

Operation Optimization of Fuel Cell Electric Vehicle-to-Grid in Alberta by Mixed Integer Linear Programming

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Abstract—Hydrogen is expected to play a vital role in decarbonizing the transportation sector, especially heavy-duty trucks due to the short fuelling time and high gravimetric energy density. These fuel cell electric vehicles (FCEVs) can be employed as mobile electricity generators to support grid peak shaving which can be both economically and environmentally desirable. This study uses a mixed integer linear programming (MILP) model to simulate a dedicated vehicle-to-grid (V2G) refuelling station that allows FCEVs to use their onboard fuel cells to supply electricity to the grid by consuming hydrogen that is produced by an on-site electrolyzer or from the hydrogen fuel market. The simulation based on data in Alberta shows a considerable potential of FCEV-to-grid (FCEV2G) to generate profit and reduce carbon emissions. When the maximum number of grid-connected vehicles is 4 or more, the station provides electricity that is cleaner than grid electricity and generates positive profits. This shows that FCEV2G can be a solution to reduce the variation and carbon intensity of the electricity in Alberta.

Index Terms—hydrogen, FCEV2G, heavy-duty truck, techno-economic analysis

I. INTRODUCTION

Energy storage is needed to balance the grid supply and demand, smoothening the supply of variable renewable energy, e.g., wind or solar farm outputs. Several grid-scale energy storage technologies are under development such as pumped-storage hydroelectricity, batteries, and hydrogen, but they usually require a large investment in site preparation and device purchases. Studies [1], [2] suggest that vehicle-to-grid (V2G) can utilize the existing electric vehicles as large energy storage and help ameliorate grid balance and stability. The electric vehicle fleet can store energy from the grid during low-demand hours at low electricity rates, e.g., midnight, and sell the stored energy during peak hours, e.g., daytime. Most of these electric vehicles are powered by lithium-ion batteries. However, in terms of heavy-duty trucks, battery electric vehicles (BEVs) are less competent because of the long recharging time and the low energy density of batteries. On the other hand, hydrogen is considered as more feasible for heavy-duty trucks due to their much shorter refuelling time and higher mass-specific energy and power. With the increasing demand to decarbonize heavy-duty vehicles, the FCEV fleet is expected to expand rapidly. Connecting these hydrogen FCEV trucks to the grid for the

peak-shifting purpose may provide economic incentives for adopting hydrogen FCEVs thus facilitating the emergence of a large-scale hydrogen economy.

II. RELATED WORK

Several studies have attempted to analyze the technical and economic feasibility of FCEV2G. The study in [3] installed an external alternating current (AC) grid connection on a commercial FCEV and experimentally verified that the parked FCEVs can act as virtual power plants. The study in [4] proposed a single-switch high-voltage direct current (DC)-DC converter to integrate the lower-voltage fuel cell (FC) energy units into the higher-voltage grid. In the simulation, they successfully used an FCEV to fulfill the energy need of a household load and supply the excess electricity into the grid and found that daily operation can considerably lower the cost of purchasing grid electricity. The study in [5] proposed an economical optimization model considering FCEV2G integrated green buildings with vehicle visiting time data simulated from the Monte Carlo method and confirms the economic potential of FCEV2G.

However, the existing studies only consider FCs interacting with a small energy consumer such as a household but not directly connecting these FCs with the grid. Besides, a large-scale FCEV2G is more feasible at fuelling stations because FCEVs can use the abundant hydrogen reserves and the existing infrastructure in the stations to lower the cost of FCEV2G. Besides, we are not aware of relevant studies on the economic planning of FCEV2G on a provincial level.

This paper presents a mixed integer linear programming (MILP) model to maximize the gross economic profit while subject to constraints such as the maximum power of electrolyzers and fuel cells. The historical data of electricity price and carbon intensity in Alberta were used. This model delivers the optimal energy storing/releasing schedule for FCEV2G.

III. METHODOLOGY

A. problem description

The FCEV2G happens when FCEVs are parked in V2G-adjusted fuelling stations where FCEVs use the hydrogen

available in the station to generate electricity for the grid during peak hours. The peak hours usually coincide with the highway rush hours (between 7:00 to 11:00 and 16:00 to 20:00) and driving becomes less efficient. Therefore, we assume that FCEV trucks are available for FCEV2G which may not affect their regular services significantly.

The hydrogen used for FCEV2G is from two sources: the hydrogen produced and stored locally in this station (i.e., grid hydrogen), and the hydrogen pipelines (i.e., market hydrogen). The grid hydrogen is produced by an on-site electrolyzer producing hydrogen using grid electricity at low costs during off-peak hours, and the market hydrogen is from a centralized production site that uses low-carbon electricity from renewables and delivered to the station via pipelines. Due to the difference in their production approaches, the grid hydrogen has a fluctuating price corresponding to the variable electricity price while market hydrogen is considered at a fixed price.

The objective of the optimization model is to find the best schedule to run the local electrolyzer and the FCEV2G to obtain the maximum profit in one V2G-adjusted fuelling station. Then, the maximum profits and carbon emissions at different system sizes are compared for analysis.

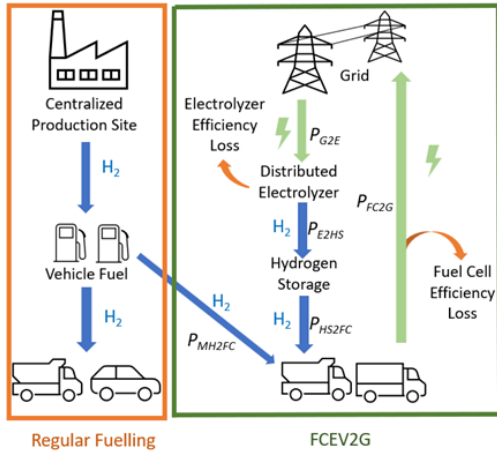


Fig. 1. Electricity and hydrogen flow in regular fuelling and FCEV2G. P_{G2E} , P_{E2HS} , P_{HS2FC} , P_{MH2FC} , P_{FC2G} are the energy flows from grid to electrolyzer, electrolyzer to storage, storage to fuel cell, market hydrogen to fuel cell, and fuel cell to grid, respectively

Figure 1 shows the hydrogen and electricity flow in this scenario. Hydrogen is produced from centralized production sites and distributed electrolyzers in fuelling stations, then it is used to power fuel cells for vehicular mobility or the grid. We assume that the grid hydrogen is only available for V2G not for regular fuelling. The overall energy flow is an open-looped circle between hydrogen and electricity, with efficiency loss occurring at the energy conversion devices and both the grid hydrogen and market hydrogen acting as hydrogen sources. Hydrogen storage in the station is the only component capable of storing hydrogen locally.

B. math model formulation

This problem is formulated as a MILP mathematical problem. The minimum time length is one hour, meaning that the electricity price and energy conversion power maintain constant for one single hour. The start-up time and shut-down time are not considered. The model is designed to maximize the operating profit represented as the following objective function:

$$\sum_{t=0}^T [Profit_{absolute}(t) - Cost_{feedstock}(t) - Cost_{fuelling}(t)] \quad (1)$$

The operating profit is not concerned with fixed costs e.g., capital expenditure (CAPEX) and operational expenditure (OPEX), because they have no effect on the energy conversion planning optimization. The operating profit at time t can be divided into three components determined by:

$$Profit_{absolute}(t) = Price_E(t) \cdot P_{FC2G}(t) \quad (2)$$

$$Cost_{feedstock} =$$

$$Price_E(t) \cdot P_{G2E}(t) + Price_{MH} \cdot P_{MH2FC}(t) \quad (3)$$

$$Cost_{fuelling} =$$

$$Price_E(t) \cdot R_{fuelling} \cdot [P_{MH2FC}(t) + P_{HS2FC}(t)] \quad (4)$$

The absolute profit at time t is the electricity price, $Price_E(t)$, times the fuel cell power output, $P_{FC2G}(t)$. The feedstock cost at time t is the sum of the costs from electrolyzers using electricity, $Price_E(t) \cdot P_{G2E}(t)$, and buying hydrogen from the market, $Price_{MH} \cdot P_{MH2FC}(t)$. The fuelling cost at time t is associated with the total hydrogen consumption, $[P_{MH2FC}(t) + P_{HS2FC}(t)]$, by the electricity price, $Price_E(t)$. The fuelling energy cost ratio, $R_{fuelling}$, is determined by the fuelling station size.

The energy flow of each process is decided by the optimization model but also subject to the following constraints:

1. Direction constraint: all the powers cannot be negative, meaning the energy flow can only happen in the directions indicated in Figure 1.

$$P_i \geq 0, i \in \{G2E, FC2G, E2HS, HS2FC, MH2FC\} \quad (5)$$

2. Power constraint: the powers of the electrolyzer $P_{G2E}(t)$ and fuel cells $P_{FC2G}(t)$ cannot reach above their maximums:

$$P_{G2E}(t) \leq P_{elec,max} \quad (6)$$

$$P_{FC2G}(t) \leq P_{fc,max} \quad (7)$$

Electrolyzer maximum input, $P_{elec,max}$, is set as a constant throughout this study by predetermining an electrolyzer size. Fuel cell maximum output, $P_{fc,max}$, is determined by multiplying the maximum power of one individual FCEV with the number of maximum simultaneous dispensing vehicles (short as number of vehicles). One single FCEV's maximum power is fixed, and the total fuel cell maximum output is adjusted by changing the number of vehicles.

3. Storage constraint: the hydrogen stored in the hydrogen tank cannot fall below zero or exceed its maximum

capacity, S_{max} . In formula 8, $[P_{E2HS}(t) - P_{HS2FC}(t)]$ is the gross hydrogen increase in the storage at time t , and $\sum_{t=0}^T [P_{E2HS}(t) - P_{HS2FC}(t)]$ is the summation of all these increases before time T , i.e. the hydrogen storage level at time T . There is no energy loss considered in the hydrogen storage.

$$0 \leq \sum_{t=0}^T [P_{E2HS}(t) - P_{HS2FC}(t)] \leq S_{max} \quad (8)$$

4. Efficiency constraint: the power output of the electrolyzer and fuel cell are always the input times the efficiency, $\eta_{Electrolyzer}$ and $\eta_{fuelcell}$.

$$P_{E2HS}(t) = P_{G2E}(t) \cdot \eta_{Electrolyzer} \quad (9)$$

$$P_{FC2G}(t) = (P_{HS2FC}(t) + P_{MH2FC}(t)) \cdot \eta_{fuelcell} \quad (10)$$

5. Rush hour constraint: the fuel cells only work for FCEV2G during the rush hours that is 7:00 to 11:00 and 16:00 to 20:00.

$$P_{FC2G}(t) = 0, \quad t \notin [7, 11] \cup [16, 20] \quad (11)$$

Besides, FCEV2G generates carbon emissions when consuming grid electricity, $CI(t) \cdot P_{G2E}(t)$, and market hydrogen, $CI_{MH} \cdot P_{MH2FC}(t)$, but also reduces carbon emissions by supplying electricity with low carbon intensity (CI), $CI(t) \cdot P_{FC2G}(t)$. The total carbon emission change is the sum of both the carbon increase and decrease:

$$Carbon \ Emission =$$

$$\sum_{t=0}^T [CI(t) \cdot P_{G2E}(t) + CI_{MH} \cdot P_{MH2FC}(t) - CI(t) \cdot P_{FC2G}(t)] \quad (12)$$

TABLE I
COST, POWER, EFFICIENCY, AND LIFETIME ASSUMPTIONS

Name	value
Market Hydrogen Production Cost	3 \$/kg [7]
Market Hydrogen Processing and Delivery Cost	2 \$/kg [7]
Storage CAPEX	8 \$/kWh [8]
Storage OPEX	0.08 \$/kWh/year
Electrolyzer Power Output	1 MW
Individual Fuel Cell Power Maximum Output	0.4 MW [9]
Hydrogen Energy Content	120 MJ/kg
Fuel Cell Efficiency	50%
Electrolyzer Efficiency	60%
Compressor Lifetime	10 yrs
Refrigeration Lifetime	15 yrs
Dispenser Lifetime	10 yrs
Electrical Lifetime	30 yrs
Cascade Lifetime	30 yrs
Storage Lifetime	20 yrs
Electrolyzer Lifetime	20 yrs

C. software and data

The mixed integer optimization problem is solved using CPLEX from IBM (academic version) with its Python API. The historical pool price from July to December 2022 is collected from the Alberta Electric System Operator (AESO) [6] and used as the electricity price in this study. The carbon intensity of electricity is calculated by considering the carbon

intensity of each type of power generation from study [7] and the power from each type of power generation from AESO. The carbon intensity of market hydrogen is regarded as that of blue hydrogen from high-performance steam methane reform with a 90% carbon capture rate in study [8]. The cost of the fuelling station is from the Hydrogen Delivery Scenario Analysis Model (HDSAM) from the Argonne National Laboratory [9], which is an Excel-embedded model that estimates the cost of each component in a fuelling station. The cost of the electrolyzers is from Future Distributed Hydrogen Production from PEM Electrolysis from the National Renewable Energy Laboratory (NREL) [10], which considers a future scenario in 2030 with projected technological advancements in reducing electrolyzer cost. The other assumptions and parameters are shown in Table 1.

The electricity price is considered insensitive to the supply and demand change caused by this FCEV2G station because the electrolyzer input and fuel cell output are negligible compared to the total supply in Alberta, which is 8,000 to 12,000 MW. Meanwhile, the electrolyzers in these fuelling stations in the study consume far less than 1% of the total electricity supply.

IV. RESULT AND DISCUSSION

A. operation analysis

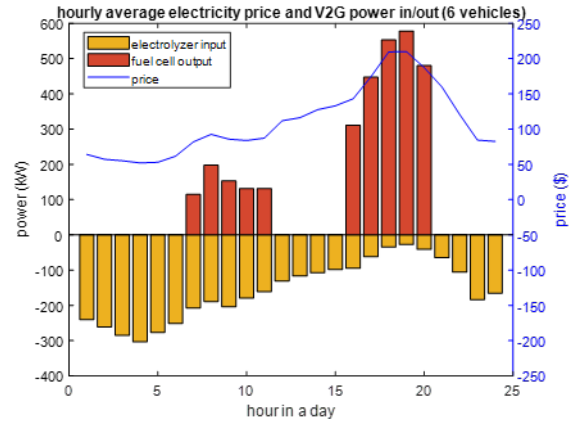


Fig. 2. the hourly average electrolyzer inputs and fuel cell outputs for the 6-vehicle FCEV2G scenario. The hourly average electricity price is also shown.

The optimization was first performed using the data of Alberta at the number of vehicles 2, 4, 6, 8, 10, and 12. Figure 2 shows the hourly average electricity price, electrolyzer power consumption and fuel cell power output for 6-vehicle FCEV2G scenario as an example, which is obtained by averaging the values on each hour for the 184 days. The fuel cells are constrained to operate during rush hours and the total power output increases considerably with more FCEVs. The electrolyzer is shown to operate mainly during off-peak hours but also runs from 16:00 to 20:00. However, the electrolyzer operating power increases disproportionately with that of the FCEVs. Note that the 24 hours in these graphs cannot be regarded as a real day for this is the average data of 184 days

(4416 hours). There are many days astray from the usual peak-off-peak daily electricity demand/supply pattern. For example, the electrolyzer is shown in Figure 2 to run minimally during peak hours (16:00-20:00), but it only runs during off-peak hours in each actual day.

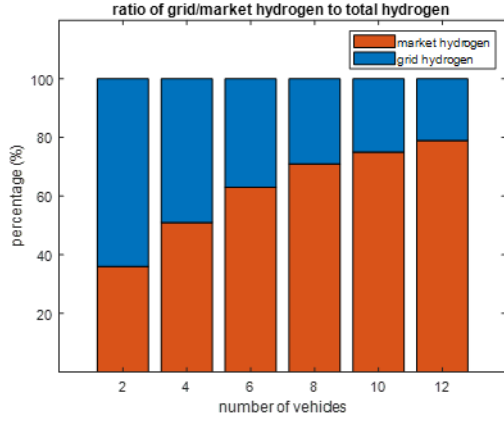


Fig. 3. ratio of grid and market hydrogen to total hydrogen

Figure 3 shows the proportion of grid hydrogen and market hydrogen of the total hydrogen used by the FCEVs for different numbers of vehicles. The market hydrogen is shown to have a larger share when increasing the number of vehicles. In the 2-vehicle scenario, only one-third of total hydrogen is market hydrogen, but it quickly increases and reaches nearly 80% in the 12-vehicle scenario. Increasing maximum fuel cell output encourages the electrolyzer to produce more hydrogen thus increasing the electrolyzer capacity factor, shown in Figure 4. However, this increase wanes with higher maximum fuel cell output. This is because the market hydrogen becomes relatively cheaper when the electrolyzer must operate during more high-price hours to meet the mounting demand. The capacity factor is expected to stop rising when the average grid hydrogen price equals the market hydrogen price.

B. finance analysis

Figure 4 shows the operating profit, fixed cost, and electrolyzer capacity factor. The capacity factor is the total hydrogen produced from the electrolyzer over the maximum amount of hydrogen that the electrolyzer can produce in the same amount of time. The operating profit is shown to increase 4 times from the 2-vehicle scenario to the 12-vehicle scenario, much more rapidly than fixed cost which only increases 2.5 times. With more vehicles available to connect to the grid, the increasing profit outruns the rising cost. One attribution of this is that FCEV2G uses the fuel cells in the FCEVs, hence increasing the maximum fuel cells output generates no cost of buying fuel cells but only requires larger compressors and other fuelling station components. The addition of the available vehicles increases the maximum hydrogen-to-electricity power capacity, thus enabling the FCEV2G to exploit more of the rush-hour window and high-price hours. However, the degradation of fuel cells in the FCEVs due to FCEV2G is not

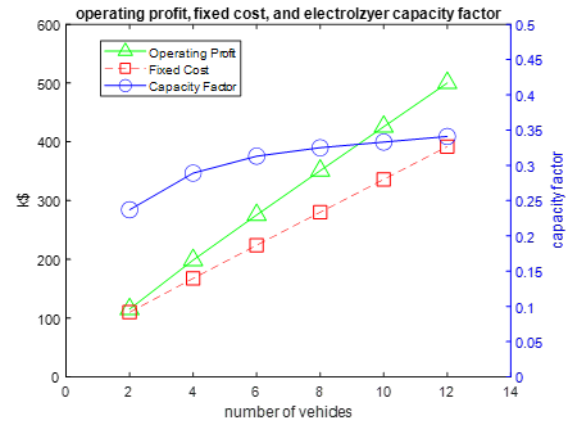


Fig. 4. the operating profit, fixed cost, and electrolyzer capacity factor at different numbers of vehicles

considered in this study, and it may reduce the overall profit due to the earlier retirement of the fuel cells.

The capacity factor increases disproportionately with the profit. It increases from 27.1% at the 2-vehicle scenario to 31.3% at the 6-vehicle scenario but only increases to 34.1% at the 12-vehicle scenario. This indicates the profit increase from selling energy is not solely from the hydrogen stored by the electrolyzer, but more from consuming more market hydrogen.

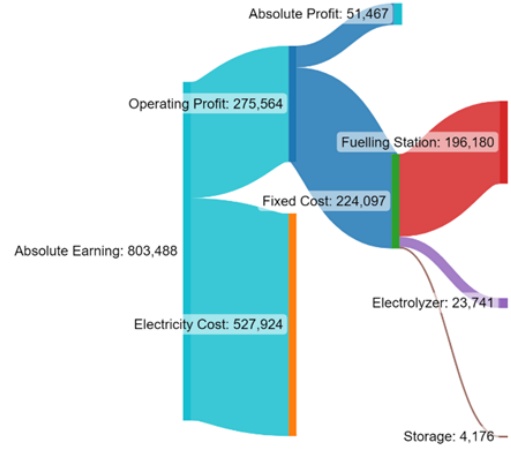


Fig. 5. cash flow chart for the V2G station in the 6-vehicle scenario (unit: USD)

Figure 5 shows the breakdown of the cost and earnings in the 6-vehicle scenario, which provides an overview on the cash flow. In this case, the electricity cost negates 65% of the absolute earning due to the high-efficiency loss in the roundtrip (i.e., electricity-hydrogen-electricity cycle). Regarding the fixed cost, almost 90% is attributed to the fuelling station. The storage only accounts for a very small part of the total cost.

C. carbon emission analysis

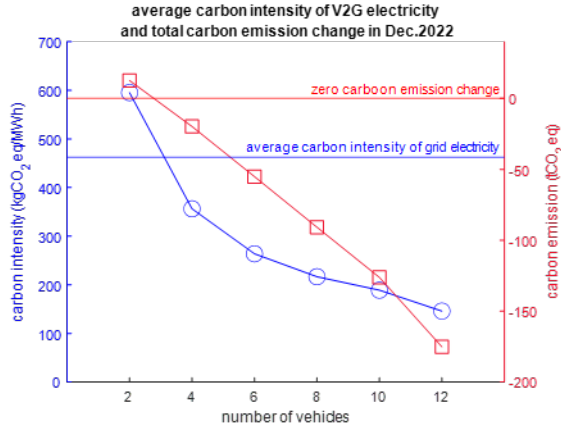


Fig. 6. average carbon intensity of V2G electricity (blue) and carbon emission reduction of V2G (red) in December 2022

In Figure 6, the blue circles are the carbon intensity of the electricity from FCEV2G, and the red squares are the total carbon emission change from this FCEV2G station. The blue horizontal line represents the average carbon intensity of current Albertan electricity, and the red horizontal line indicates zero emission change. The carbon intensity below the grid electricity line means the FCEV2G electricity is less carbon-intensive, and the emission below the zero-emission line means this FCEV2G station reduces carbon emissions. Only December 2022 data is compared due to the availability of the data. The carbon intensity of the 2-vehicle scenario is higher than that of the grid electricity but it rapidly declines with more FCEVs available for grid connection. This is due to more vehicles leading to lower grid hydrogen share, which has a much higher carbon intensity than market hydrogen. The profile of the total emissions has a similar trend to that of the carbon intensity but its declining speed does not slow down with more vehicles. This is because more vehicles connected to the grid result in not only overall cleaner hydrogen but also more total hydrogen amount.

V. CONCLUSION

In this study, a MILP optimization model is used to simulate an FCEV2G and maximize its economic earnings by finding the optimal grid-connection schedule and system power input/output. Results show that such FCEV2G stations can be financially profitable if the maximum number of simultaneous parking vehicles exceeds four. More vehicles available for grid connection leads to a larger proportion of market hydrogen compared with grid hydrogen. The feedstock cost contributes most to the total cost, followed by CAPEX and OPEX mainly from the fuelling station. This FCEV2G also shows the potential of lowering electricity carbon emissions by supplying low-carbon electricity to the grid. A larger station leads to higher carbon reduction potential. This study shows that FCEV2G can be both economically and environmentally beneficial in

regions like Alberta, Canada, whose grid electricity is price-volatile and carbon-intensive. The future step will be focused on including the driving behaviours of heavy-duty FCEVs and the sensitivity analysis.

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