variability and the necessity of tailored battery sizing methods and emphasized that the tailored nature make it unique based on each of the case Study [10].

Efforts to optimize renewable energy integration while simultaneously minimizing cost are of great importance in maximizing renewable energy generation. A hierarchical optimization algorithm has been introduced that leverages time sequence simulation to achieve this intricate balancing act [35]. Residential solar photovoltaic systems, in combination with affordable battery storage, are increasingly effective in introducing a consumer-driven transformation of modern electricity supply systems [36]. Hence, effective electricity storage solutions are now at the beginning of a cost reduction even in developing countries.

Strategies for operating Compressed Air Energy Storage (CAES) plants in electricity markets with high shares of fluctuating renewable energy sources. CAES plants aim to maximize profits by storing energy when electricity prices are low and generating electricity when prices are high [13]. Also, in Photovoltaic generation optimization of charging and discharging patterns for cost efficiency, utilizing actual PV generation data instead of simulated models based on irradiance data identifying the potential for increasing battery capacity to enhance revenue under wholesale electricity tariffs [14]. In order to minimize electricity usage costs, battery operation costs, and achieve grid-related goals concerning peak demand and load smoothing and to handle uncertainty in energy demand and generation predictions, a robust counterpart formulation is presented. The approach also enhances computational efficiency by using variable time steps and relaxing binary constraints.

In the realm of energy management through battery storage system simultaneously for peak shaving, real-world data has shown that users can cut their electricity bills by up to 12% in Romania by optimizing multiple energy storage applications simultaneously [15]. A straightforward real-time algorithm with a predefined threshold has been suggested to achieve these enhanced savings. A method for determining the ideal capacity and power specifications of a battery energy storage system has been designed for peak load reduction [16]. This approach involves evaluating a customer's energy consumption pattern to identify the most effective battery size that can minimize electricity costs. To achieve this, dynamic programming is employed to derive an optimized charging strategy for the chosen battery, ensuring efficient energy cost reduction while adhering to the battery's physical limitations.

Lead-acid BESS can be a cost-effective solution for primary reserve capacity to optimize its performance, adjustable charge limits, gradual recharging during noncritical periods, and selling excess power on the intra-day market are recommended [17]. Hydro pumped-storage units can be a valuable complement to wind generation focusing on optimizing the coordination of a wind farm and a pumped-storage facility within a market context [18]. The optimization problem is framed as a two-stage stochastic program, considering uncertainties in market prices and wind generation. A study used linear programming to optimize energy storage dispatch in a grid-connected photovoltaic-battery system aiming to reduce peak loads and minimize demand charges, considering system constraints and forecasts [19]. By comparing this optimized approach to basic strategies and real-time responses, the study found that the optimized method significantly increased the battery's financial value by extending its lifespan and reducing demand charges. Moreover, Lithium-ion batteries can be a cost-effective energy storage solution for demand-side energy management focusing on modeling strategies for energy markets, where DR aggregators offer customers different contracts for load reduction, load shifting, and utilizing onsite generation and energy storage [20].

A price-based self-scheduling optimization model has been used to determine the optimal schedules for participants in day-ahead energy markets using a stochastic dynamic program to minimize long-term electricity costs and storage investments while meeting demand [21]. Significant cost savings with energy storage through computational analysis on real data. An optimization model based on the Particle Swarm Theory was employed to determine the best system configuration and management strategy [22].

C. *Electricity Arbitrage*

A study has identified a shift by incorporating technical indicators from financial markets into Day-Ahead Electricity Market (DAM) price forecasting bringing about substantial improvements in forecasting accuracy, show casing the value of incorporating financial market insights into energy forecasting models [40]. Also, time-of-use (TOU) pricing models has been incorporated emphasizing the criticality of technology-specific ramping parameters and power system flexibility [41]. Their work provided a novel perspective on the intricacies of dynamic electricity pricing, pointing towards the need for adaptable pricing strategies in the face of evolving energy landscapes. Moreover, an exploration of the predictability of technical indicators, particularly in the context of oil prices has been conducted [42].

A method for predicting electricity prices in Ontario’s competitive markets, focusing on energy arbitrage for storage systems has been identified using classification-based techniques such as Naive Bayes (NB), Decision Tree (DT), and k- Nearest Neighbour (kNN) to forecast price classes and converts them into predictive price signals [23]. A risk-constrained arbitrage trading strategies including the day-ahead (DAM), continuous intraday (CID), and balancing (BAL) marketsleveraging DAM and CID price forecasts, predicting DAM prices using technical indicators, autoencoders, and generative adversarial networks in the Dutch markets and had been given highly accurate results [24].

Community Energy Storage (CES) as a solution to enhance power system flexibility with the integration of renewable energy sources has been conducted using two CES ownership scenarios: Energy Arbitrage (EA) and Energy Arbitrage - Peak Shaving (EA-PS) [25]. Extending the Sentana and Wadhwani (1992) trader model to explore feedback trading in carbon emission and energy futures markets and its relationship with arbitrage opportunities [26]. The viability of residential battery storage for energy arbitrage in the Australian retail electricity market has been assessed and the technical analysis demonstrates that appropriately sized and efficient battery systems can significantly reduce peak electricity demand and shift it to off-peak periods, offering a compelling case for their technical feasibility [27].

The economic evaluation reveals that many of the available battery technologies are economically profitable for energy arbitrage, particularly when considering factors like payback time, internal rate of return, and net present value. A dedicated arbitrage algorithm to a Spanish case and had conducted a techno-economic analysis to determine the optimal storage plant size in terms of benefits [26]. A methodology for maximizing revenues in the Single Electricity Market (SEM) in the island of Ireland, driven by the transition to renewable-based generation employing a multi-stage forecasting model based on neural networks to predict demand and system marginal prices in SEM ex-ante markets has been suggested [29].

So far, there have been identified 3 case studies that devising a robust power generation and energy storage capacity optimization mechanism using real time data. They are installation of a Tesla Powerpack battery in 2019 by the University of Queensland [37], the Hornsdale Power Reserve that utilizes battery storage facility to stabilize the South Australian electricity grid and reduce the chance of load-shedding events and the Tesla Autobidder that provides independent power producers [38], utilities and capital partners the ability to autonomously monetize battery assets [39]. These three case studies have used different approaches depending on the unique situation that is distinct to each case.

D. *Ancillary Services*

Ancillary services are essential for grid stability. They include functions like frequency regulation, voltage control, and operating reserves so that power plants can quickly adapt their output to balance the grid when demand surges. These services are critical, especially with the growing use of intermittent energy sources like wind and solar power, ensuring uninterrupted electricity supply and grid resilience.

Load following and area regulation are essential grid services. Load following requires rapid power output adjustments to maintain supply-demand balance, and storage is well-suited due to its flexibility and efficiency. Area regulation involves managing power flow and demand fluctuations, and efficient storage can provide this service effectively, surpassing traditional methods in flexibility and efficiency [44]. A bi-level optimization framework that efficiently integrates wind power units and battery energy storage systems into distribution networks has been developed aiming to minimize energy loss at the distribution level and optimize the management of load deviation, power loss, and voltage deviation [45]. A multi-objective three-level model, employing a multi-objective genetic algorithm, has been used to determine the optimal BESS capacity providing a methodology for incorporating energy storage into Renewable Energy systems to enhance ancillary service provision [46]. Also, the optimal performance of a wind farm with integrated battery storage in a wholesale electricity market has been conducted focusing on maximizing the Net Present Value (NPV) considering participation in energy and Frequency Control Ancillary Services (FCAS) markets and accounting for imperfect generation forecasts [47].

III. Discussion

In the above literature, several key aspects of energy management and optimization have been explored. Studies have looked into topics such as electricity demand estimation, shedding light on the complex dynamics and influencing factors within various electricity markets. Furthermore, the implementation and benefits of battery storage systems have been thoroughly investigated in different global contexts. These studies have not only revealed the technical feasibility of energy storage but have also demonstrated the potential for demand shifting and peak load management.

However, a distinct research gap becomes evident when considering the application of arbitrage methods specifically tailored to the energy market of Sri Lanka. While electricity demand estimation and battery storage have been examined in different studies, the integration of arbitrage methods within the unique energy landscape of Sri Lanka has not been adequately explored. The absence of research in this crucial area leaves a significant knowledge void, especially considering the island's evolving energy sector and the government's commitment to increasing renewable energy capacity.

Hence, it is of great importance to address this specific research gap by developing and implementing econometric models and optimization strategies that are customized to the Sri Lankan energy market. Investigating the feasibility, profitability, and environmental impact of energy arbitrage within the context of Sri Lanka will not only contribute to the academic body of knowledge but also offer valuable insights for energy policymakers and market stakeholders seeking to harness the full potential of energy arbitrage within the country's unique energy ecosystem.

IV. Conclusion

In conclusion, the literature review has brought to notice, various aspects of energy management and optimization, that includes electricity demand estimation, battery storage systems, and energy arbitrage strategies. While these topics have been extensively explored in diverse global contexts, the research gap that emerges pertains to the absence of specific studies addressing energy arbitrage methods customized for the Sri Lankan energy market.

Finally, it is crucial to recognize that the existing literature collectively highlights a notable research gap in the application of economic tools for energy optimization. It is also essential to emphasize that every country's energy market is highly unique, making it challenging to implement a single, universally applicable model [46]. Moreover, it is worth noting that this gap is particularly pronounced when considering the perspectives of developing countries.

Therefore, future studies in this field should aim to bridge this gap by developing tailored econometric models and optimization strategies that consider the distinct characteristics and dynamics of Sri Lanka's energy landscape. These studies could encompass a range of objectives, including investigating the feasibility of energy arbitrage in the context of the country's evolving renewable energy sector, assessing the profitability of such endeavors, and evaluating the potential environmental impacts. This research would not only contribute significantly to the academic knowledge base but also offer practical insights to energy policymakers and stakeholders in Sri Lanka.

Furthermore, future research endeavors can explore comparative studies, benchmarking Sri Lanka's energy arbitrage potential against other countries with similar energy profiles. Exploring emerging technologies and their implications for energy arbitrage, as well as analyzing the regulatory and market structures affecting these strategies, could provide further depth to the understanding of this field. Ultimately, the identified research gap presents a valuable opportunity for both academic and practical exploration, and future studies in this area have the potential to shape the trajectory of energy management and optimization in Sri Lanka while contributing to the broader global discourse on sustainable energy practices.

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