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Proceedings Paper:

Nunez Munoz, M., Naderi, M., Smith, M. et al. (2026) Techno-economic sizing of a renewable hybrid energy system for an EV charging station. In: PCIM Europe 2026 Conference Proceedings. PCIM Europe 2026, 09-11 Jun 2026, Nuremberg, Germany. VDE Verlag, Nuremberg, Germany. ISBN: 9783800767168.

<https://doi.org/10.30420/566716013>

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Techno-Economic Sizing of a Renewable Hybrid Energy System for an EV Charging Station

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Abstract

This paper details the techno-economic modelling and sizing of a hybrid energy system (HES) designed for an electric vehicle (EV) fleet charging station located at a logistics company. The system integrates solar panels, wind turbines, and a Hybrid Energy Storage System (HESS). An energy-balance model was employed to evaluate various designs against CAPEX and Levelised Cost of Energy (LCOE) over a 10-year period. Results indicate that the optimal configuration, based on the company's technical and economic constraints, achieves 74% of the fleet energy demand being met with renewable generated energy with a LCOE as low as 0.55 £/kWh.

1 Introduction

Transport remains the largest Greenhouse Gas (GHG) emitting sector in the UK, with the latest figures indicating a contribution of 30% to total emissions [1]. Consequently, transport electrification in the UK has accelerated significantly over the past years [2] supported by national decarbonization strategies and ambitious targets such as the banning of new internal combustion engine (ICE) vehicles sales by 2030 [3,4] and net-zero emissions by 2050 [5].

The electrification of transport, however, presents a significant challenge to local grid infrastructure [6]. Different studies highlight that local distribution networks are particularly vulnerable to increased peak loads from electric vehicle (EV) charging [6]. On a national scale, ambitious electrification scenarios predict that annual and peak electricity demands could more than double by 2050 [7]. While overall energy consumption may seem manageable at moderate EV penetration rates [8], higher market shares will require significant expansion of generation capacity and transmission infrastructure [9].

There is a long queue for grid upgrade connections that is also hindering the rollout of transport electrification and EV charging infrastructure in the UK [10]. In the meantime,

charging infrastructure in the UK remains unsteadily distributed geographically, with urban areas better served than rural regions [11,12].

A potential solution to these challenges is the use of onsite renewable energy generation and storage [13]. The use of renewable sources reduces the dependency with the grid network [14] and not only helps mitigate the strain on the local grid [15,16], but also becomes more advantageous when fossil fuel prices spike by protecting users from volatile petrol and grid prices [17]. On the other hand, using renewable energy sources in EV charging infrastructure ensures a sustainable transition to transport electrification as reduces the well-to-tank emissions associated to EV charging [18,19].

Various configurations of hybrid energy systems (HES), including off-grid and grid-connected options, have been evaluated for EV charging stations. Some studies have explored the techno-economic viability [20], others specifically address the intermittent nature of renewable sources and how to mitigate it [21] all demonstrating the potential to significantly reduce operating costs and emissions. Such systems, while promising, often face high initial capital requirements.

This paper addresses the need for long-term planning tools capable of optimizing the sizing of

EV charging 'microgrids', while balancing technical performance with economic viability. The objective of this research is to apply a techno-economic model to determine the optimal sizing of the solar, wind and the HESS systems for the Future Electric Vehicle Energy networks supporting Renewables (FEVER) research project demonstrator. The demonstrator is a hybrid energy system (HES) designed to support the charging needs of an EV fleet at a commercial site. The remainder of this paper is organized as follows. Section 2 will review relevant literature. Section 3 describes the methodology. Followed by Section 4 which will present the results and discussion. Section 5 will conclude the paper.

2 Literature review and Research contribution

2.1 HES for EV charging

HES for EV charging are increasingly recognized as a sustainable solution to support the rapid growth of EV adoption while reducing grid dependency and carbon emissions [22].

HES for EV charging infrastructure typically integrates solar photovoltaic (PV), wind turbines, and sometimes biomass or fuel cells with energy storage systems (ESS) and grid connections. These configurations enable flexible operation modes: standalone (off-grid), grid-connected, or hybrid (capable of both) [23,24].

Grid-connected HES charging stations offer the advantage of bidirectional power flow, allowing surplus renewable energy to be sold back to the utility grid whilst drawing grid power during periods of low renewable generation. This configuration generally exhibits a lower Net Present Cost (NPC) and Levelised Cost of Energy (LCOE) compared to isolated systems, as it reduces the dependency on oversized ESS. AlHammadi et al. [25] conducted a techno-economic analysis of a grid-connected solar-wind-battery system. Their optimally sized model achieved a highly competitive LCOE of \$0.067/kWh whilst concurrently reducing CO₂ emissions by 384 tons annually. Similarly, Ekren et al. [26] highlighted that grid-connected EV charging microgrids can significantly curtail operational costs and alleviate grid strain, providing robust economic returns and emission reductions in urban settings. Life-cycle analyses show significant reductions in greenhouse gas emissions compared to conventional grid-only charging [27].

Conversely, off-grid hybrid charging stations are indispensable for remote or rural locations where grid extension is either financially prohibitive or technically unfeasible. These standalone systems mandate precise sizing of generation and energy storage components to guarantee an uninterrupted power supply. Consequently, the initial capital expenditure (CAPEX) and overall NPC are higher due to the necessity of bigger ESS or backup generators. However, they provide 100% energy independence and have the potential to completely eradicate operational GHG emissions. Nallolla and Vijayapriya [28] investigated an off-grid solar-wind-battery EV charging framework, revealing that whilst the economic metrics are highly sensitive to component costs, the system effectively decouples transport energy from fossil-fuel-dominated grids, resulting in a 100% renewable energy fraction and zero operational emissions. Across simulations, case studies, and reviews, these systems are consistently shown to cut grid dependence and emissions while remaining economically viable, provided they are optimally sized to local conditions and paired with intelligent control and smart charging. Furthermore, the viability of these HES heavily relies on robust techno-economic sizing. Oversizing the generation or storage components leads to prohibitive CAPEX and stranded assets, whereas undersizing risks failure to meet the charging demand, thus necessitating supplementary power from the grid.

2.2 Research contribution

There remains a gap in the literature for holistic, multi-variable optimization tailored for commercial EV fleet constraints. The study contributes by providing a methodology for comparing diverse system architectures (e.g., varying battery sizes and turbine types), and different battery chemistries against key economic metrics over a long-term horizon considering company's constraints, including budget and technical limits. It also quantifies Greenhouse Gas (GHG) emissions and the associated reductions when compared to a base case scenario, which relies 100% on the grid for EV fleet charging. The findings directly support the decision-making process for the design phase.

3 Methodology

3.1 HES modelling

The detailed model is developed in MATLAB/Editor. The method used to model the HES is an energy-balance technical model. The core architecture of the HES, including the power sources, loads and storage, is illustrated schematically in Fig. 1. The system is a DC/AC coupled HES and comprises four primary modules considered in the sizing analysis: the solar PV system, mounted on modular canopies over the carpark, the wind turbine system, and the HESS, a Lithium Iron Phosphate (LFP) modular battery and a second-life Nickel Manganese Cobalt Oxide (SL-NMC) modular battery.

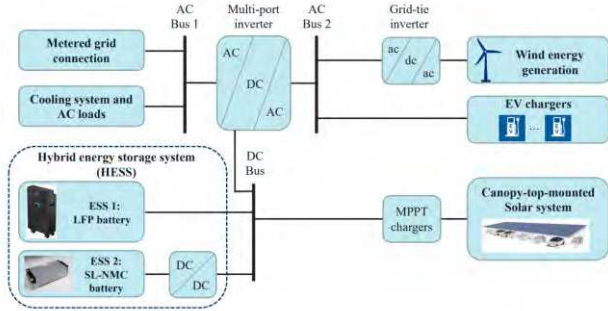


Fig. 1 Schematic of the hybrid energy system (HES) under study.

The energy demand comes from two dual-cable 7 kW chargers and 2 kW cooling system as the main electrical loads. There is a 20 kW metered grid connection limited to act as a backup source to guarantee 100% of the Met Energy Demand (MED), and the HES system is modelled to maximize the renewable share of MED. Weather data from the 2011–2020 period (PVGIS database) was used for PV and wind generation profiles. The demand from the 7 kW chargers was added to the AC bus of the HES as the charging station power profile. Detailed steps of the charging station model have been published by the authors of this study in [29]. The charging station model is based on limited data such as the size of the fleet, the make and model of each vehicle and start/end times of the charger booking. To model the random behavior of EVs such as real arrival times to the charging station, and the driver's preferred minimum EV battery state of charge (SOC) for deciding whether to charge again, probability distribution functions are used.

3.2 HES sizing

The sizing problem is solved by establishing different possible component configurations and calculating technical and economic metrics for each over the expected lifespan of the demonstrator (i.e., 10-year study period). The

performance and financial viability of each plan are assessed using the renewable share of MED and the LCOE, following Eq. (1) and Eq. (2), respectively.

$$\text{Renewable share of MED (\%)} = \frac{\text{Met demand by renewables (kWh)}}{\text{Total demand (kWh)}} \quad (1)$$

$$\text{LCOE} \left(\frac{\text{£}}{\text{kWh}} \right) = \frac{\text{Present cost (£)}}{E_{\text{tot}}(\text{kWh})} \quad (2)$$

3.3 GHG emissions methodology

To evaluate the environmental impact of the proposed energy systems, a GHG emissions assessment was conducted. The assessment calculates the carbon footprint associated with energy consumption under two distinct operational scenarios: a Base Case (relying entirely on the grid) and the HES scenario (Fig.1.).

Reporting on GHG emissions requires defining specific conversion factors (CF) for each energy source. These factors quantify the mass of carbon dioxide equivalent (CO₂e) emitted per unit of energy generated or consumed. The standard conversion factors utilized in this study are as follows:

- Grid Electricity: 0.207074 kg CO₂e per kWh. This factor is based on the 2023 UK Government greenhouse gas reporting conversion factors for electricity generated from the UK grid [30]. The UK electricity factor is prone to fluctuate from year to year as the fuel mix consumed in UK power stations and the proportion of net imported electricity changes.

- Solar Photovoltaics: 0.046 kg CO₂e per kWh. Derived from the National Renewable Energy Laboratory (NREL) life-cycle assessment harmonization data for PV systems [31].

- Wind Energy: 0.126 kg CO₂e per kWh. Sourced from NREL's life-cycle assessment data for wind turbines [32].

The GHG emissions are then calculated multiplying each conversion factor by the portion of the total annual energy generated by the corresponding source (i.e., grid, PV system or wind turbines).

4 Results

The system's performance and the HES sizing were evaluated using a sensitivity analysis

conducted across two distinct case studies, case study 1 and case study 2 as follows:

4.1 Case study 1

Case Study 1 evaluates a HES system formed by a 5 kW horizontal axis wind turbine (HAWT) and 48 kWh SL-NMC battery. The analysis explores the impact of increasing both PV capacity (number of canopies) and BYD LFP storage size on performance and cost (Fig.2).

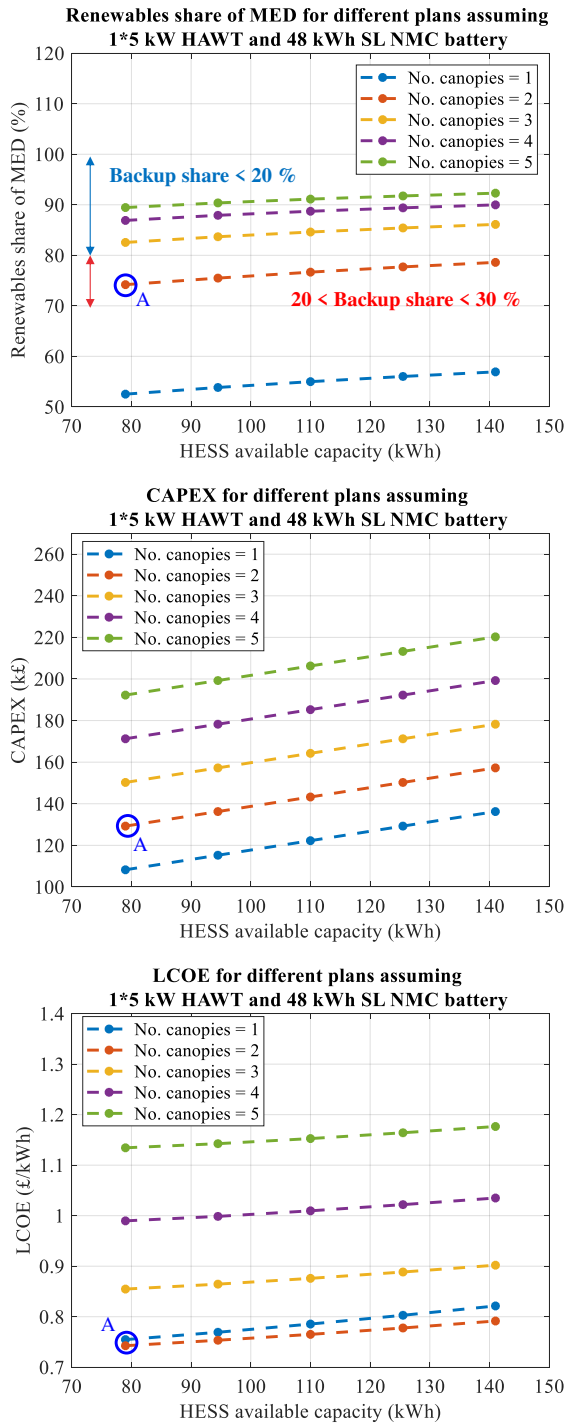


Fig. 2 Sensitivity analysis results for Case study 1

The technical benefit peaks during the transition from one to two canopies as it increases the renewable share of MED from 54% to 74%, representing the largest fractional gain in renewable penetration. While this addition increases the CAPEX from £110k to £130k, the LCOE remains almost the same. The 20% gain in renewable energy utilization provides the greatest return on investment, defining the two-canopy system as the most economically justifiable point for maximizing renewable energy relative to cost. To further contextualize the outcomes on Fig.2., an assessment of annual GHG emissions was conducted, with key individual scenarios presented in Fig. 3.

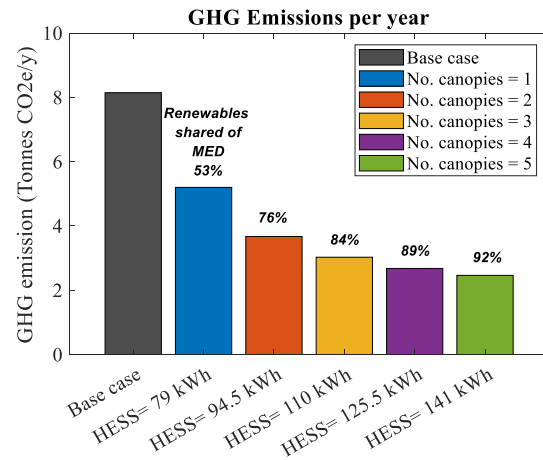


Fig. 3 GHG emissions analysis of selected Case study 1 plans.

The base case, which relies entirely on the grid, results in the highest environmental impact, generating 8.14 tons CO₂e per year. The integration of an on-site HES yields substantial environmental benefits. Implementing a single solar canopy coupled with a 79 kWh HESS reduces emissions to 5.2 tons CO₂e per year, a decrease of over 36% compared to the base case scenario.

The higher the renewables shared of MED and the HESS capacity, the lower the GHG emissions. Fig.4. provides a detailed overview of the environmental impact across all scenarios evaluated in the techno-economic analysis. It can be seen that the addition of solar canopies is the main driver for reducing the system's carbon footprint, rather than the expansion of battery storage. While increasing the HESS capacity yields lower returns in emissions reduction, the transition to a two-canopy system shows the highest drop in annual GHG emissions. This aligns with the techno-economic findings (Fig.2.), further reinforcing the two-canopy architecture as the

optimal configuration from both a financial and environmental perspective.

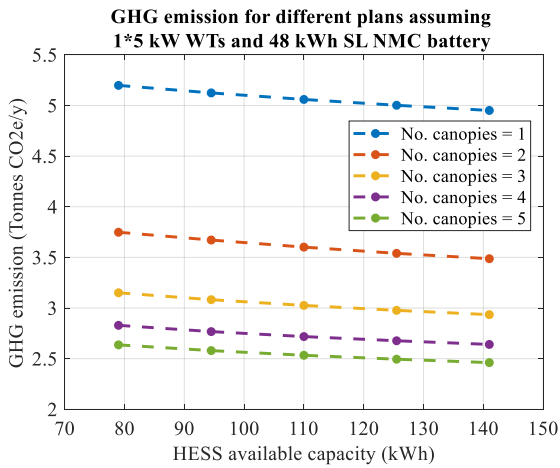


Fig. 4 GHG emissions results for Case study 1

4.2 Case study 2

Case Study 2 investigates configurations using the two-canopy PV system and a 48 kWh SL-NMC battery alongside varying numbers of 1 kW VAWTs and the capacity of the Fogstar LFP battery.

The Fogstar is a LFP battery remarkably cheaper than the BYD battery (£130/kWh vs £320/kWh). The decision to evaluate smaller, multiple wind turbines responds to site constraints and the company's preference.

The results of the analysis, as can be seen in Fig.5., show that the renewable share of MED increases across the entire HESS capacity range as the number of turbines increases from three to seven. However, a trade-off is observed between the number of turbines and the HESS capacity. Specifically, increasing the HESS capacity with three turbines (Point D) enables the system to reach a higher renewable share than configurations employing five (Point B) or seven (Point C) turbines, but at a lower base cost. Although increasing the turbine count raises the CAPEX by approximately £15k to £20k across the HESS range, Point D maintains a lower CAPEX than both Point B and Point C. Furthermore, the LCOE analysis for the 3-VAWT system demonstrates the minimum point (£0.76/kWh) at a HESS capacity of 140 kWh (Point D), representing the economically optimal size for the lower turbine count. The results confirm that increasing the number of smaller turbines beyond three, while

technically improving the renewable share, minimizes the economic return.

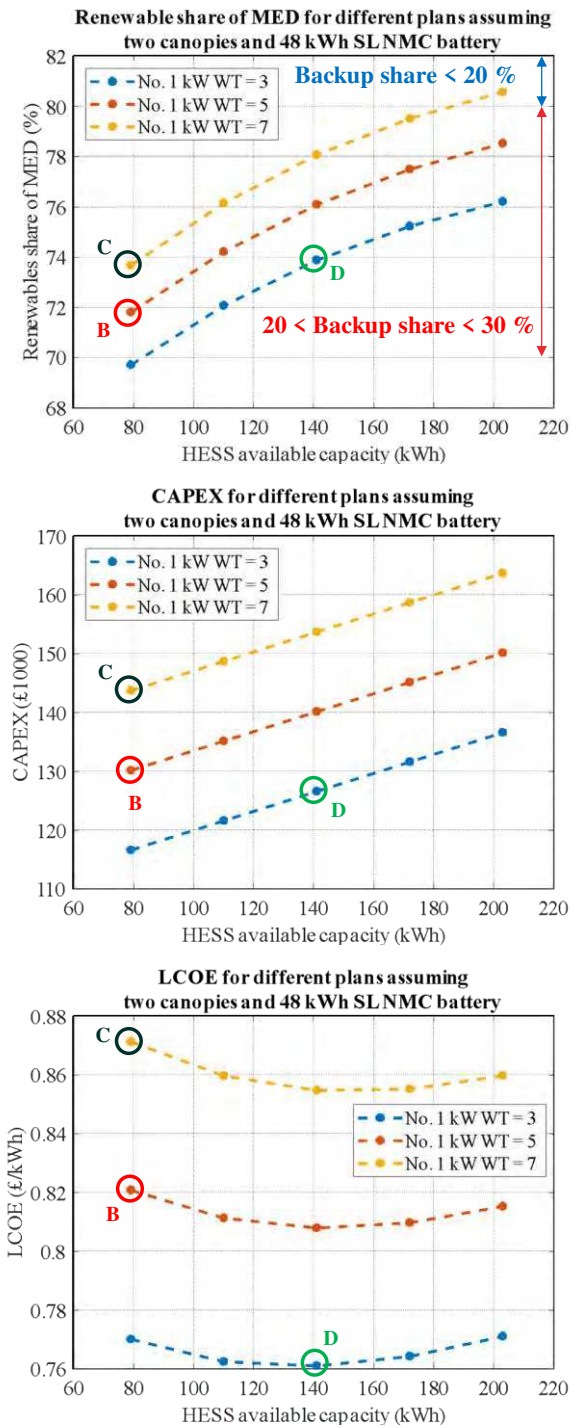


Fig. 5 Sensitivity analysis results for Case study 2

4.3 Comparing potential plans

A direct comparison of the four potential system architectures (summarized in Tables 1 and 2) reveals the techno-economic trade-offs between generation capacity and energy storage.

Plan A (utilizing a single 5 kW HAWT) and Plan D (employing three 1 kW VAWTs coupled with an

expanded 93 kWh LFP battery) emerge as the most competitive configurations. Plan A achieves the highest renewable share of MED (74%) while maintaining the lowest LCOE (0.55 £/kWh with grid support).

Plan name	Wind power (kWp)	Solar power (kWp)	New LFP cap. (kWh)	RS MED (%)
Plan A	1*5 kW (HAWT)	32	31	74
Plan B	5*1 kW (VAWT)	32	31	71.8
Plan C	7*1 kW (VAWT)	32	31	73.7
Plan D	3*1 kW (VAWT)	32	93	73.9

Table 1 Summary table of the HES for the selected plans

Plan name	CAPEX (k£)	LCOE with (without) grid (£/kWh)	GHG emissions (Tonnes CO ₂ e/y)
Plan A	129	0.55 (0.74)	3.75
Plan B	130	0.59 (0.82)	4
Plan C	144	0.64 (0.87)	4.03
Plan D	126	0.56 (0.76)	3.74

Table 2 Summary table of techno-economic outcomes of the selected plans.

However, given potential site constraints such as acoustic limitations and/or aesthetic preferences require the use of smaller VAWTs, Plan D represents a highly viable alternative. By

compensating for the reduced wind generation capacity (3 kW total versus 5 kW) with an expanded, cost-effective battery storage system, Plan D achieves a nearly identical renewable share (73.9%) and the lowest overall CAPEX (£126k). The environmental assessment also reports higher GHG emissions reductions on these two scenarios. Plan D records the lowest annual GHG emissions at 3.74 tonnes of CO₂e/year, closely followed by Plan A at 3.75 tonnes of CO₂e/year.

In contrast, Plans B and C attempt to match generation capacity by scaling up the number of VAWTs (to 5 and 7, respectively) without expanding storage. This approach ultimately increases both CAPEX (up to £144k for Plan C) and LCOE, demonstrating that given the current market pricing of LFP batteries, expanding energy storage is not only a more economically efficient strategy for this microgrid than installing numerous small-scale wind turbines, but it also achieves better environmental outcomes.

Conclusions

This study presented a 10-year techno-economic modelling framework to determine the optimal component sizing for a hybrid energy microgrid designed for an EV fleet charging station. By evaluating various solar, wind, and hybrid battery storage configurations, the study identified optimal designs capable of meeting approximately 74% of the fleet's energy demand using renewable sources. These configurations achieve a highly competitive LCOE of 0.55–0.56 £/kWh when utilizing an energy-limited grid connection as a backup, and 0.74–0.76 £/kWh in a fully off-grid scenario.

The techno-economic analysis reveals that while single, HAWTs provide strong economic returns, equivalent system performance can be achieved using smaller VAWTs by strategically increasing the capacity of cost-effective LFP battery storage. Furthermore, the environmental assessment confirms that deploying a HES significantly reduces GHG emissions compared to grid-reliant charging. However, the assessment analysis highlights that while maximizing the system size can reduce GHG emissions to below 2.5 tons CO₂e/year, the incremental reduction becomes progressively smaller with each additional solar canopy and battery expansion.

Lastly, the comparison across the different plans (Plan A,B,C and D) reveals that scaling energy storage rather than increasing small-scale wind turbines yields the greatest environmental benefit, with the Plan D configuration achieving the lowest emissions profile of 3.74 tonnes of CO₂e/year.

These findings directly inform the design of the FEVER project demonstrator and provide a scalable, evidence-based framework for future commercial fleet electrification initiatives.

Acknowledgements

The authors acknowledge the financial support received from the Engineering and Physical Sciences Research Council (EPSRC) through Future Electric Vehicle Energy Networks supporting Renewables (FEVER) grant EP/W005883/1.

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