Simulation of a Vehicle-to-Grid Station for Heavy-Duty Fuel Cell Electric Trucks

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***Abstract*— To combat the continuous increase of greenhouse gas (GHG) emissions in the transportation sector, electric vehicles are starting to be used more such as hydrogen (H_2) in fuel cell electric vehicles (FCEVs). An advantage gained from this solution is to use FCEVs as electricity generation devices in new vehicle-to-grid (V2G) stations. This research aims to model a FCEV-to-grid (FCEV2G) station under different situations and understand the profitability of such a station. The simulations consisted of power generation considering varying FCEV efficiency, hydrogen cycle, participation of FCEV, and a simplified decision-making process. Historic traffic and electricity data of Ontario were used in the analysis. Preliminary results suggested that even under the optimistic assumptions, technologies still need to be improved to make FCEV2G stations economically viable.**

Keywords—hydrogen, FCEV2G, heavy-duty truck, techno-economic analysis

I. Introduction

With the increase in greenhouse gas (GHG) emissions every year, the necessity of a sustainable energy source increases. As transportation accounted for 15% of carbon dioxide emissions in 2022 globally, there is an urgent need for the conversion to cleaner transportation [1]. To reduce the fossil fuels used in transportation, hydrogen (H_2) was proposed to be used as a clean fuel to a proton exchange membrane fuel cell (PEMFC) to produce electricity to power a vehicle, i.e., fuel cell electric vehicles (FCEVs). To minimize the emissions, hydrogen used for FCEVs needs to be green and produced in zero/low-carbon emitting ways. There are several advantages of using PEMFC with green hydrogen: PEMFC vehicles are more efficient than internal combustion engine ones; hydrogen has a higher energy density by weight, and FCEVs have a faster refueling time than battery electric vehicles [2][3][4]. In addition, FCEVs can also be used as electricity generation devices in new refueling stations with fuel cell electric vehicle-to-grid (FCEV2G) functions. FCEV2G is to use PEMFCs on the FCEVs to produce electricity for the grid. In this way, the FCEVs can be used as a power generation device to close the electricity demand-supply gap.

II. Related Work

Recent studies have explored FCEV2G systems that integrate hydrogen-powered vehicles with the electrical grid for sustainable energy solutions. One study demonstrated a modified FCEV with a 9.5 kW AC grid connection, showing its capability for both mobility and power generation. The FCEV performed well with high power gradients, outperforming traditional thermal power plants. In grid-connected mode, the hydrogen consumption was 0.55 kg/h, with an efficiency of 43% [5]. Other studies examined renewable urban energy systems using solar, wind, hydrogen, and FCEVs, suggesting a balanced system requires 20% FCEVs in the fleet [6]. Finally, a demonstration in the Netherlands showed that V2G mode reduced grid electricity imports by 71%, enhancing microgrid energy autonomy [7].

Yet there is limited knowledge on economic planning of large-scale FCEV2G accounting for electricity supply and demand. Most existing studies focus on FCEVs interacting with small energy consumers, such as residential households, rather than considering the broader economic indications of grid-level integration. Given this limited knowledge, this paper extends previous technical demonstrations by simulating the economic viability of large-scale FCEV2G integration under grid conditions.

III. Methodology

A. Problem Description

The main drive for an FCEV2G station is to capitalize on the hourly fluctuations in wholesale electricity prices, which change based on real-time supply and demand conditions in the grid. Generally, when there is a surplus of electricity, the price decreases, and vice versa. Previous observations showed that increased electricity price occurs at similar hours with the traffic rush hours [8]. We hypothesize that the participation in the FCEV2G station will be high in rush hours due to inefficiency of driving at these hours. Therefore, FCEV2G can take advantage of this.

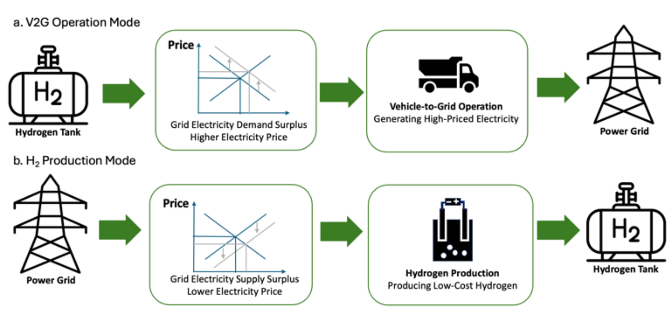

Fig. 1. The two different operation modes of the FCEV2G station: (a) V2G operation mode and (b) Hydrogen production mode.

To summarize the problem, the FCEV2G station has two modes of operation, which can be seen in Fig 1. The V2G operation mode can generate profit to provide electricity at high-prices hours. The other mode, i.e., hydrogen production mode, is operated when there is an electricity surplus, and the electricity price is low. Hydrogen onsite can also come from the green hydrogen market, produced from renewables. Market hydrogen offers stable pricing and reliable availability, but is often more expensive than hydrogen produced with electrolyzers during low electricity price periods. In this study, the FCEV2G problem is modelled in three parts, i.e., electricity production from V2G, the hydrogen cycle, and the participation of FCEV, which will be discussed in the following sections. These different parts can be simulated with historical data to evaluate whether FCEV2G can generate sufficient revenue to cover costs and remain financially viable over time.

B. Electricity Production from V2G

In this study, we considered the degradation of the PEMFCs under travelling but assumed a negligible degradation under V2G operation under a stable power output [10]. Therefore, the performance of the fuel cell in the FCEVs participating in V2G is a snapshot, which is related to the value for how much the fuel cell degraded. For finding the snapshot degradation value, the mileage (X) can be used, which is the total distance that the FCEV has been used for transportation. Mileage values of participating FCEVs can be assumed to be normally distributed to assign a random value to a participating FCEV. Using the average speed (V_{avg}) of a driving cycle for long-haul trucks, 76.56 km/h [9], we can relate mileage with the utilization time (t). The total mileage, X (in km), is calculated by multiplying the utilization time, t (in hours), by the average speed, V_{avg} (in km/h), as shown in Equation (1).

$$X = t * V_{avg} \tag{1}$$

From the Department of Energy 2030 targets for 275 kW heavy-duty trucks, the fuel cell lifetime (t_1), the beginning-of-life voltage (V_0), and the end-of-life voltage (V_1) are reported as 25000 hours, 0.779 V, and 0.70 V, respectively [11][12]. The maximum mileage value, which is 1,914,000 km, is calculated from the fuel cell lifetime, which is the maximum value of the normal distribution. By applying Equation 2, these values provide an hourly degradation rate (r_d), in volts per hour, that can be used to calculate degradation for specific mileage values.

$$r_d = \frac{V_0 - V_1}{t_0 - t_1} = \frac{0.779 - 0.70}{0 - 25000} = -3.16 * 10^{-6}\,\frac{V}{h} \tag{2}$$

The polarization curve, or I-V curve of the PEMFC was obtained from the literature [13] and the active area (A) of the fuel cell was scaled to match that for a FCEV truck, which is assumed to be 330 cm^2 [12]. The electrical power output, P (in watts), is calculated as the product of voltage, V (in volts), and current, I (in amperes). Current can be expressed as the of current density, i (in A/cm²), and the active area of the fuel cell, A (in cm²). Then the power (P), in Watts, output can be calculated as:

$$P = V * I = V * i * A \tag{3}$$

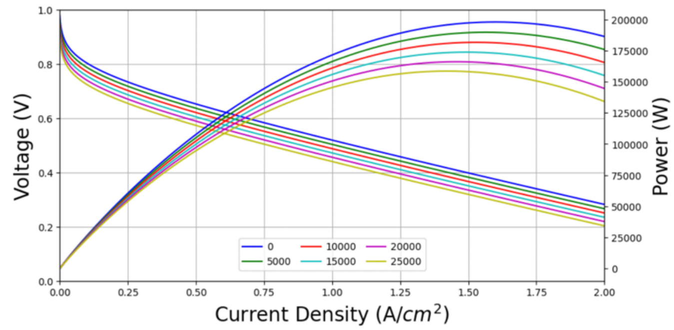

Fig. 2. Polarization and power curve with increasing utilization time

For a participating FCEV in the V2G station, firstly, a random mileage is assigned, and the FCEV's utilization time is determined using equation (1). Then using the degradation in (2), the polarization curve of the fuel cell will be obtained. After that, equation (3) is used to generate the power curve. Finally, the operation power value is extracted from this curve, considering hydrogen consumption, as explained in the next section. Thus, each participating FCEV has a random mileage corresponding to a random power output.

C. Hydrogen Cycle

The hydrogen cycle aims to calculate the production, storage, and usage of hydrogen. As the electricity price is low when there is an electricity surplus, hydrogen is produced on site using electrolyzers and then stored in gas hydrogen tanks. The capacity of the electrolyzer and the maximum amount of hydrogen stored are variables to be optimized and are highly dependable on the hydrogen usage in FCEV2G stations.

The rate of hydrogen consumption ($\dot{n}$), in number of moles divided by seconds, can be calculated with Faraday's Law in equation (4), with the assumption that PEMFC has 100% Faraday efficiency, i.e., every reactant participates in the reaction [14].

$$\dot{n} = \frac{I}{n * F} \tag{4}$$

One thing to note is that the produced current value depends on the selected power output from the power curve. As the mileage for every participating FCEV is different, their hydrogen consumption will also vary. Operating a PEMFC at maximum power outputs leads to inefficiency. A more efficient operating point exists with less power output. To optimize this, a model was used to maximize the difference between power generated and hydrogen consumed, improving efficiency by avoiding excessive hydrogen use for minimal power gain during V2G operation.

D. Participation of FCEV

In this study, we assumed all the 19 ONroute stations that are located in 401 East and West highway are used as FCEV2G stations. To calculate the total number of trucks on the highway at each hour, the Government of Ontario's Traffic Volume data [15] was used, which contains the seasonal average annual daily traffic volumes of conventional trucks in different spots in various highways in Ontario from 1988 to 2021. We filtered the data to Highway 401 in 2021, as it is the most recent. The location description of the spots closest to these ONroute stations were selected: Bainsville, Morrisburg, Malllorytown, Napanee, Trenton, Newcastle, Cambridge, Woodstock, Dutton, and Tilburg.

We assumed that half of the trucks were on the east side and the other half on the west side of the highway, since the data includes the total number of trucks for both sides without specifying their exact distribution. Because there was no FCEV operation on the highway in 2021, we assumed a market penetration of 6% [16] based on historical data to simulate the presence of FCEVs on the highway for FCEV2G. Additionally, the average annual daily number of trucks varies with the seasons throughout the year, introducing seasonal diversity in the data. The data from the Government of Ontario only includes summer and winter, so values for other seasons were obtained by calculating the average for the other 6 months. This variability is important as it ensures the model accounts for fluctuations in truck traffic and reflects real-world conditions throughout different times of the year.

The next step was to convert the annual daily average data to hourly data for each week hour using the congestion scores from the Ministry of Transportation [17]. These scores, which account for jams, delay times, travel speed, and jam length, were summed for each day to calculate hourly percentages. These percentages were then multiplied by the daily average FCEV numbers to determine the hourly truck totals. This approach provides FCEV traffic data that accounts for both seasonal and hourly variations throughout the week.

Now that we have the hourly FCEV truck counts at each location near an ONroute station, the final step is to determine how many FCEV trucks will stop at the station and participate in FCEV2G. We use the congestion scores as a measure of traffic efficiency, where the score indicates the percentage of FCEVs remaining on the road. The remaining vehicles are considered to be idling and available for V2G participation in the FCEV2G station.

E. Electricity Price Categorization

The hourly electricity price influences the operation modes, i.e., V2G operation mode and hydrogen production mode. As the fluctuation of the price can be high, categorization is firstly needed to understand which action to be taken. In this study, the categorization of the electricity price data was done using the K-means clustering method. Before applying the method, the outliers were taken out as K-means clustering is sensitive to outliers. The detection of outliers was performed using the interquartile range method. The lower and upper bounds were calculated using the first and third quartiles, and values outside these bounds were classified as outliers. Then, the outliers were added back to the categorization as the lowest or the highest price categories. Additionally, as the prices have seasonal variations, categorization was done for each season.

The mean hydrogen production cost and V2G revenue values for Ontario in 2023 are presented in Table I. The hydrogen production cost is calculated only for hours with a supply surplus, while the V2G revenue is determined solely for hours with excess demand. The hydrogen production cost is calculated by multiplying the electricity required per kilogram of hydrogen (43 kWh/kg) by the electricity price. The V2G revenue is calculated by dividing the power generated by the truck, multiplied by the electricity price, by the hydrogen consumption in kilograms. These calculations are used to obtain the values presented in Table I.

TABLE I. ONTARIO'S ELECTRICITY PRICE CATEGORIES AND THEIR CORRESPONDING POTENTIAL HYDROGEN COSTS AND V2G REVENUES

Price Category	Hydrogen Production Cost (CAD/kg)	V2G Revenue (CAD/kg)
1	0.33	0.08
2	0.98	0.24
3	1.30	0.41
4	1.67	0.53
5	3.71	1.28

In this study, we analyzed a simplified decision-making process aimed at maximizing profit through the selection of price categories. From this table, the decision of operation at each hour can be made. A simplified approach could be that when the price category is greater than or equal to 3, FCEVs participate in V2G, while the electrolyzer operates at the price category of 1. Since the hydrogen production cost is only calculated for hours with a supply surplus and V2G revenue is determined for hours with excess demand, an optimal decision should ensure that V2G revenue exceeds hydrogen production costs to be profitable. This approach represents one specific example of FCEV2G station operation, which is analyzed in the results section.

F. Base case assumptions

The simulation assume that each station has a maximum electrolyzer capacity of 1 MW, with a hydrogen storage capacity of 10 MWh The electrolyzer operates at 77% efficiency, requiring 43 kWh of electricity per kilogram of hydrogen produced [18]. The electrolyzer capital expenditure (CAPEX) for a maximum capacity of 1 MW was obtained from [21], which is 1381 CAD/kW. The simulation begins with a full hydrogen storage, assuming that the station operates in yearly cycles and ends each year with a full tank. The combined production, processing, and delivery cost of market hydrogen is approximately 7 CAD/kg [19]. The 2023 data for the demand and supply for Ontario is from IESO [20]. The demand dataset includes two types of demand data: Ontario demand, which represents electricity consumption within the province, and market demand, which accounts for both domestic consumption and trade (exports and imports). Since market demand provides a more comprehensive representation of electricity usage, it was used in this study. In contrast, there is only one type of supply data available, representing the total electricity generation in Ontario. The 2023 historic data showed that among the 8760 hours in 2023, there were demands unmet in 7110 (81%) hours and supply surplus in the remaining 1650 (19%) hours.

G. Operation Simulation

The simulation operates in two modes, each requiring three conditions to be met. The V2G operation mode occurs during price categories 3, 4, and 5, as well as during periods of demand excess, provided there is sufficient stored hydrogen. The hydrogen production mode takes place in price category 1 and during supply surplus conditions, as long as there is available storage capacity. If any of the three conditions for either mode is not met, the hour is skipped, and no operation is performed.

IV. Result and Discussion

TABLE II. Profit Distribution of the FCEV2G station

Price Category	Hydrogen Production Cost (CAD)	V2G Revenue with Stored H_2 (CAD)	V2G Revenue with Market H_2 (CAD)
1	-35,992	-	-
2	-	-	-
3	-	32,986	-
4	-	13,444	-
5	-	1,474	3,546
Total Profit (CAD)	15,458		

Table II shows the revenue gained from V2G operation, the cost of hydrogen production, and the total profit. The revenue from the V2G operation can be generated by using stored hydrogen or market hydrogen to feed into FCEV. If the CAPEX for the components of the FCEV2G station are not considered, the station is profitable for Ontario in 2023. However, adding the CAPEX of only the electrolyzer to the total profit causes the station to be unprofitable. One thing to note is that there is one price point in the whole year that uses the market hydrogen instead of the produced hydrogen, due to market hydrogen being less expensive than the mean V2G revenue of the highest price category.

Table III represents the number of hours under different conditions of the two operation modes of the FCEV2G station. Hydrogen production is analyzed under two conditions: Insufficient storage, where production does not occur due to insufficient storage capacity, and sufficient storage, where excess hydrogen can be stored for later use. V2G operation is also considered under two conditions: Insufficient hydrogen, where there is not enough hydrogen available to enable V2G, and sufficient hydrogen, where adequate hydrogen is available to perform V2G operation.

TABLE III. hours of operation modes

Price Category	Hydrogen Production Hours (h)		V2G Operation Hours (h)	
	Insufficient Storage	Sufficient Storage	Insufficient Hydrogen	Sufficient Hydrogen
1	8	264	-	-
2	-	-	-	-
3	-	-	2,784	150
4	-	-	1,523	46
5	-	-	246	8
Total	8	264	4,553	204

Of the 8,760 hours in 2023, 5,029 were identified as potential operating hours, 272 for hydrogen production, and 4,757 for V2G operation. However, the station ran for only 468 hours: 264 hours in hydrogen production mode and 204 hours in V2G mode. Consequently, 8 production hours went unutilized due to insufficient storage, while 4,553 V2G hours were unused because of hydrogen shortages. Altogether, 4,561 potential hours remained idle, highlighting an opportunity to boost profitability by optimizing storage capacity and production rates. These results demonstrate that hydrogen demand during V2G operation outpaces production capacity, making storage sizing and replenishment strategies critical to overall system performance.

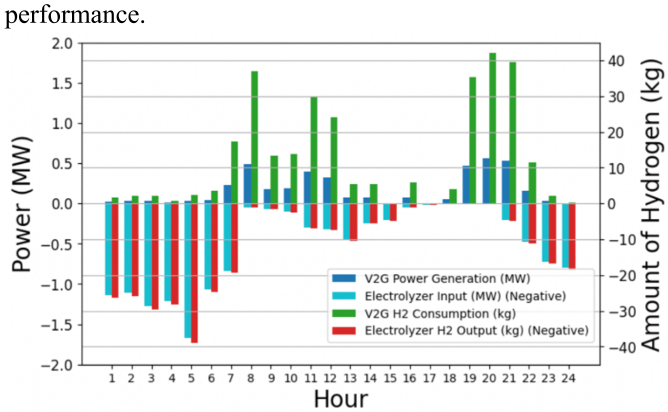

Fig. 3. The hourly average in 24 hours V2G power generation, and hydrogen consumption; and electrolyzer power input, and hydrogen production

Fig. 3 shows the hourly average in 24-hour values for V2G power output, electrolyzer power consumption, and hydrogen usage. These averages are calculated over the station's actual operation hours, 264 h in hydrogen production mode, and 204 h in V2G mode, only when there was sufficient storage capacity for hydrogen production or adequate hydrogen availability for V2G operation.

There are three factors contributing to these results, the first being the difference in energy conversion efficiency. The average energy output of an FCEV in V2G operation is 13.34 kWh/kg of hydrogen, whereas the electrolyzer requires 43 kWh of electricity to produce 1 kg of hydrogen. This discrepancy, illustrated in Fig. 3, indicates significant energy losses in the conversion process, as the hydrogen produced by the electrolyzer retains only a fraction of its original electrical input when later used for V2G. If the energy conversion efficiency of the FCEV during V2G operation were improved, less hydrogen would be required per vehicle, ensuring that more hydrogen remains available for future V2G operations. This is crucial because the hydrogen produced at any given time must be sufficient to support V2G participation across multiple hours, not just within a single operational period.

The second reason is that, as seen in Tables I and II, the cost of hydrogen production is generally higher than the revenue gained from V2G due to the efficiency loss in the fuel cells and the electrolyzers (i.e., low round-trip efficiency). Since hydrogen availability is limited, prioritizing V2G operation at higher electricity price categories would improve profitability. However, the current simulation does not include a priority model, meaning V2G is not optimized for the most profitable price categories, leading to lower overall revenue.

The final reason is that if the price of market hydrogen were lower, it could be used to compensate for hydrogen shortages, allowing for more V2G operation and increasing profitability. For FCEV2G operation to be profitable with market hydrogen, the FCEV revenue in CAD/kg must exceed the market hydrogen cost of 7 CAD/kg. However, the highest average FCEV revenue is only 1.28 CAD/kg under the base case, far below the market hydrogen cost of 7 CAD/kg. This indicates that at current electricity prices, market hydrogen remains too expensive to be a viable option, and its price would need to decrease to enable greater utilization.

V. Conclusion

To reduce GHG emissions, hydrogen is being adopted as a clean alternative fuel that can be used in FCEVs. FCEV can be used as a power generation device. FCEV2G stations can be built to generate power to the grid when there is an electricity excess demand and produce hydrogen when there is an electricity supply surplus. This study simulated an FCEV2G station using historic traffic and electricity data in Ontario. Preliminary results indicate that the operation is not currently profitable due to three key factors: low efficiency in the electrolyzer and fuel cells, missed opportunities to sell hydrogen at higher prices due to its scarcity, and the high cost of market hydrogen compared to relatively low electricity prices. By advancing fuel cell technology, optimizing decision-making protocols, and reducing market hydrogen costs, the economic viability of FCEV2G operations could be improved.

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