A techno-economic analysis of a hybrid energy storage system for EV off-grid charging

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***Abstract* — This paper presents the techno-economic advantages of a DC coupled li-ion and lead-acid hybrid energy storage systems used for EV off-grid charging using visitors arriving at Marwell Zoo car park as a case study. The analysis shows that the hybrid storage systems can reduce the overall system costs by using li-ion batteries for frequent cycling linked with lead-acid for longer, less aggressive cycles. On-site overgeneration of 600 % of the total load gives the lowest total system cost. For the optimized overgeneration, hybrid storage system can further reduce the cost of the EV off grid charging system by up to 10 % when compared with a li-ion only energy store.**

***Index Terms*— EV charging, hybrid li-ion and lead-acid battery storage, energy storage cost.**

I. INTRODUCTION

Electric vehicles (EVs) are becoming increasingly popular with a market share of nearly 10 % [1]. In an effort to decarbonize transport, in the UK, the sale of new petrol and diesel cars will be banned by 2030 [2], with a mandate that all new cars and vans are to have zero emissions across the UK and the European Union by 2035 [2, 3]. While a sizeable percentage of the population is expected to charge their EV at home or at work, public chargers will be necessary to facilitate a large EV penetration. By 2030, estimates suggest that the UK will require between 280,000 and 480,000 public chargers [4]. Obtaining a connection to electricity networks for EV chargers can be time-consuming and expensive, especially for high-power rapid chargers or for locations where existing electricity consumption is low. If improperly managed, these connections can put a strain on local electricity networks.

To maximize the decarbonising effect of the move to EVs, the electricity used to charge them must be low carbon. However, with an increased penetration of renewable generation technologies, such as solar or wind, subsequent installation of these technologies can come with challenges in terms of maintenance of grid stability in due to the variability of renewable generation and the difficulty of matching supply and demand.

Hilton et al. [5, 6] suggest co-locating renewable generation, such as solar, with EV chargers to mitigate the grid impact by using renewable energy to charge EVs. By combining such a system with an off-vehicle energy store (OVES), the impact can be further reduced. The authors, however, suggest a grid connection is still required to maintain availability over the winter, when solar generation is low.

Here we propose off-grid electric vehicle chargers as part of Future Electric Vehicle Energy networks supporting Renewables (FEVER) using hybrid energy storage coupled with wind and solar generation and other renewables, as a cost-effective alternative to high power grid connections. Hybrid energy storage systems take advantage of properties of different technologies to improve the performance, longevity, or cost of an energy storage project when compared to using a single storage technology. Such systems are often used in electric vehicles, with a bulk energy store with high specific energy, such as li-ion, combined with a high-power technology that reacts quickly, such as supercapacitors [7]. This allows the vehicle to store energy, deliver and absorb power at a high rate during harsh acceleration and braking while maintaining a reasonable range without having to oversize the battery. However, increasingly, hybrid energy stores are also being used to facilitate the installation of renewable energy generation [8].

The variable nature of renewable generation means that when coupled to energy storage, the energy stores are subjected to many partial cycles, which do not make full use of battery systems, and this results in oversized storage systems. To illustrate this, Fig 1, shows a daily energy profile delivered by an energy storage system for one month. For this profile, the storage capacity and cycle life specifications required are around 16 kWh, capable of doing 30 cycles. This his however an 'oversized' system as around 4 kWh of storage capacity is only used around 10 % of the time (red peaks Fig 1). This means that 4 kWh of storage capacity can be a cheaper battery with a lower

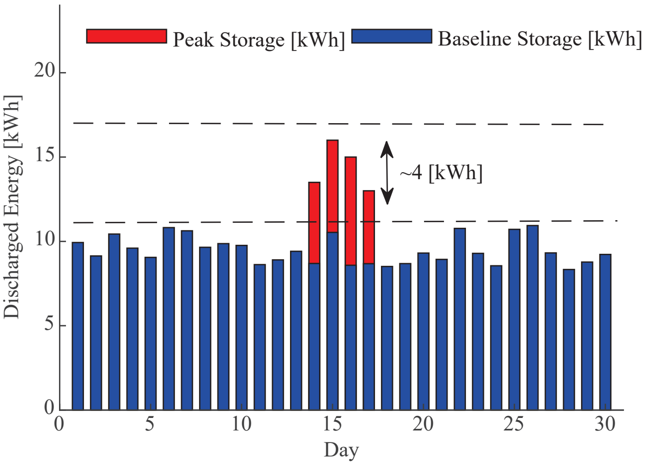

Fig 1. Example energy storage profile with a baseline storage requirement and short periods requiring additional capacity

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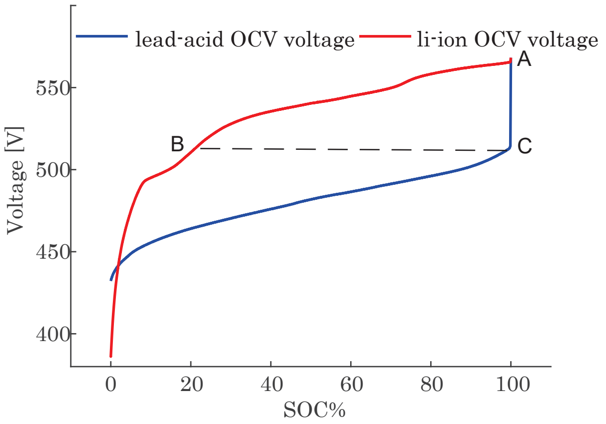

Fig 2. Voltage Profiles of Li-ion and Lead-acid Strings

cycle life. The result of this would be a lower overall storage system cost.

One promising hybrid energy store for use with renewable generation is li-ion cells directly coupled with lead-acid [9]. In this design, the li-ion deals with frequent, partial charge/discharge cycles, and the lead-acid is reserved for the less frequent cycles when a greater depth of discharge is required. The li-ion would cover the frequent, blue portions of the storage profile and the lead acid would do the occasional read peaks indicated in Fig 1. This allows for a comparatively smaller li-ion battery coupled with a much lower cost lead-acid to be used for the remaining required capacity. As the lead-acid is only cycled infrequently, the shorter cycle life is not a major issue.

By taking advantage of the different charge/discharge curves of li-ion and lead-acid, when the strings of each chemistry are directly coupled in parallel, the li-ion will discharge preferentially, as is shown in Fig 2 (between points A-B, the li-ion discharges to around 20-30 % SOC but in the same time, lead-acid will remain at 100 % SOC, points A-C). This approach negates the need for any power electronics for controlling or balancing the two battery types leading to further cost savings. Such a system, coupled with wind and storage is indicated in Fig 3.

This system allows advantages of both li-ion and lead-acid to be leveraged, primarily the cyclability of li-ion with the low cost and recyclability of lead-acid, leading to a lower total cost and, potentially, a lower environmental impact. There are, however, some challenges associated with such a hybrid system. Compared to a li-ion only system, the lower energy density of the lead-acid will increase the size of the system. Circulating currents between the two technologies may also reduce the efficiency of the system. The system is also more complex, requiring more precise design for each load profile and a maintenance and cell replacement process that considers both the li-ion and lead-acid batteries. In a well-designed, stationary energy store, however, these impacts are expected to be small.

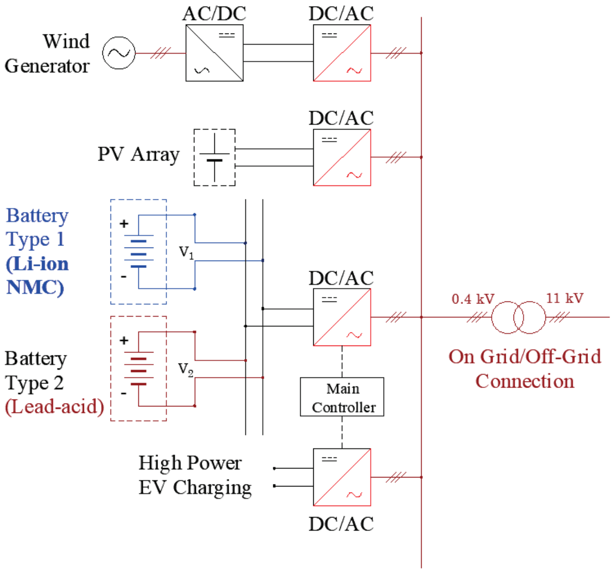

Fig 3. Hybrid DC-coupled Energy Storage System with Wind and Solar Generation.

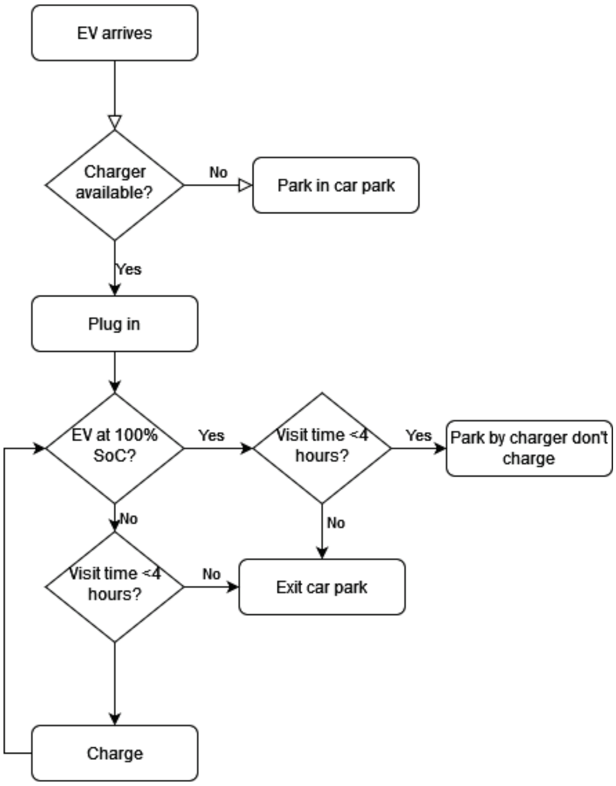

Fig 4. Decision chart to determine the EV charging status and location

This paper examines the use of this hybrid li-ion and lead-acid battery system using electric vehicle chargers for visitors at Marwell Zoo in Hampshire, UK as a case study. Initially, an energy balance model is used to determine an appropriate size for the OVES and renewable generation capacities based on estimated EV charger use. The cost and sizing impacts of a hybrid OVES with li-ion directly coupled in parallel with lead-acid are then examined in more detail using these generation and load profiles.

II. METHODOLOGY

Wind and solar generation profiles were obtained using wind speed and irradiance data from Open Meteo for 2019 at Marwell Zoo [10]. The wind profile was then mapped onto the power generation curves for an Aventa AV-7, [11], and a solar panel with a 20 % module efficiency was assumed. The system is based on a charging station with ten 3.5 kW chargers.

There are no existing EV chargers in place for this case study, so charger use was modelled based on visitor arrival data for 2019 and the following assumptions:

- Based on the maximum number of visitors in a day and the maximum number of vehicles arriving in a day, per 4 visitors arriving, 1 car arrives in the car park.
- 3 % of vehicles arriving at the car park are EVs [12].
- Visitors park their cars for 4 hours while visiting the zoo based on a suggested visit time from Marwell Zoo.
- EVs have travelled a nominal 15 miles and only require replacement of this range when charging
- EV efficiency of 4 miles per kWh
- If a charger is free when an EV arrives, the EV will use the charger.
- Cars only arrive during opening hours of 10.00 am to 4.00 pm

The hourly EV load profile was generated using the decision chart shown in Fig 4.

A typical single day EV profile is shown in Fig 5 and the whole profile over a year shown in Fig 6.

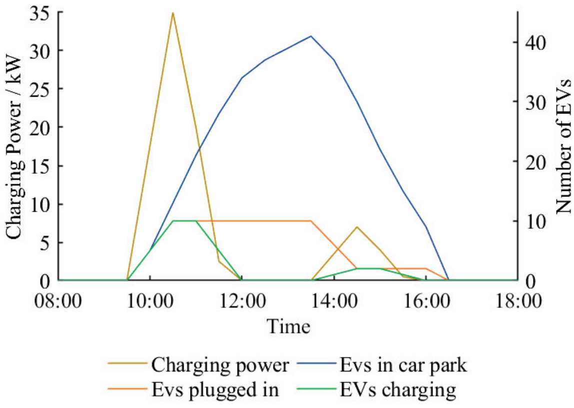

Fig 5. EV load with an example day (19/04/2019) showing charging power and number of EVs parked plugged in and charging

A. Hybrid Energy Store Description

Based on the assumptions mentioned in the previous sections, an annual hourly EV electrical demand profile was generated. The total annual electrical demand for the site is 10377 kWh and the hourly profile is indicated in Fig 6. The interaction between the EV charging demand, storage requirements, and the annual hourly wind and solar generation profiles was modelled, to understand the cost of the overall system and the storage utilization for various generation and storage scenarios. To cover the entire annual EV electrical load using only renewable generation is not generally possible without energy storage, but in practice a cost balance between overgeneration and hybrid storage capacity needs to be understood. This means sensitivity analysis is required between three main cost vectors: solar and wind generation (and overgeneration), the cost of li-ion systems, and the cost of lead-acid battery storage. To understand this, the following five scenarios have been investigated:

Scenario 1. In this scenario, the total annual electricity generation of wind and solar was set to 160 % of the total annual EV charging demand. This accounts for 8 kW of renewable generation capacity with an equal split of 4 kW of solar PV and 4 kW of wind capacity. The 160 % overgeneration has been used as a starting point from the practical perspective of considering the average round-trip efficiencies of 95 % for the li-ion and 85 % for lead-acid. In this scenario, to cover the entire annual EV load only from wind and solar renewable power, a total of 206 kWh of energy storage capacity is required, assuming a max 90 % depth of discharge. To test the economic performance of the different hybrid options, 17 hybrid battery storage systems have been investigated with different hybrid ratios, lead-acid kWh / li-ion kWh, ranging from 0 (a full li-ion option) to 5.

Scenario 2. In this scenario, the total annual renewable electricity generation is 200 % of the annual EV electrical demand. For the site, this requires a generation capacity of 10 kW, 5 kW of solar, and 5 kW of wind. For the complete renewable load coverage, the total storage requirement is 191 kWh, assuming a maximum depth of discharge of 90 %. Similarly, a sensitivity analysis for the lead-acid kWh / li-ion kWh capacity ratios ranging from 0 to 5 was tested.

Scenario 3. In this scenario, the total annual renewable electricity generation is 300 % of the total annual electrical

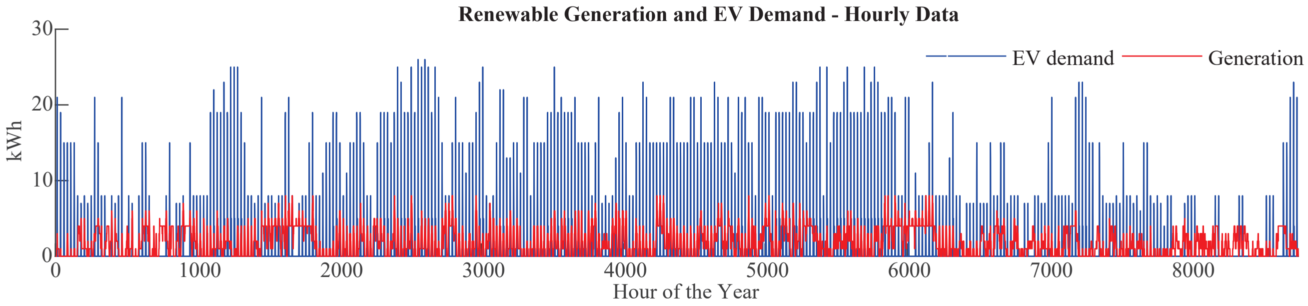

Fig 6. Total energy discharged daily by the storage system

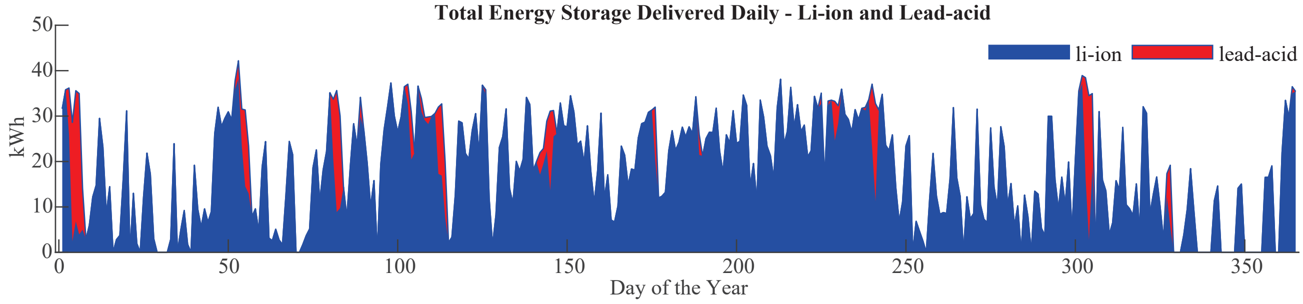

FIG 7. Total daily energy delivered by the energy storage system

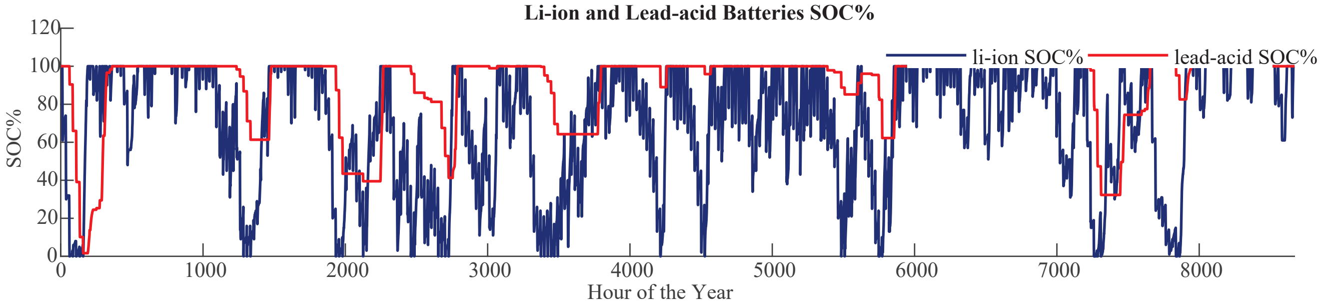

Fig 8. State of charge for the energy storage system across the year 6000

EV demand. To achieve this, a total of 15.2 kW of on-site renewable capacity is required, assuming an equal split of 7.6 kW solar and 7.6 kW wind. The total storage requirement to cover the entire EV load is 156 kWh. Sensitivity analysis was carried out for the same lead-acid kWh / li-ion kWh storage capacity ratios.

Scenario 4. In this scenario, 600 % of renewable electricity generation was considered. This translates to 30.2 kW of renewable capacity with an equal split of 15.1 kW solar and 15.1 kW of wind. The storage requirement is 105 kWh and similar lead-acid kWh / li-ion kWh capacity ratios have been investigated.

Scenario 5. The last scenario considers 1200 % renewable electricity generation of the total annual EV demand. This amounts to 60.4 kW renewable capacity, 30.2 kW of solar, and 30.2 kW of wind. The storage capacity required is 105 kWh, identical to the storage requirement of Scenario 4. Increasing the total electricity generated from renewable sources beyond a certain point, the storage capacity requirements reach a plateau.

To calculate the total storage requirements and the hybrid ratios the following three steps have been followed:

- Set the renewable generation as a percentage of the total annual load requirement assuming an equal split of installed capacity between wind and solar.
- Set the hybrid storage ratio.
- Increase the total storage capacity keeping the hybrid ratio constant until the entire load can be covered by only solar, wind and storage.

TABLE I. RENEWABLE GENERATION AND HYBRID ENERGY STORAGE SCENARIOS - SUMMARY

Scenario	Solar kW	Wind kW	Generation % annual load	Energy Storage kWh
1	4	4	160	206
2	5	5	200	191
3	7.6	7.6	300	156
4	15.1	15.1	600	105
5	30.2	30.2	1200	105

Figs. 7 – 8 illustrate the general hybrid battery storage operation for Scenario 1 and similar observations can be made for the other options. Fig 6 indicates the annual hourly EV demand profile plotted against 8 kW of renewable wind and solar capacity. A proportion of the generation will be consumed directly by the EVs, and the rest will be stored for later usage. Fig 7 indicates the daily energy delivered from the energy storage system to cover the daily EV electricity demand. Generally, it can be seen that the li-ion part of the hybrid system is cycled more often than the lead-acid cells. This is also illustrated in Fig 8, which shows the hourly SOC across the year for both li-ion and lead-acid storage capacities.

B. *Financial and Technical Assumptions*

The financial inputs for the analysis done in this paper are based on current UK industry prices. In 2023, the commercial PV and wind systems prices stand at £750/kW and £1246/kW. The overall cost of the renewable generation systems also includes the O&M (operational and maintenance) and REPEX (replacement expenditure, i.e. inverter replacements) costs. The O&M costs stand at £6.7/kW/year for PV systems and £23.5/kW/year for wind. The REPEX costs are £33.75/kW/year for PV and £36.80/kW/year for wind.

The hybrid battery system costs have been indicated in Table II and Table III below.

All price data indicated have been provided by Hydrock Consultants Ltd and used with its permission. Hydrock has signed various non-disclosure agreements (NDAs) with installers and manufacturers to feed market information and update its price database regularly.

For the technical data, the model uses a flat round-trip efficiency of 95 % for the li-ion batteries and 85 % for the lead-acid across the SOC range. The li-ion batteries used in the model can do 5000 cycles and the lead-acid only do 2000 cycles.

TABLE II. LI-ION BATTERY COST

name		2.5kW, 5kWh	5kW, 10kWh	10kW, 20kWh	15kW, 30kWh	50kW, 106kWh	100kW, 213kWh	250kW, 530kWh	0.5MW, 1MWh	1MW, 2MWh
Capacity	kW	2.50	5	10	15	50	100	250	500	1,000
Effective Charge Capacity	kWh	5	10	20	30	106	213	530	1,000	2,000
Round-trip Efficiency	%	95%	95%	95%	95%	95%	95%	95%	95%	95%
Cycles	no.	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
CAPEX	£/kW	£1,000	£950	£930	£925	£900	£850	£780	£710	£655
$O\&M_{fixed}$	£/MW	£30	£29	£28	£28	£27	£26	£23	£21	£20
Service Life	years	11	11	11	11	11	11	11	11	11
$REPEX_{annualised}$	£/kW/year	£36.36	£34.55	£33.82	£33.64	£32.73	£30.91	£28.36	£25.82	£23.82

TABLE III. LEAD-ACID BATTERY COST

name		2.5kW, 5kWh	5kW, 10kWh	10kW, 20kWh	15kW, 30kWh	50kW, 106kWh	100kW, 213kWh	250kW, 530kWh	0.5MW, 1MWh	1MW, 2MWh
Capacity	kW	2.50	5.00	10.00	15.00	50.00	100.00	250.00	500.00	1000.00
Effective Charge Capacity	kWh	5.00	10.00	20.00	30.00	106.00	213.00	530.00	1000.00	2000.00
Round-trip Efficiency	%	85.00	85.00%	85.00%	85.00	85.00%	85.00%	85.00%	85.00%	85.00%
Cycles	no.	2000	2000	2000	2000	2000	2000	2000	2000	2000
CAPEX	£/kW	666.67	633.33	620.00	616.67	600.00	566.67	520.00	473.33	436.67
$O\&M_{fixed}$	£/MW	20.00	19.00	18.60	18.50	18.00	17.00	15.60	14.20	13.10
Service Life	years	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00
$REPEX_{annualised}$	£/kW/year	24.24	23.03	22.55	22.42	21.82	20.61	18.91	17.21	15.88

III. HYBRID ENERGY STORAGE ANALYSIS RESULTS

FIG 9 shows the total system costs for the overall generation and hybrid storage systems scenarios plotted against various lead-acid kWh / li-ion kWh hybrid capacity ratios.

The first observation is that the cheapest option is Scenario 4 which assumes a generation profile of 30.2 kW of renewable PV and wind capacity. This amounts to a total annual energy generation of 600 % of the total yearly EV electricity demand. For this scenario, the PV system cost is £11300 CAPEX (capital expenditure) and £611/year OPEX & REPEX. The 15 kW wind capacity cost is £18800 CAPEX and £1012/year OPEX & REPEX. The total storage capacity required for this scenario is 105 kWh. The cost associated with this depends on the ratio between the two chemistries. For the single li-ion chemistry storage solution, the cost is £44000, which drops by 17 % for a hybrid storage option with a storage ratio of li-ion kWh / lead-acid kWh equal to 5. The overall generation and storage system cost stand at a maximum of £74000 for the li-ion only battery solution. This drops to £66500 for a hybrid system of ratio 5, a drop of 10 %.

The second observation is that Scenario 5 is the most expensive option. Considering that it requires a similar amount of energy storage capacity to cover the entire annual EV demand, the percentage price reduction by using a hybrid storage option is slightly less than 10 %. The total system cost, including generation and storage, drops from a maximum of £104400 when using a single li-ion chemistry storage system, to £93900 if a hybrid storage system of ratio 5 is used.

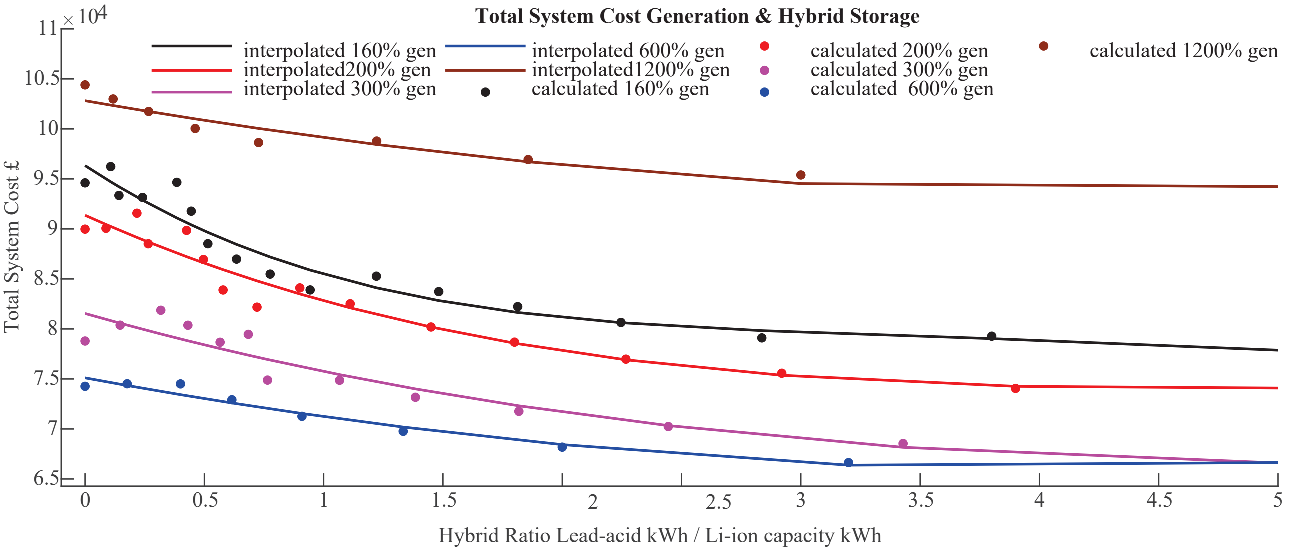

Fig 9. Total system cost of generation and hybrid energy store vs ratio of lead-acid to li-ion capacity with a range of installed generation capacities.

The third observation is that the biggest price reduction for switching to a hybrid storage system is for Scenario 1. This is not surprising as this requires the largest amount of storage because of its small yearly electricity generation, 160 % of the total yearly demand. A large storage capacity implies that greater savings are possible for higher hybrid ratios by replacing parts of the li-ion cells with cheaper lead-acid alternatives. For Scenario 1, the fastest price drop is achieved between the 0 and 2 hybrid storage ratios. For the simple li-ion chemistry solution, the total system cost is £94600 and this drops to £81200 when using a hybrid option of ratio 2, a fall of 14 % in the total cost.

As shown above in Fig 8, during operation, the li-ion part of the hybrid system does the frequent cycling, and the lead-acid battery strings cover the longer, intraday cycles.

Fig 10 shows the total equivalent cycles done by li-ion (a) and lead-acid (b) cells across the year for each scenario investigated. For simplicity, an equivalent cycle is the total yearly energy discharged by each chemistry divided by the energy storage capacity of each chemistry, assuming a maximum of 80 % depth of discharge (DOD) for li-ion and 50 % DOD for lead-acid chemistry. As indicated, for all scenarios, li-ion does more equivalent cycles across the board. Also, li-ion is cycled harder when the hybrid ratio increases. Taking Scenario 1 as an example, the number of li-ion equivalent cycles increases from 44/year, for the simple li-ion chemistry option, to 169/year for a hybrid storage system of ratio 5. Also, as we move from Scenario 1 to Scenario 2 the number of equivalent cycles decreases as less energy storage is required. However, the li-ion cycle range indicated in Fig 10 has a broader spread across the different generation scenarios when compared with lead-acid. This shows that the number of short, frequent storage cycles is reduced when a larger PV and wind system is installed. The same is valid, but to a lower extent, for the longer intraday cycles.

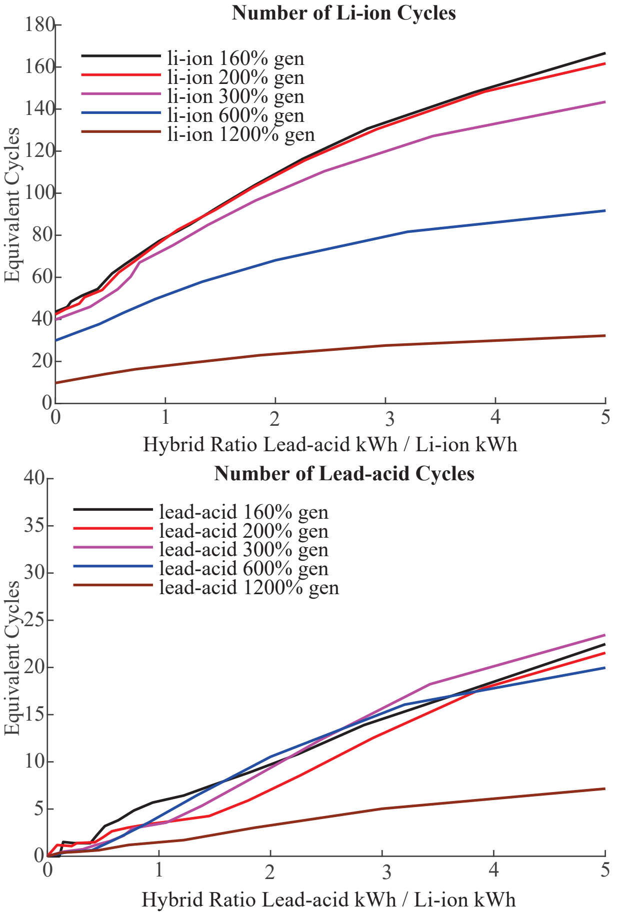

Fig 10. Number of cycles of li-ion (a) and lead-acid (b) vs ratio of lead-acid to li-ion for a range of scenarios with differing generation capacities.

As the annual load is covered entirely by renewable power and storage, part of the load will be covered directly by the generation and the rest will be supplied by the storage system. Fig 11 indicate the battery utilization, i.e., the percentage of the annual load covered separately by the li-ion (a) and lead-acid (b) cells. The total storage utilization can be as high as 66 % for Scenario 1 and lower than 8 % for Scenario 5. As indicated below, for all Scenarios 1-5, regardless of the li-ion and lead-acid hybrid ratios, the li-ion has a higher utilization rate, than the lead-acid battery.

For example, in Scenario 1, li-ion cells cover between 66 % of the load for a pure li-ion storage solution and 48 % for the hybrid ratio of 5. The lead-acid reaches a utilization rate of 20 % for a hybrid ratio of 5. The remaining 34 % is supplied directly by the wind and solar generation system.

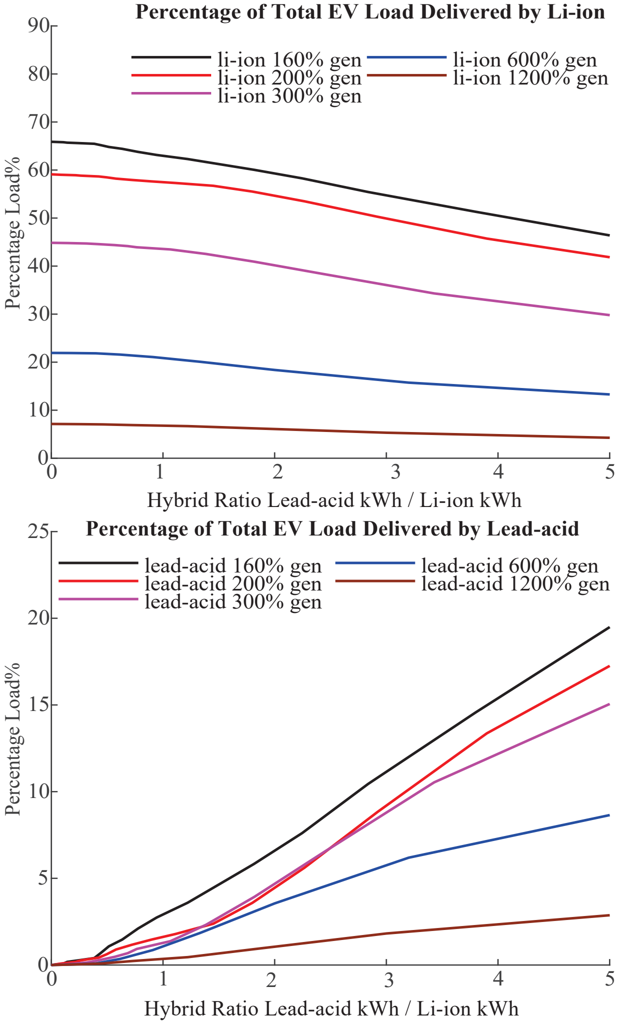

Fig 11. Percentage of the annual load covered separately by the li-ion (a) and lead-acid (b) cells vs ratio of lead-acid to li-ion for a range of scenarios with differing generation capacities.

At the other end of the scale, for Scenario 5, the li-ion utilization rate drops from 7 % for the simple 100 % li-ion solution to 4 % for the hybrid system with the lead-acid kWh / li-ion kwh ratio of 5. Lead-acid on the other hand, covers a maximum of 3 % of the load for a hybrid ratio of 5.

IV. CONCLUSION

In this work, an off-grid EV charging station combining renewable generation with a hybrid energy store has been modelled using the Marwell Zoo car park as a case study.

The model generates an annual hourly load profile for EVs charging stations. This has been analysed against the local PV and wind generation profiles to understand how much of the load can be covered directly by on-site generation, the sizing of the of the storage system required for a fully off grid solutions, the interaction between the hybrid storage system and the EV load profile and the cost of the overall system. Five scenarios were run with varying renewable overgeneration from 160 % to 1200 % of the required energy demand over a year. For each scenario, several energy storage solutions were tested with the ratio of lead-acid to li-ion capacity between 0 and 5.

The modelling shows that energy storage is critical in covering an EV load profile with only wind and solar generation. For Scenario 1, only 34 % of the total EV load can be covered by the on-site renewables. Even for Scenario 5, when the generation system is oversized to 1200 % of the annual EV load required, there is still around 7 % of the load which needs to be supplied by an energy storage system.

The modelling calculates the hybrid storage system over the whole year showing the cycling behaviour of li-ion and lead-acid. The li-ion does most of the frequent, short duration cycles and lead-acid the long duration ones. For the extremes, in Scenario 1 – hybrid ratio 5 and 160 % overgeneration, the li-ion cells do an equivalent of 0.46 cycles/day (169 cycles/year) contrary to lead-acid which does 7x less cycling, 0.06 cycles/day (23.2 cycles/year). As the overgeneration increases, most of the short duration cycles are covered by the PV and wind, for example, in Scenario 5 – hybrid ratio 5, li-ion cells performed only 34 equivalent cycles/year (0.09 cycles/day) and lead-acid only 7.8 cycles/year (0.02cycles/day).

Even at a LA/Li-ion ratio of 5, the model predicts an equivalent cycling of the lead acid battery of less than 20 times per year in all the scenarios. The lead acid battery should, therefore, comfortably last the lifetime of a 20 year project.

The modelling also shows that cost reduction of battery energy storage systems is possible by using directly coupled hybrid li-ion and lead-acid arrangements. The fundamental underlying philosophy of this is that of using cheaper batteries for the long duration energy storage peaks. This reduces the overall cost of the system by not 'oversizing' the system. The rate of cost reductions as a function of the hybrid ratio depends on the storage size required. For the cases analysed, the greatest cost reductions of around 14 % from the initial values was calculated for Scenario 1, between hybrid ratios 0–2. However, the scenario with the lowest system cost overall, including generation and battery storage, was the option with 600 % overgeneration and 115 kWh of storage (5 kWh li-ion and 110 kWh lead-acid). This is around £74000 for the li-ion only battery solution and £66500 for a hybrid system with a ratio of lead-acid to li-ion capacity of 5. This shows that for a fully optimised generation and battery storage solution, the hybrid system alone can further reduce the overall system cost by over 10 %. However, in practice it's very difficult to predict the exact EV load profile and so it is unlikely that a fully optimised ratio of generation and hybrid battery storage (with the additional optimised hybrid ratio) can be accurately calculated. For large battery storage systems, however, even a few percentages in cost reduction can bring hundreds of thousands of pounds in savings and

In terms of further work, the model can be improved by adding more parameters, such as real world EV charger use, into the system. For more precise calculations the following additions can be made: introduce a variable round-trip efficiency as a function of the SOC for the lead-acid, take into account the self-discharge of both chemistries and introduce the transient losses which happen during sharp load reduction.

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