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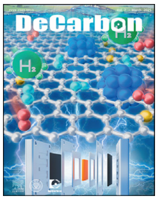

Research Article

Evaluating the economic and carbon emission reduction potential of fuel cell electric vehicle-to-grid

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ABSTRACT

As part of the effort to achieve net zero, hydrogen will become significantly used in transportation and energy generation by 2050. Hydrogen is fit for long-haul vehicles because of the short refueling time and long range of using hydrogen as onboard storage instead of batteries. Meanwhile, hydrogen can also be used for long-time grid energy storage because of the low material cost and low self-discharge. By using fuel cell electric vehicles (FCEVs) for energy generation, the fuel cells (FCs) in idle FCEVs can be connected to the grid (FCEV2G) and supply electricity to the grid by consuming hydrogen stored in a station. In this way, the hydrogen usage in the transportation and energy storage sectors can be synergically integrated. A mixed integer linear programming (MILP) model is established to simulate and evaluate the economic and environmental potential of the operation of a FCEV2G station. The station's profit and carbon emission reduction potential depend on the traffic and electricity profiles. It is estimated that a net profit of 233,976 USD can be generated and simultaneously 210 tonnes carbon emissions can be reduced, using the historic traffic and electricity data of Alberta. Furthermore, considering the Canadian carbon tax in the optimization increases the net profit and carbon reduction to 246,704 USD and 377 tonnes, respectively. Meanwhile, using electricity data with lower carbon intensity and less fluctuation, e.g., that in Ontario, significant technological improvements are needed to make the FCEV2G station operation economically viable. These results demonstrate the potential of FCEV2G in generating monetary incentives and environmental benefits by integrating the transportation and energy storage sectors.

1. Introduction

Countries are committed to achieving net-zero emissions by 2050, including Canada and all other G7 countries [1,2]. Among all the pathways to Net Zero, clean hydrogen is recognized as a promising energy carrier: many nations, including Canada [3], the UK [4], and Germany [5], have proposed strategies for promoting the use of clean hydrogen in various sectors, such as energy and transportation. For example, the government of Canada sets goals that by 2050, the country will produce 20 Mt low-carbon hydrogen per year, accounting for 30 % of its total energy delivery and reducing 190 Mt greenhouse gas emissions [3].

Hydrogen can be utilized to decarbonize different sectors such as transportation and energy storage and is expected to be widely used in these sectors by 2050 [6]. Transportation, for example, accounts for almost one-quarter of global energy-related carbon emissions [7]. According to International Energy Agency (IEA) projections, transportation carbon emissions must decrease by an average of 3 % annually to achieve Net Zero, but the sector's carbon emissions have been increasing by 1.7 % per year over the past 30 years [8]. Therefore, it is critical to reduce the dependence on fossil fuels by electrification or clean fuels to decarbonize transportation, such as adopting hydrogen in vehicles [9] and trains [10]. On the other hand, in the energy sector, implementing adequate large-scale energy storage is essential for shifting from fossil fuels to renewable sources. The intermittent nature of renewable power generation poses challenges on balancing it with the energy demand and as a result, an enormous amount of renewable energy is curtailed to balance the grid. It was reported that wind and solar power generation without enough energy storage capacity would result in large energy curtailment and negative pricing in China, Germany, and the US [11]. Large-scale energy storage can be a buffer between the intermittent renewable power generation and electricity demand, reducing energy curtailment and grid-balancing issues of integrating renewable sources into the grid. In addition, large-scale energy storage can help decouple and regulate electricity supply and demand, helping build local grids and boost grid security [11].

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A net-zero economy may benefit from integrating the transportation and electricity sectors, such as battery electric vehicle-to-grid (BEV2G), a product of decarbonizing transportation and implementing large-scale energy storage in the electrical grid. BEV2G uses battery electric vehicles (BEVs) as moving energy storage and controls the charging and discharging of these EVs to create a collective large-scale energy storage [12]. Considering the rapid growth of BEV fleets and the fact that cars are mostly parked (for example, 95 % of the time in Ontario [13]), the collection of idle BEV batteries has a considerable capacity for large-scale energy storage: it is reported that V2G can utilize 50 million BEVs worldwide [14]. By utilizing these batteries in BEV2G, the BEV utilization rate is significantly increased and the installation cost for large-scale energy storage is greatly reduced compared with other grid-scale energy storage approaches (e.g. compressed air [15], pumped hydro [16], and batteries [17]). A study concluded that BEV2G can offer significant energy storage to the grid at a low installation cost, thanks to the increase of the BEV fleet [18]. In summary, BEV2G is a cost-effective way to provide energy storage for grid balance services.

Indeed, BEV2G has great potential benefiting the grid, but it still faces some challenges. One is the high investment required for plug-in connectors and metering equipment for connecting BEVs to the grid and collecting information such as the state of charge of the batteries as well as the cost of establishing a smart and efficient telecommunication system between BEVs and grid operators [19]. Another challenge is the uncertainty of BEV owner behaviors such as the schedules of BEV charging and the states of charge at the start of BEV-grid connection [20]. As a result, probabilistic methods are frequently used in BEV2G research, such as in optimizing the coordination of BEVs with a distribution feeder reconfiguration (DFR) strategy and in analyzing the impact of BEV2G on power grids with a new stochastic framework based on unscented transformation [21]. In addition, battery degradation is also a concern for BEV2G because additional charging/discharging cycles and accelerated battery degradation lead to a higher cost of replacing the batteries [22]. A series of research has been conducted to analyze and mitigate battery degradation in BEV2G such as evaluating the impact of BEV2G on battery degradation [23] and finding the optimal charging profile to minimize battery degradation with an adaptive multistage constant current – constant voltage (MCCCV) strategy [24].

Like BEVs, FC electric vehicles (FCEVs) are an alternative for decarbonizing transportation because hydrogen is a strong clean fuel candidate, especially for heavy-duty and long-haul transportation. FCEVs usually have a longer range and shorter refueling time than BEVs and these performance parameters are very important to long-haul heavy-duty vehicles [25]. In terms of large-scale energy storage, hydrogen is a competitive energy storage medium with higher gravimetric energy density than all common conventional fuels (such as methane, liquid natural gas, and propane) [26], and higher volumetric energy density than lithium-ion batteries (e.g., compared to 700-bar compressed hydrogen) [27]. As for large-scale energy storage, hydrogen storage has lower disposal pollution [28], lower material cost [29], and lower self-discharge rate [29] compared to battery storage. It was also found that hydrogen can complement lithium-ion batteries to lower energy storage costs [30]. In summary, similar to batteries, hydrogen has a tremendous potential both as vehicle fuel and as an energy storage intermediate. Thus, the principles of BEV2G may be transferrable to integrating FCEVs with large-scale energy storage, i.e., connecting FCEVs to the grid (FECV2G) as an alternative to BEV2G.

FCEV2G integrates the usage of hydrogen in transportation and large-scale energy storage to increase the benefits of hydrogen in the future economy. There are existing pilot FCEV2G projects. For example, Robledo et al. studied the connection of a Hyundai ix35 FCEV to a residential microgrid with an off-board inverter and obtained a 44 % tank-to-grid efficiency while FCEV2G also offered balanced services including fixed power output and load following [31]. The same group also modeled a large-scale FCEV2G with predicted electricity data in five European countries in 2050 assuming that 50 % of passenger cars will be FCEVs, and they found it can fully balance a grid with 100 % intermittent renewable supply [32]. Besides, Zhang et al. experimented with a renewable-battery-FCEV-building multi-energy system and implemented a cogeneration system to recover waste heat from the FC [33]. The emerging research works on FCEV2G show a burgeoning interest in FCEV2G.

As more and more FCEVs, especially trucks and other heavy-duty vehicles, are expected in the future traffic, the coordination to connect these vehicles to the grid by using their FCs as electricity generators needs to be optimized. In addition, we also need to quantify the economic benefits of FCEV2G from selling electricity to the grid and eliminating the need for purchasing additional FCs as distributed electricity generators. The carbon emission reduction from FCEV2G also needs to be studied to understand the optimal connection strategy. Most of the reported research on FCEV2G is a FCEV connected to a microgrid of a building or a combination of FCEVs and BEVs in a larger grid, while there is a lack of research on a FCEV-only system connected to the electricity grid.

This study focuses on quantifying the economic and environmental benefits of FCEV2G under two electricity grid scenarios, e.g., the high-carbon electricity mix in Alberta and the low-carbon electricity mix in Ontario. Both the hydrogen produced onsite using off-peak electricity and produced offsite in centralized production sites with curtailed renewable energy were considered. We established a mixed integer linear programming model (MILP) to simulate the operation of a FCEV2G station that receives FCEVs, which generate electricity using hydrogen that is produced onsite and offsite, and sells electricity generated by FCEVs to the grid. We compare the result of FCEV2G using high-carbon electricity with the result of using low-carbon electricity to investigate the potential of FCEV2G in regions with different electricity carbon intensity values. We also compare the results with and without in-effect carbon tax to explore how imposing carbon tax may change the economic and environmental effects of FCEV2G. This study offers insights into the prospect of FCEV2G, helps understand the operation of a FCEV2G station, and identifies obstacles toward a large adoption of FCEV2G for combining profitability and net zero commitment.

2. Optimization methodology and MILP model establishment

2.1. Model description

The concept of FCEV2G is to combine hydrogen technologies in two sectors, i.e., FCs in vehicles and energy storage or buffering. A regular hydrogen energy storage/buffering system typically produces hydrogen from excess grid electricity or electricity generated by renewable sources that is above the transmission limit of the grid. Its primary components include electrolyzers, hydrogen storage tanks, and FCs for purposes of hydrogen production, storage, and conversion to electricity, respectively. By introducing FCEV2G to the grid energy storage, FCs on the vehicles can be used to replace standalone stationary FCs for electricity generation, which can reduce the investments in energy storage systems.

In this study, we model a FCEV2G station as shown in Fig. 1. It has the following major elements.

- Onsite electrolyzers that produce hydrogen by using electricity from the grid.
- An onsite hydrogen storage system that stores locally produced hydrogen.
- Dispensers that distribute hydrogen into FCEVs and connect them to the grid.
- Access to the hydrogen market, i.e., hydrogen pipelines.
- A connection to the local power grid.

Note that only the hydrogen in the station, either onsite produced (i.e., grid hydrogen) or offsite produced and transported to the station (i.e., market hydrogen), is used, rather than the hydrogen onboard on

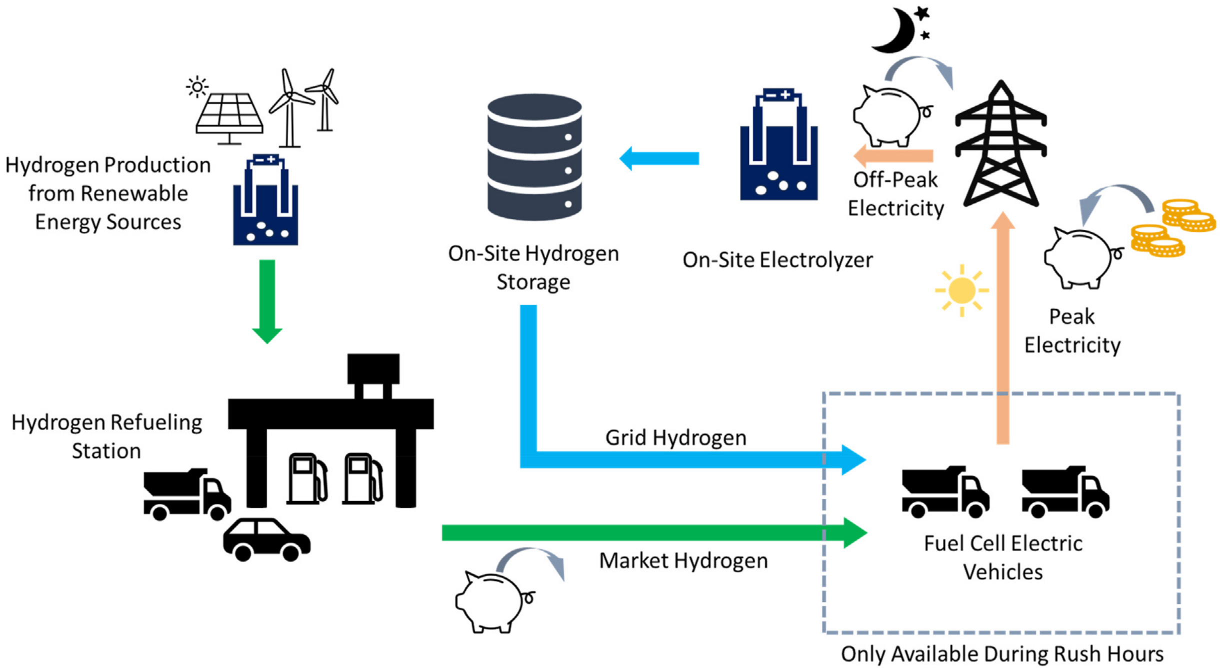

Fig. 1. Schematic of the FCEV2G using hydrogen produced onsite (i.e., grid hydrogen) and from the market (i.e., market hydrogen).

FCEVs. This is because the onboard hydrogen is usually compressed at high pressures (e.g., 350 or 700 bar) to have high volumetric energy density at a higher cost, while hydrogen in the station can be at lower pressure (20–125 bar in this study [34]). Compressing hydrogen into high pressure involves high costs and is unnecessary for FCEV2G. More of this will be discussed in Section 2.6.

Fig. 1 illustrates the electricity and hydrogen flow pathways in the FCEV2G station. Blue arrows are the pathways of grid hydrogen from the onsite electrolyzers to onsite hydrogen storage to FCEVs, while green arrows are the pathway of market hydrogen from the production site to hydrogen refueling stations and then to FCEVs. The production of this market hydrogen is assumed to be from large renewable energy sites such as wind farms and solar farms. Orange arrows are electricity supplied by FCEVs to the grid and electricity drawn from the grid by the onsite electrolyzers.

2.1.1. FCEV2G station location

To use these FCEVs in traffic streams for grid connection, FCEV2G stations must be located close to FCEV traffic. At such a location, e.g., co-location with refueling stations on highways, the FCEV2G stations can have access to both the grid and hydrogen sources.

2.1.2. Hydrogen source

Hydrogen can be produced either onsite using low-cost and low-carbon off-peak grid electricity or produced offsite in centralized production sites with low-cost and low-carbon renewable power. The onsite electrolyzers strategically select the time and amount of hydrogen production according to the grid electricity prices and carbon intensity for maximizing the net profit and minimizing carbon emissions, respectively. The hydrogen produced onsite will be stored in an onsite hydrogen storage. Meanwhile, hydrogen may also come from the low-carbon hydrogen fuel market that is produced offsite. The market hydrogen is assumed to have a fixed price and carbon intensity in this study.

2.1.3. Grid connection strategies

It is important for the FCEV2G stations to strategically decide the time and amount of energy buying and selling to achieve and maximize profit generation and carbon reduction. The decision should be made according to the prices and carbon intensities of the electricity at different times in addition to the capacities of the FCEV2G stations. This study aims to simulate this operational optimization to investigate the potential of FCEV2G to generate profits and reduce carbon emissions under different circumstances. A mathematical model is established to simulate this process.

2.1.4. Revenues and costs

The operating expenditure of the FCEV2G station occurs when purchasing market hydrogen and grid electricity. On the other hand, revenue is generated when FCEVs are generating electricity to the grid. The net profit of this FCEV2G station is the difference between the revenue and the expenditure. This generated profit can be shared between the FCEV2G coordinator and the FCEV owners, the process of which is out of scope in this model.

2.1.5. FCEV2G station operation

The modeled FCEV2G station operates as follows. Some of the FCEVs in the traffic decide to stop in a FCEV2G station to connect to the grid during regular rush hours on a highway, i.e., from 7:00 to 11:00 and 16:00 to 20:00 each day. When connected to the grid, the FCEV utilizes the hydrogen available at the station to generate electricity and supply the electricity to the grid. In this study, we only consider operating FCEV2G in regular rush hours. That is because FCEVs' main purpose is the transportation service, and it is undesired to stop a FCEV and connect it to the grid except during hours when the drivers are required to take a break or when it is inefficient to be on road. During rush hours, traffic congestion reduces the efficiency of transportation and hence encourages the FCEVs to stop and connect to the grid. Moreover, the electricity demand is also usually high during the same time as the traffic rush hours, which makes it more profitable to operate FCEV2G to generate electricity during these periods. The peak-hour electricity is usually with higher carbon intensity due to the use of load-following natural gas power plants. Replacing them with the electricity generated using low-carbon hydrogen in a FCEV2G station may also reduce the overall electricity carbon intensity. However, high prices and high carbon intensity of grid electricity may not always happen at the same time. Therefore, in our model, we set the target functions to maximize net profit and carbon reduction, which will be discussed separately.

2.2. Objective function and constraints

The profits or carbon emission reductions achieved by these FCEV2Gs stations are contingent on the timing and duration of the operation of the electrolyzers and the FCs, and the sources of hydrogen. A mathematical model was built to simulate the operation of such a station which determines the optimal schedule to run the local electrolyzers and connect the FCEVs to the grid.

This optimization problem is formulated as a MILP mathematical problem. We used a minimum time step of 1 h, meaning that the electricity price and power generation/consumption were assumed to be constant within 1 h. The start-up time and shut-down time of the devices were not considered. The problem is formulated in Python and solved with the educational version of a commercial solver, Gurobi.

In the profit optimization, the objective function is to maximize the difference between the revenue from selling electricity to the grid and the cost from buying grid electricity and buying market hydrogen, or in other words, the profit of the FCEV2G without considering the cost of onsite equipment. The equipment cost includes capital expenditure (CAPEX) and fixed operation expenditure (OPEX) of equipment. The reason why we exclude this part of the cost during the optimization is that this study focuses on studying the operation of an FCEV2G station with fixed equipment sizes and thus the site costs are constant. Despite that the equipment sizes are fixed in a base-case optimization, several optimizations with different equipment sizes were conducted for sensitivity analyses in Section 3.2. On the other hand, carbon tax also impacts the profit of this FCEV2G station, and it is clearly stated when it is applicable. Section 4 is dedicated to analyzing how embedding carbon tax into optimization decision-making impacts the overall profit and carbon emission.

The revenue without considering the equipment cost at hour *t* can be expressed as:

$$R(t) = (E_{FC2G}(t) - E_{G2E}(t))P_{GE}(t) + E_{MH2FC}(t)P_{MH} \qquad \text{Eq. 1}$$

Here, $E_{FC2G}(t)$ (MWh) and $E_{G2E}(t)$ (MWh) are the energy from the FCs to the grid and the grid to the electrolyzers at hour *t*, namely the electricity generation and consumption of the FCEV2G station, respectively; $E_{MH2FC}(t)$ (MWh) is the energy in the market hydrogen used in FC operation; $P_{GE}(t)$ (USD/MWh) and P_{MH} (USD/MWh) are the prices of the grid electricity and market hydrogen, respectively. In this equation, the energy input, output, and grid electricity price are time-variant except the market hydrogen price which is assumed constant.

The FCEV2G station consumes two types of energy: grid electricity and market hydrogen. This study uses the historic prices of grid electricity, and they were considered insensitive to the supply and demand change caused by this FCEV2G station. This is because the electrolyzer input and FC output are negligible compared to the total supply (e.g., 8000 to 12000 MW in Alberta [35]). For example, the base case maximum capacities of electrolyzers and FCs in the study are 1 MW and 3.2 MW, respectively, significantly lower compared to the total power supply. The electricity prices are obtained from historical data as elaborated in Section 2.8 and the cost of market hydrogen is shown in Table 1.

Besides, to uniformize the units of different costs, including those of hydrogen, electricity, and equipment, prices in CAD are converted into USD with the average conversion factor (0.75) between the two currencies from 2019 to 2023 [37]. Besides, in the optimization, hydrogen prices are converted from USD/kg to USD/MWh by dividing it by 120 MJ/kg, the lower heating value of hydrogen [38].

Table 1
Cost of market hydrogen in the base case.

Name	Value	Source	Remark
Market hydrogen production cost	3 USD/kg	[36]	Median value of green hydrogen with an electrolyzer capacity factor of 68 %
Market hydrogen processing and delivery cost	2 USD/kg	[36]	Tube-trailer delivery of 5 km

The objective of the optimization is to maximize the sum of the revenue without considering the equipment cost in a defined time period (one year in this study):

$$Obj = max \sum R(t) \qquad \text{Eq. 2}$$

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

2.2.1. Direction constraint

All the energy values cannot be negative, meaning the energy flow can only happen in the directions indicated in Eq. (3).

$$E_i(t) \geq 0, i \in \{G2E, FC2G, E2HS, HS2FC, MH2FC\} \qquad \text{Eq. 3}$$

$E_i(t)$ (MWh) represents the energy flow between different components at hour *t*. The subscript of *E* indicates the two components between which the energy flows and the direction of the energy flow. The subscripts include: G2E (electricity from the grid to the electrolyzers), FC2G (electricity from the FCs to the grid), E2HS (hydrogen from the electrolyzers to the onsite hydrogen storage), HS2FC (hydrogen from the onsite hydrogen storage to the FCs), and MH2FC (imported market hydrogen consumed in the FCs).

2.2.2. Capacity constraint

The input of the electrolyzers and the total output of the FCs are capped by their capacities:

$$E_{G2E}(t) \leq Cap_{El} \times 1h \qquad \text{Eq. 4}$$

$$E_{FC2G}(t) \leq Cap_{FC} \times 1h = N_v(t) \times O_{FCEV,max} \times 1h \qquad \text{Eq. 5}$$

$$N_v(t) \leq N_s \qquad \text{Eq. 6}$$

$$N_v(t) \leq N_t(t) \qquad \text{Eq. 7}$$

Electrolyzer maximum input, Cap_{El} (MW), is preset as constant in a single optimization. $E_{FC2G}(t)$ (MWh) is capped by the product of the number of FCEVs participating in the FCEV2G at hour t, $N_v(t)$ (#), and the maximum power output of one individual FCEV, $O_{FCEV,max}$ (MW). $N_v(t)$ (#) is restricted by two other values: one is the available spots for FCEV2G in the station, N_s, which is the maximum capacity of the station accommodating FCEVs; the other is $N_t(t)$, the number of passing-by FCEVs that are willing to stop and contribute their FCs to FCEV2G, the determination of which will be discussed later.

The storage capacity of the onsite hydrogen storage is expressed as:

$$0.16 \times Cap_{HS} \leq A_{GH}(t) \leq Cap_{HS} \qquad \text{Eq. 8}$$

$$A_{GH}(t) = \sum (E_{E2HS}(t) - E_{HS2FC}(t)) \qquad \text{Eq. 9}$$

The amount of onsite stored grid hydrogen at hour *t*, $A_{GH}(t)$ (MWh) must be between 16 % and 100 % [34] of the storage capacity of the onsite hydrogen tank, Cap_{HS} (MWh). The amount of onsite stored grid hydrogen at hour *t* is determined as the accumulation of incoming grid hydrogen from the electrolyzers, E_{E2HS} (*t*) (MWh), minus the accumulation of grid hydrogen supplied to the FCs, E_{HS2FC} (*t*) (MWh). Cap_{El}, Cap_{HS}, $O_{FCEV,max}$, and N_s in the base case are shown in Table 2.

2.2.3. Efficiency constraint

The energy in the hydrogen entering the onsite hydrogen storage, $E_{E2HS}(t)$, equals the electrolyzer input, $E_{G2E}(t)$, times its efficiency, η_{El}, as

$$E_{E2HS}(\text{t}) = E_{G2E}(\text{t}) \bullet \eta_{El} \qquad \text{Eq. 10}$$

Table 2
Maximum capacity values in the base case.

Name	Value	Source	Remark
Maximum electrolyzer power output (Cap_{El})	1 MW	–	This electrolyzer size makes the amount of used grid hydrogen comparable to the used market hydrogen
Geological gaseous hydrogen storage size (pressure 20–125 bar) (Cap_{HS})	11.9 MW h	[34]	The available storage is 10 MW h, enough for storing 10 hours of maximum hydrogen production using onsite electrolyzers (the impact of this factor is analyzed in Section 3.2)
Maximum power output of one individual FCEV ($O_{FCEV,max}$)	0.4 MW	[39]	The maximum continuous power output of the TRE FCEV model from Nikola Motor
Maximum simultaneous refueling vehicles at the FCEV2G station (N_s)	8	–	As a typical vehicle refueling station

The electricity coming from the FCs and entering the grid is the total hydrogen use, $E_{HS2FC}(t) + E_{MH2FC}(t)$, times the FC efficiency, η_{FC}. η_{FC} and η_{El} in the base case are shown in Table 3.

$$E_{FC2G}(t) = (E_{HS2FC}(t) + E_{MH2FC}(t)) \bullet \eta_{FC} \qquad \text{Eq. 11}$$

2.2.4. Rush hour constraint

The FCEV2G only operates during the rush hours, 7:00 to 11:00 and 16:00 to 20:00. Note that the hours are discrete.

$$E_{FC2G}(t) = 0, \text{if } t \notin [7, 11] \cup [16, 20] \qquad \text{Eq. 12}$$

2.3. Traffic

The FCEV2G station is assumed to be situated beside a highway where some of the passing vehicles choose to stop and participate in the FCEV2G. The number of possible participating vehicles, $N_t(t)$ (#), is determined by multiplying the ratio of trucks to total vehicles, r_{truck}, the market penetration rate of FCEVs in all trucks, r_{pene}, and the drivers' willingness to participate, r_{will}, to the total passing traffic volume, $N_{total}(t)$ (#). In addition, Poisson distribution is adopted to ensure the multiplication result of the four values to be an integer for $N_t(t)$ and introduce traffic unpredictability to the model.

$$N_t(t) = Poisson\left(r_{will} r_{pene} r_{truck} N_{total}(t)\right) \qquad \text{Eq. 13}$$

For $N_{total}(t)$, we used the hourly traffic counts at one location near Calgary as $N_{total}(t)$, in the segment of Alberta Provincial Highway No. 2 from Calgary to Edmonton as an example, as this is one of the busiest highways in Alberta and may have a large number of FCEVs in the future [42]. The values of r_{pene}, r_{will}, and r_{truck} are shown in Table 4.

Table 3
Efficiency values in the base case.

Name	Value	Source	Remark
FC efficiency (η_{FC})	50 %	[40]	Median value of proton exchange membrane (PEM) FCs (this number is the rate of direct current (DC) output energy to the lower heating value (LHV) and excludes power electronics and electric drive)
Electrolyzer efficiency (η_{El})	60 %	[41]	Approximate of several electrolyzer models, including unipolar alkaline from Avalence, PEM from proton, and bipolar alkaline from Stuart (this number is calculated by considering the LHV of H_2 and the required system energy (kWh) for producing 1 kg of H_2)

Table 4
FCEV truck market penetration rate, FCEV2G participation willingness rate, and truck ratio to the total traffic in the base case.

Name	Value	Source	Remarks
FCEV truck market penetration rate (r_{pene})	6 %	[43]	Median value of a forecast range of the market penetration rate of FC heavy-duty vehicles in 2030
Willingness rate (r_{will})	0.6	[44]	Mean ratio of surveyed population supporting energy transition in Alberta
Truck ratio (r_{truck})	0.05	[45]	Ratio of vehicles weighting more than 4.5 t versus total vehicle registration in Canada from 2015 to 2019

2.4. Carbon emission and carbon tax saving

The carbon intensity of electricity, CI ($kgCO_2/MWh$), is the weighted average of the carbon intensity of each electricity supply source, S (MWh): nuclear, gas, coal, etc.

$$CI(t) = \frac{\sum CI_i(t) \bullet S_i(t)}{\sum S_i(t)} \qquad \text{Eq. 14}$$

FCEV2G has a carbon impact on the grid. When FCEV2G supplies electricity to the grid, it works like a power generator and decreases the need of power generation from other generators, thus reducing carbon emissions generated by these generators. Whether FCEV2G decreases overall carbon emissions depends on how the carbon intensity of FCEV2G electricity is compared with grid electricity. The carbon intensity of the electricity provided by FCEV2G electricity may be higher or lower than that of grid electricity, depending on the hydrogen carbon intensity and the FC efficiency. The carbon emission impact caused by the FCEV2G station, which can be either positive or negative, can be determined as the carbon emissions from consuming electricity and hydrogen minus the carbon emission reduction by replacing grid electricity at any time, t:

$$CE(t) = CI(t) \bullet E_{G2E}(t) + CI_{MH} \bullet E_{MH2FC}(t) - CI(t) \bullet E_{FC2G}(t) \qquad \text{Eq. 15}$$

where the first two terms, $CI(t) \cdot E_{G2E}(t) + CI_{MH} \cdot E_{MH2FC}(t)$, are the carbon emissions generated by FCEV2G from consuming grid electricity and market hydrogen, where $CI(t)$ and CI_{MH} are carbon intensities of grid electricity at time t and market hydrogen, respectively. The last term, $CI(t) \cdot E_{FC2G}(t)$ is the carbon emission reduction when the grid electricity is replaced by the FCEV2G electricity.

The carbon intensity of the market hydrogen used in this study in the base case is 20 $kgCO_2/MWh$ [46], which is estimated from wind-powered electrolytic hydrogen, i.e., the carbon intensity of wind power over electrolyzer efficiency η_{El}. The reason why wind power is selected as the energy source of market hydrogen is that the largest renewable energy source in Alberta and Ontario was wind power in 2022 as shown in Fig. S3 [47] and Fig. S4 [35].

By reducing carbon emissions, FCEV2G may generate additional revenues from saving carbon taxes. We used the carbon tax set by the government of Canada in this study, which was 20 CAD/tCO_2 in 2019, increased by 10 CAD/tCO_2 per year between 2019 and 2023, and will increase by 15 CAD/tCO_2 per year starting from 2023 to 2030 [48]. Assuming a constant carbon tax, CT ($USD/kgCO_2$), in each year, the revenue from saving carbon tax, $R_{CT}(t)$ (USD), is determined by:

$$R_{CT}(t) = CT \bullet CE(t) \qquad \text{Eq. 16}$$

Carbon tax savings can either be negative or positive at each hour depending on the carbon emission impact caused by FCEV2G as determined by Eq. (15).

2.5. Grid hydrogen price

The cost of grid hydrogen depends on the grid electricity price at the hour of hydrogen production. The price of grid hydrogen in the onsite hydrogen storage at hour t, $P_{GH}(t)$ (USD/MWh) is defined as the value of the remaining grid hydrogen at hour t, $V_{GH}(t)$ (USD), divided by its amount in the onsite storage at hour t, $A_{GH}(t)$ (MWh).

$$P_{GH}(t) = \frac{V_{GH}(t)}{A_{GH}(t)} \quad \text{Eq. 17}$$

Then, the value of the remaining grid hydrogen at hour t is the value at the previous hour plus the spending on the electricity used for producing the incoming hydrogen minus the value of the hydrogen leaving the onsite storage.

$$V_{GH}(t) = V_{GH}(t-1) + E_{G2E}(t-1)P_E(t-1) - E_{HS2FC}(t-1) \times P_{GH}(t-1) \quad \text{Eq. 18}$$

2.6. Site cost estimation

In the FCEV2G station, FCEVs use the FCs to convert hydrogen to electricity. Different from vehicle refueling, where hydrogen fuel is stored in onboard hydrogen storage, hydrogen in FCEV2G is directly supplied to the FCs. A large proportion of the cost in hydrogen refueling stations is attributed to components related to refueling hydrogen to high pressure, including high-power compressors, cascade tanks, and refueling coolers [34]. Regarding the pressure difference between electrolyzers (30 bar, taking the HyLYZER from Cummins as an example [49]), hydrogen pipelines (50–140 bar for existing natural gas transmission pipelines [50]), onsite storage tanks (>15 bar), and the FC anode pressure (1–2 bar) [51–53], there is a large pressure difference along the path of hydrogen refueling and utilization. To reduce the cost, FCEV2G stations do not need large compressors to raise hydrogen pressure to high levels of a typical hydrogen refueling station at 350–700 bar. Therefore, the primary components of the FCEV2G station may only be the onsite storage and dispensers, as shown in Fig. 2.

The cost of the fueling station is obtained from the Hydrogen Delivery Scenario Analysis Model (HDSAM) from the Argonne National Laboratory [34], which is an Excel-embedded model that estimates the cost of each component in a fueling station. The FCEV2G station in this study adopts gaseous storage. The cost of the electrolyzers is from Future Distributed Hydrogen Production from PEM Electrolysis from the National Renewable Energy Laboratory (NREL) [54], which considers a future scenario in 2030 with projected technological advancements in reducing electrolyzer cost. Financial costs including tax and interest are not included in the site cost estimation.

$$CAPEX_{annualized} = CAPEX_{initial} \times \frac{dr(1+dr)^{LT}}{(1+dr)^{LT}-1} \quad \text{Eq. 19}$$

The CAPEX from the referenced source is the initial capital cost, $CAPEX_{initial}$ (USD). In this study, it is annualized within each component's lifetime, LT (yr) and combined with the optimized annual profit to investigate the profitability of this FCEV2G station. The relation between $CAPEX_{initial}$ and annualized cost, $CAPEX_{annulized}$ (USD), is determined by the equation below [55].where dr is the discount rate. The values of the discount rate, the cost of onsite hydrogen storage, and the lifetimes of different equipment are listed in Table 5.

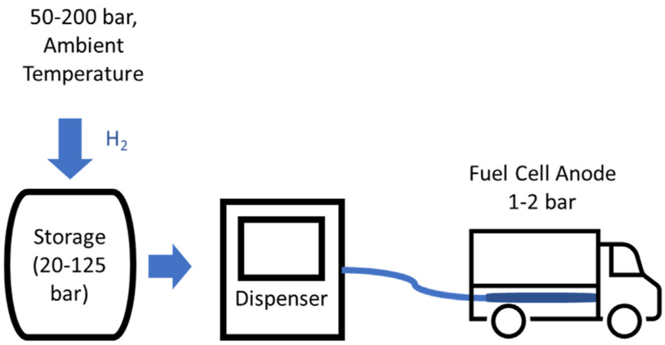

Fig. 2. Schematic of a fueling station using the pressure difference between the hydrogen storage tank and the FC anode.

Table 5
Costs of hydrogen storage, lifetime of FCEV2G components, and annual discount rate.

Name	Value	Source	Remark
Gaseous Geological storage CAPEX	8 USD/kWh	[56]	
Gaseous Geological storage annual OPEX	0.08 USD/ kWh/yr	[57]	Assumed as 1 % of the CAPEX
Dispenser lifetime (LT_D)	10 yr	[34]	
Hydrogen storage tank lifetime (LT_{HS})	20 yr	[30]	
Electrolyzer lifetime (LT_{El})	20 yr	[54]	
Annual discount rate (dr)	0.07	[30]	

2.7. Sensitivity

The generated profits by FCEV2G vary with different parameters such as component sizes and efficiencies. Sensitivity analyses are performed to evaluate different parameters that affect the optimization result. In this study, these parameters include market hydrogen cost, onsite hydrogen storage maximum capacity, electrolyzer efficiency, FC efficiency, number of parking spots for participating FCEVs, market penetration rate of FCEVs to trucks, willingness of participating truck drivers, and input capacity of the onsite electrolyzers.

The sensitivity of the optimization result towards a parameter is the relative change of the result, $\Delta R/R$, over the relative change of the parameter, $\Delta i/i$, as shown below.

$$S_i = \frac{\Delta R/R}{\Delta i/i} \quad \text{Eq. 20}$$

2.8. Electricity data

To analyze the performance of FCEV2G in revenue generation and carbon reduction with different electricity mixes, two sets of electricity prices and carbon intensity data are used in this study. One set of electricity data is from Alberta, Canada, where most of the electricity supply is produced from fossil fuels (gas and coal) and electricity prices are high and volatile. This dataset represents the regions where the grid heavily relies on gas and coal power plants, the grid is carbon-intensive, and the electricity rates are high and unstable. Another set of electricity data is from Ontario, Canada, where most of the electricity is produced from nuclear and hydro energy with steady supply and stable rates. This dataset represents the regions with abundant and stable low-carbon electricity supply that have low grid carbon intensity and stably low electricity prices.

The historical data on the electricity prices and supply breakdown of grid electricity in Alberta are obtained from the Alberta Electric System Operator (AESO) website [35], and the data for Ontario is found from Independent Electric System Operator (IESO) [58]. IESO and AESO are

Table 6
Carbon intensity of different types of electricity supply [46].

Type of Electricity Supply	Carbon Intensity (kgCO$_2$/MWh)
Nuclear	12
Hydro	24
Coal	820
Natural gas	490
Wind	12
Solar	48
Biomass	230

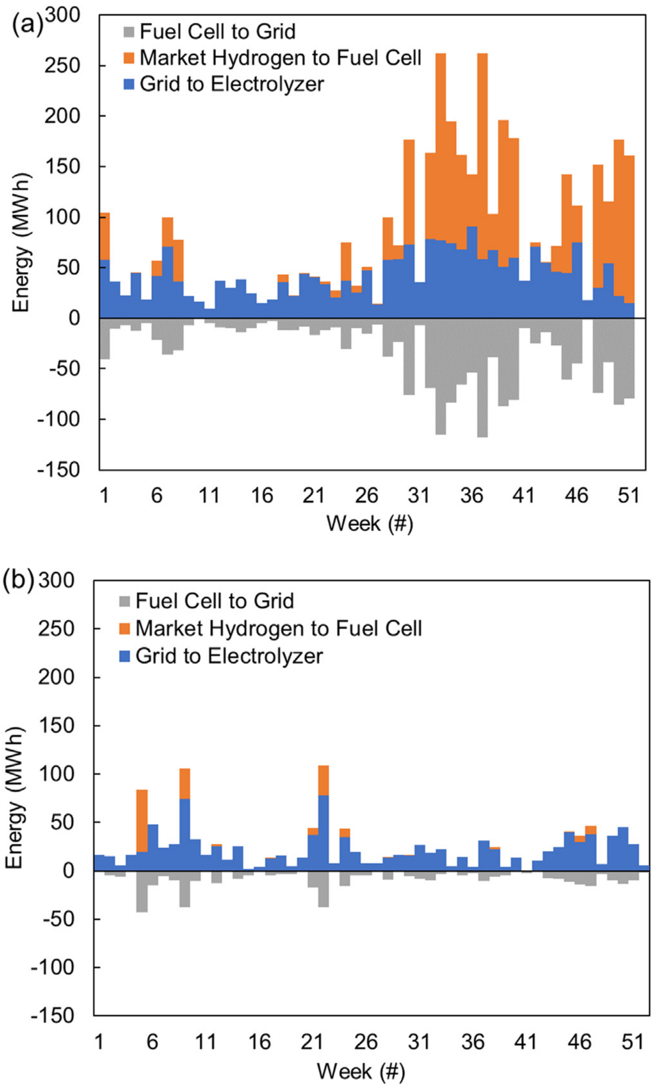

Fig. 3. Amounts of electrolyzer input, FC output, grid hydrogen consumption, and market hydrogen consumption (a) in the base case and (b) in the 2019 case.

Table 7
Annual operation Data in the base case and the 2019 case.

Name	Base Case	2019 Case	Base Case	2019 Case
Annual operating hours	Total (#)	Total (#)	Share of year (%)	Share of Year[a] (%)
Electrolyzer	2222	1132	25.37	12.92
Market hydrogen Buy-in	443	46	12.13	1.26
FC	634	168	17.37	4.60
Annual capacity factor	Total (MWh)	Total (MWh)	Capacity factor (%)	Capacity factor (%)
Electrolyzer	2180.04	1098.96	24.89	12.55
Market hydrogen Buy-in	2048.00	163.20	–	–
FC	1678.00	411.20	100	100

[a] For FCs, only rush hours are considered.

the coordinators and integrators of the electricity systems in each province, offering the historical data of the power output of each generator at each hour and the energy types of these generators. The carbon intensity of different supply types is obtained in a report from Inter governmental Panel on Climate Change (IPCC) as listed in Table 6, and the median values of carbon intensity for each power source are selected for this study [46].

3. Results of high-carbon electricity mix scenario

3.1. *Revenue optimization in base case analysis*

Grid energy storage is particularly needed when there is unstable mismatch between the electricity supply and demand that leads to higher electricity prices. In this scenario, FCEV2G could potentially provide economic benefits. We analyzed the optimized revenue of FCEV2G using the historic electricity generation mix and prices in Alberta in 2022 in the base case, which represents a scenario with rather high and unstable prices and high carbon intensity. The results using the historic data in Alberta in 2019 are also shown for comparison.

3.1.1. *Operation and energy flow*

Fig. 3a summarizes the total energy buying and selling every week in the base case, which are the sums of the hourly buying and selling in each week separately. The grid electricity and market hydrogen consumption are positive values while the electricity generated by FCEVs are negative values, indicating the incoming and outgoing energy flow of the FCEV2G station, respectively. The amounts of the total energy input in a year are higher than that of energy output, because of the efficiency loss occurring in the electrolyzers and FCs. Note that market hydrogen consumption happens simultaneously with FCEV electricity generation because market hydrogen is directly used from the pipelines.

One task for the optimization is to choose which type of hydrogen to be used for electricity production in FCs. According to the data of FC electricity generation in the base case (shown in the supplementary spreadsheet), the following two conditions should be simultaneously fulfilled when the optimization algorithm chooses to use market hydrogen instead of grid hydrogen. One is that when the grid electricity price is higher than 300 USD/MWh, equal to the operational cost of the electricity provided by FCs using market hydrogen. This condition ensures that the electricity generated by using market hydrogen remains cost-competitive with grid electricity in that specific hour. The other condition is that the onsite hydrogen storage should be empty or approaching depletion, as grid hydrogen is not available. This is because the operational cost of producing grid hydrogen from grid electricity needs to be always lower than the market hydrogen cost. There is no incentive to produce grid hydrogen that is more expensive than the market hydrogen, as the latter is assumed to be always available. Therefore, market hydrogen plays a role of supplementing grid hydrogen when grid hydrogen is or is about to deplete. The actual operational cost of producing grid hydrogen and market hydrogen price will be discussed in Section 3.1.3.

In comparison to the base case, the energy buying and selling every week in the 2019 case is significantly lower than the base case, as shown in Fig. 3b. This is because the electricity prices in Alberta in 2022 were much higher and more volatile than those in 2019, shown in Fig. S1, and the function of FCEV2G is to generate profit from buying energy at low prices and sell energy at high prices.

Table 7 reports the annual operation data in the base case and the 2019 case. The top half of the table reports the number of total operating hours and its share in the hours when each component can operate, which is all the hours for electrolyzers but only rush hours for FCs. The bottom half reports the total annual energy inputs, i.e., electricity consumed by the electrolyzers, the purchased market hydrogen, and the total energy output of the FCs. The electrolyzer capacity factor is calculated by comparing its annual hydrogen production with its maximum possible production at its rated capacity. Similarly, the FC capacity factor is calculated by comparing the annual electricity generation of these FCs with the electricity generation when operating at their rated power output in every rush hour.

Key observations from the base case based on 2022 data include the following. First, the capacity factor of the electrolyzers is very similar to the share of the whole year because there are only a few hours when the electrolyzers run at a lower capacity than the maximum capacity, i.e., the hours when the onsite hydrogen storage is close to full. For other hours, the electrolyzers either run at the maximum capacity or idle. Second, the capacity factors of the electrolyzer in the two cases are rather low, which means the electrolyzers only work for a small part of the time in a year. This low utilization of the electrolyzers makes the CAPEX on the electrolyzers account for a substantial proportion of the levelized grid hydrogen cost. The FC capacity factors, on the contrary, are 100 % in both cases, meaning every FCEV occupied in the FCEV2G station always runs at maximum power to maximize the electricity sold to the grid. Unlike electrolyzers whose maximum capacity is constant, the FCEV2G station can adjust the number of FCEVs to change the total maximum capacity of FCs which avoids having unused capacity.

Comparing the base case with the 2019 case, we can find that market hydrogen import in the base case is nearly 10 times that in the 2019 case. This significant difference in market hydrogen use is caused by the higher electricity prices in 2022 than those in 2019 and 2022 (see Fig. S1). In comparison, the onsite hydrogen production in the base case is only around twice that in the 2019 case, indicating that in the scope of this study, the use of grid hydrogen is not as sensitive as market hydrogen to electricity prices because of the limited capacity of using grid hydrogen and the assumed infinite availability of market hydrogen.

Fig. 4 illustrates the energy flows between different components of the FCEV2G process in the base case. There is a large amount of efficiency loss at the onsite electrolyzers and FCs. A total amount of 4228 MWh energy of electricity and hydrogen is consumed by the FCEV2G station in the FCEV2G station, then 1678 MWh is supplied back to the grid and 2550 MWh becomes waste heat, which accounts for 60 % of the total energy input. The large amount of energy waste is a result of the low efficiency of the electrolyzers and FCs. This suggests that FCEV2G is more suitable for where there is large renewable energy production whose unstable output is easier to be stored as hydrogen than transmitted via the electric grid, and this process is abstracted as using market hydrogen in this study. Furthermore, the higher amount of energy waste from the FCs than the electrolyzers suggests increasing FC efficiency will have a higher impact on increasing the overall efficiency of FCEV2G than increasing electrolyzer efficiency.

3.1.2. Onsite hydrogen storage

Fig. 5 illustrates the amount of onsite stored hydrogen in the FCEV2G station whose available storage capacity is 10 MWh of hydrogen. It shows that there is frequent charging and discharging of the hydrogen storage.

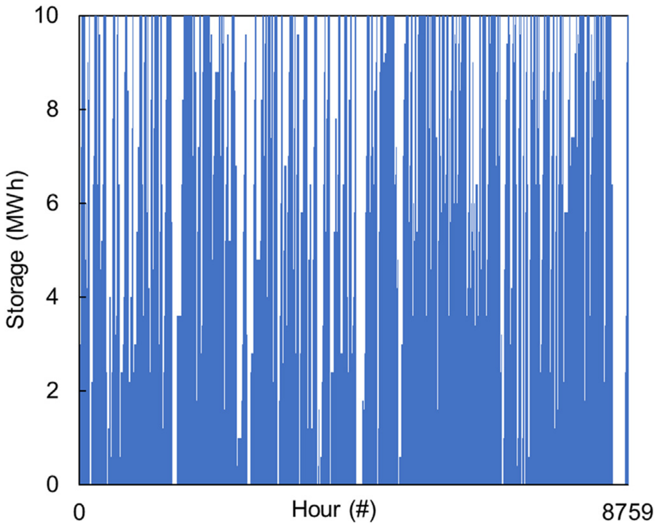

Fig. 5. Amount of onsite stored hydrogen at each hour in the base case.

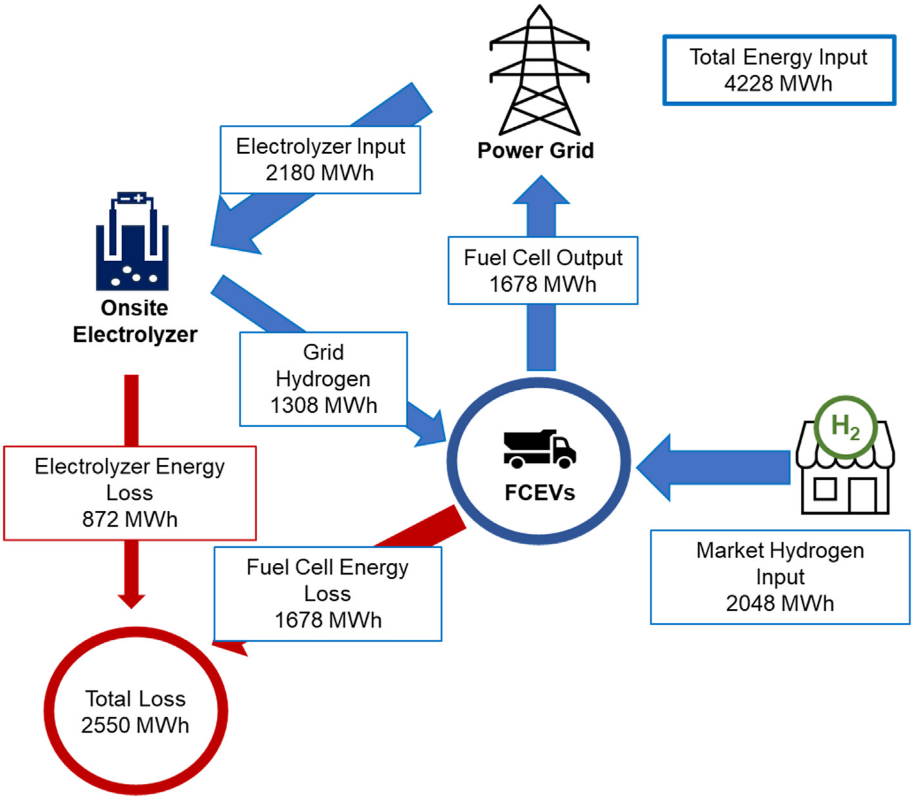

Fig. 4. Energy flow in FCEV2G in the base case with 2022 Alberta data (energy loss is indicated in red).

This is different from the long-term or seasonal patterns seen in some studies where the hydrogen storage levels show clear periods of storing and releasing seasons [30,59]. This is likely a result of the requirement to meet a transient need in the grid in this study, so hydrogen is used as a transient energy storage.

3.1.3. *Comparison between grid and market hydrogen prices*

Grid hydrogen and market hydrogen are the two types of hydrogen supplied to the FCEV2G station. The advantages of grid hydrogen include no delivery cost and the potential to utilize very cost-effective electricity for production. Meanwhile, market hydrogen is assumed to have no storage cost, unlimited availability, and a constant price and carbon intensity.

Fig. 6 shows the hourly operational cost of producing grid hydrogen (depicted in blue) and market hydrogen price (represented by a green horizontal line) in the base case and the 2019 case. Note that the operation cost of grid hydrogen shown in the figure only reflects the electricity cost of producing hydrogen, while excluding the fixed site cost of station components as it is not part of the variable operational optimization. The annual average operational cost of producing grid hydrogen is 61 USD/MWh (2.03 USD/kg) in the base case, which is 40.67 % of the market hydrogen price (5 USD/kg). The operational cost of producing grid hydrogen at each hour is always lower than the market hydrogen price, because there is no incentive to produce onsite hydrogen at a higher operational cost when cheaper market hydrogen is always available. Nevertheless, if including the price of the electrolyzer and onsite hydrogen storage, the grid hydrogen price rises to 187 USD/MWh (6.23 USD/kg), which underscores the significant impact of electrolyzer costs on hydrogen production. The levelized cost of the electricity supplied by the FCEV2G station is 311 USD/MWh, including all the costs, and it is less than 60 % of the average grid electricity price during FC electricity generation, i.e., 529 USD/MWh. Besides, the levelized FCEV2G electricity cost (standard deviation: 65 USD/MWh) is also more stable than the 2022 Alberta grid electricity (standard deviation: 149 USD/MWh, see Fig. S1 and Fig. S2), which is attributed to the electrolyzer's ability to selectively operate during low-price hours. Compared with the base case, the operational cost of producing grid hydrogen in the 2019 case is 39.34 % lower, i.e., 37 USD/MWh, a result of lower electricity prices mentioned above.

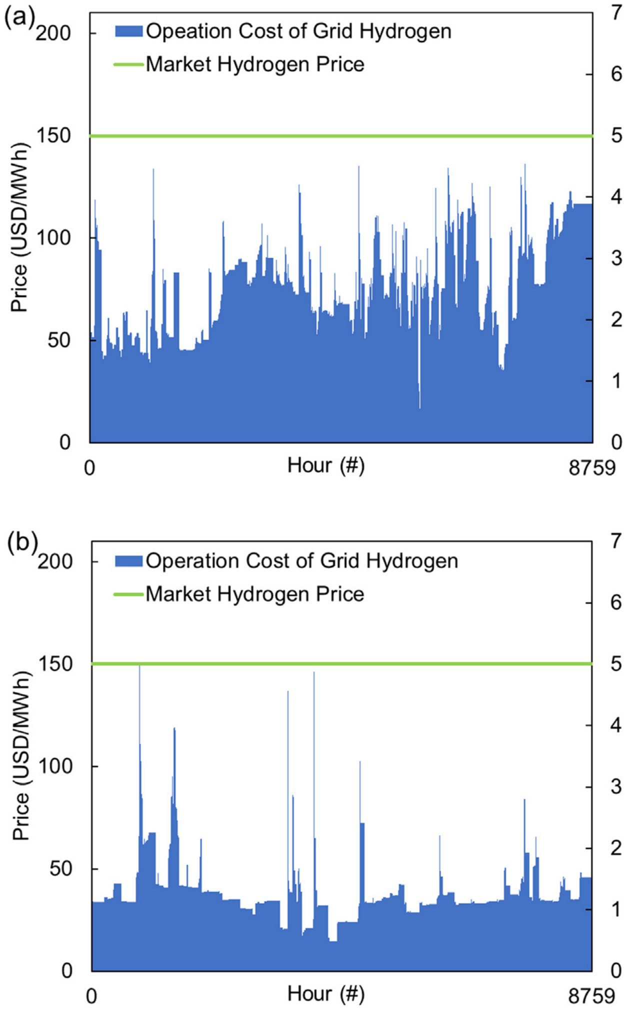

Fig. 6. Operational cost of producing grid hydrogen and market hydrogen price at each hour in (a) the base case and (b) 2019 case (the prices are shown in USD/MWh on the left axis and USD/kg on the right axis, related by using the lower heating value of hydrogen: 120 MJ/kg [38]).

3.1.4. *Cash flow*

A detailed breakdown of the revenue and expenditure in each step of the FCEV2G system in the base case is provided in Fig. 7, illustrating how revenue from electricity sales is allocated among various expenses and ultimately results in net profit. Selling electricity during high-demand hours creates 816,878 USD of earnings. The FCEV2G site cost is the combination of annualized CAPEX and OPEX, which is determined through the method in Section 2.6. About 21 % of the absolute earnings (equivalent to 174,310 USD) is spent on the site where 102,807 USD is on the onsite electrolyzer, indicating a substantial portion of the total cost, and 61,561 USD is allocated to dispenser-related expenses, as storage cost only constitutes a relatively small part of the overall expenditure. In addition, the feedstock costs, i.e., market hydrogen and grid electricity, account for the largest amount of expenditure (408,583 USD), i.e., about half of the absolute earnings. Most of the feedstock cost comes from purchasing market hydrogen even though market hydrogen is used less than grid hydrogen, because market hydrogen is more expensive than the electricity cost of producing grid hydrogen as discussed in Section 3.1.3. As a result, the net profit amounts to 233,976 USD, which constitutes about 29 % of the absolute earnings. Taking the 2019 case for comparison (see Fig. S5), where the operation of the FCEV2G station is not as much as the base case as discussed in Section 3.1.1 and there is a deficit of 85,587 USD from running the FCEV2G station as the operation is not enough to cover the cost of equipment, which is a result of relatively lower and more stable electricity prices in 2019 than in 2022 in Alberta.

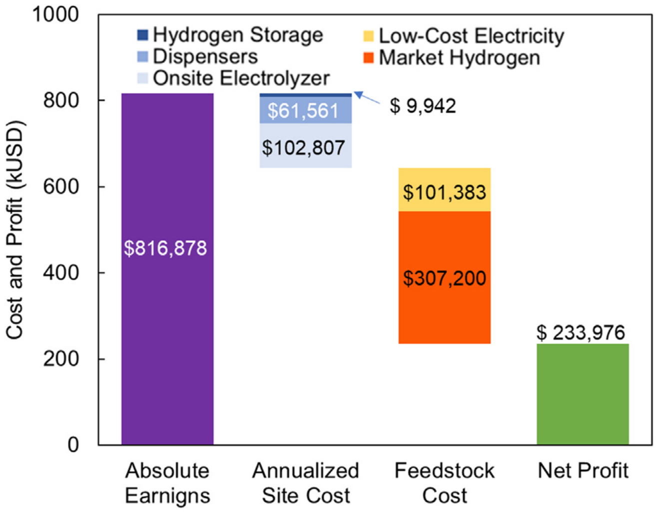

Fig. 7. A breakdown of earnings and costs in the FCEV2G station in the base case with electricity data in Alberta, 2022 (values in USD).

Table 8
Grid hydrogen and market hydrogen use in the base case and 2019 case.

	Base Case	2019 Case
Total hydrogen use (MWh)	3356	822
Market hydrogen (MWh)	2048 (61.02 %)	163 (19.83 %)
Grid hydrogen (MWh)	1308 (38.98 %)	659 (80.17 %)

3.1.5. Carbon emissions

The carbon emission reduction from the FCEV2G operation is also analyzed, which depends on the market hydrogen carbon intensity and the electricity mix used for grid hydrogen production. For the two cases studied, the carbon intensity of the electricity produced from grid hydrogen is more than that of the grid electricity because of the high carbon intensity in the grid even during off-peak hours and the efficiency loss from the electrolyzers. In contrast, the low-carbon market hydrogen has significantly smaller carbon content and can be used to lower the carbon emissions associated with electricity generation. Therefore, the ratio of using market hydrogen over grid hydrogen is a key factor in understanding the different carbon emission impacts of the FCEV2G station under the two cases, which is shown in Table 8. In the base case, the FCEV2G station relies significantly more on market hydrogen, i.e., 61.02 % of the total hydrogen consumption. As a result, the carbon emissions are reduced slightly by 210 t in the base case. By including the carbon tax in Canada, which was 50 CAD/tCO_2 (37.5 USD/tCO_2) in 2022 [60], an extra saving of 7875 USD (241,851 USD in total net profit) can be created in FCEV2G operation. On the other hand, the 2019 case consumes a much lower proportion of market hydrogen, i.e., only 19.83 % of the total hydrogen consumption, because the lower grid electricity prices make electricity generation from market hydrogen less profitable. The significant use of grid hydrogen in the 2019 case leads to an increase in carbon emissions by 361 t, resulting in an additional carbon tax charge that further increases the deficit in the 2019 case.

3.2. Sensitivity analysis in revenue optimization

The sensitivity analysis evaluates the impacts of various parameters on the optimization results of the FCEV2G system, such as the market hydrogen cost, onsite hydrogen storage maximum capacity, electrolyzer

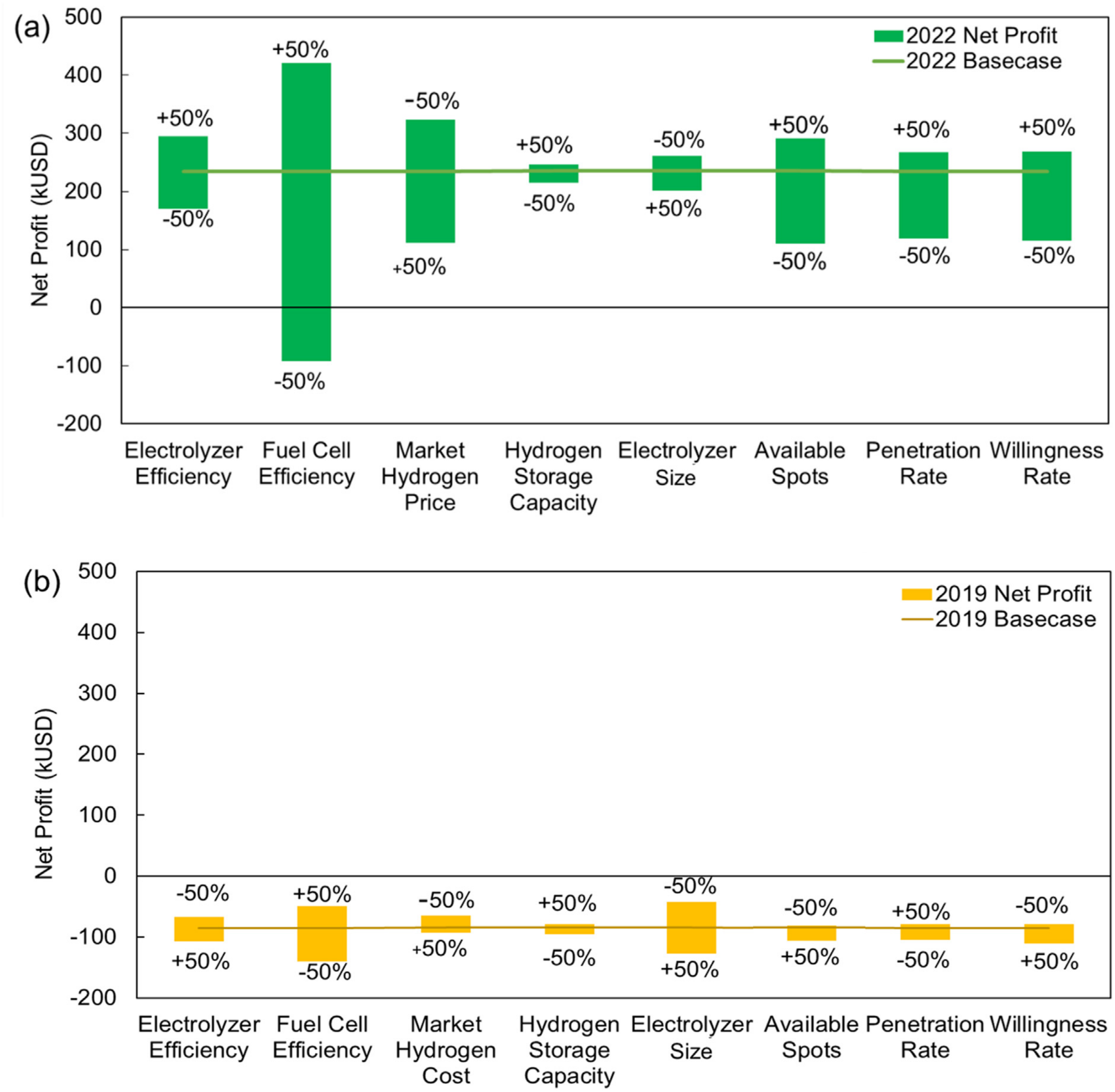

Fig. 8. Optimized profits in cases where each parameter is changed −50 % and 50 % from the base case scenario using electricity data in Alberta in (a) the base case and (b) the 2019 case.

efficiency, FC efficiency, number of parking spots for participating FCEVs, market penetration rate of FCEVs to trucks, willingness of participating truck drivers, and input capacity of the onsite electrolyzer. The primary objective of the sensitivity analysis is to understand how changes in these parameters affect the operation and profitability of the FCEV2G system. For each parameter, it is altered −50 %, −25 %, 25 %, and 50 % from the base case scenario. Note that changing the parameters of the station equipment not only affects the operational optimization but also the site cost.

The variations from the base case for changing each parameter by ±50 % are shown in Fig. 8 (the entire sensitivity data including those of changing parameters by ±25 % are shown in Table S1), and the sensitivities of net profit to different parameters are numerically reported in Table 9. All the base case scenarios show positive net profits except when the FC efficiency drops by 50 %; the positive net profits are due to the higher electricity price and price volatility in 2022 data. As for the 2019 case, every scenario fails to have a positive net profit. The difference between using the 2022 and 2019 electricity data confirms that the electricity price profile determines the profitability of the FCEV2G operation.

As is shown in Fig. 8, FC efficiency is the most influential factor, and it affects energy loss during electricity generation. FC efficiency varies for different FC technologies. For example, the peak energy efficiency is about 40 % for Phosphoric Acid FC (PAFC), about 50 % for Molten Carbonate (MCFC), as high as 60 % for PEMFC, Solid Oxide FC (SOFC), and Alkaline FC (AFC) [40]. The US Department of Energy sets its ultimate target of peak energy efficiency of 80-kWe (net) integrated transportation FC power systems operating on direct hydrogen at 70 % [61]. Meanwhile, actual FC efficiency decreases significantly under non-optimal power outputs [62], temperatures, pressures [63], etc. Each or the combination of these adverse factors causes the actual FC efficiency to be lower than the peak performance efficiency. For example, depending on the power output, it may lower efficiency from 60 % at peak to only 30 % [62]. In the sensitivity analysis, FC efficiency changes from 25 % to 75 % to reflect different situations ranging from future improvements in FC efficiency to non-optimal operation FC conditions. With the high carbon electricity mix in the base case, increasing the FC efficiency by 50 % increases the net profit by about 79 % to 419,499 USD, higher than the potential profits by improving other parameters. On the other hand, when the FC efficiency is as low as 25 %, it makes the net profit negative in the base case.

The second most impactful parameter in the 2022 base case is market hydrogen cost. The base case market hydrogen price is 5 USD/kg, including 3 USD/kg on production and 2 USD/kg on delivery and processing as in Table 1 [36]. The clean market hydrogen production cost varies with different clean electricity prices and electrolyzer capacity factors. This cost becomes lower with reduced clean electricity price and elevated electrolyzer capacity factor and vice versa. The delivery and processing cost varies with different delivery methods, scales, and distances. Overall, longer distances and smaller delivery scales raise costs. In addition, liquid delivery is more expensive than gaseous delivery, and pipeline delivery is cheaper than the other two but only for large scales of hydrogen delivery [36]. The total market hydrogen costs are set to 2.5, 3.75, 5, 6.25, 7.5 USD/kg in the sensitivity analysis to investigate its effect on the net profit. Decreasing market hydrogen cost to 2.5 USD/kg increases the net profit by 93 % to 451,750 USD. Yet the negative impact of raising market hydrogen cost is not as impactful as that of lowering FC efficiency, which may be attributed to the fact that expensive market hydrogen can be substituted by grid hydrogen.

Table 9
Sensitivity of net profit toward each parameter.

Name	2019	2022	Name	2019	2022
Electrolyzer efficiency	13.46	41.75	Electrolyzer size	−28.40	−20.06
FC efficiency	30.32	171.02	Available spots	8.23	60.46
Market hydrogen cost	−8.60	−70.77	Penetration rate	8.61	49.39
Hydrogen storage capacity	5.24	10.31	Willingness rate	10.50	51.33

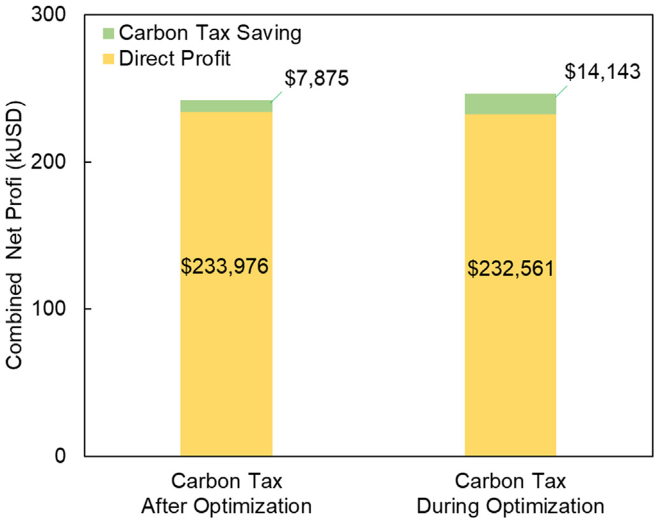

Fig. 9. The direct net profits and carbo tax savings of the FCEV2G station when carbon tax is considered at different stages (the left column is the case to consider carbon tax after optimization, where carbon tax saving is added after the FCEV2G operation is optimized, while the right column is the case to consider carbon tax during optimization where carbon tax saving is added in the target function).

The parameters related to the station and vehicles (e.g., available spots, market penetration rate, and willingness rate) directly affect the maximum number of simultaneously grid-connected vehicles at each hour and have similar sensitivity impacts on the net profit according to Table 9. A higher number of available spots increases the capacity of the FCEV2G station to receive FCEVs for parking and grid connection while more CAPEX is required in expanding the dispensing facility. As 2019 data is less favorable for FCEV2G, the increased profits made by more available spots cannot exceed the extra CAPEX caused by more available spots, so this factor has opposite effects in the two cases. Meanwhile, FCEV penetration rate and driver's willingness represent the social acceptance of FCEVs and FCEV2G, respectively, and raising their values means more FCEVs will be available to the FCEV2G operation. The sensitivity values of these three parameters are close to each other in both cases with the 2019 and 2022 data.

The rest of the parameters have less significant impacts on the net profit. Hydrogen storage capacity has a relatively lower impact likely because hydrogen stays in the onsite storage for a rather short time as discussed in Section 3.1.2. Electrolyzer efficiency, which directly impacts the costs of producing grid hydrogen, has a lower impact compared to market hydrogen cost with the 2022 data while it has a higher impact with the 2019 data. This result corresponds to the findings in Section 3.1.5 that significantly more market hydrogen is used in the base case with 2022 data as electricity prices are higher and more volatile. Different from other parameters, increasing the electrolyzer size decreases the net profit because the increasing cost of the electrolyzer exceeds the profit brought by producing more grid hydrogen. However, as PEM electrolyzer cost is expected to reduce by around 90 % from 2023 to 2030 [64], increasing onsite electrolyzer size may have a positive effect on overall FCEV2G profitability at lower electrolyzer costs in the future.

4. Alternative scenarios

4.1. Scenario 1: considering carbon tax in the optimization

The carbon tax is an important way to financially encourage efforts to lower carbon emissions. For example, the carbon tax in Canada increases by 10 CAD/tCO$_2$ per year starting from 20 CAD/tCO$_2$ in 2019 and will increase by 15 CAD/tCO$_2$ per year from 2023 to 2030 [48]. It is discussed in Section 3.1.5 that FCEV2G can generate profit while reducing carbon emissions. Therefore, in this study, we considered the scenario where carbon tax saving from emission reduction was considered in the optimization, i.e., 50 CAD/tCO$_2$ in Canada (converted to 37.5 USD/tCO$_2$ in this study). Fig. 9 compares the direct profits from selling electricity and the carbon tax savings in FCEV2G operations with or without considering the carbon tax when optimizing the station operation. With the carbon tax saving in revenue optimization, we find that total net profit slightly increases to 246,704 USD from 241,851 USD where carbon tax savings are considered after the optimization is done. The profit from electricity sales falls by 1,415 USD but carbon emission reduction increases to 377 t, resulting in 14,143 USD additional carbon tax savings. Adding carbon tax savings in the target function allows more weight on reducing carbon emissions to raise the total profits of FCEV2G.

4.2. *Scenario 2: optimization using low-carbon electricity mix*

The base case uses the high-carbon electricity mix from Alberta 2022. A similar analysis is done on a scenario using the low-carbon electricity mix data from Ontario for comparison. Results show that, with the base case assumptions and the data either in 2019 or 2022 in Ontario, there is hardly any profit generation or carbon reduction. For example, only 83,723 USD is generated during the operation with the base case assumptions in Section 3.1, which fails to recover the 174,310 USD of equipment cost. The carbon reduction (i.e., 0.2 t) is also significantly smaller than that in the base case with the high-carbon electricity mix (i.e., 210 t discussed in Section 3.1.5). This smaller profit generation is attributed to the relatively low and stable prices in a low-carbon electricity mix in Ontario, the same reason why the FCEV2G profit in the 2019 Alberta case is significantly lower than the base Alberta case discussed in Section 3. Similarly, the low and stable carbon content of the grid reduces the potential of FCEV2G to lower the grid carbon intensity.

To investigate under which circumstances FCEV2G operations can become profitable with the Ontario low-carbon electricity mix, we analyzed how improving the two most impacting factors identified in Section 3.2, i.e., FC efficiency and market hydrogen cost, may increase the profitability in a low-carbon grid electricity mix. Furthermore, the onsite-produced grid hydrogen is excluded in this part and only market hydrogen is used for power generation to increase the profitability of the FCEV2G station. As a result, dispensers are the only equipment considered in the FCEV2G station in this case.

The optimized net profits of the FCEV2G station with the Ontario 2022 data under different market hydrogen costs and FC efficiencies are shown in Fig. 10. The FC efficiency ranges from 50 % to 75 %, and market hydrogen costs from 1.5 USD/kg to 5 USD/kg. FC efficiency is set to 50 %–75 % to reflect the current and the ultimate proton exchange FC technologies identified by the US Department of Energy [65]. The market hydrogen cost is set to 1.5–5 USD/kg because the delivered cost of renewable-based hydrogen will fall to a range of 1.3–4.5 USD/kg (equivalent to 39–135 USD/MWh) according to IEA, if the planned electrolyzer projects in the pipeline and the scale-up in manufacturing capacities are realized [66]. The results shown in Fig. 10 exhibit the optimized net profits in different scenarios in different colors where red represents positive profits and blue represents negative profits. The profit increases at a higher gradient in the profitable zone compared to in the non-profitable zone and most of the non-profitable zone has values equal to the amount of deficit from dispenser purchases. The profitable zone and non-profitable zone are distinguished by a zero-profit line where the operational cost of generating electricity in the FCEV2G station, i.e., market hydrogen price over FC efficiency, is 3.3 USD/kg (equivalent to 100 USD/kWh). In comparison, the average electricity price in 2022 in Ontario was 81 USD/MWh. Although FCEV2G is not profitable using Ontario data in the base case assumption, it can become lucrative after technological advancements make the FC efficiency and hydrogen production cost across the zero-profit line into the profit zone. However, this zero-profit line is quite far from the base case assumptions on FC efficiency and market hydrogen cost, which means significant improvements would be required.

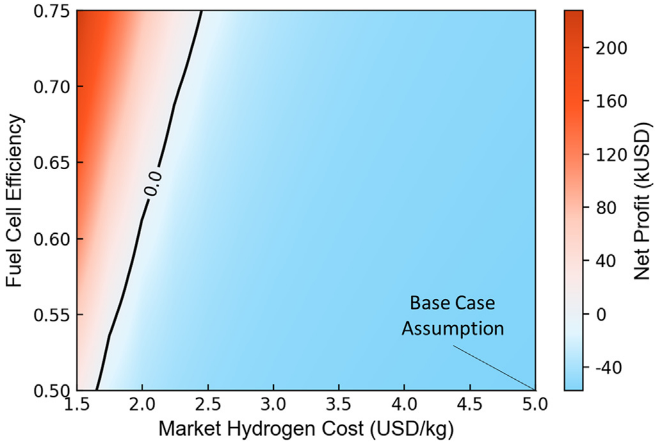

Fig. 10. The optimized net profits with different FC efficiencies and market hydrogen costs in the case with Ontario 2022 data.

5. Conclusion

In this study, we evaluated the potential of FCEV2G to generate monetary profit and reduce carbon emissions. We used the traffic and electricity data in Alberta as a base case and compared the results with low-carbon grid data in Ontario. The considered FCEV2G station consists of an onsite electrolyzer, onsite hydrogen storage, and hydrogen fuel dispensers.

The FCEV2G station is found to be able to generate a net profit of 233,976 USD and reduce carbon emissions of 210 t simultaneously in the base case using Alberta 2022 data. Yet using cheaper and less volatile electricity prices in the 2019 case, a deficit of 85,587 USD occurs. The largest part of the site cost is the electrolyzer followed by the hydrogen dispensers. The sensitivity analysis reveals that FC efficiency and market hydrogen cost are the two most influential factors on FCEV2G profitability.

We also considered adding carbon tax savings to the profits and found that net profit increases to 246,704 when carbon tax savings are added to the target function. A comparison is also made using the low-carbon grid data in Ontario in 2022 with the base case assumptions and we found that FCEV2G fails to yield net profits because the electricity prices in the Ontario 2022 case were much lower and more stable than those in the base case. By varying the two most influential factors, i.e., the FC efficiency and market hydrogen price, we found that when the operational cost of generating electricity, i.e., the market hydrogen price divided by the FC efficiency, is below 100 USD/MWh, FCEV2G will be able to generate profits in the 2022 low-carbon Ontario grid case. However, this requires significant improvements in FC efficiency or a reduction in market hydrogen price.

CRediT authorship contribution statement

Daniel Ding: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Xiao-Yu Wu:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Xiao-Yu Wu reports financial support was provided by Natural

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.decarb.2024.100096.

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