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Optimal energy exchange of two electric vehicle charging stations with solar-hydrogen-battery storage systems

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***Abstract*—This paper presents an optimisation method for the direct energy exchange between two electric vehicle (EV) charging stations located in the UK. Each EV charging station consists of solar panels, hydrogen and battery energy storage systems (SHBS). The stations are interconnected through a energy exchange system that enables the transfer of excess energy from one station to the other. The objective function of SHBS charging stations is to minimize the capital and operation and maintenance costs of the stations. The system constraints are the power output of individual components, as well as the power balance between SHBS charging stations and EV charging demand. Genetic Algorithm is used to optimize the system, considering various factors such as the size of the solar panels and hydrogen storage tanks, the capacity of the electric vehicle chargers, and the amount of energy exchanged between the two stations. The optimized system yields substantial cost savings.**

Keywords— ***electric vehicle charging, photovoltaic, hydrogen storage system, battery storage system, energy exchange, Genetic Algorithm***

I. Introduction

The low-carbon economy has become an integral part of modern social life. Electric vehicles (EV) are poised for significant growth given the prevailing macro trends. However, the development of the EV industry hinges on the availability of charging infrastructure. The charging points are crucial for both hybrid and pure electric vehicles. The current practice of using the existing power grid to charge new energy vehicles needs to be replaced as it creates problems such as conflicts between fast charging and power settings in the grid, pollution caused by charging sources, and energy storage and distribution challenges. Thus, new environmentally friendly integrated power systems are necessary to address these issues.

From the review of existing studies on EVs [1] [2], adoption of such vehicles has clear benefits for the society in terms of environmental impact as well as economic impact on EV buyers through lower running costs. However, EV charging infrastructure has over the years remained a key barrier to encourage higher EV adoption rates. [3] indicates that growth in the number of charging stations for EVs has remained relatively slow thus affecting purchase of EVs among potential users. In agreement, [4] attribute the slow development of EV charging infrastructure to the high capital costs experienced by developers of the infrastructure coupled with the EV demand uncertainty. In the UK, fast charging stations have increased significantly over the years (see Fig. 1). In the case of London, it is estimated that the city and its surrounding environs will need an excess of 500,000 charging points by 2040. Out of this, over 47,000 charging points will need to be in public places [5].

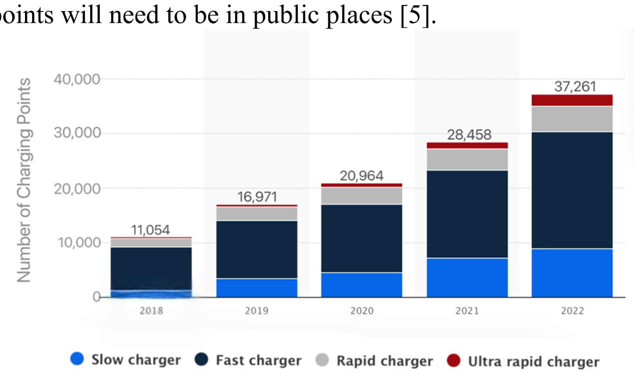

Fig. 1 Number of public charging points for electric vehicles by charging speed in the UK from 2018 to 2022 [6]

Multi-energy EV charging stations can charge electric vehicles using different energy sources, such as solar, wind, hydrogen, and grid electricity. These charging stations are designed to provide a flexible and sustainable solution for EV charging. This renewable energy is collected using various methods such as photovoltaic panels, wind turbines, or hydroelectric generators. To ensure a continuous supply of energy, even during low renewable energy periods, these charging stations can be integrated with energy storage systems.

In addition to providing a range of energy sources, multi-energy EV charging stations can also incorporate different charging technologies, such as fast charging and wireless charging [7]. This allows for a wider range of charging options and can help reduce charging times for drivers. One of the main benefits of multi-energy EV charging stations is that they can help reduce the environmental impact of EV charging. By using renewable energy sources, such as solar or wind power, these charging stations can significantly reduce greenhouse gas emissions associated with charging electric vehicles. EV charging stations energy exchange refers to the ability of two or more electric vehicle charging stations to exchange electricity among each other. This exchange allows for a more efficient use of electricity, as charging stations with surplus power can

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provide electricity to those that need it, reducing the need for the grid to provide additional power. The EV charging stations can be integrated with smart grid technologies to enhance grid stability and reliability. As the demand for EV charging infrastructure continues to grow, the deployment of renewable energy electric vehicle charging stations is expected to accelerate, creating a cleaner, more sustainable transportation system [8].

The simulation performed in this study provides a realistic representation of the real-world dynamics of EV charging stations. Using MATLAB to simulate a 24-hour cycle enables a comprehensive analysis of the total load of each charging station based on traffic flow in Hammersmith & Fulham and Richmond upon Thames, considering factors like time-of-use electricity prices and power demand fluctuations. By applying Genetic Algorithm optimization, the simulation can determine the most efficient solution to the energy management problem, improving the overall performance of the system.

While distributed networks are often used as a conduit for energy exchange between EV charging stations and the grid, this study considers a direct exchange approach between two charging stations, which is using Vehicular Energy Network (VEN) [9], which can transfer energy through the EVs and regulated by the national grid as well. VEN charging stations can potentially be more efficient, reducing distribution loss and minimizing the cost of infrastructure investment and operation and maintenance (O&M).

II. MATHEMATICAL MODELLING

Fig. 2 shows the energy system design for two solar-hydrogen-battery storage (SHBS) EV charging stations which is composed of a hydrogen fuel cell generator for off-grid and high-density power generation, a local solar power facility, an electrolysis component for producing hydrogen from both the power grid and solar power, and storage facilities for both hydrogen and batteries, which facilitate local energy balancing. The SHBS charging station has the capability to purchase and sell electricity from the power grid, which is influenced by the daily changes in electricity pricing. EV charging stations energy exchange is that it allows for more efficient use of energy resources. By exchanging power between charging stations, energy can be shared and distributed more evenly, reducing the overall demand for grid-supplied electricity during peak usage times. Additionally, energy exchange can help reduce the cost of electricity for charging station owners and users by allowing them to access cheaper electricity from neighboring stations or renewable energy sources. Energy exchange can also help promote the use of renewable energy sources, such as solar or wind power, by allowing stations to share excess energy with one another. Finally, energy exchange can help increase the resilience and reliability of the
energy grid by enabling charging stations to operate even during power outages or other disruptions.

A. Hydrogen system model

Hydrogen production plays a pivotal role in all areas of utilizing hydrogen energy. It is essential for hydrogen production to fulfill certain criteria including environmental protection, affordability, safety, and high efficiency in order to effectively supply hydrogen energy.

This article outlines a method for converting surplus renewable energy or low-cost electricity to hydrogen energy through the process of electrolyzing water to produce hydrogen [10]. The energy conversion efficiency of this procedure ranges from 65% to 75%. Following this, the hydrogen is stored in hydrogen tanks and subsequently used in hydrogen-fired gas turbines.

The equivalent electric power of hydrogen output in t period of hydrogen production by electrolyser is:

$$P^t_{H_2,i} = P^t_{E2H}\alpha_{E2H} \quad i \in \mathrm{N_{HSS}} \tag{1}$$

The power generation of hydrogen fuel cell is:

$$P^t_{H2P,i} = P^t_{H-FC}\beta_{E2P}, \quad i \in \mathrm{N_{HSS}} \tag{2}$$

The equivalent State of Charge (SoC) of hydrogen storage capacity of hydrogen storage tank in *t* period is:

$$E^t_{H_2,i} = E^{t-1}_{H_2,i} - (P^t_{H-FC,i} + P^t_{SH,i} + P^t_{H_2,i})\Delta t, \quad i \in \mathrm{N_{HSS}} \tag{3}$$

Where P^t_{E2H} and P^t_{H-FC} are the power consumption of electrolysis and fuel cell respectively; α_{E2H} and β_{E2P} are the conversion efficiency of electrolyser and fuel cell respectively; $E^{t-1}_{H_2,i}$, $P^t_{SH,i}$ and Δt are the residual hydrogen storage equivalent electricity in *t*-1 period, the equivalent power of hydrogen load and unit time period respectively; $\mathrm{N_{HSS}}$ is the set of hydrogen system nodes.

B. Photovoltaic Power Model

A simplified model for generating photovoltaic power is utilized, which assuming that the output power is solely influenced by the intensity of light and the temperature of the surrounding environment. [11]:

$$P_{pv} = P_{STC}G_{AC}\frac{[1+k(T_c-T_r)]}{G_{STC}} \tag{4}$$

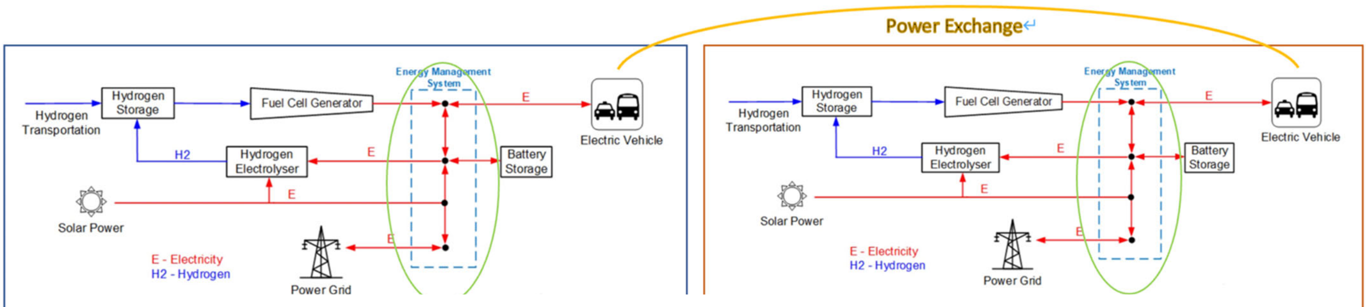

Fig. 2. Energy system design for SHBS charging stations with power exchange using EVs

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Where P_{pv} is photovoltaic cell output power; G_{AC} is light intensity; P_{STC} is the maximum test power under standard test conditions (sunlight incident intensity of 1000W/m^2, ambient temperature of 25°C); G_{STC} is the illumination intensity under standard test conditions, and its value is 1000W/m. k is the power temperature coefficient; Tc is the operating temperature of the panel; Tr is the reference temperature.

C. Battery Storage Model

$$S_{Bat,a,t} = S_{Bat,a,t1}\left(1 - \sigma_{Bat,a}\right) + (P_{Bat,a,t}^{cha} * \eta_{Bat,a}^{cha} + \frac{P_{Bat,a,t}^{dis}}{\eta_{Bat,a}^{dis}})\Delta t \quad (5)$$

Where $S_{Bat,a,t}$, $S_{Bat,a,t1}$ are the residual capacity of battery pack a in time t and $t1$, respectively; $\sigma_{Bat,a}$ is the self discharge rate of battery group a; $P_{Bat,a,t}^{cha}$ and $P_{Bat,a,t}^{dis}$ are the charging power and discharge power of battery pack a in time t, and the power during discharge is negative; $\eta_{Bat,a}^{cha}$, $\eta_{Bat,a}^{dis}$ are the charging efficiency and discharge efficiency of battery pack a in time t [12].

D. Objective function

The design objective is to minimize both the capital and O&M costs of the EV charging stations by optimal energy exchange. This optimization objective can be divided into two main components: the initial capital cost C_0 and the subsequent micro-grid operating cost C_1. The initial capital involves the construction and procurement expenses for each distributed unit within the micro-grid system, with the capacity of the energy storage device affecting this cost.

$$minF = \min\left(C_0 + \sum_{m=1}^{N} \sum_{n=1}^{Y} C_1\,[m,n]\right) \quad (6)$$

$$C_0 = \frac{r \times (r+1)^y}{(r+1)^y - 1} \sum_{m=1}^{N} C_m^0 \quad (7)$$

$$C_1[m,n] = C_{OM}[m,n] + C_{Fuel}[m,n] + C_{grid}[m,n] + \left(M_{buy1} - M_{sell1}\right) \quad (8)$$

Where N is the number of charging stations which is 2, Y is 24 hour, C_m^0 is the initial capital cost in the m subsystem; $C_{OM}[m,n]$, $C_{Fuel}[m,n]$, and $C_{grid}[m,n]$ are the (O&M) cost, fuel cell cost and selling and buying electricity price from grid cost; r is discount rate, in this paper the discount rate is 6%; y is 10 years; M_{buy1} and M_{sell1} are the buying and selling electricity prices to another EV charging station, which the number could be both positive and negative.

E. Constraints

a) Photovoltaic Power Output

Due to the randomness and volatility of solar energy, the coordination of photovoltaic output is adjusted based on the predicted power:

$$P_{Pv,k,t}^{for}, 0 \le P_{Pv,k,t} \le P_{Pv,k}^{n} \quad (9)$$

Where $P_{Pv,k,t}^{for}$, $P_{Pv,k}^{n}$ are the predicted power and rated power of the k photovoltaic cells at time t.

b). Battery Energy Storage

The battery, serving as an energy storage device, does not produce electrical energy. Therefore, the capacity of the battery remains constant throughout the specified duration of coordination.

$$S_{Bat,a,T} = S_{Bat,a,0} \quad (10)$$

Where $S_{Bat,a,T}$ and $S_{Bat,a,0}$ are the ending capacity and initial capacity of the battery pack a in the coordination period.

c). Hydrogen Energy Storage

$$E_{H_2,i}^{min} \le E_{H_2,i}^{t} \le E_{H_2,i,CAP}, i \in N_{HSS} \quad (11)$$

Where $E_{H_2,i,CAP}$ and $E_{H_2,i}^{min}$ are the capacity and lower limit of hydrogen storage tank respectively, and the lower limit is 20%.

d). The Power Output of each Energy Sources

$$\begin{cases} 0 \le P_t^{pv} \le P_{t,pv}^{max} \\ P_{min}^{in,electrolyser} \le P_t^{in,electrolyser} \le P_{max}^{in,electrolyser} \\ P_{min}^{FC} \le P_t^{FC} \le P_{max}^{FC} \end{cases} \quad (12)$$

Where P_t^{pv} is the power output of PV at time t, and $P_{min}^{in,electrolyser}$ and $P_{max}^{in,electrolyser}$ are the upper and lower limits of $P_t^{in,electrolyzer}$, P_{min}^{FC} and P_{max}^{FC} are the upper and lower limits of fuel cell generation [13].

F. Genetic Algorithm

Genetic Algorithm is a global optimization search algorithm that simulates the genetic and evolutionary process of organisms in a natural environment to achieve adaptability. This algorithm involves the formation of a new generation of groups, gradually evolving the group into a state that contains or is close to the optimal solution [14]. In this algorithm, the n-dimensional decision vector X is regarded as a chromosome that is made up of n genetic genes, and finding the chromosome X is equivalent to searching for the optimal solution of the problem [14]. The algorithm imitates the evolution process of organisms by continuously crossing and mutating, and passing on the better individual to the next generation according to the rule of survival of the fittest. After iterative calculations, an excellent individual that is close to or is the optimal solution to the problem is obtained [15].

i. Get initial population: N=100, S=capacity; each component's parameters.

ii. Calculate fitness: zeros(N,1); inverse the fitness value before the individual selection due to the smallest is best.

iii. Choice: chrom_best= zeros (1, N_chrom+1)

iv. Crossover: arithmetic crossover, each individual range is random number between [0,1], for i=1: N.

v. Mutation: if c is in the range of 1 and 2.

vi. Get the new generation, if it's got the minimum cost for each charging station, then stop.

vii. Get the best generation: CalAveFitness(fitness).

viii. Plot the figures.

III. Case Study

Fig. 3 displays the projected profile of EV charging demand (load curve) in the SHBS charging stations of two London boroughs. Each EV charging load curve corresponds to a specific SHBS charging station. It is assumed that

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Hammersmith & Fulham will have 5 SHBS charging stations, while Richmond upon Thames will have 14, based on the existing number of petrol stations in these boroughs. Among these stations, Richmond generally exhibits the highest EV charging load, reaching a peak value of 2.8 MW. To cater to this peak charging load, 8 chargers are required in the charging stations. The calculation assumes that a 360 kW charger is needed to charge an EV with a 60 kWh battery. Hence, by employing 8 chargers, the peak charging load in Richmond can be met. On the other hand, the SHBS charging station in Hammersmith & Fulham experiences the lowest charging load, which remains below 1000 kW. Consequently, 3 chargers with a capacity of 360 kW each are sufficient for this station.

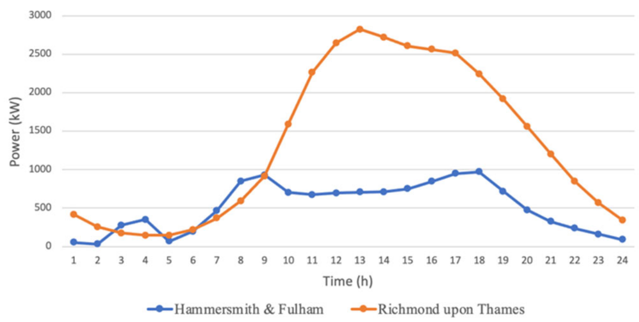

Fig. 3: Case studies in two London boroughs for SHBS charging stations

Table 1 displays the primary technical and economic parameters of each station. For the case study, a 24-hour scheduling period was employed, with an hourly energy dispatch solution used on a summer reference day. The common parameters of the charging stations include:

- Charging capacity (kW): 360.
- PV capital cost (£/kW): 1112.
- PV O&M cost (£/kW): 0.01.
- Battery capital cost (£/kW): 331.55.
- Battery O&M cost (£/kW): 0.01.
- Battery initial state of charge (%): 40.
- Rated charge and discharge power of battery (kW): 500.
- Minimum battery state of charge (%): 25.
- Maximum battery state of charge (%): 100.
- Battery charge and discharge efficiency (%): 85.
- Initial capacity of gas tank (%): 30.
- Hydrogen tank cost (£/kW): 27.63.
- Hydrogen tank O&M cost (£/kW): 0.01.
- Tank storage efficiency (%): 95.
- Fuel cell generator capacity (kW): 600.
- Fuel cell generator capital cost (£/kW): 705.9.
- Fuel cell generator O&M cost (£/kW): 0.15.
- Electric to gas efficiency (%): 75.
- Electricity-to-gas coefficient (kWh/m^3): 0.2.
- Gas-to-electric efficiency (%): 65.
- Gas-to-electricity coefficient (m^3/kWh): 0.295.
- Renewable energy feed-in tariff (£/kW): 0.03.

Table 1: The parameters of SHS-EV charging station.

Parameter	Hammersmith & Fulham	Richmond upon Thames
Number of chargers per station	3	8
PV installed capacity (kW)	500	1000
Battery capacity (kW)	1000	800
Hydrogen tank capacity (m^3)	1000	1000
Fuel cell generator capacity (kW)	800	1500

IV. SIMULATION RESULTS

Fig. 4 shows that the solar energy is the main source of energy output between the hours of 7 am and 7 pm, with a maximum output capacity of up to 500 kW. This means that during this period, the charging station is heavily reliant on solar energy to meet the energy demands required for charging EVs. To ensure that there is enough energy to power the charging station during this time, both hydrogen energy storage and electric energy storage work in conjunction with one another. This coordinated effort helps to guarantee that the charging station can fulfil the energy demands required for charging during each time.

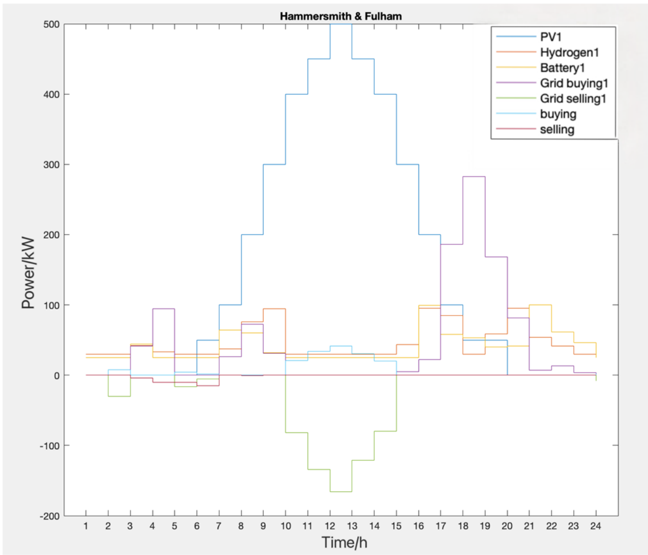

Fig. 4: Hammersmith & Fulham optimal energy dispatch solution.

Furthermore, it is observed that during the time when electricity prices are at their highest, from 10:00 to 15:00, the charging station interacts with the power grid to guarantee a sufficient electricity supply. During these peak hours, the charging station may have to rely on the power grid to meet the energy demands for charging, which can be costly. However, by leveraging the time-of-use pricing strategy, the charging station can potentially save money by purchasing electricity during off-peak hours when prices are lower and storing it for use during peak hours. Overall, by optimizing the energy flow between different sources of energy and taking advantage of different pricing strategies, the charging station can ensure a cost-effective and efficient energy supply.

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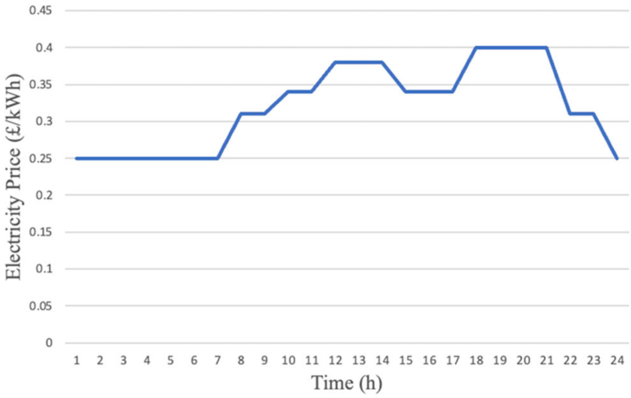

Fig. 5: Electricity price for a day.

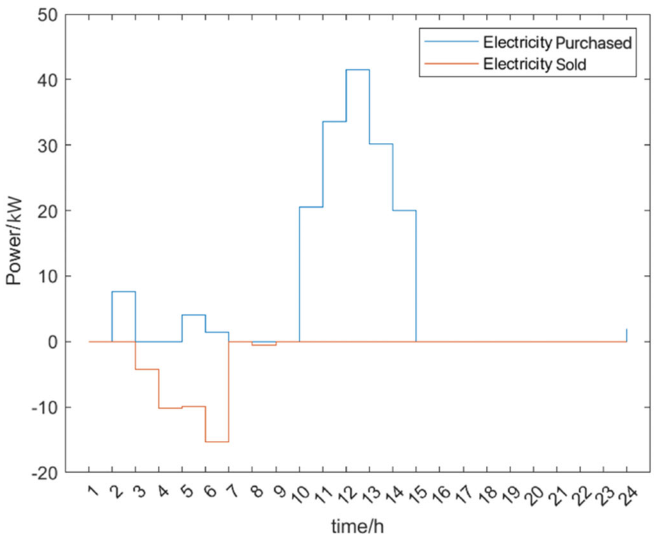

Fig. 6: Energy exchange between two SHBS charging stations (H&F).

Fig. 6 displays the energy exchange between the two charging stations during the specified time periods, which is limited to a maximum of 50 kW. The energy exchange is carefully analyzed by implementing Genetic Algorithm to achieve the lowest cost. As per the results depicted in Fig. 5, the energy exchange between two charging stations is insignificant when an autonomous energy generation system is installed in the charging stations and connected to the grid. This indicates that energy exchange does not have a significant impact on achieving the minimum cost of the charging stations, and therefore the energy exchange between two charging stations can be neglected in somehow. This observation is critical as it helps in designing the charging stations to be energy-efficient and cost-effective. By analyzing and optimizing the energy exchange between two charging stations, the overall cost of operating the charging stations can be minimized while maintaining optimal energy supply.

Table 2: SHBS charging station minimum capital and O&M cost.

Cost	Hammersmith & Fulham	Richmond upon Thames
Capital cost for initial years (£) C_m^0	1,338,720	1,828,410
Discounted capital cost (£) C_0	181,889.15	248,422.33
Grid electricity purchase per day (£)	575.09	1994.36
Energy exchange per day (£)	77.12	30.25
O&M cost per day (£)	205.65	232.79
Minimum daily cost (£) *minF*	1273.32	2887.81

Table 3: EV charging station cost only buy electricity from grid.

Cost	Hammersmith & Fulham	Richmond upon Thames
Daily cost (£)	4,195.88	11,225.81

Table 2 presents important information regarding the economic aspect of two SHBS charging stations, outlining both their capital and O&M costs. It is notable that if the SHBS charging station's lifespan is 10 years, and it undergoes daily maintenance while replacing each component every 10 years, the cost allocated per day would only be £4163.13. Comparing this to Table 3, it is evident that the daily cost for the two charging stations is three times higher than the SHBS charging station. Utilizing energy conversion between SHBS charging stations not only optimizes energy utilization but also reduces operational expenses. To integrate these stations with the large power grid, certain adjustments must be made. It is crucial to consider these costs and benefits when making decisions regarding the establishment and maintenance of charging stations, especially in the context of promoting sustainable transportation practices.

V. CONCLUSION

The primary focus of this paper is on the economic analysis of two SHBS charging stations energy exchange, and each charging station's power distribution involves various energy production equipment, energy conversion equipment, and energy storage equipment. The paper systematically conducts an economic analysis of the system, considering the electric load demand of charging stations in Hammersmith & Fulham and Richmond upon Thames during different time periods and the energy interaction between two charging stations. A mathematical model of SHBS power generation is constructed, considering the energy-flow coupling relationship between equipment and the factors of time-of-use electricity price. Furthermore, the paper studies the operation optimization of the system under grid-connected electricity sales.

During the coordinated planning process, considering the interplay among charging stations, and power lines can enhance the capacity of distributed generation usage while diminishing the need for grid investment. In SHBS charging station's coordinated planning, the charging stations can conduct flexible interaction with other smart devices, which can efficiently increase the utilization of equipment and overall economic gain.

Expanding further, the SHBS charging stations with the power grid can optimize the allocation of renewable energy

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resources and reduce the reliance on traditional power sources. By leveraging the flexibility of smart devices, the charging stations can coordinate their operation with other energy-consuming devices, such as home appliances and electric vehicles, to maximize the utilization of available resources. This coordinated planning approach can also enable demand response mechanisms, where the charging stations adjust their energy consumption based on the grid's needs, leading to more efficient and cost-effective energy use. Overall, a holistic approach to charging station planning that considers the interplay among various devices and the power grid can lead to a more sustainable and resilient energy system.

Future modelling will not only consider the capital costs of charging stations but also other factors like their distance and location. This will enable a more holistic evaluation of the costs and benefits associated with setting up and maintaining charging stations. These enhancements will improve the effectiveness and efficiency of renewable energy electric vehicle charging stations and promote the adoption of sustainable transportation practices.

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