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Original Article

A Case Study of Powering the EV Revolution: Balancing Grid Challenges with BESS and TOU Strategies

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Abstract - *The accelerating adoption of electric vehicles (EVs) creates opportunities and technical challenges for electrical distribution networks. As transportation electrification increases, the additional charging demand threatens to overload existing grid infrastructure. This research analyses the projected effects of Electric Vehicle (EV) proliferation on distribution systems. It evaluates potential solutions, particularly on Battery Energy Storage Systems (BESS) and Time-Of-Use (TOU) pricing mechanisms. Furthermore, this study examines BESS's development prospects and growth potential within the UK energy sector, aiming to preserve and strengthen its competitive position. The research demonstrates that EV integration presents challenges, including amplifying demand surges and voltage regulation issues. Although battery storage technologies provide technical solutions, their economic feasibility remains questionable. Time-of-use pricing strategies and distributed behind-the-meter storage emerge as viable alternatives. An integrated methodology incorporating multiple approaches is crucial for integrating Electric Vehicles (EVs) into the grid. Future research directions should include long-term system reliability analysis, sophisticated control mechanisms, and comprehensive integration of various Distributed Energy Resources (DERs).*

Keywords - *BESS, EV, TOU, DERs, Distribution system.*

1. Introduction

The shift toward electric mobility represents a fundamental transformation in transportation infrastructure, delivering significant advantages such as decreased petroleum dependency and a reduced environmental footprint. Electric vehicles (EVs) demonstrate superior energy conversion performance to conventional internal combustion engines (ICEs). Traditional ICEs achieve only 20–30% fuel-to-mechanical energy conversion efficiency, whereas EVs attain 60–90% efficiency rates, according to Khan et al. (2021) [1].

EVs can be categorised into three primary types: all-electric vehicles (AEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). AEVs and BEVs operate solely on electrical power stored in rechargeable batteries, exemplified by the Tesla Model 3 and BMW i4 [1, 2]. FCEVs utilise hydrogen fuel cells, producing only water vapour as emissions, with models like the Toyota Mirai achieving ranges of 480–640 kilometres [3]. The charging ecosystem has developed to support diverse applications through three primary levels: Level 1 (230V UK standard) provides 3–8 kilometres of range per charging hour, Level 2 (400V UK/European standard) delivers 16–96 kilometres per hour, and Level 3 DC rapid charging enables fast charging of 96–320 kilometres within 20–30 minutes [4, 5].

Research indicates substantial growth in electric vehicle adoption throughout Europe and the United Kingdom. Analysis from Transport & Environment, incorporating projections from BloombergNEF, IHS Markit, LMC Automotive, and UBS, forecasts 30 million EVs across the EU by 2030, constituting 12% of the EU's total vehicle population. In conjunction with National Grid's Future Energy Scenarios, the UK's Climate Change Committee anticipates 12–14 million EVs on British roads by 2030, representing approximately 35% of the UK's automotive fleet [6-8]. These estimates align with the EU's "Fit for 55" initiative and the UK's ban on selling new petrol and diesel vehicles, which is set to take effect in 2030.

2. Research Gap and Problem Statement

The acceleration of electric vehicle adoption across the United Kingdom presents considerable environmental benefits; however, it simultaneously introduces complex operational challenges for existing electrical distribution networks, which current research has not comprehensively addressed through coordinated mitigation approaches. Contemporary academic literature predominantly investigates singular solutions, including grid infrastructure reinforcement, Battery Energy Storage Systems (BESS), or Time-Of-Use (TOU) pricing mechanisms, without examining their collective implementation potential. This fragmented approach creates a substantial knowledge gap regarding the practical and economic viability of integrating electric vehicles into the grid. The fundamental challenge centres on the significant disparity between electric vehicle charging demand patterns and current grid infrastructure capacity, particularly during peak consumption periods when concurrent charging activities could overburden distribution transformers and destabilise voltage regulation systems. Economic uncertainties surrounding various mitigation approaches further exacerbate this operational difficulty, as utility companies must navigate complex decisions between expensive infrastructure modernisation and emerging technological solutions such as BESS, often without access to comprehensive comparative economic analyses.

2.1. Research Gap

Contemporary research lacks a thorough examination of the synergistic implementation of BESS deployment, TOU rate frameworks, and behind-the-meter storage solutions as a comprehensive strategy for addressing electric vehicle grid integration challenges. Most existing studies focus on evaluating the effectiveness of individual solutions rather than investigating the collaborative benefits and economic considerations of integrated approaches across varying electric vehicle penetration scenarios.

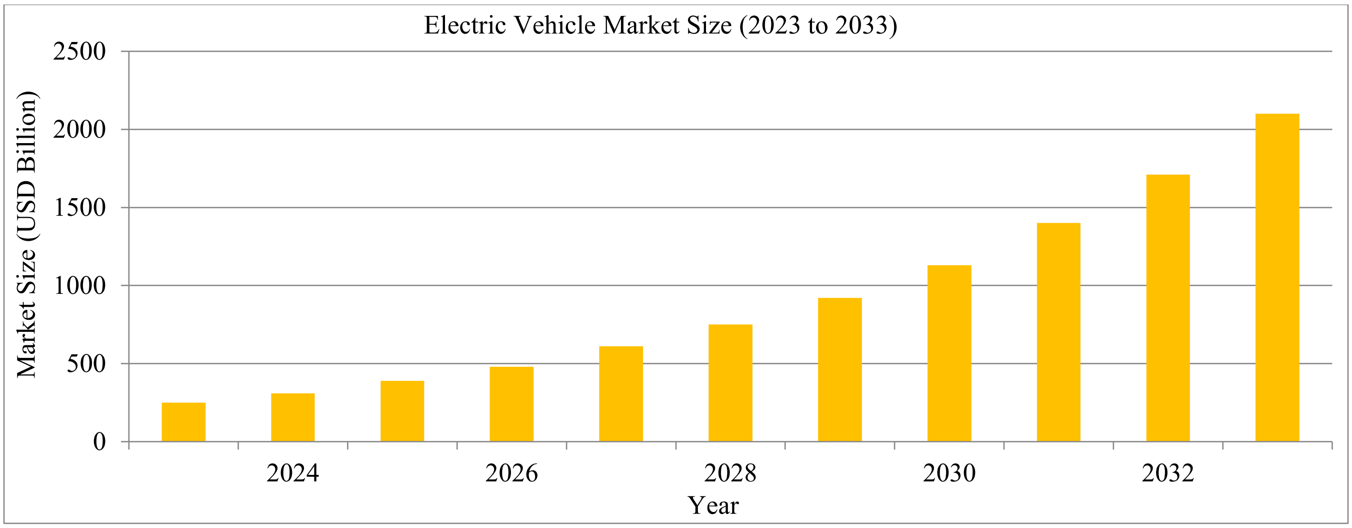

Fig. 1 Projected EV stock in the USA

This sophisticated infrastructure environment, coupled with the fundamental efficiency benefits of electric powertrains, establishes electric vehicles as a pivotal technology in transforming sustainable transportation systems. Nevertheless, it presents distinctive challenges for power distribution networks that require careful management, particularly in regions experiencing high electric vehicle adoption rates [3, 4]. This research addresses these challenges through a comprehensive techno-economic analysis of integrated mitigation strategies, providing utility companies and policymakers with evidence-based recommendations for the sustainable integration of electric vehicles.

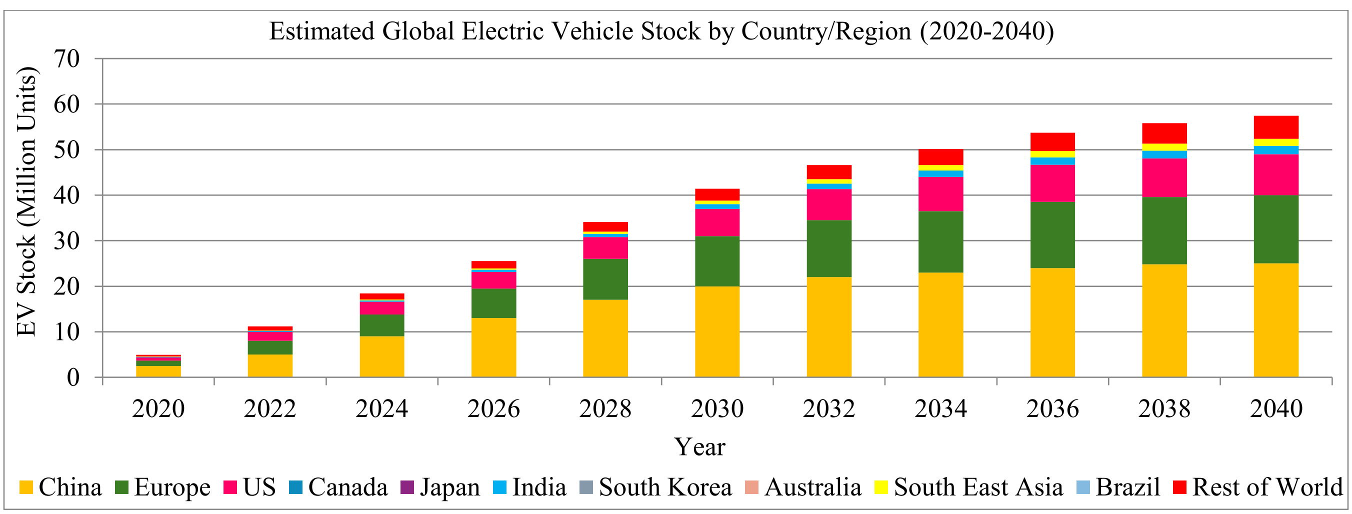

Fig. 2 Comparing penetration numbers in different country's averages

3. Literature Review and Research Novelty

In [1], the authors investigated the complexities of large-scale electric vehicle integration, focusing particularly on power quality concerns and distribution system vulnerabilities. Their research highlighted the advantages and stresses electric vehicles impose on electrical grids. Tasnim et al. [3] examined the effects of light-duty electric vehicle charging, identifying critical concern areas, including intensified peak demand and infrastructure stress. Ahsan et al. [9] focused on integrating electric vehicles and the influence of innovative charging mechanisms, while Anastasiadis et al. [10] examined the impacts on distribution systems, providing fundamental insights into system weaknesses.

3.1. Battery Energy Storage Systems Investigation

Prakash et al. [2] comprehensively evaluated BESS applications within distribution grids, discussing contemporary challenges and future opportunities. Das et al. [11] evaluated how electric vehicle standards and infrastructure influence grid integration from a technological perspective, establishing battery energy storage systems (BESS) as a technically viable mitigation strategy; however, their analysis provided limited cost-effectiveness evaluation.

3.2. Time-of-Use and Demand Management Studies

Jones et al. [12] investigated customer responsiveness to time-of-use pricing and its impact on the distribution system, determining that such pricing models could effectively mitigate peak load challenges. Nicolson et al. [13] systematically examined consumer responses to time-of-use tariffs, finding that adoption rates varied considerably depending on the implementation approach. Tomic and Kempton [14], alongside Stowe [15], established foundational concepts for vehicle-to-grid technologies by investigating electric vehicles as a grid support.

3.3. Voltage Stability and Technical Challenges

Dharmakeerthi et al. [16] examined the impact of electric vehicle fast charging on voltage stability, demonstrating that voltage deviations become particularly problematic at radial distribution network extremities. Whilst these studies provide valuable insights, they frequently overlook the economic implications of their technical findings.

3.4. Energy Storage Cost Analysis

Economic forecasting by Murray [17] through the National Renewable Energy Laboratory projected a 47% cost reduction in lithium-ion battery energy storage systems by 2030. Although this analysis provided insights into future pricing trends, it did not investigate how such changes might influence integrated electric vehicle-grid strategies.

3.5. Policy and Market Development

Venegas et al. [18] investigated regulatory and structural barriers to integrating electric vehicles, proposing frameworks for enhanced flexibility. However, their study lacked robust quantitative approaches, particularly in cost-benefit evaluations.

4. Research Novelty and Unique Contributions

This study addresses critical gaps in the existing literature through novel contributions combining technical, economic, and regional considerations for EV integration. Unlike previous research, which primarily examines mitigation measures in isolation, this study provides a holistic framework that integrates Battery Energy Storage Systems (BESS), Time-Of-Use (TOU) pricing strategies, and Behind-The-Meter (BTM) storage solutions. Table 1 below compares the innovation in the current work with previous research papers.

Table 1. Current research comparison with previous works

Novel Contribution	Previous Research Gap	This Study's Innovation	Key Benefit
Integrated Multi-Strategy Analysis	Prior work explored individual strategies such as BESS or TOU independently [2, 9, 11].	First comprehensive techno-economic comparison of combined BESS, TOU, and BTM approaches	Quantifies synergistic effects of integrated solutions
Real-World Infrastructure Modelling	Theoretical models and simplified systems.	Actual UK Medway area data with realistic transformer configurations (NOA/DFA/FOA)	Unprecedented granularity in EV impact assessment
Quantitative Economic Framework	Most studies focus on technical performance and overlook cost implications [15].	Specific cost comparison: BESS (£6.92-£9.15M) vs traditional upgrades (£2.4-£2.5M)	Direct utility investment decision support
Multi-Temporal Scenario Analysis	Single-point scenario studies	Three-time horizons (2025/2030/2035) with varying EV penetration (4%/8%/20%)	Actionable timeline-based planning data
UK-Specific Market Integration	Global or US-focused literature	First analysis linking UK BESS capacity (4.4 GW operational, 95.6 GW pipeline) with EV challenges	It fills the geographic knowledge gap.
Behind-the-Meter Innovation	Minimal BTM exploration for EV integration	BTM batteries as a cost-effective BESS alternative with consumer cost-shifting	Novel virtual power plant approach
Transformer Thermal Analysis	Operational factors overlooked	First detailed cooling mode analysis (NOA/DFA/FOA) for EV load impacts	Critical reliability assessment integration

This research uniquely addresses the gap between technical feasibility studies and the economic reality of implementation, providing the first integrated framework for cost-effective Electric Vehicle (EV) grid integration strategies based on real-world analysis of UK infrastructure.

5. Integration of Electric Vehicles into Power Distribution Systems: Critical Analysis

The integration of Electric Vehicles (EVs) into existing power distribution infrastructure introduces three core technical challenges that have been widely explored in academic literature but rarely unified in practical frameworks.

5.1. Peak Demand Amplification

EV adoption significantly intensifies peak power demand. Studies have shown that a 20% EV penetration can lead to a 35.8% increase in peak load. However, deploying smart charging strategies, particularly when combined with solar PV and BESS, can reduce peak demand by up to 55% [19].

5.2. Infrastructure Stress and Capacity Constraints

Distribution infrastructure is especially vulnerable during summer when ambient temperatures reduce transformer capacity. Transformers remain the key constraint, with uncoordinated charging potentially causing overloading up to 270% beyond rated capacity. While distribution lines perform adequately, transformer limitations restrict EV integration to approximately 40% of anticipated numbers. Advanced charging coordination has been shown to contain transformer loading within acceptable thresholds [9, 19].

5.3. Voltage Stability Challenges

Uncontrolled charging contributes to voltage fluctuations, particularly at the extremities of radial feeders. While voltages typically remain within permissible ranges (above 0.95 p.u.), TOU-based charging has been associated with the steepest voltage drops. In contrast, randomised charging patterns help stabilise voltage closer to baseline levels. Residential and mixed-use feeders demonstrate more volatility than industrial or commercial ones [3, 12]. These findings confirm that while technical barriers are well-documented, comprehensive mitigation requires an integrated approach that combines Time-Of-Use (TOU) pricing, Battery Energy Storage Systems (BESS), and targeted infrastructure upgrades. This study utilises these foundations to construct a unified framework for techno-economic planning in Electric Vehicle (EV) integration.

6. Case Study on EV Integration Impacts

Due to its capacity and loading characteristics, the selected feeder required the integration of multiple voltage regulators and auxiliary equipment. Photovoltaic (PV) penetration levels were modelled at 20% and 40% of net output to reflect medium and high renewable integration scenarios. Two adoption levels of Electric Vehicles (EV),15% (low) and 25% (high), were analysed to assess system impact variability. Battery Energy Storage Systems (BESS) emerged as a technically effective solution to mitigate system vulnerabilities; however, they remain significantly more expensive than traditional equipment upgrades. According to projections by the National Renewable Energy Laboratory (NREL), lithium-ion BESS costs are expected to decline by 47% by 2030 and up to 67% by 2050, primarily due to reductions in battery cell and pack manufacturing costs [17]. The analysis indicates that longer-duration batteries are generally more cost-effective when evaluated per kilowatt-hour (kWh) basis. In contrast, shorter-duration systems provide greater value per kilowatt (kW). These findings suggest a favourable trajectory for renewable energy storage deployment, although actual cost reductions will depend heavily on technological innovation and market dynamics [20].

Table 2. Comparison of grid upgrade vs BESS solution costs

EV Penetration Level	Grid Upgrade Costs (£M)	BESS Solution Costs (£M)	Cost Difference (£M)
Light-Medium (15%)	2.5	6	3.5
Heavy (25%)	2.5	7.52	5.02

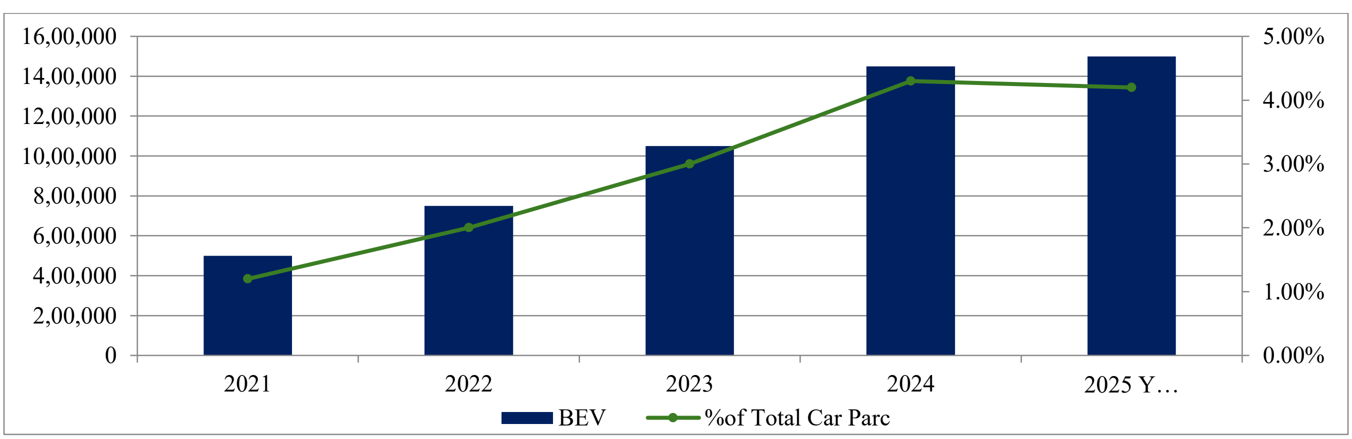

Fig. 3 UK Electric Vehicle Adoption: Growth Trends from 2021 to 2025 [16]

The analysis found that BESS solutions cost more than twice as much as conventional equipment upgrades, rendering them economically unviable in this context. The study modelled the effects of EV integration for 2025, 2030, and 2035 on a heavily loaded residential feeder in Medway, southeast England, home to around 250,000 residents.

The simulation assumed a current UK EV penetration of 4% (approximately 9,000 vehicles), a mix of home (7 kW), commercial (22 kW), and rapid (50 kW+) chargers, and a diversity factor of 0.3 to reflect non-simultaneous usage. The network comprised a 33/11 kV primary substation with two 20 MVA transformers, several 11/0.415 kV substations (1–2 MVA), and larger 3–4 MVA transformers at strategic rapid charging hubs. System vulnerabilities were assessed annually under medium and high EV adoption levels, with key indicators including the total length of overloaded lines, defined as conductors operating at more than 100% of their rated current capacity.

An analysis of the UK‘s EV adoption trend reveals rapid growth, with numbers rising from 978,832 to 1.4 million in two years, a 43% increase. Market shares also grew from 2.91% to 4.09%, while new EV registrations surged from 16.5% to 21.3%, reflecting a shift toward mainstream adoption [13]. This trend imposes considerable thermal stress on transformers, underscoring the critical role of cooling capacity in managing the increasing demands for EV charging. Despite this progress, electric vehicles still account for only around 4% of all vehicles, suggesting that the transition is still in its early phase. The relatively minor growth in plug-in vehicles from 2024 to 2025 may signal a decline in interest in PHEVs as consumers shift to fully electric models [15]. Grid impact was assessed using the total length of overloaded conductors under various EV penetration scenarios. This metric, presented in Table 3, serves as a key indicator of system vulnerability and supports N-1 reliability up to approximately 20% of the electric vehicle (EV) penetration.

Table 3. The length of overloaded wires per violating scenario

Year	Estimated Wire Stress (meters)	
	Low-Medium	High
2025	200	1700
2030	1640	5460
2035	3655	7700

This data highlights the growing strain on the grid infrastructure due to increasing EV penetration, underscoring the need for mitigation strategies such as battery energy storage systems (BESS) and grid reinforcements.

The focus on transformer cooling modes is critical because overheating due to increased electric vehicle (EV) charging loads can significantly reduce transformer lifespan and potentially cause system failures. The three-stage cooling system helps manage the thermal stress as loading increases from 12 MVA to 20 MVA. These components are essential in any electrical system. The list does not include the centre transformer or the individual distribution transformers, as they are considered separately. Without proper cooling management, transformers can fail prematurely under the increasing loads from electric vehicle (EV) charging, making the design and operation of the cooling system a critical consideration for grid reliability. The transformer has three cooling modes corresponding to its ratings [12, 13]:

1. NOA (Natural Oil Air) mode at 12 MVA nominal rating
2. DFA (Directed Forced Air) up to 16 MVA
3. FOA (Forced Oil and Air) up to 20 MVA

Table 4. Estimated statistical cooling mode of substation

Year	Penetration	NOA	DFA	FOA	Overload
2025	Low -Medium	7.2	6.2	4.8	2
	High	6.4	5.4	5.8	3
2030	Low -Medium	7.4	5.6	6.39	3
	High	6.6	4.8	7.39	4
2035	Low -Medium	6.7	5.4	6.7	4
	High	5.9	4.6	7.7	5

A critical analysis reveals that tap-changing transformers are crucial for EV grid integration, primarily for dynamic voltage regulation. The shift from traditional voltage regulators to Load Tap Changer (LTC) transformers is driven by the need to manage increased voltage fluctuations from Electric Vehicle (EV) charging while preserving the equipment's lifespan. This evolution highlights the necessity for grid infrastructure to adapt efficiently and meet the increasing demands of Electric Vehicles (EVs).

Table 5. Expected daily tap-change penetration

Penetration	Low-Medium	High
2023-Base	105	
2025	136	171
2030	169	306
2035	285	450

As shown in Table 5, voltage abnormalities should be noted, and voltage below 0.94 pu or 10.34 kV (line-to-line) was considered Undervoltage on this feeder. The results showed a clear trend of increasing system stress with higher EV penetration levels. For example, the number of tap changes increased dramatically, with the high penetration case in 2035 showing a 163% increase from the 2023 base case.

7. Mitigation Strategies

To address the challenges posed by integrating Electric Vehicles (EVs), this study evaluated three key mitigation strategies: Time-of-Use (TOU) scheduling, Battery Energy Storage Systems (BESS), and a combined TOU–BESS approach.

7.1. Time-of-Use (TOU) Scheduling

TOU rates incentivise EV owners to charge during off-peak hours by offering lower electricity prices. This aligns with typical charging behaviour, as most vehicles remain parked for extended periods at home (Nicolson et al., 2018). Two main pricing models exist: static TOU rates, which apply during fixed time windows, and real-time pricing, which varies based on wholesale market conditions. Adoption rates vary significantly, ranging from 1% to 43%, with opt-out schemes reaching as high as 57% [21]. Utilities promoting TOU options tend to achieve higher uptake [10]. Smart chargers with programmable timers can enhance participation by allowing users to schedule charging automatically, typically after midnight.

7.2. Battery Energy Storage Systems (BESS)

BESS technology reduces system stress by storing energy during periods of low demand and discharging it during peak consumption times. Lithium-ion batteries prove particularly suitable due to their high energy density, with modern designs achieving up to 570 Wh/L [11]. This study specifically sized BESS to prevent feeder overloads and support grid stability.

Table 6 showed that BESS improved voltage profiles and reduced the frequency of transformer tap changes. For instance, without BESS, tap changes reached 142, 169, and 285 across scenarios, while with BESS, they dropped to 112, 114, and 149, demonstrating the effectiveness of BESS in smoothing demand fluctuations. The technology operates through sophisticated power electronics systems responding rapidly to grid conditions, providing active and reactive power support. Modern BESS installations incorporate advanced battery management systems that optimise charging and discharging cycles to maximise battery life whilst maintaining grid support capabilities. The modular nature of contemporary Battery Energy Storage System (BESS) designs enables scalable deployment, allowing utilities to increase storage capacity as electric vehicle penetration grows incrementally. However, economic considerations surrounding BESS deployment remain complex, with current installation costs including battery systems, power conversion equipment, protection systems, and grid connection infrastructure. Additionally, BESS systems require ongoing maintenance and eventual replacement, typically within 15 to 20 years, depending on usage patterns and technological advancements.

Table 6. BESS impact analysis on system performance

Year	EV Penetration	BESS Specifications	Minimum voltage (pu)	Tap Changes			
		Energy (kWh)	Rating (MW)	Without BESS		With BESS	
2025	4%	8	1.44	0.945	142	0.952	112
2030	8%	21	3.7	0.943	169	0.948	114
2035	20%	38	6.5	0.941	285	0.945	149

7.3. Combined BESS and TOU Strategies

The study examined a hybrid mitigation strategy integrating Battery Energy Storage Systems (BESS) with Time-Of-Use (TOU) pricing. Two adoption scenarios were evaluated: 15% and 40%. Table 7 in the study outlines the resulting BESS capacity requirements. Findings indicated higher TOU adoption rates could reduce the required BESS capacity, particularly in higher Electric Vehicle (EV) penetration scenarios. This combined strategy provides a cost-effective approach that enhances voltage regulation and peak demand management (Jones et al., 2022; Nicolson et al., 2018). The synergistic relationship between these technologies creates opportunities for more efficient grid operation whilst reducing overall infrastructure investment requirements. Under the combined approach, TOU pricing incentivises electric vehicle owners to shift charging behaviour towards off-peak periods, thereby reducing the peak shaving burden on BESS systems. This behavioural shift allows for smaller BESS installations whilst maintaining equivalent grid support capabilities. The economic benefits become increasingly apparent as electric vehicle penetration increases, with TOU adoption rates of 40% demonstrating potential BESS capacity reductions of up to 10% by 2035. Combining strategies requires sophisticated coordination between utility pricing and Battery Energy Storage System (BESS) control algorithms. Smart charging infrastructure enables this coordination, allowing real-time communication between electric vehicles, charging points, and grid management systems. This technological integration enables dynamic response to price signals and grid conditions, optimising economic and technical outcomes for sustainable grid operation.

Table 7. SIZE BESS to mitigate vulnerability in TOU deployment scenarios

Year	Violation	BESS	Hours in Each Cooling Mode			
			NOA	DFA	FOA	Overload
2025	4%	Without	7.0	6.0	4.5	0
		With	7.5	9.5	3.5	0
2030	8%	Without	7.0	5.5	6.0	3
		With	5.0	15.5	4.0	0
2035	20%	Without	6.5	5.0	6.5	4
		With	6	10.0	6.0	0

8. Economic Analysis of Mitigation Strategies

The cost-effectiveness of implementing the Battery Energy Storage System (BESS) was evaluated across various scenarios of electric vehicle (EV) penetration. Findings show that BESS remains significantly more expensive than conventional system upgrades.

8.1. Capital Costs

BESS installation demands a substantial upfront investment, including batteries, inverters, transformers, and protection components.

In the case study, costs ranged from £6.92 million to £9.15 million, over twice the cost of traditional infrastructure upgrades.

8.2. Maintenance and Lifetime Costs

BESS systems also entail recurring maintenance costs. Fixed annual maintenance was estimated at £10.49 per kW, with additional energy-based costs of £0.024 per kWh. Most lithium-ion systems have a lifespan of 10–20 years, with an average of 15 years, necessitating reinvestment over time [22, 23]. Table 8 shows the details of EV, BESS and total annual maintenance.

8.3. Comparison with System Upgrades

2035, for a 15% EV penetration scenario, BESS costs were projected at £10.58 million compared to just £5.59 million for traditional upgrades, confirming a more than twofold cost disparity.

8.4. Impact of Renewable Integration

The integration of Photovoltaic (PV) systems led to modest cost savings. An 8% reduction in BESS expenditure was observed when PV penetration rose from 15% to 40%. Nevertheless, conventional upgrades remained the more cost-efficient option.

8.5. Time-of-Use (TOU) Considerations

Scenarios incorporating Time-Of-Use (TOU) pricing revealed that higher adoption (40%) resulted in reduced Battery Energy Storage System (BESS) costs of up to 13% in later years. Despite this improvement, BESS still incurred higher overall costs than traditional infrastructure solutions.

Table 8. Approximate summary of maintenance costs

Sector	EV Maintenance	BESS Maintenance	Total Annual Maintenance
Residential	£50–£150	£100–£300	£150–£450
Commercial (Fleet)	£500–£2,000	£1,000–£5,000	£1,500–£7,000
Industrial (Large)	£5,000–£20,000	£10,000–£50,000	£15,000–£70,000
Public Infrastructure	£1,000–£5,000	£5,000–£20,000	£6,000–£25,000

9. Transforming Energy Storage as a Game-Changing Alternative to the New Generation

Although BESS may not be economically viable for deferring distribution system upgrades, it shows strong potential as an alternative to new peaking generation facilities. The study compared the projected costs of battery storage systems with those of traditional generation technologies to meet rising peak demand. The analysis indicates that BESS could be more cost-effective than conventional peaking plants, particularly when considering non-financial benefits:

1. Smaller footprint - BESS units require significantly less space, making them ideal for urban or land-constrained settings.
2. Reduced transmission losses - Locating BESS near load centres minimises distribution losses.
3. Lower emissions - BESS can utilise surplus renewable energy, offering a cleaner solution than fossil-fuel-based plants.
4. Operational flexibility - Besides peak shaving, BESS can provide frequency regulation and voltage support services.

However, BESS has a notably shorter lifespan, typically 15 years, than conventional generation assets. Hydropower plants may operate for up to 100 years, and Natural Gas Combined Cycle (NGCC) plants often last around 30 years [23].

As a result, multiple BESS replacements would be required over the lifetime of a single traditional plant, affecting its long-term economic feasibility.

Table 9. Cost estimations for different technologies in power plants

Technology	2025 (Mil £)	2030 (Mil £)	2035 (Mil £)	Lifespan (Years)	Lifetime Cost (Mil £)
Hydropower	4.1	11	22.4	50	9.1
NGCC	3.36	9.76	19.5	30	24.36
Battery	1.84	5.76	11.9	15	25.64

10. Behind-The-Meter Batteries Method for Mitigating

An innovative alternative to utility-scale battery storage involves promoting individual consumers' use of Behind-The-Meter (BTM) battery systems. BTM batteries shift the economic responsibility of purchase, installation, and maintenance from utilities to end-users, reducing capital strain on grid operators [24, 25]. These systems enable users to store electricity during off-peak hours and discharge it during periods of high demand, thereby helping to alleviate grid stress and reduce peak load [26, 27]. In addition to demand management, BTM batteries offer potential grid services when integrated through proper infrastructure and contractual agreements. This transforms individual systems into a form of distributed power plant, enhancing grid flexibility and resilience [28-30]. BTM systems also provide backup power during outages, offering consumers an additional incentive to adopt them [31]. Moreover, when paired with residential solar PV, BTM batteries allow for efficient storage of surplus solar generation, maximising self-consumption and improving the economic return of solar installations [32].

11. BESS Opportunities In The UK and Beyond

This paper explores the development potential of Battery Energy Storage Systems (BESS) in the UK, highlighting emerging projects and strategic opportunities for maintaining the nation's competitive edge. As of 2023, the UK has 4.4 GW of operational BESS capacity and a project pipeline totalling 95.6 GW, second only to the United States [33]. While this trajectory is encouraging, meeting the UK's short-term energy flexibility target of 55 GW by 2035 will require significant acceleration in investment, permitting, and deployment.

Energy storage is essential to support the UK's renewable energy goals: 50% renewable generation by 2035 and 100% by 2050. The variable nature of solar and wind energy and anticipated demand growth from electric vehicles and climate-adaptive heating and cooling systems complicate these targets. Achieving reliable storage capacity will depend on technological innovation, streamlined regulation, and sustained financial support. Emerging technologies, such as sodium-ion batteries, are projected to capture over 7% of the market by 2040, complementing dominant lithium-ion systems due to their cold-weather resilience and lower cost [34].

To remove barriers, the UK government has eased planning rules for BESS installations under 100 MW and accelerated approvals for larger projects through its 2023 Battery Strategy [35]. However, financial challenges remain as private investors face uncertainty due to long project lead times and complex regulatory requirements. In response, the government is offering public funding support and working to simplify the grid connection process [36].

12. UK BESS Capacity and Development Status

The UK's Battery Energy Storage System (BESS) infrastructure has expanded rapidly in recent years, driven by policy support and the urgent need to integrate renewable energy sources. As of 2023, there are 116 operational BESS facilities nationwide, 40% of which have been commissioned since 2022, demonstrating accelerated momentum in deployment [37, 38]. Additionally, 86 projects are currently under construction, with over 1,000 planning applications either approved or in progress, reflecting exponential growth in the sector [39, 40].

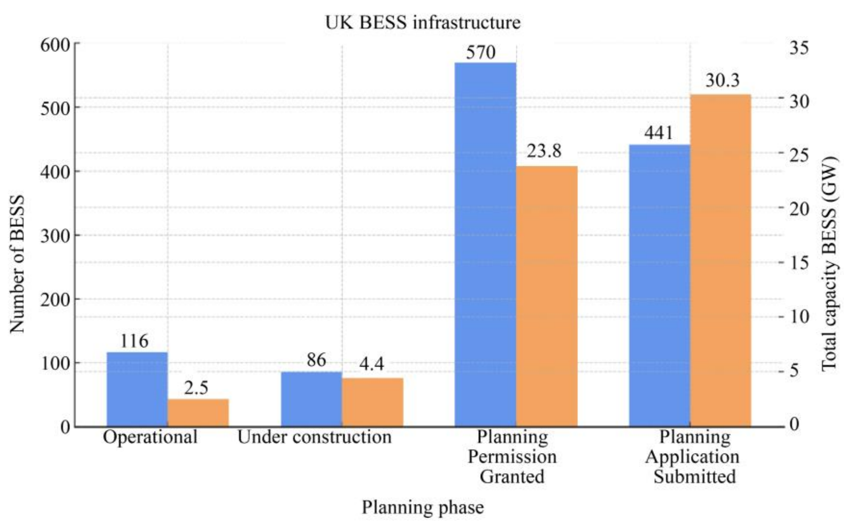

Fig. 4 UK BESS infrastructure, python production

Alongside this increase in installations, BESS capacity is also scaling up. Regulatory reforms have eased planning requirements for systems under 50 MW, enabling faster approvals and broader developer participation. Consequently, 33% of all new BESS facilities built since 2022 fall within the 45–50 MW range, underscoring the influence of these streamlined planning pathways [36].

13. Future Projections for BESS Capacity

Looking ahead, the UK's BESS sector is set for continued expansion. If current planning and construction timelines hold, the 1,000 facilities in the pipeline could substantially increase operational capacity over the next three years. Recent trends show a concentration of projects near the 50 MW threshold, with a growing number just below 100 MW. This clustering suggests that developers strategically sizing projects to benefit from simplified regulatory processes (Solar Energy Industries Association, 2023; Aurora Energy Research, 2024).

14. Policy Implications and Recommendations

The concentration of BESS project capacities near regulatory thresholds (e.g., 50 MW and 100 MW) suggests that developers are optimising for planning simplicity rather than system performance. While this strategy aids deployment, it may limit technical potential. As the UK advances toward targets for Renewable Energy Generation and Storage (REGS), significantly more storage capacity will be needed.

To support this growth, policy measures should include:

1. Updating regulatory frameworks to ease planning for BESS projects above 100 MW, encouraging larger-scale investments.
2. Incentivising innovation through grants or subsidies for advanced storage technologies that enhance grid stability.
3. Streamlining grid connections to reduce approval delays and accelerate project execution (Aurora Energy Research, 2024).

15. Comparison with Existing Research Findings

Table 10 below compares the findings of the current work and those of previous research papers published online.

Table 10. A thorough comparison of existing research findings

Research Area	Existing Research	This Study's Findings	Key Advancement
Grid Impact Studies	Tasnim et al. (2023) identified general grid stress from EV charging but provided limited quantitative impact data.	Quantifies specific impacts, showing a 35.8% peak demand increase at 20% EV penetration and detailed wire overload projections (200m in 2025 to 7,700m by 2035 under high penetration scenarios)	Provides specific quantitative metrics vs. general observations
BESS Effectiveness Studies	Das et al. (2019) examined the technical capabilities of BESS without conducting a comprehensive economic analysis.	Demonstrates that while BESS reduces tap changes by 21-47% and improves voltage profiles (0.941 to 0.945 pu), the 2-3x higher costs compared to traditional upgrades challenge their economic viability	Integrates technical performance with economic feasibility analysis
TOU Rate Impact Studies	Nicolson et al. (2018) analysed consumer adoption rates (1-43%) but lacked integration with storage solutions.	Shows that 40% TOU adoption combined with BESS can reduce required storage capacity by up to 10% by 2035, offering a more economically feasible hybrid approach	Demonstrates synergistic effects of combined strategies
Behind-the-Meter Storage Research	Limited studies have examined BTM batteries as grid-scale solutions for EV integration.	Proposes BTM batteries as a cost-effective alternative to utility-scale BESS, shifting economic burden to consumers while providing grid benefits through virtual power plant concepts	Introduces novel cost-sharing approach for grid-scale benefits

The concentration of BESS project capacities near regulatory thresholds (e.g., 50 MW and 100 MW) suggests that developers are optimising for planning simplicity rather than system performance. While this strategy aids deployment, it may limit technical potential.

As the UK advances toward targets For Renewable Energy Generation and Storage (REGS), significantly more storage capacity will be needed. To support this growth, policy measures should include:

- Updating regulatory frameworks to ease planning for BESS projects above 100 MW, encouraging larger-scale investments.
- Incentivising innovation through grants or subsidies for advanced storage technologies that enhance grid stability.
- Streamlining grid connections to reduce approval delays and accelerate project execution

16. Conclusion

The UK's Electric Vehicle (EV) integration strategy reveals a nuanced challenge of balancing technological innovation with economic pragmatism. While Battery Energy Storage Systems (BESS) offer a technical solution to grid challenges, their current implementation costs (£6.92-£9.15 million) significantly outweigh traditional grid upgrades (£2.4-£2.5 million), rendering them economically prohibitive. The most promising pathway emerges through hybrid approaches, which combine Time-Of-Use (TOU) rates with behind-the-meter batteries. This strategy could potentially reduce BESS capacity requirements by up to 10% by 2035, presenting a more financially viable and adaptive solution to grid modernisation.

The UK's ambitious BESS deployment with 116 operational facilities and 1,000 planning applications signals a strategic commitment to energy transformation. However, success hinges on infrastructure expansion and developing sophisticated, cost-effective integration strategies that balance technical capabilities with economic constraints.

Table 9 presents the comparative analysis, demonstrating the systematic advancement of this research beyond existing literature through quantified metrics and integrated methodologies. Unlike previous studies that provided general observations or isolated technical analyses, this work presents specific quantitative data, including a 35.8% peak demand increase and detailed cost comparisons (2-3 times higher BESS costs versus traditional upgrades).

The research uniquely demonstrates the synergistic effects of combined strategies, showing a 10% reduction in storage capacity through TOU-BESS integration. Most significantly, the introduction of behind-the-meter batteries as a novel cost-sharing approach addresses the critical economic barrier identified in deploying utility-scale Battery Energy Storage Systems (BESS), providing practical implementation pathways for sustainable Electric Vehicle (EV) grid integration. Future research must prioritise advanced control algorithms, comprehensive reliability assessments, and exploration of emerging battery technologies to support the nation's renewable energy transition.

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