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Scheduling Fuel Cell Electric Vehicles as Power Plants in a Community Microgrid

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***Abstract*—This paper presents a community microgrid with renewable generation, storage, and Fuel Cell Electric Vehicles (FCEV) that are used when renewable sources are scarce. To fairly distribute the demand for FCEV power among cars, a Vehicle-to-Grid (V2G) power scheduling mechanism is implemented using as a criterion the number of times every car has been started up for power generation. It can be concluded that with the fair scheduling mechanism the system can be self sufficient most of the months. At the end of a year, this results in a bell-shaped distribution of the number of start-ups per car and in using, on average, each FCEV about three times per week.**

***Index Terms*—electric vehicles, energy management, fuel cells, hydrogen storage, power generation dispatch**

I. Introduction

Microgrids are distribution networks consisting of aggregated loads, distributed generation, and storage technologies that are controlled locally. They can be operated either connected to or isolated from the main grid [1]–[3]. Benefits of microgrids include reliability, resiliency and power quality [1], but also better integration of distributed renewable generation, reduction of losses in transmission and distribution of power [3], [4], and delayed investments in the expansion of transmission grids [5], [6]. A big part of the current research focuses on microgrid architecture aspects [7], [8], as well as planning, operation control and islanding issues [6], [9], which are investigated both in computer-based environments and in experimental settings [10]. With the role of microgrids in the future smart grids, there is growing interest towards implementation aspects, such as regulatory issues [5], [11], social acceptance [4] and business models [3], [10], [12].

Electric Vehicles (EV) are gaining relevance in the research of future power systems, given the accelerated adoption of EVs and their impact on distribution grids as new variable demand [1], [13], [14]. Although initially seen as passive loads, EVs are now being regarded as valuable resources [15], [16]. Plug-in EVs can provide flexibility as controllable loads or distributed storage [17], [18] and all types of EVs can potentially provide Vehicle-to-Grid (V2G) power [19]. While Plug-in EVs are more suitable for providing demand side response, Fuel Cell Electric Vehicles (FCEVs) are more suitable for supplying power [19], [20], especially at times of peak demand.

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Based on the idea of using FCEVs to provide V2G power, the Car as Power Plant (CaPP) concept is proposed as integrated transport and energy systems that are efficient, reliable and flexible [21]. The CaPP concept can be especially valuable for microgrids, where variable renewable energy sources (RES) can be combined with dispatchable generation by FCEVs and storage in the form of hydrogen to manage local distribution systems in a flexible way [15]. This paper presents a case study of a CaPP community microgrid where the operation of FCEVs as power plants is scheduled fairly. To learn if the microgrid could be managed under varying weather conditions using such scheduling mechanism, the hourly operation of the system is modeled for different months and for an entire year. Using load and weather data the residual load is calculated to determine the demand of vehicles. The availability of vehicles for V2G scheduling is determined using driving data from the Netherlands. The average number of times each vehicle has been started up is determined at the end of the year, as well as the dependency of the system on power and hydrogen imports.

The rest of the paper is structured as follows: in section II the approaches used in scheduling problems are briefly discussed. Section III shows a description of the different elements of the CaPP microgrid. In Section IV the model and assumptions are formulated. In Section V the experiments and results are described, and finally, conclusions about this study are drawn in Section VI.

II. Microgrids and Vehicle-to-Grid scheduling

Experimental setups and test beds of microgrids around the world use mainly variable RES such as PV and wind [10], [22], sometimes in combination with dispatchable generators like combined heat and power (CHP), diesel generators or stationary fuel cells. At present, most of the experimental systems use stationary batteries (or EVs) for storage, with a few systems using hydrogen [10], [23]. Despite the scarce literature on scheduling of FCEVs in microgrids, there are a number of studies on scheduling of EVs [24], [25] and (stationary) fuel cells in microgrids [25]–[27] which show that central optimization approaches are the common practice. This is done by minimizing either costs, power losses or imports from the main grid. Others use the information on the availability of EVs to coordinate the allocation of resources to meet the demand of a microgrid [28]. Decentralized decision-making mechanisms are applied usually for large-scale integration of distributed EVs in the grid [29], [30].

Studies that include hydrogen storage have stationary fuel cells that are operated as dispatchable generators [23], [31], [32]. However, FCEVs cannot be treated in the same way, since their availability depends on driving needs. An optimization model with FCEVs in a microgrid shows that an optimal schedule of the vehicles can be achieved taking into account the driving behavior of the vehicles in the system [27].

An issue that can appear when FCEVs are the only dispatchable generators in a microgrid is that if vehicles are used often for V2G, their fuel cell stack could lose performance more rapidly due to the increased number of start-ups and shut-downs [33]. When this is not considered in the scheduling process, some FCEVs might be used more frequently than others, resulting on the long term in higher and uneven degradation levels among vehicles. Therefore, a different scheduling approach is needed to take into account not only vehicles' driving behavior but also the number of times each FCEV has been used for V2G.

III. The Car as Power Plant community microgrid

The CaPP community microgrid is depicted in Fig. 1. The system is located in a neighborhood of 200 households, each one equipped with a rooftop PV system. The energy management system (EMS) balances the supply and demand of electricity, using dispatchable generation and storage. When there is shortage of PV generation, FCEVs are used as power plants. When there is excess renewable generation it is stored in the form of hydrogen. In the electrolyzer, electricity and water are used to produce hydrogen, which is compressed (C) and stored (S) in the central refilling station. There is an external wind-to-hydrogen system that consists of a wind turbine and an electrolyzer. The hydrogen produced is compressed and transported directly to the refilling station in the neighborhood via a pipeline. The role of the microgrid with respect to the main grid is that of a net exporter, since it will use FCEVs before importing power, and will export whenever the capacity of the electrolyzer and/or hydrogen storage are exceeded.

IV. Model description

A. Model assumptions

The assumptions for the system described in Fig. 1 are:

- Driving and refilling of FCEVs occur within 1 hour timesteps.
- The generation of electricity from each household's PV system is equal.
- The electricity demand from each household is also equal.
- Hydrogen produced in the wind-to-hydrogen system is transported directly to the neighborhood's central hydrogen storage without losses and is readily available.
- The availability of water for electrolysis is not constrained.

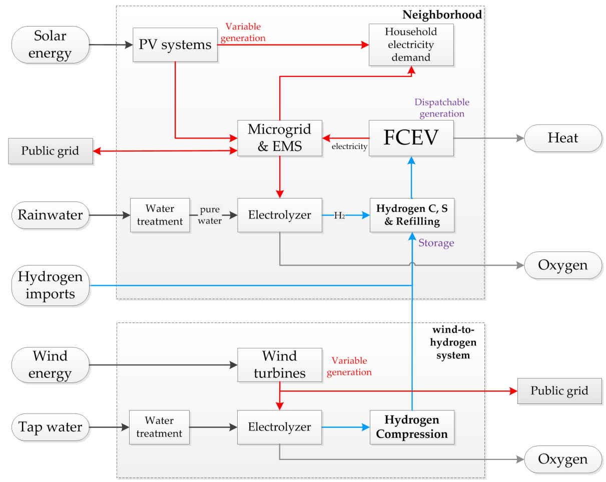

Fig. 1. Description of the CaPP microgrid system

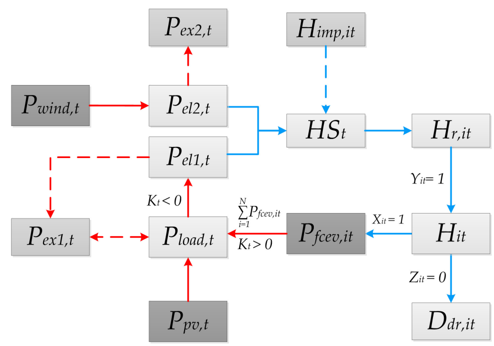

Fig. 2. CaPP microgrid model

- Electricity consumption for water purification, compression and storage of hydrogen are ignored.
- The preferred operating point of FCEVs as power plants is around 10kW[1].
- Hydrogen and power can be imported. Surplus power can also be exported.
- The frequent switching on-off of FCEVs is avoided by operating FCEVs that have been already switched on whenever possible.

B. Problem formulation

The flows and relationships between the system components are shown in Fig.2. The red arrows indicate flow of electricity, and the blue arrows indicate flow of hydrogen. The imports of hydrogen and exchanges with the public grid are indicated in dashed lines. The symbols used in this section are explained in the Nomenclature section.

1) System balance: The imbalance between the PV generation and load is expressed by K_t:

$$P_{pv,t} - P_{load,t} + K_t = 0 \tag{1}$$

[1]Higher outputs are less efficient and not recommended in stationary mode due to thermal management needs [20]. The highest efficiency is approximately 10kW [34]

$$K_t = \sum_{i=1}^{N} P_{fcev,it} - P_{el1,t} + P_{ex1,t} \quad (2)$$

$$if \begin{cases} K_t > 0 & \sum_{i=1}^{N} P_{fcev,it} > 0,\, P_{el1,t} = 0 \quad (3a) \\ K_t < 0 & \sum_{i=1}^{N} P_{fcev,it} = 0,\, P_{el1,t} > 0 \quad (3b) \\ K_t = 0 & \sum_{i=1}^{N} P_{fcev,it} = 0,\, P_{el1,t} = 0 \quad (3c) \end{cases}$$

Power is used for electrolysis ($P_{el1,t}$) when there is a surplus of PV generation. FCEVs are used to provide power when there is a shortage. Power exports are expressed with a negative $P_{ex1,t}$ and imports are expressed by a positive value.

The number of vehicles needed when $K_t > 0$ is determined based on the preferred operating point, P_{pop}:

$$N_{fcev,t} = \frac{K_t}{P_{pop}}\ ,\ N_{fcev,t} \geq 0 \quad (4)$$

$$P_{fcev,it} = \frac{K_t}{N_{fcev,t}}, \quad (5)$$

in which $N_{fcev,t}$ is rounded up to the nearest integer.

Power constraints in the microgrid are:

$$0 \leq P_{pv,t} \leq P_{pv}^{max} \quad (6)$$

$$0 \leq P_{fcev,it} \leq P_{fcev}^{max} \times X_{it} \quad (7)$$

$$-P_{ex1,t}^{max} \leq P_{ex1,t} \leq P_{ex1,t}^{max} \quad (8)$$

2) Electrolysis and hydrogen storage: Electrolysis in the wind-to-hydrogen system is defined by:

$$P_{wind,t} - P_{el2,t} - P_{ex2,t} = 0 \quad (9)$$

The level of hydrogen in the central storage system (HS) at time t is determined by:

$$HS_t = HS_{t-1} + (P_{el1,t} + P_{el2,t}) \times \frac{\eta_{el} \times \Delta t}{HHV} - \sum_{i=1}^{N} H_{r,it} + H_{imp,t} \quad (10)$$

The power and hydrogen storage contraints are:

$$0 \leq P_{wind,t} \leq P_{wind}^{max} \quad (11)$$

$$0 \leq P_{el1|2,t} \leq H_{el}^{max} \times \frac{HHV}{\eta_{el} \times \Delta t} \quad (12)$$

$$HS^{min} \leq HS_t \leq HS^{max} \quad (13)$$

$$0 \leq P_{ex2,t} \leq P_{ex2,t}^{max} \quad (14)$$

3) Availability of FCEVs as power plants: FCEVs can be used ($X_{it} = 1$) as a power plant depending the vehicle's location ($Z_{it} = 1$), the refilling needs ($Y_{it} = 0$) and the hydrogen available in its tank.

$$X_{it} + Y_{it} \leq Z_{it} \quad (15)$$

$$Y_{it},\, X_{it},\, Z_{it} \in \{0, 1\}$$

a) Location: The vehicles' location Z_{it} is determined by the driving behavior, $D_{dr,it}$, which indicates the daily distance driven, the departure time, and the arrival time of a driver.

b) Refilling needs: The refilling needs of the FCEVs are determined by modeling the hydrogen tank in the vehicles:

$$H_{it} = H_{it-1} + H_{r,it} - \frac{P_{fcev,it} \times \Delta t}{\eta_{fcev} \times LHV} - D_{dr,it} \times E_{fcev} \quad (16)$$

The constraints of the hydrogen tank are:

$$H_{it}^{min} \leq H_{it} \leq H^{max} \quad (17)$$

$$H_{it}^{min} = E_{fcev} \times D_{exp,it} \times sf, \quad (18)$$

where $D_{exp,it}$ is the vehicle's daily expected driving distance, and sf a security factor with respect to the daily fuel needs. Refilling occurs when:

$$\text{if } H_{it-1} \leq H_{it}^{min} \begin{cases} Y_{it} = 1 & (19a) \\ H_{r,it} = H_{it}^{max} - H_{it-1}, & (19b) \end{cases}$$

with the following constraints:

$$Y_{it} \times H_{r,i}^{min} \leq H_{r,it} \leq H_{r,i}^{max} \times Y_{it} \quad (20)$$

$$\sum_{i=1}^{N} Y_{it} \leq N_Y^{max} \quad (21)$$

c) Start-up and shut-down of FCEVs: The start-up and shut-down of the FCEVs as power plants is determined using the binary variable X_{it}.

$$X_{it} - X_{it-1} = SU_{it} - SD_{it} \quad (22)$$

$$SU_{it} + SD_{it} \leq 1 \quad (23)$$

$$SU_{it},\, SD_{it} \in \{0, 1\}$$

C. Scheduling mechanism

To schedule power from FCEVs fairly, the controller uses total start-ups done by every vehicle i at time t. For each timestep t, if $K_t > 0$:

- Vehicle indices i are re-ordered from smalles to biggest $\sum_{t=1}^{T} SU_{it}$.
- The required number of FCEVs are selected following said order.
- For every car, the location, refilling status, and hydrogen level are checked. If a vehicle is available, $X_{it} = 1$.
- If a car needs to refill, $Y_{it} = 1$.
- If there are not enough vehicles, power is imported.

V. Test Case

In this section we explain the input data used in the test case, the system parameters, and the results.

A. Input data

Data from the Netherlands was used to simulate the load pattern, PV generation, wind power generation and travel behavior of the FCEV drivers. To represent the load profiles of the 200 households, standardized profile fractions for 2014 were used [35]. The data was used to determine the hourly consumption throughout the year, assuming an average yearly

TABLE I
SYSTEM PARAMETERS

Parameter	Value
N	50
H_{i0}	random from 3 to 5.64 kg
H^{max}	5.64 kg
sf	1.5
HS_0	215 kg
HS^{max}	430 kg
HS^{min}	43 kg
$H^{max}_{el1\|2}$	10.8 kg/h
N^{max}_{Y}	5
P_{pop}	10 kW
η_{el}	70%
η_{fcev}	60%
HHV	39.4kWh
LHV	33.3kWh
E_{fcev}	0.01 kg/km

demand of 3,400kWh. The aggregated load was obtained by multiplying by 200.

The PV generation profile was determined using the PVWATTS calculator [36]. The hourly PV output with a 5kWp system located in Amsterdam and with standard specifications was calculated and multiplied by 200. Raw windspeed data from 2014 measured at the station in *Hoek van Holland* by the Royal Netherlands Meteorological Institute (KNMI) [37] was used to calculate the power generated with a 335kW *Enercon* E-33 wind turbines. The power output was multiplied by two to estimate wind generation using two identical wind turbines with a total capacity of 670kW. Finally, travel data was obtained from the annual report on "Research on Movements in the Netherlands" [38]. Using only displacements made by car drivers, the distribution of drivers was determined for daily distance traveled (on weekdays and weekends), earliest time of departure, and latest time of arrival.

B. System parameters

Using the input data described and system parameters shown in Table I the simulation was run for individual months and a whole year. Monthly runs were done to compare the CaPP requirements and imports in different weather conditions, and the yearly run was done to obtain the annual performance of the microgrid and the distribution of FCEV start-ups.

C. Results

Fig. 3 shows the total monthly generation and consumption of electricity. Wind generation is highly variable throughout the months. PV generation is also variable but follows a clear trend, as well as the load. As a result, power needed from FCEVs varies across the seasons. Table II shows the yearly balance of electricity generation, use, and exchanges with the grid. Very little power is imported during the year, whereas the exports exceed yearly consumption.

The distribution of total start-ups per car at the end of a yearly simulation run (Fig.4) shows that about 60% of the

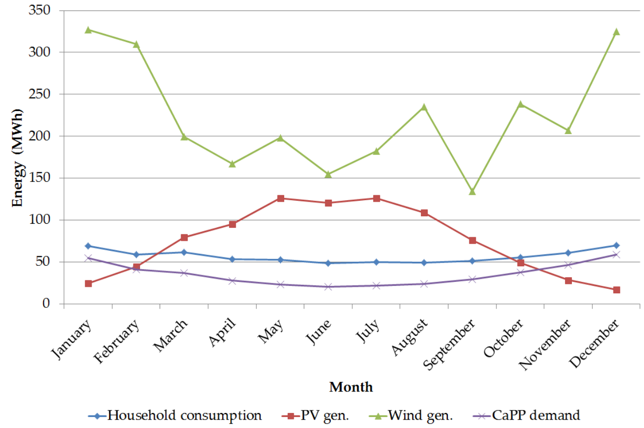

Fig. 3. Monthly renewable supply, household consumption and CaPP demand

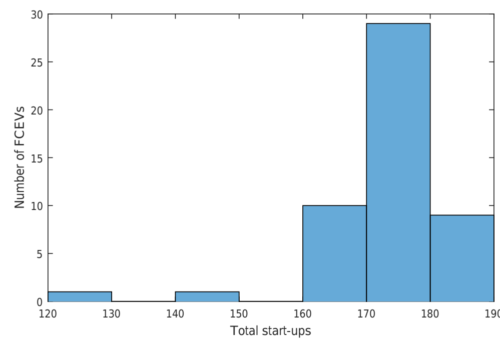

Fig. 4. Yearly distribution of start-ups

cars are used between 170 and 180 times per year. On average, every car is used 173 times during the year, i.e. around 3.3 times per week. The distribution has a bell-shaped curve, with only two outliers. The reason for the low number of two vehicles is that one car drives 5 km every day, and the other one drives 5 km in weekdays and 15 km in weekends. This causes the minimum hydrogen needed to be very low. As a result, the car might be able to drive for many days without refilling, but it is not available for power generation due to the insufficient level of hydrogen for V2G.

Monthly simulation runs show the trend in start-up times in different seasons. In Table III the electricity needed from FCEVs in the months of March, June, September and December is presented. The demand for CaPP power influences the

TABLE III
CAPP POWER (MWH), AVERAGE START-UPS AND REFILLS PER CAR

Month	$\sum_{t=1}^{T}\sum_{i=1}^{N} P_{fcev,it}\Delta t$	Start-ups/car	Refills/car
March	36.55	16.1	9
June	20.05	8.5	5.8
September	29.15	12.5	7.5
December	58.70	21.9	12.7

TABLE II
YEARLY BALANCE, ELECTRICITY GENERATION AND CONSUMPTION IN MWH

Renewable generation	Electricity from FCEVs	Electricity imported	Household consumption	Electrolysis	Electricity exported
$\sum_{t=1}^{T}[P_{pv,t}+P_{wind,t}]\Delta t$	$\sum_{t=1}^{T}\sum_{i=1}^{N}P_{fcev,it}\Delta t$	$\sum_{t=1}^{T}(P_{ex1,t}>0)\Delta t$	$\sum_{t=1}^{T}P_{load,t}\Delta t$	$\sum_{t=1}^{T}P_{el,t}\Delta t$	$\sum_{t=1}^{T}(\lvert P_{ex1,t}<0\rvert+P_{ex2,t})\Delta t$
3,573.66	413.37	6.55	680.01	1,527.73	1,785.83

start-up times and therefore refills per car. June and December are the months with lowest and highest start-up times per car, respectively. Summing up the results from all individual monthly runs, the average start-up times per car in a year is 175, thus only slightly higher than in the yearly run.

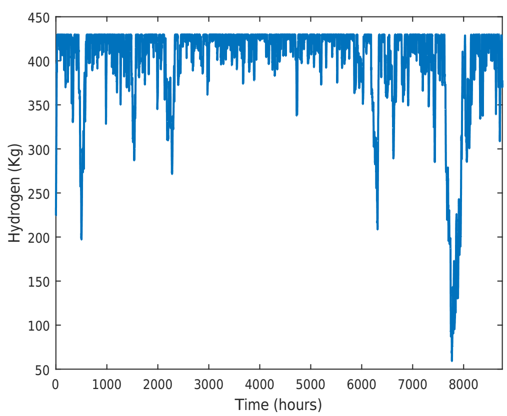

Fig. 5. Hydrogen level in the refilling station throughout the year

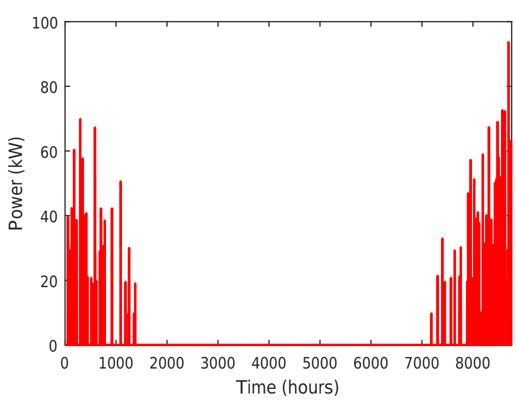

Fig. 6. Power imports throughout the year

Hydrogen does not need to be imported throughout the year, and therefore a storage capacity of 430kg is sufficient for the system described in this paper. Power imports are required in January and February, and from October to December. January and December are the months in which renewable generation is most insufficient.

VI. CONCLUSIONS

In this paper a fair V2G scheduling mechanism for FCEVs was implemented, using the sum of start-up times of every vehicle as a criterion. By using on average each vehicle 3.3 times per week, the system can be operated without power imports during most of the months. The results show that cars need to be used regularly for V2G during the whole year, thus a fair scheduling mechanism can help avoid inequalities in the degree of degradation attributed to V2G operation.

This research and the results could be further improved by introducing stochasticity in the input data and by introducing demand side response. Moreover, the sizing of the system and input parameters could be optimized for a more efficient use of the resources and to reduce exchanges with the grid.

Furthermore, the conditions needed to achieve a fair use of FCEVs need to be investigated. The vehicles in this study are treated as physical devices and drivers' preferences and willingness to participate are ignored. This is part of our further research on the organizational structures, institutional arrangements, and incentives needed to align the behavior of participants with the goals of the microgrid.

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NOMENCLATURE

i	Index for FCEV units, where $i = 1...N$
t	Index for time steps, where $t = 1...T$
$D_{dr,it}$	Distance driven by FCEV i at time t (km)
$D_{exp,it}$	Expected driving distance for FCEV i at time t (km)
Δt	Length of time step (h)
η_{el}	Conversion efficiency of electrolysis (%)
η_{fcev}	Conversion efficiency in FCEVs (%)
E_{fcev}	Hydrogen consumed per km driven (kg/km)
H_{it}	Amount of hydrogen in FCEV i at time t (kg)
H_{it}^{min}	Minimum limit for hydrogen stored in FCEVs (kg)
H^{max}	Maximum limit for hydrogen stored in FCEVs (kg)
$H_{exp,it}$	Hydrogen needed for expected driving needs (kg)
$H_{el1\|2}^{max}$	Max. production capacity, electrolyzers 1, 2 (kg/h)
$H_{r,it}$	Hydrogen refilled by FCEV i at time t (kg)
H_{r}^{max}	Maximum hydrogen refilling quantity (kg)
H_{r}^{min}	Minimum hydrogen refilling quantity (kg)
HHV	Hhigh heating value of hydrogen (kWh/kg)
HS_t	Hydrogen storage quantity at time t (kg)
HS^{max}	Maximum hydrogen storage quantity (kg)
HS_t^{min}	Minimum hydrogen storage quantity (kg)

K_t	Imbalance in the microgrid (kW)
LHV	Low heating value of hydrogen (kWh/kg)
N_Y^{max}	Maximum sum of FCEVs refilling at any time t.
$N_{fcev,t}$	Number of FCEVs needed for V2G at time t.
$P_{el1\|2,t}$	Power used in electrolyzers 1, 2 at time t (kW)
$P_{ex1\|2,t}$	Power exchanged with the grid at time t (kW)
$P_{fcev,it}$	Power delivered by FCEV i at time t (kW)
$P_{load,t}$	Aggregated load at time t (kW)
P_{fcev}^{max}	Maximum generation capacity of FCEVs (kW)
$P_{pv,t}$	Aggregated PV generation at time t (kW)
P_{pop}	Preferred operating point of FCEVs for V2G (kW)
$P_{wind,t}$	Aggregated wind generation at time t (kW)
sf	Security factor for minimum hydrogen in tank
SU_{it}	Binary variable: Start-up of FCEV i at time t
SD_{it}	Binary variable: Shut-down of FCEV i at time t
X_{it}	Binary variable: V2G status of FCEV i at time t
Y_{it}	Binary variable: Refilling status of FCEV i at time t
Z_{it}	Binary variable: Location of FCEV i at time t

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