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Coordinated operation of hydrogen refuelling and fast charging combo station under normal and contingent conditions

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Abstract

Fuel cell electric vehicles (FCEVs) are rapidly growing owing to the increased public awareness of energy and environmental issues. Infrastructure for hydrogen production, transportation, and allocation is essential for FCEV promotion. For consumers, availability of few hydrogen refuelling stations is the primary concern. Currently, public charging infrastructure for battery electric vehicles, for example, fast charging station, has a more widespread coverage compared to infrastructure for hydrogen refuelling. With an electrolyser, the existing power grid can be used as an alternative to hydrogen supply and transportation infrastructure, which is still being developed. The authors propose a new conceptual combo station acting as both a hydrogen refuelling station and a fast charging station. This station can satisfy the requirement of FCEVs and battery electric vehicles, and even operate under a blackout situation. To quantify the value of coordinated operation, an optimal operation formulation of a combo station is developed. It is found that such a combo station is capable of saving land rents, reducing power network reinforcement cost, and boosting energy self-balance capability under blackout condition.

1 | INTRODUCTION

Hydrogen can easily be stored, and electricity is convenient for transportation. Their complementary characteristics allow for an efficient usage of highly uncertain renewable energy sources. By decoupling the production and consumption of energy, energy can be stored and need not be consumed instantly. This significantly reduces the curtailment of renewable energy generation [1].

Hydrogen has one of the highest energy density values per mass and does not emit greenhouse gases during consumption; thus, it is suitable for the transportation sector. As pointed out in [2], approximately 25% of primary energy consumption and global CO₂ emission is attributed to the transport sector, primarily road transport. Compared with the battery electric vehicle (BEV), the refuelling rate of the fuel cell electric vehicle (FCEV) is much faster, and typically, the FCEV offers better mileage. Therefore, hydrogen is considered as an alternative fuel for future road transport.

The development of hydrogen refuelling stations (HRSs) and FCEV cannot be carried out independently. FCEVs can obtain hydrogen conveniently after an adequate number of HRSs are available, and this will also promote the usage of FCEVs. However, at the early stage of adopting FCEVs, HRS will face the challenges of expensive hydrogen supply and low hydrogen demand because of the undeveloped infrastructure of hydrogen production and transportation; these challenges directly hinder the construction of HRSs.

The results presented in [3] highlight that it is essential to build sufficient HRSs to promote the growth of FCEVs in the early stages. To address the problem of ‘chicken and egg’ [2], the transition scheme of hydrogen production on-site was proposed.

There are two common methods to produce hydrogen on-site:

(i) Water electrolysis. Many researches have been conducted on economic evaluation of on-site water electrolysis. Results presented in [4] indicate that the levelised cost of hydrogen (LCOH) is $7.72/kg with hydrogen production capacities of 300 Nm³/h, considering capital expenditures (CAPEX) and operating expenses (OPEX), including equipments,
(ii) Steam methane reforming (SMR). This method is commonly used to produce hydrogen in industry. In SMR method, natural gas is required for production of hydrogen. Therefore, natural gas rather than hydrogen will be transported into the station, and SMR is not a low-carbon method to produce hydrogen. The LCOH is $6.8/\text{kg} in Shenzhen [8], $9/\text{kg} in California [9], and $7.59/\text{kg} in Korea [4]. Although SMR usually has the advantage of low cost, it is preferable that hydrogen is produced from renewable sources. Moreover, for the areas where natural gas cannot be transported, using water electrolysis, such as PEM, can serve as an ideal alternative.

As pointed out in [10], with an electrolyser, the existing power grid can be used for supplying hydrogen in all places. Because PEM-based on-site hydrogen production can be flexibly controlled, PEM-based on-site production HRSs are usually combined with uncertain wind [11,12] or solar [13–15]. Therefore, the HRSs can use wind and solar energy to produce hydrogen, participate in power market, and provide ancillary services for power grid.

An economic assessment of centralised hydrogen production and on-site hydrogen production is comprehensively studied in [16]. From the perspective of efficiency and capital expenditures, central hydrogen production and truck delivery are advantageous. However, on-site production allows small gas inventory, more compact stations, high gas purity, and carbon-free emission. PEM on-site hydrogen production is more suitable for station with hydrogen demand less than 75,000 scf/day (approximately 180 kg/day) [17]. Considering the potential of on-site water electrolysis to reduce carbon footprint, many projects have been conducted to build on-site water electrolysis HRSs. Proton OnSite [18] is a company that has on-site water electrolysis HRSs in five cities in the U.S. and Germany. There is a solar-powered on-site hydrogen production HRS in Italy [13]. Furthermore, as pointed out in [19], approximately 70% HRSs in North and South America are on-site production stations (using SMR or electrolyser); 58% in Europe and 64% in Asia. Out of the 224 HRSs globally, 65 are based on water electrolysis, of which 28 are using renewable energy, such as solar and wind power, and 35 are using grid electricity to produce hydrogen.

The operation and control strategy of HRS with an electrolyser is studied in [20]. The result shows that a self-sustainable HRS that relies on renewable resources for hydrogen production, storage, and distribution is feasible. In [21], a hybrid refuelling station that can serve BEVs, FCEVs, and natural gas vehicles (NGVs) is proposed. An optimisation model considering operation constraints of different equipment is built to obtain an optimal operation. [22] considers three types of ancillary services to gain more benefits in both distributed and centralised hydrogen production. From the economic point of view, the results show that the distributed production is ideal. For a hydrogen refuelling station with a generation capacity of 100 kg, the land rents account for approximately 15–27% of total O&M costs [23]. The current levels of utilisation of commercial chargers is below 10% [24]. The average utilisation rate of HRSs in California is 36% based on the station’s hydrogen capacity [25]. An FCEV can be refilled in less than 10 min [26], and the rate of hydrogen production is high, approximately 89.9 kg/h [27]. Thus, low utilisation of FCSs and HRSs and high speed of refuelling make it possible for FCSs HRSs to share their parking spaces. Moreover, the grid connection fee for FCS and on-site HRS is high in Europe. Because the electrolyzers and chargers do not operate 24/7, they can be operated coordinately to reduce peak power capacity [28]; this can save their grid connection fee.

In this study, a combo station that acts as both a hydrogen refuelling and fast charging station is proposed. Its daily optimal operation models are built considering BEV charging facilities, batteries, hydrogen electrolyzers, and hydrogen vessels under both normal and blackout conditions of power grid. Both operation models can be easily extended to scenario-based model considering renewable energy uncertainty. Through simulations, the advantages of a combo station in saving land rents, reducing expanding cost of power grid capacity, and boosting energy self-balance capability under blackout condition are verified.

2 | SYSTEM DESIGN OF THE ON-SITE COMBO STATION

In this section, we describe the framework of a combo station. A combo station combines a fast charging station (FCS) and a hydrogen refuelling station (HRS). The combo station can be achieved by rebuilding an FCS or HRS, or considering both stations at the beginning of the construction.

Here, electricity is provided by the power distribution system, and hydrogen is supplied by a PEM electrolyser inside the station. The operation cost of the station primarily includes the cost of purchasing electricity, and its revenue is from providing charging and hydrogen refuelling services. In extreme cases, if charging or hydrogenation requirements cannot be satisfied, the combo station should bear compensation costs for the unmet refuelling demands, among which the critical demand will require more compensation. The combo station should forecast the refuelling demands of FCEVs and BEVs, forecast the purchasing and selling price of electricity, and create a schedule for the next day.

As illustrated in Figure 1, a combo station is composed of a battery, water electrolyser device, compressor, storage vessel for high pressure hydrogen (70 MPa), charging piles, and hydrogen dispensers. The compressor only operates between an electrolyser and a high pressure storage vessel. The combo station owner/operator can buy/sell electricity from/to power system. Besides charging mode, the charging pile can operate in vehicle to grid (V2G) mode.

The charging process is as follows. After a BEV is connected to a charging pile, the BEV user can set the charging parameters, including the target SOC, expected charging time, and the...
minimum SOC that can be accepted if he/she terminates charging process ahead of schedule. Then the charging pile will start the charging process. The electricity used in the station (charging and electrolysis) can be from three sources, that is, the power grid, battery storage, and discharging of BEVs. Power grid is the main electricity source for the station. Batteries and EVs play the role of arbitrager, which are set to charge at low price periods and discharge at high price periods. The coupling between charging and hydrogen is reflected in the discharging of batteries and BEVs. During normal operation of power grid, the battery storage provides support for the electrolysis; however, during blackout of power grid, V2G has the same effect.

For charging services, the combo station purchases electricity from power grid. The electricity is stored in a battery or it charges BEV directly. A battery can also be used to charge BEV. For refuelling services, because a combo station is equipped with electrolysis devices, it supplies hydrogen locally. After compression, the high pressure hydrogen is stored in a vessel, and then FCEVs are refuelled through hydrogen dispensers. Note that the electrolysis and compressing processes require electricity and high power input.

Battery storage has multiple functions in the station. Firstly, in normal operation condition, because the prices may change over the day in both electricity purchase and sale, batteries can implement price arbitrage by proper charging/discharging power control. Secondly, batteries can be flexibly controlled to coordinate with the charging loads of BEVs. Thirdly, because of the high speed of hydrogen production, the electricity in the battery can be used to produce hydrogen rapidly. Therefore, batteries can be used as an alternative to hydrogen storage. Fourthly, local electrolysis requires a high capacity from power grid, and batteries can reduce the peak power exchange of the whole station with the power grid. Finally, batteries can also act as a power source for critical loads when the power grid fails. However, batteries degenerate during the charging/discharging process, which increases the operating cost.

For a BEV, the charging and discharging efficiencies are denoted by $\eta_{cha, BEV}$ and $\eta_{dis, BEV}$ respectively. For a battery, the charging efficiency, discharging efficiency, and degeneration rate are denoted by $\eta_{cha, battery}$, $\eta_{dis, battery}$, and $\lambda_{batt} (€/kWh)$, respectively. The electricity-hydrogen (high pressure) conversion rate in an electrolyser and a compressor is $\alpha (kg/kWh)$. In addition, the cost of refrigeration before dispensation is converted to the loss of hydrogen dispensing, denoted as $\eta_{F}$.  

3 | OPTIMAL OPERATION MODEL IN BOTH NORMAL AND BLACKOUT SITUATIONS

In this section, we develop two optimisation models, that is, the normal operation model and the blackout operation model. The discrete models have $T$ slots per day, and the duration of each slot is $\Delta t$ hours. The optimal operation schedule for the next day is created based on the forecasts of FCEV and BEV refuelling demands and the electricity prices.

3.1 | General description

The aim of combo station operator is to maximize its operating profit. In the time slot of $t$, the charging and discharging prices for BEV are set as $\rho_{sell, BEV}^c, \rho_{buy, BEV}^c (€/kWh)$. Simultaneously, the hydrogen price for FCEV is set as $\rho_{F} (€/kg)$. The purchase price $\rho_{buy, BEV}^c (€/kWh)$ and selling price $\rho_{sell, BEV}^c (€/kWh)$ are determined by the electricity market of distribution network operator. The degeneration of a battery is converted into the operating cost with a coefficient of $\lambda_{batt} (€/kWh)$.

For a combo station equipped with $N_C$ charging piles and $N_F$ hydrogen dispensers, there exists $N_B$ BEVs and $N_F$: FCEVs to serve in the next day according to forecast. The
\textit{kth BEV (FCEV) plugs in the \textit{n}th charging pile (hydrogen dispenser). Their energy demands are \(E_{R,k}\) and \(W_{f,k}\), the time period of charging or refuelling is notation as \([\text{start}_{R,k},\text{end}_{R,k}]\) and \([\text{start}_{f,k},\text{end}_{f,k}]\); the allowable charging electricity rage \([E_{\text{min},k},E_{\text{max},k}]\) is set by BEV user. \(E_{\text{min},k}\) can be negative, and \(E_{\text{max},k}\) is \(E_{R,k}\). For the extreme situation, some charging and refuelling demands cannot be met. For the unsatisfied demands, consumer will receive compensations of \(\lambda_B\) (\$/kWh) and \(\lambda_F\) (\$/kg), respectively.

At the \(t\)th time interval, the \(n\)th charging pile may not only charge at \(P^{\text{OUT},n}_{R,t}\) kW, but also discharge to the station at \(P^{\text{IN},n}_{R,t}\) kW. Hydrogen dispenser \(a\) can only obtain hydrogen flow at \(Q^{\text{IN}},a\) kg/h from the station. The input power from the power grid to the station is denoted as \(P^{\text{IN}},G\), and the output power from the station to the power grid is denoted as \(P^{\text{OUT}},G\).

In addition, the power transferred between the components of the station is denoted as \(P_{R/B}, P_{B/PV}, P_{B/G}, P_{G/B}, P_{G/P}, P_{G2/H}, P_{2/G2}, P_{2/B}, P_{2/H}, P_{1/H}\) (please see Figure 1 for your reference). Here, subscripts \(R, H, V,\) and \(G\) are battery, hydrogen, BEV, and power grid, respectively.

Note that the superscript IN and OUT are based on the combo station, for example, \(P^{\text{OUT},n}_{R,t}\) is the power from the station to BEV and \(P^{\text{IN},G}_{G}\) is the power from grid to the station. Furthermore, power \(P_{X2Y}\) is from component X to Y. This power is after component X output efficiency conversion but before Y input efficiency conversion, as shown in Figure 2.

### 3.2 Normal operation condition

For normal operation, the combo station decides electric power \(P\) and mass flow rate of hydrogen \(Q\) of the station at each time slot. Let \(\mathcal{N}_B, \mathcal{N}_F, \mathcal{N}_C, \mathcal{N}_{JI},\) and \(\mathcal{T}\) be the set of BEVs, FC EVs, charging piles, hydrogen dispensers, and time intervals, then the station gains revenue from electricity and hydrogen refuelling services can be calculated by (1).

\[
f_p(Q,P) = \sum_{i=1}^{T} \left( \rho_{ji} \sum_{n=1}^{N_{ji}} Q^{\text{IN}},n_{ji} + \rho_{B,t} \sum_{n=1}^{N_{B,t}} P^{\text{OUT}},n_{B,t} + \rho_{\text{sell}} \sum_{n=1}^{N_{C,t}} P^{\text{OUT}},n_{C,t} - \rho_{\text{buy}} \sum_{n=1}^{N_{C,t}} P^{\text{IN}},n_{C,t} \right) \Delta t
\]

The station provides hydrogen refuelling service through \(N_{JI}\) dispensers at price of \(\rho_{ji}\), and provides charging service through \(N_C\) charging piles at price of \(\rho_{C,t}\). Some of charging piles may operate at V2G mode and the corresponding BEVs sell electricity to the station at price of \(\rho_{B,t}\). Simultaneously, the station may purchase or sell electricity to power grid at price of \(\rho_{\text{buy}}\) and \(\rho_{\text{sell}}\).

The compensation to the unsatisfied energy demands and degeneration of a battery are considered part of the cost, and can be calculated by (2).

\[
f_c(Q,P) = \sum_{i=1}^{T} \left[ E_{R,i} - \sum_{t=\text{start}_i}^{\text{end}_i} (P^{\text{OUT},n}_{R,i} - P^{\text{IN},n}_{R,i}) \Delta t \right] + \sum_{i=1}^{T} \sum_{t=\text{start}_i}^{\text{end}_i} (\psi_{ji} - \psi_{\text{IN}},n_{ji} - \psi_{\text{OUT}},n_{ji}) \Delta t
\]

There are \(N_B\) BEVs and \(N_F\) FCEVs to serve in the next day. For the \(k\)th BEV, we assume it connects to the \(n\)th charging pile. It obtains \(\sum_{t=\text{start}_k}^{\text{end}_k} (P^{\text{OUT},n}_{R,i} - P^{\text{IN},n}_{R,i}) \Delta t\) kWh electricity during its charging period \([\text{start}_k, \text{end}_k]\). For the mismatch between the charged energy and the energy demand \(E_{R,i}\), the station compensates the consumer at the price of \(\lambda_B\). FCEVs are dealt in the similar way. The degeneration of a battery is converted to operating cost, \(\rho_{\text{batt}}\) (\$/kWh).

To reduce the power fluctuations from and to BEVs, power grid, and battery, the additional penalty term is introduced as (3).

\[
f_p(Q,P) = \sum_{i=1}^{T} \left( \sum_{n=1}^{N_{ji}} \psi_{ji} - P^{\text{OUT},n}_{B,i} \right) + \sum_{n=1}^{N_{C,t}} \left( \psi_{\text{IN}},n_{C,t} - P^{\text{OUT}},n_{C,t} \right) + \sum_{t=1}^{T} |P^{\text{OUT}},n_{B,t} - P^{\text{OUT},n}_{B,t} - P^{\text{IN},n}_{B,t} - P^{\text{IN}},n_{B,t}| \Delta t
\]

When \(\lambda_{\text{pena}}\) is significantly small, the impact of (3) on the optimal value of objective function is negligible.

Several constraints should be considered for the operational schedule of the combo station.

#### 3.2.1 Complementarity constraints for charging piles and hydrogen dispensers

\[
(1 - O^{\text{IN}},n_{R,i}) P^{\text{IN}},n_{R,i} = 0, \forall n \in \mathcal{N}_C, t \in \mathcal{T}
\]

\[
(1 - O^{\text{IN}},n_{R,i}) P^{\text{OUT}},n_{R,i} = 0, \forall n \in \mathcal{N}_C, t \in \mathcal{T}
\]

\[
(1 - O^{\text{IN}},n_{F,j}) Q^{\text{IN}},n_{F,j} = 0, \forall n \in \mathcal{N}_{JI}, t \in \mathcal{T}
\]
In equations (4), $ON_{B,t}$ and $ON_{G,t}$ are binary variables, which represents whether the $n$th charging pile or hydrogen dispenser is occupied in the $t$th time period. $ON_{B,t} = 1$ means the charging pile is occupied by an EV, and vice versa. According to prediction, these $ON$ variables are known.

### 3.2.2 Energy constraints for BEVs and FCEVs

\[
\sum_{i=\text{start}_{B,k}}^{\text{end}_{B,k}} (P_{B,t}^{\text{OUT},s_k} - P_{B,t}^{\text{IN},s_k}) \Delta t \leq E_{B,k}, \quad \forall k \in N_B
\]

(5)

When a charging or refuelling process completes, the total output energy of charger/dispenser cannot exceed the energy demand for the BEV or FCEV.

### 3.2.3 V2G constraints for BEVs

\[
E_{\text{min},k} \leq \sum_{i=\text{start}_{B,k}}^{\text{end}_{B,k}} (P_{B,t}^{\text{OUT},s_k} - P_{B,t}^{\text{IN},s_k}) \Delta t \leq E_{\text{max},k}, \quad \forall k \in N_B, \quad \forall \tau \in [\text{start}_{B,k}, \text{end}_{B,k}]
\]

(6)

When a BEV is connected to the charging pile, the input energy range is set as $[E_{\text{min},k}, E_{\text{max},k}]$. By default, $E_{\text{min},k} = 0$ and $E_{\text{max},k} = E_{B,k}$. The BEV users can adjust them according to their own demands, for example, $E_{\text{min},k} < 0$ means that the BEV could have a lower state of charge (SOC) than the initial SOC during the charging period.

### 3.2.4 Power balance constraints at the point where the combo station connects to the power grid

\[
P_{G,t}^{\text{IN}} = P_{G21,t} + P_{G2H,t} + P_{G2B,t}
\]

\[
P_{G,t}^{\text{OUT}} = P_{B2G,t} + P_{V2G,t}
\]

(7)

The energy from power grid $P_{G,t}^{\text{IN}}$ is allocated to BEVs $P_{G21,t}$, hydrogen production and compression $P_{G2H,t}$, and battery $P_{G2B,t}$. Occasionally, the station may discharge to the power grid $P_{G,t}^{\text{OUT}}$, where the electricity is from battery $P_{B2G,t}$ and BEVs $P_{V2G,t}$.

#### 3.2.5 Power balance constraints for battery storage

\[
R_{\text{batt},t} = (P_{G2G,t} + P_{V2G,t}) \eta_{\text{batt}}^{\text{dis}}
\]

\[
- (P_{G2G,t} + P_{V2G,t}) \eta_{\text{batt}}^{\text{cha}} \forall \tau \in T
\]

(8)

\[
\text{SOC}_0 E_{\text{batt}} + \sum_{\tau=1}^{T} R_{\text{batt},\tau} \Delta t \leq \text{SOC}_{\text{max}} E_{\text{batt}} \forall \tau \in T
\]

(9)

\[
\sum_{\tau=1}^{T} R_{\text{batt},\tau} \Delta t = 0
\]

In Equation (8), $\text{SOC}_0$ is the initial SOC of the battery, $E_{\text{batt}}$ is the battery capacity, and $R_{\text{batt},t}$ is the net power input of the battery. In operation, the SOC of the battery must be in $[\text{SOC}_{\text{min}}, \text{SOC}_{\text{max}}]$. Ultimately, the battery should recover to its initial SOC.

#### 3.2.6 Power balance constraints for hydrogen storage

\[
Q_{\text{stor},t} = \alpha (P_{G2H,t} + P_{G2B,t} + P_{V2H,t}) - \sum_{n=1}^{N_T} Q_{n}^{\text{dis}} \eta_{F}^{\text{dis}}
\]

(10)

\[
\text{SOC}_0 W_{\text{stor}} + \sum_{\tau=1}^{T} Q_{\text{stor},\tau} \Delta t \geq \text{SOC}_{\text{min}} W_{\text{stor}} \forall \tau \in T
\]

(11)

\[
\text{SOC}_0 W_{\text{stor}} + \sum_{\tau=1}^{T} Q_{\text{stor},\tau} \Delta t \leq \text{SOC}_{\text{max}} W_{\text{stor}} \forall \tau \in T
\]

(12)

\[
\sum_{\tau=1}^{T} Q_{\text{stor},\tau} \Delta t = 0
\]

In Equation (11), $\text{SOC}_0$ is the initial state of storage (SOS) for hydrogen storage vessel, $W_{\text{stor}}$ is the storage capacity and $Q_{\text{stor},t}$ is the mass flow injecting into the storage. In operation, the SOS of storage must be in $[\text{SOC}_{\text{min}}, \text{SOC}_{\text{max}}]$. Eventually, the storage state should be equal to its initial SOS.

#### 3.2.7 Power balance constraints for BEVs

\[
\sum_{n=1}^{N_T} P_{B,t}^{\text{IN},s_n} = (P_{V21,t} + P_{V2G,t} + P_{V2B,t}) \eta_{B}^{\text{dis}}
\]

(13)

\[
\sum_{n=1}^{N_T} P_{B,t}^{\text{OUT},s_n} = \eta_{B}^{\text{cha}} (P_{V21,t} + P_{G21,t} + P_{V2H,t})
\]
When a BEV is connected to a charging pile for a long time, it can be treated as a battery. This virtual battery can provide energy to the power grid, battery, hydrogen devices, and other BEVs, notated as $P_{G,t}^2$, $P_{B,t}^2$, $P_{H,t}^2$, and $P_{G,21}^2$. The energy sources of BEVs are power grid, battery, and other BEVs, notated as $P_{G,t}^2$, $P_{B,t}^2$, and $P_{G,21}^2$.

3.2.8 Bounds for operating variables

There exists upper and lower bound for the operating variables. The input and output power magnitudes of BEVs, power grid, and battery are limited. Furthermore, the rate of hydrogen production and refuelling is constrained. These constraints are
### TABLE 1  Scenario description

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>• Operate FCS and HRS separately</td>
</tr>
<tr>
<td></td>
<td>• No battery and storage</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>• Operate FCS and HRS separately</td>
</tr>
<tr>
<td></td>
<td>• Have battery and storage</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>• Operate combo station coordinately</td>
</tr>
<tr>
<td></td>
<td>• Have battery and storage</td>
</tr>
</tbody>
</table>

listed in (11).

\[
0 \leq P_{B,t}^{\text{OUT},n} \leq P_{B,n}^{\text{max}}, \forall n \in \mathcal{N}_C, t \in \mathcal{T} \\
0 \leq P_{B,t}^{\text{IN},n} \leq P_{B,n}^{\text{max}}, \forall n \in \mathcal{N}_C, t \in \mathcal{T} \\
0 \leq Q_{B,t}^{n} \leq Q_{B}^{\text{max}}, \forall n \in \mathcal{N}_H, t \in \mathcal{T}
\]

To maximise the daily operating revenue, the combo station operator should solve an optimisation problem as (12).

\[
\begin{align*}
\max_{Q,P} & \ f_Q(Q,P) - f_C(Q,P) - f_A(Q,P) \\
\text{s.t.} & \ (4) - (11)
\end{align*}
\]

![Available BEV FCEV](image1.png)

**FIGURE 5**  FCS and HRS share parking spaces. (a) Assuming 500kg hydrogen demand. (b) Assuming 1000kg hydrogen demand
This optimisation is a linear programming problem and can be solved by mature solver.

### 3.3 Operation under power outage

For an accidental or planned power outage, the combo station cannot continue obtaining energy from power grid. The station is operated in island mode. The energy can be obtained from three sources, that is, battery, hydrogen storage vessel and BEVs, to meet the requirements of critical outage.

We assume that the expected failure time is $[t_{\text{start}}^{\text{black}}, t_{\text{end}}^{\text{black}}]$ and advance notification time is $t_{\text{noti}}$. $t_{\text{noti}} = 0$ is for an accident and $t_{\text{noti}} > 0$ is for a planned blackout.

Let $P_{t \in [t_{\text{start}}^{\text{black}} - t_{\text{noti}}, t_{\text{end}}^{\text{black}}]}$ be the operating variables during $[t_1, t_2]$. In normal operation, the combo station operates in optimal solutions, $P^*$ and $Q^*$ of (12). Before $t_{\text{start}}^{\text{black}} - t_{\text{noti}}$, the operator does not know when a power failure will occur, and the station is run according to the optimal schedule. After $t_{\text{start}}^{\text{black}} - t_{\text{noti}}$, the operator will ask for expected failure duration from power grid and form another schedule, as shown in (13).

\[
\begin{align*}
\max_{Q, P} f_P(Q, P) - f_Q(Q, P) - f_a(Q, P) \\
\text{s.t.} (4) - (11) \\
P_{t \in [t_{\text{start}}^{\text{black}} - t_{\text{noti}}, t_{\text{end}}^{\text{black}}]} = P^* \\
Q_{t \in [t_{\text{start}}^{\text{black}} - t_{\text{noti}}, t_{\text{end}}^{\text{black}}]} = Q^* \\
p_{\text{IN}}^t \big|_{t \in [t_{\text{start}}^{\text{black}} - t_{\text{noti}}, t_{\text{end}}^{\text{black}}]} = 0 \\
p_{\text{OUT}}^t \big|_{t \in [t_{\text{start}}^{\text{black}} - t_{\text{noti}}, t_{\text{end}}^{\text{black}}]} = 0
\end{align*}
\]

During power outage, the combo station is operated in island mode. The power exchange between the combo station and the power grid is zero. This optimisation is a linear programming problem.

Under unplanned outages, the expected time of failure for unplanned outages is difficult to predict. The two basic operating strategies for the combo station are as follows:

(i) Greedy operation strategy. Maximising the residual stored energy to serve the refuelling demands. When the stored energy is depleted before restoration of the power grid, the combo station should be closed.

(ii) Steady operation strategy. Optimally operating the combo station to maintain service for a preset duration. This preset duration can be equal to the expected unplanned outage duration.

Specifically, for the greedy operation strategy, the operator should assume this outage only lasts for one-time slot and solve the optimal operation (13) of the next time slot, and then the combo station follows this optimal operation during the next time slot. The operator continues solving one-time-slot outage optimal operation and the combo station continues following until the failure ends. This approach does not necessarily yield the ideal operation because BEVs can leave without discharging when battery storage is sufficient to meet the hydrogen demand. It will yield a reasonable operation for a combo station.

### 4 CASE STUDIES

#### 4.1 Basic setting

We consider a combo station with actual charging demand, hydrogen refuelling demand, and particular electricity price. This station has 30 charging piles and 30 parking spaces to settle all cars.

For charging demands, we randomly choose a whole-day charging loads of a public FCS in Beijing as charging demands of our combo station. There are 219 BEV charging demands at the FCS during the day. The charging load profile is shown in
Figure 3, which is high from 10 AM to the next day’s 4 AM and low from 4 AM to 10 AM. The average charging time is 1.3 h and average charged electricity is 16.4 kWh. The total charging power fluctuates between 0–300 kW. We assume that BEV users set allowable charging fluctuation range as -0.1–1.1 times of the corresponding charging demand.

For hydrogen refuelling demands, we adopt a modified Chevron profile from [29]. The peak time of this demand is at 5 PM. In the following case studies, the total hydrogen demand is provided; thus the hydrogen demand for each time slot changes correspondingly.

For the electricity prices, the average electricity spot prices in Denmark [30] from January to December 2019 are adopted, and are shown in Figure 4. Note that there are two spot prices at 2 AM on 27 October 2019 in this data, and we randomly delete one price. The price curve has two peaks: 9 AM and 8 PM. The electricity purchasing and selling prices from the power grid are set as the average electricity spot prices.

The conversion rate for electricity to high pressure hydrogen is set as 55 kWh/kg [31]. The hydrogen price for FCEV users is set as €9.5/kg [32]. The charging price is set as €0.2/kWh, and BEV users can receive a reward of €0.25/kWh for V2G. To encourage the development of FCEVs, the compensations for unmet demand of FCEVs are set higher than those for BEVs. The compensation for FCEVs is set as €15/kg, while that for BEVs as €0.15/kg.

Three scenarios are considered for the simulation and their descriptions are listed in Table 1.

For scenario one, hydrogen refuelling and fast charging facilities are operated separately without energy storage equipment. For scenario two, HRS and FCS are also operated separately, but they have energy storage equipment, that is, battery and hydrogen vessel, to run their operation separately. For scenario three, HRS and FCS are aggregated into a combo station. This station has energy storage equipment, and they operate in a coordinated manner.
4.2 | Share parking spaces to reduce land rents

Because of the low utilisation of charging station, there are many parking spaces available even during peak time. An example of this is shown in Figure 5a; it is from actual charging records, and it can be seen that the BEVs cannot occupy all parking spaces. More than 1/4 parking spaces are available during the peak time. Furthermore, the refuelling time for FCEVs is short, which allows sharing of parking spaces with BEVs. In this section, we examine the ability of combo stations to satisfy hydrogen demand when FCS and HRS share parking space in a combo station.

According to [33], the Toyota Mirai’s fuel tank can store 5 kg of hydrogen. Therefore, we set a FCEV’s hydrogen demand as 5 kg. The hydrogen refuelling time is set as a random number between 0 and 30 min. Because the time slot of Chevron hydrogen demand profile is an hour, we randomly assign start time and refuelling time to corresponding number of FCEVs in that hour.

The charging records for BEVs are shown in Figure 5. We increase daily hydrogen demand and meet the hydrogen demand of corresponding FCEVs until the parking spaces are insufficient. We find that the original FCS with 30 parking spaces for charging still has many spaces available. If the FCS is rebuilt into a combo station, the remaining parking spaces can meet the hydrogen refuelling demands of nearly 200 cars (approximately 1000 kg) in one day. The utilisation rate of parking spaces will increase, from 0.4 to 0.5, shown in Figure 6.

Because the duration of each time slot in this case study is 15 min, the hydrogen refueling time of the red (0–15 min) and yellow (15–30 min) curves are one and two time slots, respectively. The hydrogen refuelling time of the blue curve (0–30 min) is randomly set as one or two time slots. Therefore, with the increase in hydrogen demand (FCEVs), the total hydrogen refuelling time (utilisation rate of parking spaces) increases both linearly in the red and yellow curve and with fluctuation in the blue curve.

The available parking spaces in the FCS can be used for 300 FCEVs (1500 kg) per day at a fast rate of hydrogen refuelling (<15 min), or 150 FCEVs (750 kg) per day at a slow rate of hydrogen refuelling (15–30 min).

The results show that the parking spaces in a combo station can be shared. Compared with building HRS and FCS separately, land rents can be reduced in a combo station. For low utilisation of existing FCS, the parking spaces can also meet the hydrogen demands of a significant number of FCEVs when the charging station is rebuilt into a combo station.

4.3 | Reduce the expansion cost of grid capacity

A local hydrogen production and refuelling station will have impact on the power grid owing to its power capacity requirement. It may be necessary to reinforce or expand the power grid to accommodate the integration of this type of station.

We assume that all refuelling demands are met, and separately calculate the minimum grid capacity required under three scenarios, as shown in Figure 7.

When only the demand of BEVs is met, the grid capacity requirement of optimal operation for the charging station should be at least 1233.7 kW.

We set the daily hydrogen demand, superimpose the demand for charging, and minimise the grid capacity without considering the operation cost. The operation under daily hydrogen requirement of 150 kg is shown in Figure 8.

For the scenario without energy storage equipment, because the peak time of charging demand and hydrogen demand do not coincide, the minimum grid capacity grows gradually with the increase in hydrogen demand, with small hydrogen demand (0–50 kg). After 50 kg, the hydrogen production power is dominant, as shown in Figure 8a,b. Therefore, the capacity requirement increases rapidly, and presents linear increasing trend.

In scenario 2, the FCS has a 1 MWh battery energy storage with a maximum input and output power rate of 200 kWh. The HRS has a high-pressure hydrogen vessel that stores 20 kg
FIGURE 10 | Operation of combo station under unexpected blackout between 4:00 and 6:00 PM at daily hydrogen demand of 150 kg. (a) Input power from grid. (b) Power to produce hydrogen from grid. (c) Power to produce hydrogen from BEVs. (d) Power to produce hydrogen from battery. (e) Battery’s state of charging. (f) Hydrogen vessel’s state of storage

hydrogen. Owing to the balance of hydrogen storage and battery, the power requirement of each station from the grid is smooth. However, without the coordination of FCS and HRS, the energy of a battery and V2G cannot be used to produce hydrogen.

In scenario 3, the combo station can effectively smoothen the fluctuation of power exchange with the grid, as shown in Figure 8. During the peak time of hydrogen energy demand, battery (shown in Figure 8), power grid, and V2G can be used for hydrogen production. Moreover, hydrogen storage equipment can be used to transfer hydrogen demand. At this point, power grid is not the only source for hydrogen production. Therefore, coordination between HRS and FCS can reduce investment costs for power capacity expansion by increasing utilisation of power grid.

Hence, if the power grid can meet the charging behaviour of BEVs (>1233.7 kW), rebuilding the FCS into a combo station can additionally meet the daily hydrogen requirements of a maximum of 220 kg.

The results show that a combo station has minimum grid capacity requirement, that is, the peak power can be reduced by a combo station. For a combo station operator, the expensive grid connection fee can be reduced. For the distribution network operator, the cost of network expansion can be reduced.

4.4 | Energy self-balance capability

Owing to the coordination between HRS and FCS in a combo station, the critical demands (usually FCEVs) can be satisfied during power outage. The BEVs and battery storage can fulfill the electricity requirements for hydrogen production. When there is power outage for scheduled maintenance, the combo
station can receive blackout information, including expected start time and planned duration in advance.

We set daily hydrogen demand to vary between 0 and 300 kg with power grid capacity fixed at 1 MW. The power outage begins at 4:00 PM and lasts for 2 h. The blackout is totally unexpected; thus, the advance notification time is zero. The daily revenue and energy demand completed ratio are shown in Figure 9.

With hydrogen vessel and battery, the second scenario can meet maximum daily hydrogen demand of 60 kg, while the third scenario can satisfy nearly 100 kg hydrogen demand with coordination. The revenue and completed ratio of hydrogen are much better in the combo station compared to other two scenarios.

The operation of the combo station with 150 kg daily hydrogen demand is shown in Figure 10. At 4:00 PM, the combo station begins to operate in island mode, as shown in Figure 10a,b. The battery and BEVs begin discharging to produce hydrogen at maximum rate, as shown in Figure 10c,d. The hydrogen vessel is also used to provide the stored hydrogen to meet critical loads, as shown in Figure 10f. With the coordination between FCS and HRS, the energy self-balance capability is significantly improved.

If the outage is for scheduled maintenance, the combo station will have sufficient time to prepare to manage it. For example, it can charge batteries in advance and forgo servicing unimportant demands. Therefore, the total revenue will increase with the increase in the advance notification time, as shown in Figure 11.

In Figure 11, the revenue increases with the increase in advance notice time. In this study, when the advance notice time is more than 1.25 h, the combo station cannot adjust its operation to gain more profits. When the advance notice time is significantly short, the combo station will dispatch more BEVs to discharging to produce hydrogen. The BEVs, which are scheduled to charge during the outage, will be charged instantly when a blackout occurs. Therefore, the uncompleted ratio of BEVs will decrease gradually.

5 | CONCLUSION

In this study, we investigate the advantage and operation of a conceptual combo station, which consists of an FCS and HRS. Furthermore, the battery storage and hydrogen vessel are considered in the combo station. We develop a daily optimal operation model to evaluate advantages of a combo station, which can be easily extended to the scenario-based optimisation considering uncertain factors. The actual charging demand of a fast charging station in Beijing, the modified hydrogen demand profile of Chevron, and the electricity spot price of Denmark are used for the simulations. Simulation results show that the combo station offers advantages of saving land rents, reducing the expansion cost of power grid capacity, and promoting energy self-balance capability.

The results of this study can guide the future construction of hydrogen refuelling stations. Moreover, the renewable energy and standby fuel cells can be deployed in the combo station to make it self sustainable, whose optimal operation can be obtained easily based on the proposed model. Further research directions include the optimal operation of the combo station with renewable energy generation and optimal planning method for the station.
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