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Exploring the potential of the vehicle-to-grid service in a sustainable smart city

Aarav Vijay Sahu, Esther H. Park Lee, Zofia Lukszo
Faculty of Technology, Policy and Management
Delft University of Technology
Delft, The Netherlands
aaravsahu@gmail.com

***Abstract*—The vehicle-to-grid (V2G) service is slowly gaining momentum in its capacity to engage as a means of distributed generation. An aggregator's role is pivotal in the need to coordinate vehicles for V2G and maintain the security of supply of its customer base. The paper focuses on comparing the performance of the energy system when an aggregator adopts different strategies in selecting the vehicles for participating in V2G under varying scenarios. A deterministic model is formulated to gauge the extent to which a vehicle can contribute to energy valley filling, in a system powered only by renewables. The difference in the selection strategy results in having an impact on the performance of the energy system. The presentation of different scenarios and their perceived benefits can help an aggregator in decision making and formalizing its strategies.**

Keywords*—*vehicle-to-grid, vehicle aggregator, battery electric vehicle, fuel cell electric vehicle

I. INTRODUCTION

Renewable energy generation from solar and wind is marked by its intermittency and unpredictability. In energy systems with high penetration of renewables, flexible power plants with quick reaction time, demand side responses and energy storage are needed to cope with the intermittency of renewables [1]-[2]. With an increase in the share of renewables in the power mix, there arise situations when there is a mismatch between the time of power generation and demand [2]. Electricity differs from a conventional commodity as it cannot be stored. However, if the surplus energy generated can be stored, it could provide a window of opportunity to improve performance of energy systems [3]. The motivation behind using vehicles for grid support has sprung from the understanding that most vehicles are parked almost 95% of the time. The time the vehicles are parked, they can potentially serve as virtual power plants by feeding power to the grid [4].

There are some inherent characteristics of vehicles with electric drivetrains which favour their usage for grid support. Both battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) have quick starting times and can reach their nominal power output in a matter of seconds [5]. The bidirectional flow of power is a well exercised phenomenon and the power quality issues arising out of the bidirectional flow of power are generally well managed [6]. It has been ascertained that adding BEVs and allowing the V2G provision also allows for much higher levels of integration of wind energy while curtailing the excess energy generation at the same time [7].

The role of FCEVs in providing the V2G service within a Car as Power Plant (CaPP) community microgrid, where the variation in renewable energy generation is balanced by utilising it for hydrogen production, was investigated by [8]. The authors inferred that using FCEVs for the V2G can help the microgrid in minimising its power imports to become self-sustaining. They applied a scheduling mechanism where the microgrid operator selected the FCEVs for V2G based on their number of start-ups in the year the decision variables would yield the optimal refuelling strategy. Binary parameters to indicate the availability of FCEVs within a neighbourhood for engaging in the V2G service was covered by [9]. The authors formulated their problem as a Mixed Integer Linear Programming (MILP) program to minimise the power imports. The authors inferred that the bottleneck in the hydrogen demand satisfaction lay in hydrogen production. In [10], the authors formulated a Model Predictive Control (MPC) algorithm minimise the operational costs of the CaPP microgrid based on calculating the sequence of future decisions within the microgrid. The provision of using FCEVs for V2G for the near and far future timelines was investigated by [11].

A comparison between FCEVs and BEVs measuring their potential to cover for the power generation deficiency is yet to be conducted. A comparison of different algorithms for scheduling and selection of the vehicles for participating in the V2G service was also scarcely covered by previous literature. The paper aims to make a comparison between the FCEVs and BEVs in their extent to cover for the power deficiency from renewable sources. In addition, the effect of the selection algorithms on the overall performance of the vehicles during V2G is also studied. The rest of the paper structure is as follows: Section II describes the individual components of the energy system model in its mathematical representation. Section III defines the different scenarios where the system model was applied and simulated. The results of scenario simulations and modelling are discussed in Section IV, and finally, the conclusions of the paper are drawn in Section V.

II. SYSTEM MODEL

The model formulated and simulated is an extension of the CaPP community model [8]-[10]and is applied in the context of a sustainable smart city. A city has been designated as sustainable smart because it meets its household and transport energy requirements from renewable energy and the V2G service. The model is individually comprised of an offshore wind farm, rooftop solar PV systems, 1000 households, electrolysers, 500 BEVs and 500 FCEVs. A schematic description of the system model is shown in Fig. 1 below.

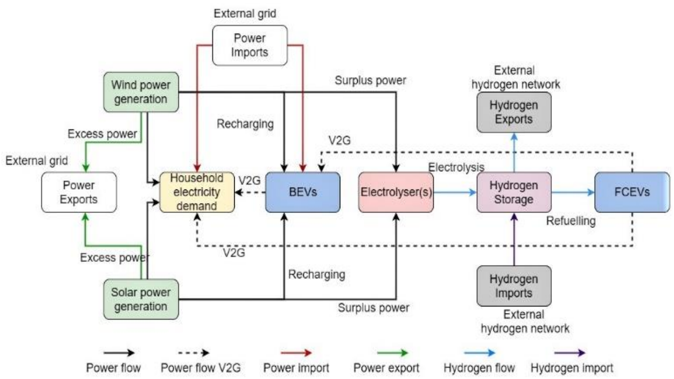

Fig. 1. Schematic diagram of the energy system model

TABLE I SYSTEM PARAMETERS

System parameters	Value
$\eta_{Electrolyser}$	70%
$N_{electrolysers}$	3
HS^{max}	645 kgs
HS^{min}	64.5 kgs
$P_{recharging}$	11.5 kW
$\eta_{grid\ connection}$	97%
η_{FCEV}	55%
P_v^{V2G}	10 kW

A. Power generation

The power generation from renewables is supplied by an offshore wind farm and rooftop solar PV systems. A single Vestas V164 8MW wind turbine was used for power calculations in the designated offshore location in the South Holland coast (52^{o}28 N, 4^{o}08 E) [12]. The solar power yield was calculated using the locational climatic and ambient parameters of Rotterdam [13]-[14]. An approximate area of 15m^2 was considered as the usable rooftop area for solar panel installation in a typical Dutch household [15]-[16]. The total electricity demand for 1,000 households (1 GWh) was accessed from [17], where the electricity demand was scaled down to 1,000 households. It is essential to mention that the energy system was designed in excess corresponding to the energy demand. The aim of the research was not to optimally design a sustainable smart city powered by renewables, but to evaluate the performance of V2G in an energy system powered exclusively by renewables. The total energy renewable energy generation was 4.85 GWh.

B. Electrolyser

The surplus renewable energy generation is used to produce hydrogen by means of electrolysers. The essence of utilising the surplus energy generation by means of an electrolyser is to avoid the additional grid reinforcements otherwise required to cope with the intermittent surplus generation [18]. The produced hydrogen is then compressed and stored in a central hydrogen storage facility. The expression for the hydrogen production and storage at any hourly time instant 't' is expressed by (1) and (2). The power input to the electrolyser was in accordance with their operational constraints [19].

$$HP_t = \frac{P_t^{electrolyser} \times \eta_{Electrolyser} \times \Delta t \times 1000}{HHV} \#(1)$$

$$HS_t = HS_{t-1} + HP_t - RFHD_t \pm H_{imp/exp,t} \#(2)$$

C. Load Balance

If the power generation is not sufficient to satisfy the demand at that time interval, a V2G requirement ($V2GR_t$) is signalled to an aggregator. The aggregator then needs to coordinate vehicles to cover the deficit in power generation.

$$If\ TP_t^{demand} > TP_t^{production} :\ V2GR_t = 1 \#(3a)$$
$$If\ TP_t^{demand} \leq TP_t^{production} :\ V2GR_t = 0 \#(3b)$$

The number of times the V2G service is required in the year is registered by the parameter 'V2G requirement count ($V2GRC$)'.

$$V2GRC = \sum_{t=1}^{t=8784} V2GR_t \ \#(4)$$

D. Driving Model

The driving data used as inputs for the model were accessed from [21]. The driving schedule of the vehicles were distributed amongst the vehicles considering their daily average travelling distance, travel hours, driving motive and average number of trips per day for the entire the year. The average driving distance based on the travel motive was assigned to the corresponding available hours in the traffic hour segment. The vehicle availability is indicated by the binary variable 'Car Availability ($CA_{i/j,t}^V$)' and is determined from the driving distance ($DD_{i/j,t}$). The definition of the binary variable is expressed by the following conditions (5a) and (5b)

$$If\ DD_{i/j,t} > 0 : CA_t^V = 0 \#(5a)$$
$$If\ DD_{i/j,t} = 0 : CA_t^V = 1 \#(5b)$$

This implies that a vehicle is only available (for recharging/refuelling or generation) if it is not driving at the time instant 't'.

E. Battery Electric Vehicles

The choice of battery electric vehicle was a Tesla Model S (90 kWh edition). The corresponding vehicle characteristics were used for the model calculations accordingly. The parameter used to define the energy content in the BEV is the battery energy level (BEL). The BEL is expressed by (6)

$$BEL_{j,t} = BEL_{j,t-1} - \frac{P_v^{V2G} \times \Delta t}{\eta_{discharging}} - \left(P_{charger} \times \Delta t_{charging} \times \eta_{charging}\right) - DD_{j,t} \times \left(\frac{1}{M_{BEV}}\right) \#(6)$$

The recharging state of a BEV is possible if it has recharging need due to its depleted $BEL_{i,t}$ and if it is not constrained by a driving trip in the same time period. The recharging status is achieved by (7). The total recharging energy consumed by all BEVs is expressed by (8).

$$RCS_{j,t} = RCN_{j,t} \times CA_{j,t}^{V} \#(7)$$

$$TRCEC = \sum_{t=1}^{t=year} \sum_{j=1}^{j=N_{BEV}} RCS_{j,t} \times P_{recharging} \times \Delta t_{recharging} \#(8)$$

F. Fuel Cell Electric Vehicles (FCEVs)

The choice of FCEV was a Toyota Mirai [20], because the mileage of the Toyota Mirai and the Tesla Model S were almost similar and thus allow for an even comparison between an FCEV and BEV. The parameter used to describe the fuel content in an FCEV is defined as the 'Hydrogen Fuel Level ($HFL_{i,t}$)' which is expressed in (9).

$$HFL_{i,t} = HFL_{i,t-1} + RFA_{i,t}^{FCEV} - \frac{P_v^{V2G} \times \Delta t}{\eta_{FCEV} \times LHV} - DD_{i,t} \times \left(\frac{1}{M_{FCEV}}\right) \#(9)$$

The refuelling state of a FCEV is possible if has refuelling need due to depleted its $HFL_{i,t}$ and if it is not constrained by a driving trip in the same time period. The refuelling status is achieved by (10). The total consumption of hydrogen for refuelling of the FCEVs is expressed by (11)

$$RFS_{i,t} = RFN_{i,t} \times CA_{t}^{V} \#(10)$$

$$TRFHD = \sum_{t=1}^{t=8784} \sum_{i=1}^{i=N_{FCEV}} RFS_{i,t} \times RFA_{i,t}^{FCEV} \#(11)$$

G. Vehicle-to-grid

For a vehicle to participate in the V2G service, it must have a minimum of 50% HFL/BEL of its full HFL/BEL capacity. If a vehicle meets this requirement and is neither in the process of recharging/refuelling nor if it is occupied by a travel schedule at that time instant, it is qualified and available to participate in the V2G service. The vehicles which meet the criteria for V2G are marked by their V2G availability status ($V2GAS_{i/j,t}$). The number of vehicles to cover for the deficiency in power generation is expressed by (12)

$$N_{R,t}^{V2G} = \frac{PBV2G_t}{P_v^{V2G} \times \eta_{grid\ connection}} \#(12)$$

The number of times a vehicle is used for the V2G service in the year is recorded by means of a binary start-up variable (13) through the difference its V2G participation status.

$$V2GPS_{i/j,t} - V2GPS_{i/j,t-1} = SU_{i/j,t}^{V2G} \#(13)$$

The total supply of power by engaging the V2G service is the cumulative sum of the power generation from all the vehicles participating at that time instant 't' (14).

$$P_t^{V2G} = \sum_{1}^{N_{BEVs/FCEVs}} \left[V2GPS_t \times P_v^{V2G}\right] \times \eta_{grid\ connection} \#(14)$$

H. System balance and system performance

The power, energy and hydrogen in the system is always in balance. The time intervals when the energy and hydrogen demand cannot be satisfied by local production from renewables, the balance amount is imported from an external source. Purely from a self-sustaining stance of the sustainable smart city, the import of hydrogen and energy is undesirable. The excess energy and hydrogen production after the energy and hydrogen demand is satisfied is then exported to the maintain the energy balance.

$$TP_t^{production} - TP_t^{demand} + B_t = 0 \#(15)$$

$$B_t = P_t^{V2G\ gen} - P_t^{electrolyser} \pm P_t^{import/export} \#(16)$$

The extent to which the available vehicles can cover the shortage in power generation through V2G is expressed by a factor 'V2G power coverage' in (17). The extent to which the total power demand is met from renewables and the participation of the vehicles in the V2G service is recorded by the parameter named as 'Power supply coverage' (18).

$$V2GPC_t = \frac{P_t^{V2G}}{Power\ balance_t} \#(17)$$

$$PSC_t = \frac{TP_t^{generation} + P_t^{V2G}}{TP_t^{demand}} \#(18)$$

III. SCENARIOS

A total of four different scenarios were formulated where the system model was applied and simulated. There were two scenarios each for BEVs and FCEVs. The two scenarios with respect to the way the vehicles are selected from the vehicle fleet for participating in the V2G service are the 'Priority Participation (PP)', and 'Safe Participation (SP)'. The four scenarios: BEV Priority Participation (BPP), BEV Safe Participation (BFP), FCEV Priority Participation (FPP) and FCEV Safe Participation (FSP) are listed in Table II.

TABLE II SCENARIO DEFINITIONS

Scenario name	**Scenario FPP**	**Scenario FSP**	**Scenario BPP**	**Scenario BSP**
V2G provision	FCEVs exclusively	FCEVs exclusively	BEVs exclusively	BEVs exclusively
V2G count	686	686	748	714
V2G selection	Index selection	Descending sort of HFL	Index selection	Descending sort of BEL

A. Priority Participation

The Priority Participation (PP) scenarios are defined such that the vehicles selected from the available pool of vehicles for V2G are chosen on basis of their vehicle index number. This represents a 'first-come first-serve scenario', where the vehicle which arrives early signals an aggregator of its availability is given priority based on their time of signalling. The algorithm for assigning the V2G participation status at a vehicle at a time instant started with the count from i/j=1 till i/j=500 where all vehicles which met the requirements for participating in V2G service were marked active and available ($V2GAS_t$). A counting variable 'count', was initialised to 0, was introduced to keep track of the number of vehicles assigned with the V2G participation status. As the iteration proceeds from i/j=1 till i/j=500, the $V2GPS_t$ was assigned a value equal to 1 as long as the count variable was less than or equal to the number of vehicles required for V2G. Each time a vehicle was assigned a positive V2G participation status, the count variable was increased by one count. The iteration stops if the count variable is equal to the number of vehicles required for V2G. All the other available vehicles present in larger number than required for V2G were assigned a V2G participation status of 0.

B. Safe Participation

The Safe Participation (SP) scenarios correspond to situations where the aggregator after having noted all the available vehicles for V2G arranges the available vehicles in descending order of their HFL/BEL. After arranging the vehicles in the descending order of their HFL/BEL, the algorithm assigns the V2G participation status based on the number of vehicles required to balance the shortfall in power at that time interval, just as in the normal participation scenario. Through this algorithm, the vehicles selected for V2G participation were selected based on the maximum distribution of their HFL/BEL. It is also quite possible that an aggregator while coordinating the different vehicles for the V2G service will sort the vehicles in accordance with their maximum HFL/BEL so that the HFL/BEL levels in the respective vehicles still lie within the range where the vehicle can further be used for driving without needing to refuel/recharge. This method of choosing vehicles based on their HFL/BEL and not their vehicle index number would leave the vehicle ready for further use and hence the name 'Safe Participation' for the scenario.

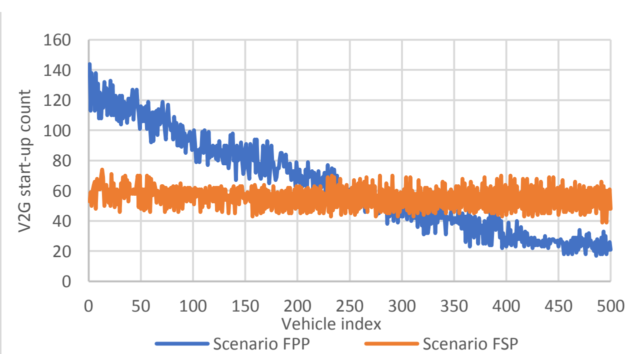

Fig. 2. Comparison of FCEVs V2G start-up count

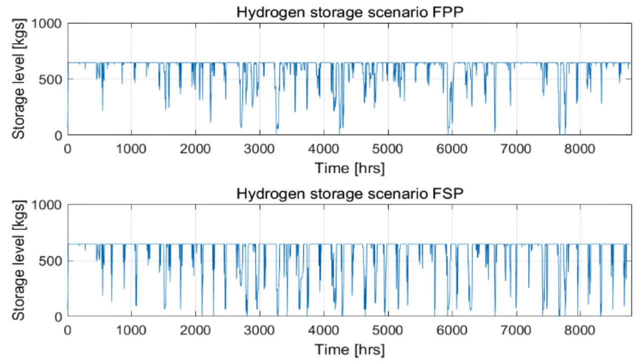

Fig. 3. Comparison of hydrogen storage

IV. Results and Discussion

In all the scenarios, it is observed that FCEVs have a better V2G power coverage than BEVs. This is understood by the reasoning that a FCEV spends much less time refuelling than what a BEV spends for recharging. The times of V2G requirement coincided with the recharging hours of the BEVs which limited their participation in the V2G service. This finding reiterates the inference of [5] that FCEVs are better suited over BEVs due to their faster refuelling. The V2G performance results are listed in Table III and Table IV.

It is observed in Fig. 2 representing the SP scenarios, that the participation of vehicles in V2G is more evenly distributed, albeit with a few variations across the spectrum of the V2G start-up count. In the priority scenarios, the vehicles with early indices, or representing earlier arrival of vehicles are used for more frequently for the V2G service. In the SP scenarios, the aggregator can fulfil one of its many multi-objective activities to ensure a level playing field for all its customers. But the fair participation among all its customers comes with a penalty of lower power coverage from the V2G service.

In the future, stronger collaboration between an aggregator and distributions systems operator (DSO) is expected [22]. An aggregator must provide a level playing field and lucrative propositions to its customers [23]. The DSO, which has financial stake in the grid network, would want to recover its investment in the future. The comparison between the performance parameters in scenario BPP and scenario BSP point out to a possible confusion in decision making for an aggregator and DSO. Scenario BSP demands for more power intensive charging infrastructure to cope with the higher power demand, but its degree of usage is less than that in scenario BPP (0.69% less charging energy consumption). The total charging count in scenario BSP (32,282) is less than in scenario BPP (32,699). A scenario which requires a larger investment in infrastructure and has a lower degree of utilisation of the infrastructure may delay the return on investments or deem it unprofitable. The aggregator on one hand may want to ensure a fair and uniform participation of all its customers in the V2G service, but at the same time the DSO may experience under-utilisation of its charging infrastructure. This conflict of interest becomes even more problematic if the bidirectional charging/discharging poles are used for the charging/V2G process, where the total V2G start-up count is again lower in scenario BSP (28,434) than in scenario BPP (29,809).

TABLE III BEV SCENARIO RESULTS

Results	Scenario BPP	Scenario BSP
Total recharging energy consumption	2.024 GWh	2.01 GWh
Maximum recharging power demand	1.80 MW	2.39 MW
Total recharging count	32,699	32,282
Total power import count	321	316
Total imported energy	183.48 MWh	229.24 MWh
Total V2G start-up count	29,809	28,434
V2G power coverage	71.67 %	65.22 %
Power supply coverage	98.66 %	98.48 %

TABLE IV FCEV SCENARIO RESULTS

Results	Scenario FPP	Scenario FSP
Total hydrogen consumption	93,237 kgs	91,019 kgs
Maximum refuelling demand	277.26 kgs	418.90 kgs
Total refuelling count	26,214	25,606
Total hydrogen import count	80	118
Total imported hydrogen	3101.1 kgs	7311.2 kgs
Total V2G start-up count	31,731	27,749
V2G power coverage	79.65 %	68.06 %
Power supply coverage	99.08 %	98.83 %

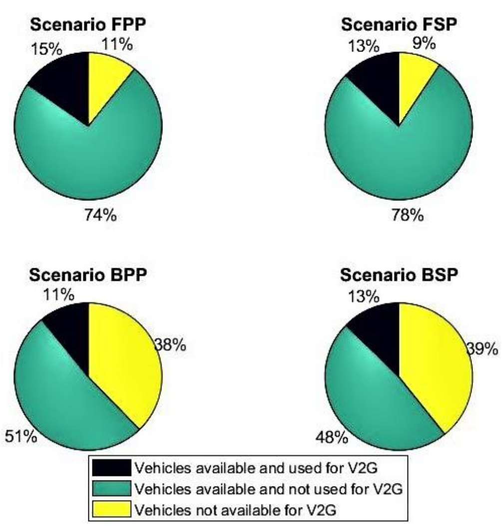

Fig. 4. Comparison of vehicle availability

The major difference when the hydrogen storage timeline horizons of scenario FPP and scenario FSP are compared in Fig.3 is that the hydrogen storage level is depleted more regularly and in the form of spikes as compared to scenario FSP where it is depleted in almost discrete time intervals. The storage level in scenario FSP remains steady for many hours in its timeline, but during its depletion, it depletes by a large amount. This sort of hydrogen profile would demand for larger central storage and more hydrogen import operations. The additional imports in scenario FSP implies a higher requirement of tube trailers to facilitate the hydrogen imports. In scenario FPP, the hydrogen depletion profile would cater to more continuous, but steady transport demand of hydrogen. Scenario FPP would require less hydrogen storage capacity and lesser number of refuelling stations to cope with the hydrogen refuelling demand. An aggregator would always intend for more even participation of all its customers, but the even participation can come at the cost of more investment in the supporting infrastructure.

V. CONCLUSION

In this paper, the difference in system performances that resulted from adopting different scheduling and selection algorithms for engaging the vehicles during V2G was analysed. The V2G service, helped in energy valley filling during times of lower renewable power generation, but could not completely cover the power deficiency. The PP scenarios indicating a first come first serve situation was better in overcoming the power shortage through V2G, but it concentrated the participation of the vehicles amongst the vehicles with earlier index numbers.

The research used a deterministic model which limited the results to fixed situations and data inputs. For further research, stochastic modelling is recommended to capture the uncertainty of vehicle availability and the variation in climate data and can, thus, help ascertain the potential of V2G with better accuracy. The effect of smart charging is likely to mitigate the requirements for the V2G service. It would be particularly interesting to understand the relevance of the V2G service after implementing smart charging strategies to balance the variable generation from renewable energy.

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NOMENCLATURE

Δt	Hourly time interval (h)
$\eta_{charging}$	Charging efficiency (%)
$\eta_{discharging}$	Discharging efficiency (%)
$\eta_{Electrolyser}$	Electrolyser efficiency (%)
$\eta_{grid\ connection}$	Grid connection efficiency (%)
i	FCEV vehicle index ($i = 1,2..N = 500$)
j	BEV vehicle index ($i = 1,2..N = 500$)

t	Time hours ($t = 1,2..N = 8784$)
$BEL_{j,t}$	Battery energy level of BEV 'j' at time 't' (kWh)
CA_t^V	Binary variable: Vehicle availability of FCEV 'i' or BEV 'j' at time 't'
DD_t	Driving distance of vehicle at time 't' (km)
$H_{imp/exp,t}$	Hydrogen import or export at time 't' (kgs)
$HFL_{i,t}$	Hydrogen fuel level of FCEV 'i' at time 't'
HHV	Higher heating value of hydrogen (kWh/kg)
HP_t	Hydrogen production at time 't' (kgs)
HS_t	Hydrogen storage level at time 't'(kgs)
LHV	Lower heating value of hydrogen (kWh/kg)
M_{BEV}	Mileage of BEV (km/kWh)
M_{FCEV}	Mileage of FCEV (km/kg)
$N_{BEVs/FCEVs}$	Number of BEVs/FCEVs (500)
$N_{R,t}^{V2G}$	Number of vehicles required for V2G at time 't'
$P_t^{electrolyser}$	Power input to electrolyser (MW)
$P_t^{import/export}$	Power import/export at time 't' (MW)
P_v^{V2G}	Nominal vehicle V2G power output (MW)
P_t^{V2G}	Power supplied through V2G (MW)
$PBV2G_t$	Power balance needed to be satisfied by V2G (MW)
PSC_t	Power supply coverage (%)
$RCN_{j,t}$	Binary variable: Recharging needs of BEV 'j' at time 't'
$RCS_{j,t}$	Binary variable: Recharging status of BEV 'j' at time 't'
$RFA_{i,t}^{FCEV}$	Refuelling amount for FCEV 'i' at time 't'
$RFS_{i,t}$	Binary variable: Refuelling status of FCEV 'i' at time 't'
$SU_{i/j,t}^{V2G}$	Binary variable: V2G start-up count variable
TP_t^{demand}	Total power demand (MW)
$TP_t^{generation}$	Total power generation (MW)
$TRCEC$	Total recharging energy consumed (GWh)
$V2GAS_{i/j,t}$	Binary variable: V2G availability status of vehicle 'i' or 'j' at time 't'
$V2GPS_{i/j,t}$	Binary variable: V2G participation status of vehicle 'i' or 'j' at time 't'
$V2GR_t$	Binary variable: V2G requirement at time 't'

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