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Research Article

ICT-Based Vehicle-to-Grid Operation Based on the Fast Discharge Power for Economic Value

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ABSTRACT

Renewable energy sources require effective energy management systems to be efficient in smart grids. Although electric vehicles are all potential consumers, using electric vehicle batteries is an effective utilisation strategy for smart grids. Vehicle-to-grid (V2G) is a crucial future technology for the smart grid. V2G technology proposes employing electric vehicles to contribute the stored energy to the other intelligent grid users. Expansion of the V2G technology is possible by funding, installing, and optimal managing the charging stations. In this work, an economic value of V2G operation is proposed. An advanced scheme of a V2G operations communication protocol that enables flexible control of the charging and discharging operations of the E.V. in an optimisation way has been developed, based on an energy arbitrage service, using two different discharge rates study. An economic study based on energy arbitrage using problem optimisation has been depicted. A use case based on the Nissan Leaf 40 kWh was simulated. The results show the economic benefit of using high discharge rate power (i.e., 3C) to the Li-ion battery over the regular discharge rate (1C).

1. INTRODUCTION

The fitful energy resources cause a decrease in the reliability of the generation and distribution network of national electric grids. The energy demand-supply inequities occur due to the unpredictability of renewable energy generation and demand from grids. This case causes load volatility and inefficiency of the resource. In the initial stages of vehicle electrification adoption, ‘demand-responsive’ vehicle charging could assist in redistributing peak loads on the electric grid [1-5]. As the population of plug-in electric vehicles grows, their potential to contribute to the grid by supplying electricity becomes more significant and sophisticated. This concept, known as vehicle-to-grid or V2G, was initially introduced by Kempton [6]. Vehicle batteries can connect to grids, so electric grids can be involved in energy markets. In this way, the volatility and inefficiency of the power supply installation can be compensated.

Energy arbitrage performs the most significant earnings opportunity for battery storage. In the open energy market, it is well known that low energy prices correspond to periods of low energy demand, indicating an abundance of energy in the grid. In contrast, high energy prices align with periods of high energy demand, indicating energy scarcity in the grid. With this mindset, the energy price can be leveraged to create a market where electric vehicle (E.V.) batteries are charged when energy prices are low. Energy stored in E.V. batteries is fed back into the grid when energy prices are high, supporting the grid. This study proposes that the Vehicle-to-Grid (V2G) process is a function of the energy market and aims to maximise gains from energy exchange transactions. The profit from arbitrage consists of buying the cheapest energy when low energy demand occurs and selling it at the highest price when the highest energy demand occurs. The maximisation of profit depends on optimising the buying and selling periods. The comprehensive research has majored in optimising energy storage arbitrage problems to maximise profit. In [7-8], the authors calculated the anticipated revenue generated by V2G services across different power markets, i.e. frequency regulation, spinning reserve, or energy arbitrage. In the context of V2G energy arbitrage (charging during low-cost periods and discharging during high-cost periods), Rahman et al. [9] approximated the V2G advantage to be in the range of $392 to $561 annually for a single E.V. operating under typical conditions, with limited discharging power. This estimation could incentivise users to engage in V2G services voluntarily. In [10-11], a mixed integer linear approach was proposed to optimise the profits in real-time markets. A scenario-based stochastic formulation was developed against the electricity price’s uncertainty [12]. In [13], a bidding mechanism utilising a two-stage stochastic programming approach is proposed for a consortium of energy storage systems participating in the day-ahead reserve market. Some robust optimisation-based bidding strategy is demonstrated in [14-15].

However, the Lithium-Ion Battery (LIB) is considered a high-energy and low-power density storage system [16]. Hence, increasing the discharge power during V2G operation could provide more benefits for the E.V. owner.

The accomplishment of the V2G solution depends on the consumers' collaboration and perspective. The location number of charging stations determines how to use E.V.s, such as some people prefer charging at home or work.

Several techniques are engaged for charging and discharging E.V.s [17]. V2G operations require a controllable charge/discharge station that allows the operator to decide when to charge and discharge, providing more freedom and control to the grid. When the energy demand is high, the operator can stop charging to the market less. Uncontrollable charge/discharge does not need to know about energy demand or generation. That method does not seem to be popular in the future for E.V. charging. Intelligent techniques decide when to charge/discharge E.V. according to grid requirements such as energy prices. The methods allow users to set their car for a lower price or discharge, probably for a small profit. That requires demand-side efficient management strategies.

Numerous communication technologies facilitate monitoring data exchange and control commands between smart meters and external systems. A V2G communication system differs from other existing communication systems in many conditions, such as charging/discharging operations, locations, fast authentication, etc. Besides, classified information such as vehicle and station I.D., vehicle type, and charging/discharging time are required to be secured over the communication network. The Information and Communication Technologies (ICT) sector is crucial in smart grids [18-22]. The concept specifies the power grid modernised with ICT technology or a digital network that merges the electrical providers and consumers. ICT is used in power grid systems, allowing energy and information to flow two-way [23-26]. It facilitates renewable energy integration into the power grid and entrusts energy-optimising tools for optimal consumption and prices. In other words, that concept imposes advanced communication techniques into the conventional power distribution base. That case enables the communication systems' two-way data transmission.

Smart grid establishment takes time due to requirements such as large-scale changes in existing classical power grids. ICT ensures the security, performance, reliability, and control of all smart grid elements, such as power generation, storage, transmission, and consumption. It also roles grid usage authorisation, detection of faults and errors, and control of charge period timing.

This paper's main contributions are as follows: Energy management-arbitrage strategy is proposed to maximise the profit of the parking lot. The energy flow control and charging/discharging periods are provided and decided by ICT-based novel communication protocol. Another innovation of the proposed V2G strategy is using rapid discharge operations to bolster the power grid frequency. Unlike the conventional approach of achieving a 1C discharge rate, the proposed strategy enhances control power by a factor of three by discharging the vehicle's battery at a rate of 3C, with the primary aim of supporting the power grid.

The objective is to highlight the economic value of the proposed operating environment of V2G operation based on energy arbitrage service. The rest of this paper is outlined in Section II - a U.K. scheduling approach for energy arbitrage based on V2G operation, Section III - UK ICT-Based communication, and Section IV – Economic study results. Conclusions are drawn in Section V.

2. UK SCHEDULING APPROACH FOR ENERGY ARBITRAGE BASED ON V2G OPERATION

The goal of energy arbitrage utilising battery storage is to maximise revenue. The literature includes three comparably simple assumptions in energy storage arbitrage that obstruct their adoptions: Sufficient foresight about energy prices, battery charging/discharging stabilisation, and battery lifetime modelling. Based on a proposed energy arbitrage service within the U.K. energy market, this study aims to understand the economic benefits of using high-rate discharge during V2G operation throughout the day. An E.V. participating in V2G operation using an energy arbitrage approach can charge at off-peak hours when there is a low electricity price and then discharge at on-peak hours when the price is high - thus making 'arbitrage' profit from the price difference. This study proposes a scheduling approach based on an optimisation problem to achieve maximum daily arbitrage profits. The process would maximise the E.V. owner's return revenue. The proposed optimisation scheduling method is based on the typical daily electricity price pattern - the E.V.'s plug-in and plug-out times and the desired final E.V. battery SOC. The historical U.K. grid pricing was used to examine the general impact pattern of the daily electricity price on the economic benefits of using V2G. The historical data chosen was over all four seasons during 2019 - Wednesday, 6th February, Wednesday, 6th May - Wednesday, 6th August - Wednesday, 6th November (from winter to autumn, respectively). The data was extracted as sample electricity price profiles (Figure 1) [27]. It is clear from the samples of the selected days demonstrated in Figure 1 that seasonal U.K. system prices show the highest volatility during off-peak and on-peak hours. It has been noted that the system price exhibits a notably higher level in February, May, and November. The high energy demand on the grid peaks during these colder months and is reflected in the higher price per M/Wh when more costly peak-load power stations are typically employed. The system price sharply decreases in the summer season, especially in August, due to better weather conditions where base load generation provides most of the electricity.

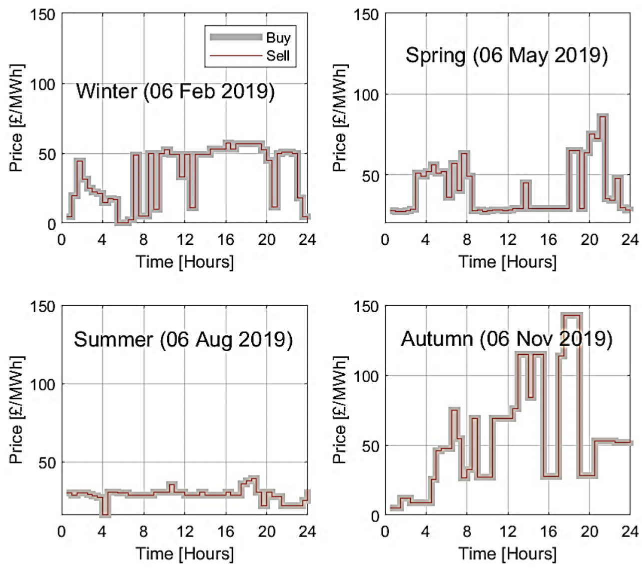


Figure 1. UK electricity system price of 6th February, 6th May, 6th August and 6th November of 2019

This study implemented an energy arbitrage optimisation method in the proposed scheduling approach to generate profits from energy arbitrage for E.V. owners. The scheduling optimisation problem using the objective function $J(\bullet)$ can be stated to maximise E.V.'s revenue by participating in V2G operations for energy arbitrage service during vehicle parking periods. To buy electricity during low-price periods and sell it during high-price periods, effective management of electric vehicle (E.V.) charging and discharging is essential. The objective function consists of the difference between the total cost of energy sold and the total cost of energy purchased. As the $£_{sell}$ and $£_{buy}$ are sales and purchase prices, the above objective function is as follows.

$$J = E^{\uparrow}(t) \times £_{\mathrm{sell}}(t) - E^{\downarrow}(t) \times £_{\mathrm{buy}}(t). \quad (1)$$

where $E^{\uparrow}(t)$ and $E^{\downarrow}(t)$ are the amount of energy exchanged within the power grid of the E.V. under consideration during discharging and charging operations, respectively, for each half hour, such as;

$$E^{\uparrow}(t) = P^{\uparrow}(t) * T_{step}. \quad (2)$$

$$E^{\downarrow}(t) = P^{\downarrow}(t) * T_{step}. \quad (3)$$

where $P^{\uparrow}(t)$ and $P^{\uparrow}(t)$ are the E.V.'s discharge and charge power rates are under consideration to control the energy exchanged within the power grid during participation in V2G operations. $E^{\uparrow}$ and $E^{\downarrow}$ are discharged and charged energy. T_{step} is the step time corresponding to periods of charging/discharging decisions. The optimisation algorithm generates the different charge/discharge operation scenarios. They also depend on different pricing and investment strategies. The optimisation mentioned above problem is subject to the four sub-mentioned constraints: constraints (4) specify the lower and upper bounds of the charging power;

$$-P^{\max} \leq P^{\downarrow}(t) \leq 0. \quad (4)$$

Constraints (5) specify the lower and the upper bounds of the discharging power;

$$0 \leq P^{\uparrow}(t) \leq P^{\max}. \quad (5)$$

The linear battery model can be used to predict the SOC behaviour for any E.V. Constraints defined in (6) are the instant energy constraints, which require the energy of E.V. at the end of step time $t+T_{step}$ to be between 5% and 95% SOC, so 90% DOD;

$$0.05 \leq \mathrm{SOC}\ \ (t) + \left(\frac{P^{\downarrow}(t)\times\eta^{\downarrow} - \frac{P^{\uparrow}(t)}{\eta^{\uparrow}}}{E^{\max}}\right) \times T_{\mathrm{step}} \leq 0.95. \quad (6)$$

where η is efficiency, and E^{max} is E.V.'s maximum energy. Constraints (7) are the final energy constraints; the E.V. should meet the absolute energy requirement (i.e., $\mathrm{SOC}^{\mathrm{fin}}$ of battery, E.V.) at the end of V2G operation to allow the outgoing E.V. enough energy for the following travel plan. The following equation can be used to build a final value for the SOC.

$$\mathrm{SOC}^{\mathrm{ini}} + \sum_{\mathrm{T}^{\mathrm{ini}}}^{\mathrm{T}^{\mathrm{fin}}} \left(\frac{P^{\downarrow}(t)\times\eta^{\downarrow} - P^{\uparrow}(t)/\eta^{\uparrow}}{\mathrm{E}^{\max}}\right) \times T_{\mathrm{step}} = \mathrm{SOC}^{\mathrm{fin}}. \quad (7)$$

The abovementioned problem represents a constrained nonlinear multivariable problem with $P^{\uparrow}$ and $P^{\downarrow}$ as the decision variables. The object of the optimisation problem with (4)-(7) constraints is to maximise the revenue by charging when the energy price is minimum and discharging when the energy price is maximum. An optimisation algorithm makes the charging or discharging decisions with a communication protocol.

3. ICT-BASED COMMUNICATION

This section focuses on a charging station used to charge an E.V. The charging station is considered equipped with smart meters and an electrical storage system. It is deemed that the daily energy cost profile and double-way flow are available.

Upon plugging the charging plug into the charging point and establishing powerline communication, communication via the higher-level smart charge protocol can commence. The protocol rigorously pursues communication between the client and the grid server so the vehicle sends requests and gets responses. The charging point can trigger a request by setting specified flags. This chapter proposes a communication protocol between electric vehicles and the grid. Figure 2 depicts the ICT-Based communication scheme for smart grid-based V2G operation.

The problem is defined in a discrete-time setting, where the sampling time is T_{step}. Each plugged-in vehicle is charged at a constant power P_{ref}. The E.V. arrival T_{in} and departure T_{fin} times are uncertain. Assume that the reference charging/discharging time interval between T_{in} and T_{fin} is divided into $(T_{fin}-T_{in})/T_{step}$ time slots where the initial time slots start at $t=0$, while the last at $t=T_{fin}-T_{in}$.

At first, the charger plug in the charge station grid receives the plug, and the grid requests bidirectional V2G/G2V operations. The grid then demands the availability of electric vehicles. Suppose the V2G operation is disabled for the car. In that case, the charging is finalised, and the vehicle requests to complete the charging process (FCP) from the grid. When the car is available for V2G operations, the vehicle logs in and initialises the communication session. Initialisation includes submitting the session identification number (session I.D.) and vehicle identification number (vehicle I.D.) to the grid.

The vehicle triggers service discovery requests to obtain the offered services, such as ways of payment. The grid then responds to service discovery. The vehicle then sets up the charging process (SCP). The setup charging process includes the defining initial and final time of charging/discharging (T_{in} and T_{fin}); the charge/discharge time interval (T_{step}); initial and final state of charge (SOC_{in} and SOC_{fin}); maximum energy capacity (E_{max}); full power (P_{max}) and efficiency of the vehicle. The vehicle sends the SCP request to the grid, which processes these SCP parameters. The grid also interacts with energy markets and obtains energy price vectors at different intervals. T_{step} is the sample rate as belonging to a digital control system.

There is an optimisation problem about when to charge/discharge process. According to an optimisation rule, the electric vehicle decides when to launch or buy the energy. The solution to the optimisation problem gives a dynamic charging profile power array, including charge/discharge power reference values for each step. The grid sends the power reference array P_{ref} to the electric vehicle charger. The symbol t is the current time as minutes. The current power reference value is taken from the array according to element number k.

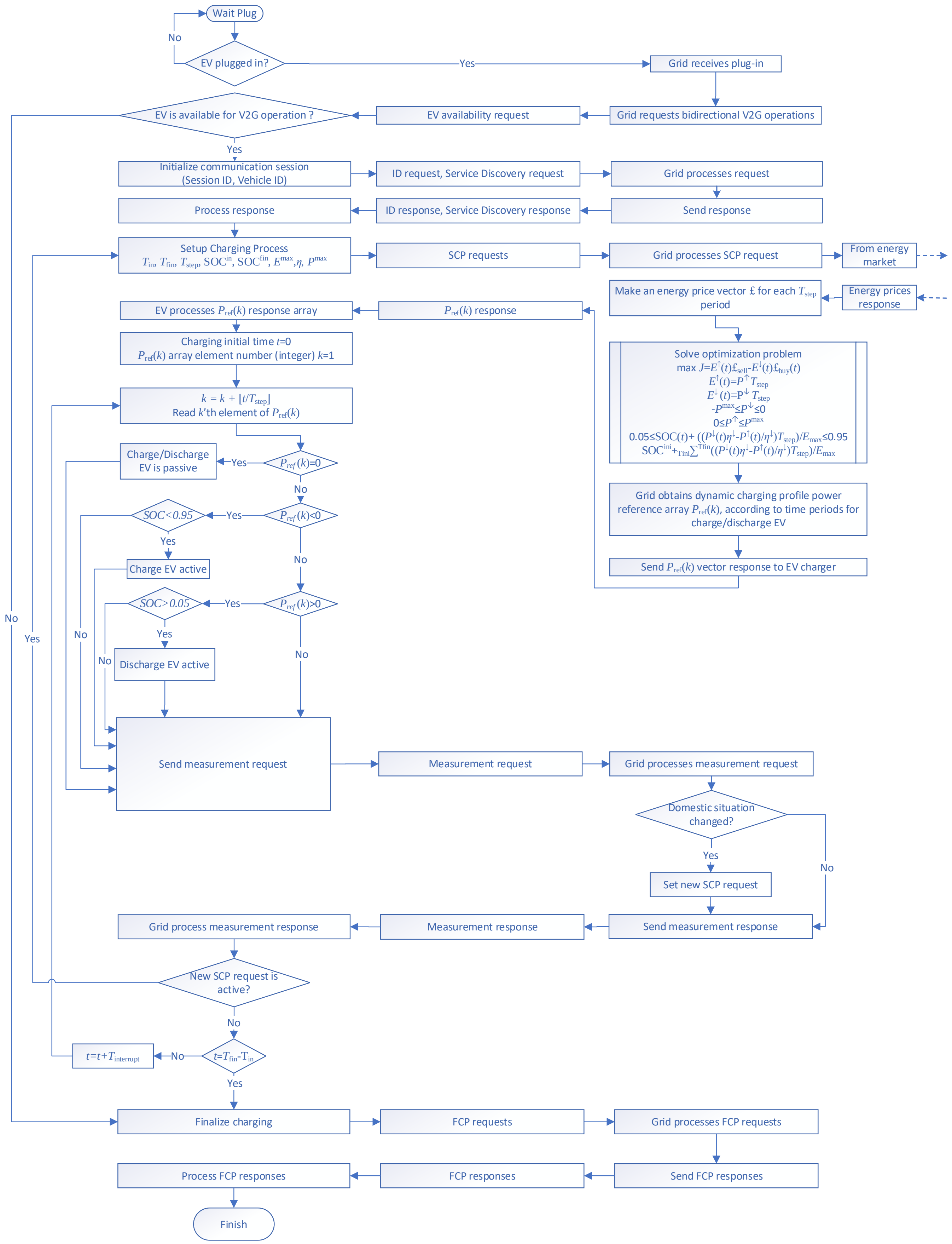


Figure 2. ICT-Based communication scheme

If the reference power value equals zero, the charging/discharging will be passive. If the reference power value is negative and the state of charge is smaller than 0.95, the charging process will be active; otherwise, the discharging will be busy. The grid must check the charging and discharging cycles. That requires momentary measurement values from the charge station to the grid. The measurement values are processed and investigated whether there is a domestic situation change, such as plug disconnection or fuse failure. That kind of problem requires changing the charge profile. If the domestic situation changes, the grid sends a new charge processing setup request to the electric vehicle. When the new setup request is active, the program changes the setup charging process. Suppose a new setup charging request is inactive, and the final time is not yet. In that case, the algorithm adds the processing interruption time $T_{interrupt}$ to the time index t. The program then jumps to read the new reference power value. The algorithm begins a charge process finalisation when the final time finishes. The electric vehicle sends the final charge process (FCP) request to the grid and receives a response. The response finishes the charge/discharge processing, and the state of charge value of the battery becomes the SOC_{fin} value at the end of the V2G operation.

4. ECONOMIC STUDY RESULTS

The optimisation problem is simulated in MATLAB/ Simulink using a real-energy price data set obtained from the [27].

This paper examines the battery used in the Nissan LEAF 40 kWh, composed of Lithium Nickel Manganese Cobalt Oxide (NMC) prismatic/pouch cells. These cells are arranged into 24 modules, each containing 8 cells, and these modules are then grouped to form the battery pack [28] Table I.

TABLE I
NISSAN LEAF 40 KWh BATTERY CHARACTERISTICS [28]

	Cell level	Module level (8 cells)	Pack level (24 Modules)
Rated capacity [Ah]	56.30	56.3	112.6
Nominal voltage [V]	03.65	29.2	350.4
Rated energy [kWh]	0.205	1.64	39.50
		Battery pack price [k£]	06.00

This electric vehicle (E.V.) and its battery size were selected because they represent the typical storage capacity of E.V.s since the battery can meet users' needs in various countries [28]. It is based on the same chemistry studied and presented in section II of this work.

Table II shows the load current, load power and discharge duration of the Leaf battery back under two different discharge rates, i.e. 1C and 3C; as it can be seen, the maximum current and power that can be extracted from the battery are 112.6A and 39.5 kW at 1C discharge rate, and 337.8A and 118.5 kW at 3C discharge rate.

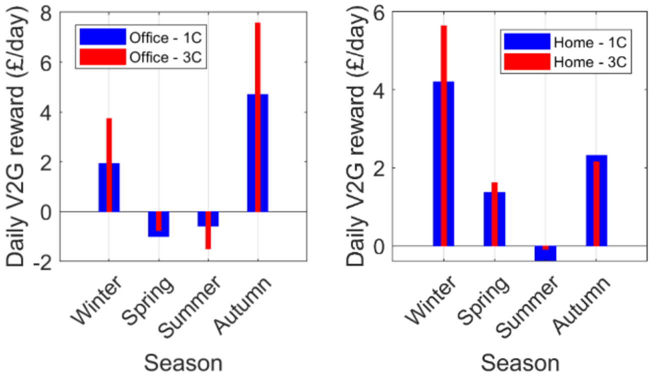
TABLE II
NISSAN LEAF 40 KWh BATTERY CURRENT AND POWER OUTPUT FOR DIFFERENT DISCHARGE RATES (I.E., 1C AND 3C)

Discharge rates	1C	3C
Load current [A]	112.6	337.8
Load power [kW]	39.5	118.5
Discharge duration [min]	60	20

TABLE III
V2G BENEFIT IN £/DAY FOR WINTER, SPRING, SUMMER AND AUTUMN PERIODS, AT DIFFERENT DISCHARGE RATES (I.E., 1C AND 3C) AND DIFFERENT PARKING LOCATIONS (I.E., HOME AND OFFICE)

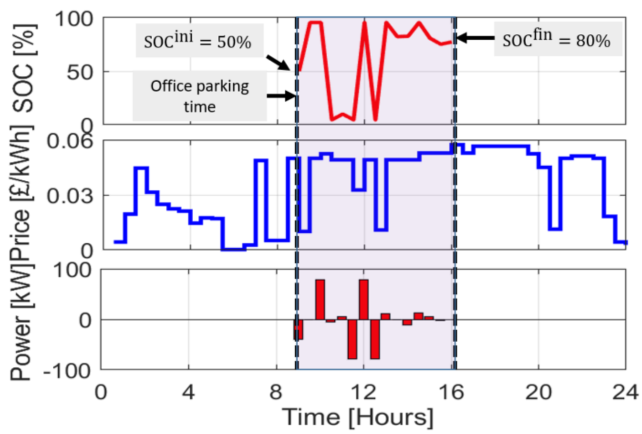
			Winter	Spring	Summer	Autumn
V2G benefit (£/day)	1C	Home	+5.33	+2.98	+0.78	+3.69
		Office	+2.75	+0.05	+0.33	+5.43
	3C	Home	+7.39	+4.33	+1.38	+3.75
		Office	+4.98	+0.71	+0.06	+8.73

Table III shows the daily V2G benefit in £/day for one Nissan Leaf participating in V2G operation two times per day, during office parking time, during home parking time, for four seasons and based on both regular discharge rates (1C) and fast discharge rate (3C). To highlight the actual reward/cost of the E.V. owner participating in V2G operation, Figure 3 depicts the total benefit/cost of the E.V. participating in V2G during four seasons.

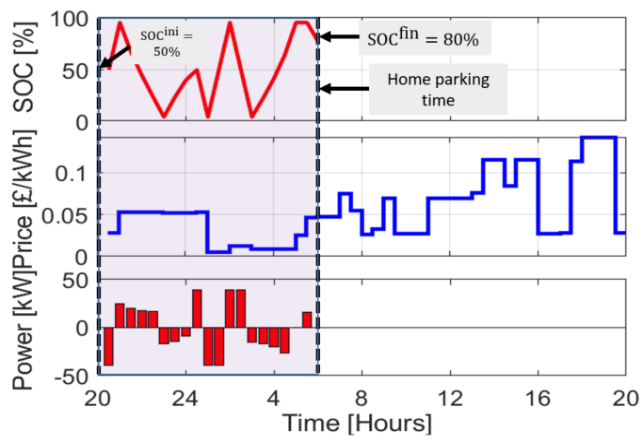


(a) Office parking time (daytime) (b) Home parking time (nighttime)

Figure 3. Daily E.V. owner benefits for Winter, Spring, Summer and Autumn periods, participating in V2G operation, (a) during office parking time, and (b) home parking time



(a) Office parking time - 6th February 2019



(b) Home parking time – 6th November 2019

Figure 4. Daily EV SOC and Power profile participating in V2G operations, (a) during office parking time of winter season, and (b) home parking time during the autumn season.

As can be seen from Figure 3, two seasons of economic benefit for the owner in V2G were highlighted during office parking time (daytime), i.e. winter and autumn, while three seasons were of benefit during home parking time (nighttime), i.e., winter, spring, and autumn. In all cases, the summer season showed an additional cost while participating in V2G. For all benefit cases, the E.V. owner could benefit by an average of 1.6 times by using a high discharge rate over the regular discharge rate, except in the autumn season during home parking time; in this case, the normal discharge rate provided more benefit - of 1.1 times more than fast discharge rate.

Figure 4 shows an example of a daily V2G operation during day and night for the winter and autumn, respectively. As seen, the V2G scheduling for the E.V. considers the final desired SOC, allowing the E.V. owner to plan the next trip after performing a V2G operation.

5. CONCLUSIONS

Supplying energy without adverse ecology is the decisive factor for sustainable development worldwide. This paper's economic study is based on an energy arbitrage service for an E.V. participating in a V2G operation. To develop an effective revenue strategy under certain E.V. demand, an optimisation algorithm problem is defined. An economic survey of the energy arbitrage for an E.V. participating in V2G operation has been presented. Simulation results based on a Nissan Leaf 39.5 kWh battery model highlight the extra financial benefit to the E.V. owner participating in V2G and using a high discharge rate in preference to the standard discharge rate, yielding an average of 1.6 times the benefit per day during the winter and autumn season.

Smart grid requires integrating information technology with renewable energy to advance how to generate and consume electricity. Using ICT is an inevitable way of supporting two-way data and power, which facilitates the integration of renewable energy sources into the grids. An ICT-based smart communication protocol is proposed. Economic solution on the energy arbitrage required to solve an optimisation algorithm. The algorithm is settled in the protocol scheme. The communication protocol provides instructions for power stabilisation of the grid.

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Hakan Kızmaz earned his Electrical and Electronics Engineering bachelor’s degree from Sakarya University’s Faculty of Engineering in 2006. Subsequently, he pursued his academic journey at the same institution, obtaining his master’s degree from the Faculty of Science in 2009 and completing a second master’s degree in 2015. With a commitment to academia and industry, Kızmaz gained valuable experience as an automation engineer at Kromel Makine Sanayi A.Ş. from 2007 to 2009. His passion for research and teaching led him to join Sakarya University as a research assistant in the Faculty of Engineering, where he contributed from 2009 to 2016. In 2016, Kızmaz embarked on a new academic endeavour by joining Siirt University, where he served until 2018. He holds the position of Assistant Professor at Batman University, a role he has held since 2018. His primary research interests lie in Control Systems and Control Theory, where he has made significant contributions to the academic community through his research and teaching efforts.