Proceedings Paper:

Zuo, W. and Li, K. orcid.org/0000-0001-6657-0522 (2024) Electrical vehicle charging strategy for electric road systems considering V2G technology. In: Proceedings of 2023 IEEE International Conference on Energy Technologies for Future Grids (ETFG). 2023 IEEE International Conference on Energy Technologies for Future Grids (ETFG), 03-06 Dec 2023, Wollongong, Australia. Institute of Electrical and Electronics Engineers (IEEE) . ISBN 978-1-6654-7991-2

https://doi.org/10.1109/etfg55873.2023.10407724

2023 IEEE International Conference on Energy Technologies for Future Grids
Wollongong, Australia, December 3-6, 2023

Electrical vehicle charging strategy for electric road systems considering V2G technology

1st Wei Zuo
School of Electronic and Electrical Engineering
University of Leeds
Leeds, UK
elwz@leeds.ac.uk

2nd Kang Li
School of Electronic and Electrical Engineering
University of Leeds
Leeds, UK
K.Li1@leeds.ac.uk

***Abstract*—The accelerated adoption of electric vehicles (EVs) introduces a substantial amount of load to the power grid. The electric road system (ERS) emerged as a promising solution to decarbonize heavy good vehicles and extend the driving range of EVs, will further complicate the operation of power grid. Therefore, optimal scheduling of EV charging in ERS is vital in minimizing the impact of variable EV loads to the power grid that provides power supply to the ERS. This paper proposes a charging strategy based on load floating (LOF) electricity price. The approach divides a day into different time periods, counting the grid-connected and off-grid time of vehicles, and then establish dispatching and charging cost models, based on which the EV charging cost is minimized. The simulation results confirm the efficiency of the proposed scheduling strategy.**

***Index Terms*—EVs, ERS systems, dynamic charging, V2G, optimizing strategy.**

I. Introduction

In response to the climate challenge, to replace fossil fuel vehicles with electric vehicles (EVs) has become a development trend for road transport decarbonization. However, the introduction of a large number of EVs will bring significant pressure on the power grids which are already congested. Currently, the limited battery capacity limits the development of EVs [1]. To address above issues, the electric road system (ERS) with dynamic charging has emerged, first piloted in Sweden [2]. ERS is a road that supplies electric power to vehicles travelling on it, and the EV charging includes contact and non-contact modes [3]. The unique charging mode of ERS allows for a reduction in battery power consumption while an EV is in operation, effectively extending the travelling on a single fully charged battery [4]. This technology can effectively address the issue of limited battery capacity in EVs, yet, the charging demand of ERS may exacerbate the pressure on the power grids during peak periods. Thus, it is necessary to optimize the EV charging to address these issues.

For road power supply systems, EVs are generally considered as controllable loads. However, with the potential application of vehicle-to-grid (V2G) technology [5], [6], EVs can be aggregated to serve as energy storage to support the power grid through discharging control strategies. Consequently, for ERS systems, optimal charging and discharging strategies for EVs can be used to support peak shaving and valley filling of the grid. This is an essential step towards the development of a smart grid incorporating ERS systems.

The dynamic charging mode of the ERS distinctively differs from the conventional stationary charging and discharging. Thus, managing EVs' charging and discharging is crucial for the efficient operation of the ERS integrated with the power grid. For traditional road systems, various scheduling strategies have been proposed to achieve smoother supply-demand balance and lower charging costs [7]–[9], including scheduling for wireless charging of EVs [10]. However, these scheduling methods only account for the static EV charging, little has been done on the optimal scheduling of dynamic wireless charging of EVs via ERS. To fill this gap, this paper presents a time-sequence scheduling algorithm that optimizes costs for ERS systems, offering a practical solution for their efficient operation.

The remainder of the paper is organized as follows. The EV charging scheduling model for the ERS system is formulated in section II. Sections III and IV present the details of the proposed optimization strategy and the optimization results obtained in case studies, respectively. Finally, Section V summarizes all the results and concludes the paper.

II. The EV charging Model for ERS

For traditional EV charging and discharging, the process can be described as absorbing energy while parking and consuming energy while driving. However, when EVs run on electric roads, their charging model needs to be updated by adding a dynamic charging mode [11]. In this process, EVs can not only extract energy from the grid but also supply energy to the grid using V2G technology when necessary, mainly through EV energy scheduling strategies. It is obviously that introducing V2G technology into ERS systems is one of the future development trends, providing a more efficient and sustainable solution for the power grid. In addition, the charging and discharging behavior of EVs can be regulated based on real-time power grid demand by using V2G scheduling strategies, resulting in a more stable power grid system. Therefore, this section will mainly introduce the dynamic charging and V2G scheduling models for EVs travelling on the electric roads.

A. The dynamic charging model of EVs

The dynamic charging mode refers to the process of charging EVs while in motion on electric roads. Compared to static charging, dynamic charging has several advantages, including the ability to charge without parking, reducing the EV battery capacity, especially for heavy good vehicles (HGVs), the absence of the need for a large number of fixed high-power charging stations, and avoiding the long queues of EVs waiting for charging. This charging model also offers a great potential in the utilization of distributed renewable energy integrated with the feeder stations for the ERS.

Fig.1 is a typical example of an EV's daily travel itinerary where ERS is integrated. It shows that EVs may travel between different locations each day, starting and ending at home and travel to work, school, shopping malls, and also may pass across dynamic charging road sections. Therefore, the EVs can be charged at home, school, work place, or shopping malls using fixed charging facilities via static charging, they can also be charged while running on ERS. Unlike traditional journeys, the road charging section provides a charging mode defined as "driving while charging." As a result, the EV charging model for ERS systems can be formulated as follows.

It is assumed that the i_{th} car enters the grid at time t_{in} for charging, and leaves the grid at a predetermined time t_{off}. When the i_{th} car is connected to the grid and its battery state of charge (SOC) is higher than the threshold γ, it can function as an energy storage device and supply energy back to the power grid if necessary. In addition, when the car is driving on a dynamic charging section from time t_{in} to t_{off}, the battery can be replenished through wireless charging. Consequently, the power demand of EVs in various time periods can be expressed by the equation (1).

$$\begin{cases} -P_{discha} < P_{i,t} < P_{char} & \text{(a)} \\ 0 < P_{i,s,t} < P_{char} & \text{(b)} \\ 0 < P_{i,d,t} < P_{dyncha} & \text{(c)} \end{cases} \quad (1)$$

where P_{discha}, P_{char} and P_{dyncha} present the set power of discharging, and static and dynamic charging for EVs, $P_{i,s,t}$ and $P_{i,d,t}$ are the static and dynamic charging power of i_{th} vehicle at time t, and $P_{i,t}$ is the charging power of i_{th} vehicle at time t.

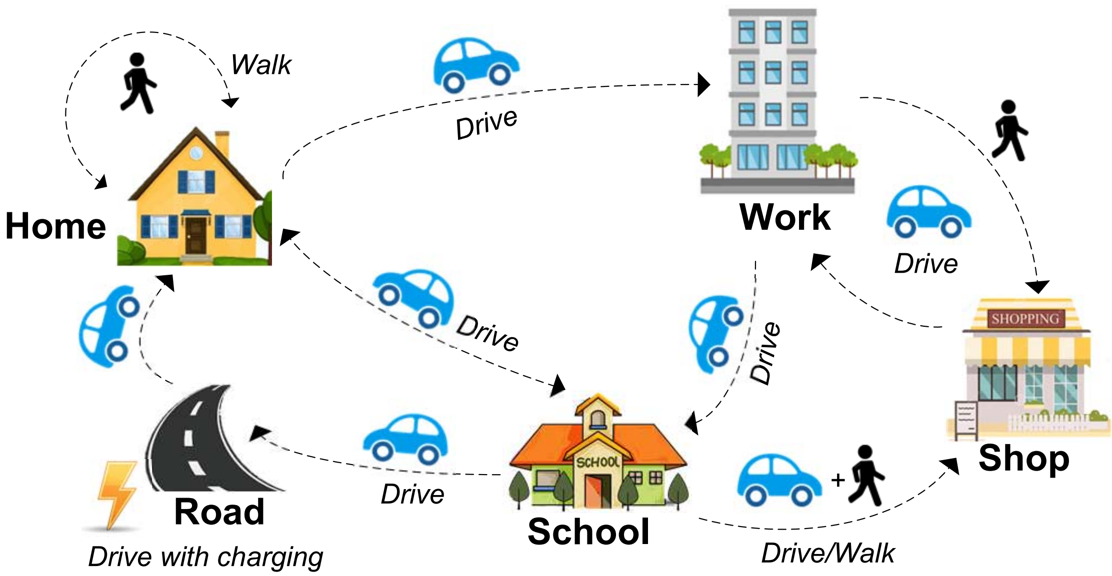

Fig. 1. A complete daily travel itinerary example of EVs

Then, the total electricity demand of all EVs at time t can be calculated by the equation (2).

$$P_{ev,t} = \sum_{i=1}^{N} \left(P_{i,s,t} + P_{i,d,t}\right) \tag{2}$$

where $P_{ev,t}$ is the total charging power of all EVs, and N is the total number of EVs.

B. The V2G scheduling model of EVs

The V2G scheduling model refers to the coordination of EV charging and discharging based on the power system's demand. Specifically, the EVs connected to the grid can act as distributed energy storage, with their charging and discharging behavior controlled to balance the power supply and demand of the grid. In this section, the V2G model uses vehicle data from the dispatching center to schedule the charging and discharging of EVs, which are treated as both loads and energy storage devices. That is to say, the dispatch center controls whether each EV absorbs or releases energy to the grid, while ensuring that each EV's charging requirements are met. Therefore, making sure that vehicles can feed back a certain amount of energy to the grid while ensuring that the charging requirements are completed is the premise of dispatching. Besides, the scheduling is performed on a daily basis, with the day divided into multiple time intervals. Assuming that there are N charging vehicles per day, a proportion of α of the EVs can realize V2G, while the remaining $(1-\alpha)N$ vehicles only support charging from the grid. The power when an EV enters the grid is defined as $E_{i,in}$, and the power when it leaves the grid is $E_{i,off}$. The power relationship between the EVs and the grid must satisfy the following formulas.

$$E_{i,off}^{sta} \leq E_{i,in}^{sta} + E_{i,cha}^{sta} \leq E_{i,cap} \tag{3}$$

$$E_{i,off}^{sta} \leq E_{i,in}^{sta} + E_{i,cha}^{sta} - E_{i,disc}^{sta} \leq E_{i,cap} \tag{4}$$

where $E_{i,cha}^{sta}$ and $E_{i,disc}^{sta}$ are the total absorbed energy and released power of i_{th} EV by static charging at home, school, shopping center or work place. $E_{i,cap}$ is the maximum battery capacity of i_{th} EV. $E_{i,in}^{sta}$ and $E_{i,off}^{sta}$ present the battery SOC at the moments when i_{th} EV enters and leaves the grid. Among them, all the values of energy are assumed to be positive.

For the ERS system, it is assumed that all EVs are capable of functioning dynamic charging while passing through the dynamic charging road section. Additionally, with the introduction of dynamic charging, it is assumed that the ground wireless charging module of the i_{th} vehicle will cooperate with the EV charging module to charge the battery continuously once it enters the dynamic charging section at time t. It is further assumed that the energy dynamically charged during driving is sufficient to cover the power consumed by the vehicle. However, it is important to note that this assumption is subject to the condition that the power consumption of the vehicle is within the limits of the energy dynamically charged. Therefore, it is necessary to present an additional constraint as follows (5).

$$E_{i,off}^{dyna} \leq E_{i,in}^{dyna} + P_{i,dyna} * t_{i,dyna} \leq E_{i,cap} \tag{5}$$

where $E_{i,in}^{dyna}$ and $E_{i,off}^{dyna}$ present the battery SOC at the moments when i_{th} EV enters and leaves the driving charging road section. $P_{i,dyna}$ and $t_{i,dyna}$ are the charging power and time when i_{th} EV charging dynamically. Among them, all the values of energy are assumed to be positive.

To conform to the requirements of EV dispatching, each EV should be registered at the dispatch center upon connecting to the grid system. The total number of dispatchable EVs is then recorded as N_p, and the dispatchable time for each EV, represented by the length of its connection period to the grid, is set as T_{opti}, as shown in equation (6).

$$T_{opti} = t_{i,off} - t_{i,in} \tag{6}$$

Finally, the battery SOC of EVs at any dispatchable time will satisfies the formula (7).

$$0 \leq E_{i,in} + \sum_{t_{i,in}}^{t_q} \left(P_{i,t} * \tau\right) \leq E_{i,cap} \tag{7}$$

where $E_{i,in}$ is the battery SOC of i_{th} EV when enters the grid. $P_{i,t}$ and τ are the charging power and unit time of i_{th} EV, while $t_{i,in}$ and t_q are the moment of i_{th} EV entering and leaving grids.

III. The Optimal Scheduling Strategy

With the increasing number of EVs on the road, there is a growing pressure on power consumption, and the balance between power supply and demand becomes increasingly volatile. However, the dynamic electricity pricing offers a potential mechanism to enable the shifting of peak electricity demand to off-peak period, thus alleviating stresses on power grid and balance the demand and supply.

A. Load-floating (LOF) electricity price for ERS systems

The implementation of time-of-use (TOU) electricity pricing is an effective strategy for balancing power supply and load demand. It involves dividing electricity consumption periods into different time slots and setting varying electricity prices accordingly. During periods of high demand, electricity prices are positioned at a high regime, while during low-demand periods, prices are lower to encourage users to adjust their electricity consumption time, achieving peak shaving and valley filling. However, the pattern of electricity consumption varies with the season, and the timing of peak electricity consumption may shift. Therefore, using the same time classification throughout the year may not meet the seasonal peak shaving and valley filling needs.

To address this issue and make the TOU pricing strategy more suitable for dynamic EV load, this paper proposes a dynamic TOU electricity pricing model called the Load-Floating (LOF) electricity price. This model is defined as a dynamic electricity price model that follows changes in the overall load of the grid. That is, the electricity price will increase or decrease in accordance with overall load conditions. The price function $g(L)$ can be expressed using equations (8)-(10).

$$\begin{aligned} g(L) &= \frac{(L - L_{min}) * (R_{max} - R_{min})}{L_{max} - L_{min}} + R_{min} \\ &= aL + b \end{aligned} \tag{8}$$

$$a = \frac{R_{max} - R_{min}}{L_{max} - L_{min}} \tag{9}$$

$$b = R_{min} - \frac{(R_{max} - R_{min}) * L_{min}}{L_{max} - L_{min}} \tag{10}$$

where L_{max} and L_{min} are the projected maximum and minimum loads within a period of time, say a day or a week. These numbers can be estimated based on the historic EV charging load data. The R_{max} and R_{min} are the upper and lower limits for the electricity price.

B. Charging cost for EVs in ERS

The charging cost of EVs in ERS is mainly determined by two factors: the consumed energy and the energy price. In the ERS system, it is assumed that there are currently N EVs, and the charging demand of the i_{th} vehicle at time t is $X_{i,t}$. Hence, the total charging load of EVs at time t can be obtained by (11).

$$L_{ev,t} = \sum_{i=1}^{N} x_{i,t} = \sum_{i=1}^{N} (x_{i,s,t} + x_{i,d,t}) \tag{11}$$

where the $L_{ev,t}$ is the total charging demand of EVs at time t, which contains the static and dynamic charging. The $x_{i,s,t}$ and $x_{i,d,t}$ represent the static/dynamic charging power of the i_{th} EV, while $x_{i,t}$ is the charging power of the i_{th} EV.

Then, the total power grid load considering the EV charging load can be expressed as follows.

$$L_{total,t} = L_{base,t} + L_{ev,t} \tag{12}$$

where the $L_{base,t}$ is the base load value of grid at time t.

Based on equations (8) and (12), the charging cost at time t of EVs in the ERS system including static and dynamic charging modes can be calculated as below.

$$\begin{aligned} C_t &= \int_{L_{base,t}}^{L_{tota,t}} g(L)\, dL = \int_{L_{base,t}}^{L_{tota,t}} (aL + b)\, dL \\ &= \frac{1}{2} a \left(L_{tota,t}^2 - L_{base,t}^2 \right) + b \left(L_{tota,t} - L_{base,t} \right) \end{aligned} \tag{13}$$

Therefore, the total EV charging cost can be calculated as below.

$$C_{cha} = \sum_{t=1}^{T} C_t \tag{14}$$

C. Real-time scheduling optimization strategy

As the EV charging demand is random and dynamic, it is not feasible to use a global algorithm that requires the whole day's EV data. To address this issue, a real-time scheduling strategy is proposed in this paper, which divides the daily time into multiple intervals. The objective of the ERS system is to dispatch the EVs during each time period to achieve the lowest charging cost while meeting their travel demand.

The problem can be formulated as follows.

Minimize $\sum_{i=1}^{N} C_{cha}$

$$\sum_{i=1}^{N} \left(\frac{1}{2} a \left(L_{tota,t}^2 - L_{base,t}^2 \right) + b \left(L_{tota,t} + L_{base,t} \right) \right) \tag{15}$$

subject to

$$Z_t = L_{base,t} + L_{ev,s,t} + L_{ev,d,t} \tag{16}$$

$$E_{i,off} \le E_{i,in} + E_{i,char}^{ev} - E_{i,disc}^{ev} \le E_{i,cap} \tag{17}$$

$$0 < x_{i,t} < P_{cha}, i \epsilon N_{cha} \tag{18}$$

$$P_{disc} < x_{i,t} < P_{cha}, i \epsilon N_{V2G} \tag{19}$$

where Z_t is the system total load at time t. P_{cha} and P_{disc} are the rated charging and discharging power, respectively. $E_{i,cha}^{ev}$ and $E_{i,disc}^{ev}$ present total absorbed energy and released power of i_{th} EV by static and dynamic charging. N_{cha} and N_{V2G} are the EV number set which using charging and discharging technology, respectively.

The optimal scheduling divides the daily time into z equal intervals of duration t_z. At the beginning of each interval, the dispatch center receives data from connected vehicles, including the number of vehicles that can provide V2G services and their estimated off-grid time, which are combined to form the set N' of all available vehicles for dispatch. There are several constraints that must be met, including ensuring that the EV battery SOC reaches the desired value before it leaves the ERS, maintaining the battery SOC within the range of 0-100% after charged, and limiting the discharge power to a certain range.

The objective function in formula (15) is a convex function, which is enabling the use of convex optimization methods. This approach can generate an optimal charging and discharging strategy to minimize the charging cost while fulfilling travel needs.

IV. A CASE STUDY

A. Experiment settings

To evaluate the proposed optimal scheduling scheme for EVs driving on electric roads, simulations were conducted for charging and discharging. The simulation period for each day began at 0:00 am and ends at 0:00 am the following day, during which the charge and discharge status of the EVs were monitored. Each day was divided into 96 time intervals, with each interval containing 15 minutes. The base load per time unit of grid system was adopted from [12]. The LOF dynamic electricity price model, introduced in section II, was adopted. The EV charging parameters and other relevant parameters are listed in Table I.

TABLE I
PARAMETERS FOR THE ERS SYSTEM

Parameters	Value	Parameters	Value
g_{min}	£0.24/kWh	a	0.001
g_{max}	£0.34/kWh	b	0.1037
Δg	0.1	P_{char}	7 kW
T	96	P_{disc}	-3 kW

In this study, it is assumed that the total number of EVs is set to 500. Based on the realistic situation, it is assumed that there are two load peak time for EVs, for 7-10 am, they drive to work/school and other place, while during 5-7 pm, people go home. The arrival time of these EVs is distributed throughout the day, and their initial energy levels are uniformly distributed between 0-100%.

B. Simulation results

For calculating the dynamic electricity price for the ERS system, the parameters listed in Table I are plugged into equation (8) to obtain the daily floating electricity price, as illustrated in figure 2. The red line in the figure represents the LOF electricity price for the ERS system, which varies with the total load demand of the grid. During the peak period of electricity consumption, from 10:00 am to 8:00 pm, the electricity price is relatively high. In other periods, the price drops to a lower level, specially in the midnight, it reaches its lowest price, close to 0.

In electric road systems, EVs typically charge their batteries at maximum power when connected to the grid. Figure 3 displays the original load of the power grid and the updated load for both the static charging and dynamic charging considering the impact of V2G technology.

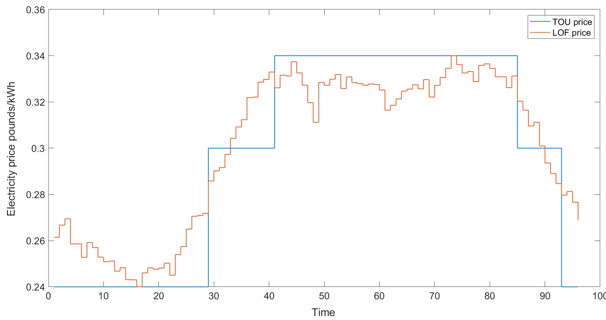

Fig. 2. The dynamic electricity price for grid system

The proposed cost-optimized scheduling strategy for EVs which considers V2G was also implemented, and the results are shown in Figures 3 and 4. The figures clearly demonstrate that the total load value of the power grid becomes more stable during the peak period when the optimization strategy is implemented. Specifically, the peak electricity consumption between 10am and 8pm has decreased, and the power demand has increased from the trough around 5am. Therefore, it can be concluded that the use of V2G technology in combination with optimal dispatching can smoother the load changes of the electric road.

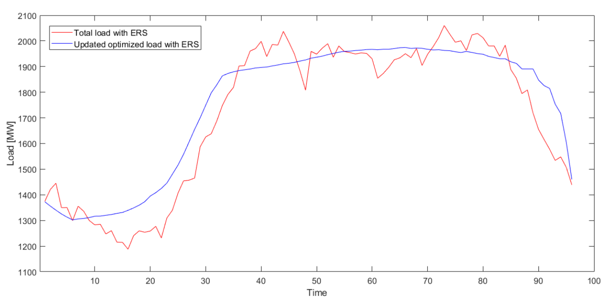

Fig. 3. System daily load including ERS

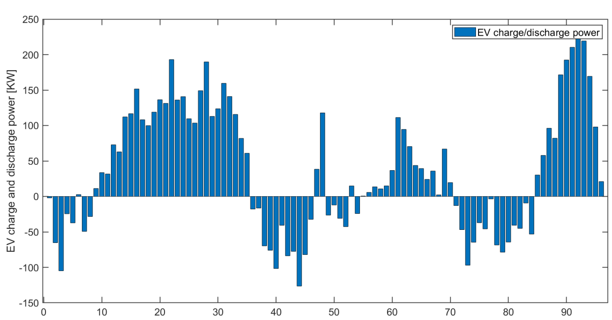

Fig. 4. EV charging and discharging time chart in ERS system

These figures show that the fluctuations of the power grid loads can be effectively smoothed if the V2G scheme is introduced. This indicates that by shifting the charging of EVs from peak periods to off-peak periods, the cost of charging can be considerably reduced. The detailed cost results including unified electricity price (UEP), TOU, and LOF are shown as below Table II.

The charging cost analysis was conducted by comparing original EV charging, electric road charging, and EV charging with optimized dispatching strategy. The results show that when EVs were charged using time-of-use (TOU) electricity pricing on ordinary roads, the total daily charging cost was £4,620.89, with an average daily charging cost per vehicle of £9.24. It has a roughly 7% reduction. However, when the EVs were charged using the proposed LOF electricity pricing model and subjected to the designed scheduling strategy, the total daily charging cost was reduced to £3135.53, with an average daily charging cost per vehicle of £6.27. It is evident that the dispatch strategy reduced the EV's charging cost on the electric road by approximately 36% per day compared to UEP charging price. These results confirm that by incorporating V2G technology and dispatching strategy into the electric road system, it is possible to significantly reduce the charging costs for EV users while smoothing the fluctuations in the low, hence benefiting both power grid operation and EV users.

TABLE II
COST RESULTS OF EVS FOR THE ERS SYSTEM

Electricity price	**Total cost**	**Average cost /per vehicle**
UEP	£4,957.51	£9.92
TOU	£4,620.89	£9.24
LOF	£3,135.53	£6.27

V. CONCLUSIONS

This paper has proposed a V2G-based cost optimization strategy for EV charging in the ERS system. The daily charging plan for EVs is divided into different time intervals. By collecting real-time data for EVs at each time interval, the charging and discharging scheduling can be optimized by the dispatching center to achieve overall load smoothing of the power grid. To better manage power consumption during peak periods, this paper selects the LOF dynamic electricity price to guide EV charging behavior and timing, achieving greater peak shaving and valley filling, and reducing grid power supply pressure. The simulation results demonstrate that the electric road system can effectively reduce charging costs while meeting EV charging requirements, under the control of the LOF dynamic electricity price and the proposed charging and discharging strategy.

ACKNOWLEDGMENT

This work is partially funded by the China Scholarship Council to Wei Zuo for sponsoring her PhD study at University of Leeds.

REFERENCES

[1] S. Manzetti and F. Mariasiu, "Electric vehicle battery technologies: From present state to future systems," *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 1004–1012, 2015.

[2] D. Jelica, M. Taljegard, L. Thorson, and F. Johnsson, "Hourly electricity demand from an electric road system–a swedish case study," *Applied energy*, vol. 228, pp. 141–148, 2018.

[3] D. Bateman, D. Leal, S. Reeves, M. Emre, L. Stark, F. Ognissanto, R. Myers, and M. Lamb, *Electric road systems: A solution for the future?*, 2018, no. 2018SP04EN.

[4] D. Kosmanos, L. A. Maglaras, M. Mavrovouniotis, S. Moschoyiannis, A. Argyriou, A. Maglaras, and H. Janicke, "Route optimization of electric vehicles based on dynamic wireless charging," *IEEE Access*, vol. 6, pp. 42 551–42 565, 2018.

[5] W. Kempton and S. E. Letendre, "Electric vehicles as a new power source for electric utilities," *Transportation Research Part D: Transport and Environment*, vol. 2, no. 3, pp. 157–175, 1997.

[6] W. Kempton, J. Tomic, S. Letendre, A. Brooks, and T. Lipman, "Vehicle-to-grid power: battery, hybrid, and fuel cell vehicles as resources for distributed electric power in california," 2001.

[7] H. Li, Z. Wan, and H. He, "Constrained ev charging scheduling based on safe deep reinforcement learning," *IEEE Transactions on Smart Grid*, vol. 11, no. 3, pp. 2427–2439, 2019.

[8] W. Yin and X. Qin, "Cooperative optimization strategy for large-scale electric vehicle charging and discharging," *Energy*, vol. 258, p. 124969, 2022.

[9] L. Yao, Z. Damiran, and W. H. Lim, "Optimal charging and discharging scheduling for electric vehicles in a parking station with photovoltaic system and energy storage system," *Energies*, vol. 10, no. 4, p. 550, 2017.

[10] Y. Jin, J. Xu, S. Wu, L. Xu, and D. Yang, "Enabling the wireless charging via bus network: Route scheduling for electric vehicles," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 3, pp. 1827–1839, 2020.

[11] Z. Danping, C. Yuchun, L. Yuhang, C. Zhongjian *et al.*, "Research on electric energy metering and charging system for dynamic wireless charging of electric vehicle," in *2019 4th International Conference on Intelligent Transportation Engineering (ICITE)*. IEEE, 2019, pp. 252–255.

[12] W. Li *et al.*, *Reliability assessment of electric power systems using Monte Carlo methods*. Springer Science & Business Media, 2013.