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Hydrogen Mass Balance of Hydrogen Refuelling Stations in British Columbia, Canada

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Introduction

In the realm of clean energy innovation, hydrogen fuel cell technology has become one of the most outstanding applications to minimize pollution and alleviate energy crisis [1, 2]. However, a study revealed that hydrogen is an indirect greenhouse gas which could perturb distributions of methane and ozone due to its reaction with radicals in the atmosphere [3]. Thus, a future hydrogen economy may have greenhouse consequences if hydrogen leakage and losses are not being controlled in the application systems.

In recent years, many studies of hydrogen refuelling stations (HRSs) were conducted on optimizing station configuration and operation parameters using simulation modules [4, 5, 6]. To date, only one study has analysed hydrogen station mass balance on a commercially operated station, suggesting an average percentage of hydrogen losses at an HRS to be between 2% to 10% with an uncertainty of ±5% [7].

At a refuelling station, most hydrogen losses originate from the hydrogen manifold connectivity, and operational venting and purges. The mass balance analysis for a given station involves calculations of hydrogen mass input and output, as well as the estimation of hydrogen losses. Thus, such analysis can provide an insight of the supply and demand of hydrogen at the stations and meanwhile indicating trends in hydrogen losses. Understanding the mass balance of HRSs is needed to monitor station performance and ensure safe operations of the stations while minimizing operational costs. The following definitions are used for evaluations of hydrogen mass balance:

- Hydrogen (or station) mass input: the amount of hydrogen being transferred to the station from the transfer modules on a hydrogen delivery truck;
- Hydrogen (or station) mass output: the amount of hydrogen is flowing through the dispenser nozzle and is calculated by a mass flow meter;
- Hydrogen losses: the predictable amount of hydrogen being vented for operational and maintenance purposes, and the unpredictable amount of hydrogen leaked throughout the refuelling station;
- Leakage rate: the rate at which the hydrogen is leaking from components of the refuelling station;
- Mass balance: the ratio between the amount of hydrogen dispensed to the vehicles and the amount of hydrogen supplied to the station within a given amount of time;
- Mass margin: the small amount of mass change of hydrogen in the storages calculated between two consecutive evaluation periods when the station is at standby state.

Four hydrogen refuelling stations in BC were investigated in this study to analyse and evaluate hydrogen losses and mass balance in the most recent years. The hydrogen flow control system of those stations is a dynamic system which allows several concurrent processes to improve station availability of hydrogen supply to customer vehicles.

Figure 1 illustrates a system configuration overview of the investigated refuelling stations in BC. The hydrogen supply to the stations is from off-site H_2 production delivered by road trucks. Pressure sensors were installed to monitor hydrogen pressures in low- and high- pressure storage systems. A hydrogen compressor was installed to compress hydrogen from the low-pressure storage to the high-pressure storage. A Coriolis Mass Flow Meter (CMFM) was integrated in the hydrogen dispenser to measure hydrogen mass flow out of the dispenser nozzle.

Three relevant operations shall be monitored for mass balance analysis at the stations.

1. Hydrogen delivery for low-pressure storage system refill (to around 450 bars);
2. Hydrogen compression for high-pressure storage system refill (to around 850 bars);
3. Hydrogen dispensing to vehicle.

Each operation can be performed individually and two or more operations can be performed simultaneously. This adds a significant level of complexity to establish an accurate determination of the station hydrogen mass balance.

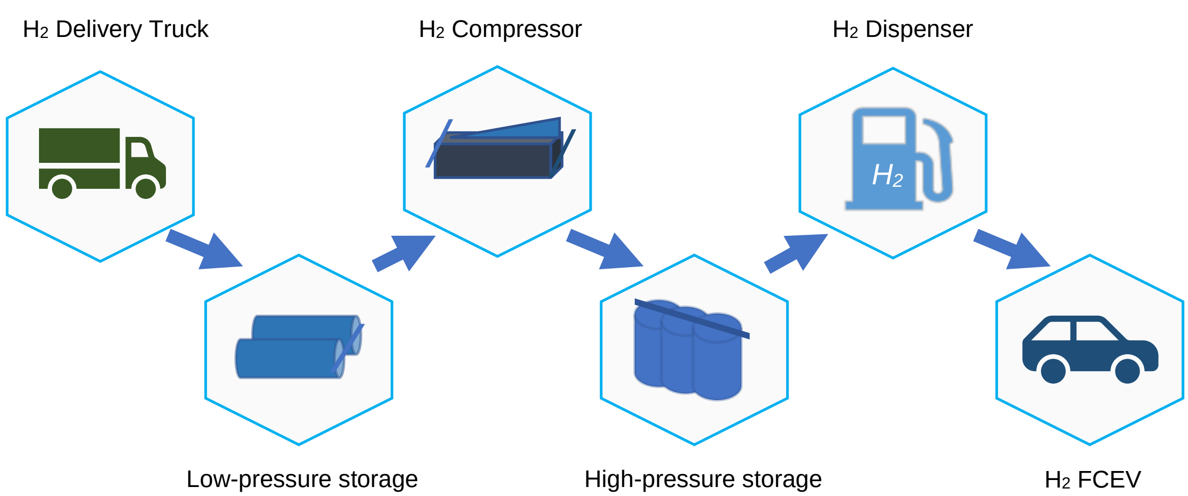

Figure 1. HRS System Configuration Overview

To accurately assess mass balance, hydrogen mass input and output, as well as internal mass transfer within the system storages, need to be monitored and calculated when the system is in or close to a thermodynamic equilibrium. A method has been developed to periodically evaluate hydrogen flow throughout the system by utilizing a top-down approach to monitor station operating and standby periods [8]. By applying the method, hydrogen mass input and output, and hydrogen mass stored in each storage system are calculated post operating periods and periodically during standby periods. Based on these results, mass margins and hydrogen losses are determined periodically. The method was implemented on a data platform to actively monitor mass balance of one of the HRSs in BC, and recently the method was applied on all the stations to dynamically analyse mass balance of the stations in real time.

Methodology

NIST PVT Method

To calculate the mass of hydrogen accurately, the system shall be in thermodynamic equilibrium while evaluating the mass of hydrogen in each storage to apply the ideal gas law equation (eq.1).

$$PV = nRT \qquad \text{- (1) -}$$

Where V, P, T are the water volume of the storage, the pressure and temperature of the hydrogen gas respectively; n is the number of moles of hydrogen, R is the universal gas constant.

The ideal gas law equation is commonly used to calculate the amount of gas at high temperature and low pressure. For high pressure conditions, mass calculations of gases require correction factors to be added to the ideal gas law equation if used.

NIST provided a standardized equation for hydrogen gas densities for fuel consumption applications [9]. The equation is essentially an expression for the compressibility factor of gaseous hydrogen, as shown below:

$$Z(P,T) = \frac{P}{\rho RT} = 1 + \sum_{i=1}^{9} a_i \left(\frac{100K}{T}\right)^{b_i} \left(\frac{P}{1MPa}\right)^{c_i} \qquad \text{- (2) -}$$

Where ρ is the density of hydrogen in the storage; P is the equilibrium pressure of the storages in MPa; T is the equilibrium temperature in Kelvin; a_i, b_i, c_i are constant terms, a total of 9 terms.

Equation 2 was validated with available experimental data for the density of normal hydrogen, within *0.04%* uncertainty of hydrogen density, over the temperature range from 255 K to 1000 K with pressures up to 120 MPa.

Combining the ideal gas equation with compressibility factor correction, and the mass of hydrogen in the storage of the station in standby state is calculated using the equation below:

$$m = n \cdot M = Z(P,T)M\frac{PV}{RT} \qquad \text{- (3) -}$$

Where V, P, T are the water volume of a hydrogen storage, the pressure and temperature of the hydrogen gas respectively; n is the number of moles of hydrogen, M=2.01568 g/mol is the molar mass of the hydrogen molecule, R=8.314472 $J \cdot mol^{-1} \cdot K^{-1}$ is the universal gas constant.

Mass balance for a time-period at an HRS can be simply written as:

$$me = 100\% \times \frac{m_{output}}{m_{input}} = 100\% \times \frac{\sum m_{dispensed}}{\sum m_{delivery} - \Delta m_{storage}} \qquad \text{- (4) -}$$

Where $\sum m_{dispensed}$ is the total mass of hydrogen dispensed at the station, aggregated from Coriolis mass flow meter readings. $\sum m_{delivery}$ is the total mass of hydrogen from deliveries that is calculated from the holistic evaluation in system operating periods where refills of the low-pressure storage system occur. $\Delta m_{storage}$ is the mass difference of the hydrogen storage at the beginning and end of the evaluation period.

Holistic Evaluation

Estimating the mass of hydrogen in low-pressure and high-pressure storage systems, and the amount dispensed to vehicle, is crucial in calculating the station mass input because the only available data to dynamically calculate mass input are pressure measurements of the low-pressure storage. To accurately calculate the station input after the hydrogen delivery that refills the low-pressure storage, we must take simultaneously the internal mass transfer and station output into account, otherwise, the station mass input would be under-evaluated since compressing and dispensing operations may occur concurrently.

Two mass calculation approaches, the gas equation with compressibility factor correction (eq.1) and *mass flow measurement* are commonly applied in mass balance analysis of gaseous substances in a system. The current system configuration of the investigated HRSs in BC utilises both approaches in their applications; typically, a Coriolis mass flow meter is used to measure hydrogen output per fuelling event, and data logs from the temperature and pressure sensor network allows hydrogen mass calculation from the gas equation with compressibility factor correction.

A holistic evaluation method has been created to actively monitor and evaluate hydrogen flow in the system – hydrogen mass transfer in the system, station mass input and output when the station is at standby status at a certain time interval. The requirement for accurate evaluations at each checkpoint of the time interval are:

1. Evaluate hydrogen input and output, as well as hydrogen mass in the storages when the system or the relevant subsystems are in thermodynamic equilibrium;
2. Ensure accurate measurements of pressures and temperatures at low-pressure storage banks and high-pressure storage banks;
3. Ensure accurate capture of fueling events (hydrogen output) and correct interpretation of Coriolis flow meter readings.

A ten-minute interval is assumed to be reasonable amount of time to allow the system, once in standby, to reach a state where the errors due to thermodynamic imbalances are negligible. Figure 2 shows an example of evaluation checkpoints labelling for the holistic evaluation method. At every 10-minute interval during the standby period, the mass of hydrogen in the storage system was calculated. For evaluation checkpoints in the same standby period (e.g., b1, b2… b6), the assessed hydrogen mass shall be fairly the same until the next system operating period. The calculated mass difference in the storage between two adjacent checkpoints furnishes leakage monitoring of the station at standby status with a numerical mass margin. Any significant changes of the hydrogen mass in the storage (mass margin) shall indicate leaks in the isolation trenches, or pressure sensors signal loss.

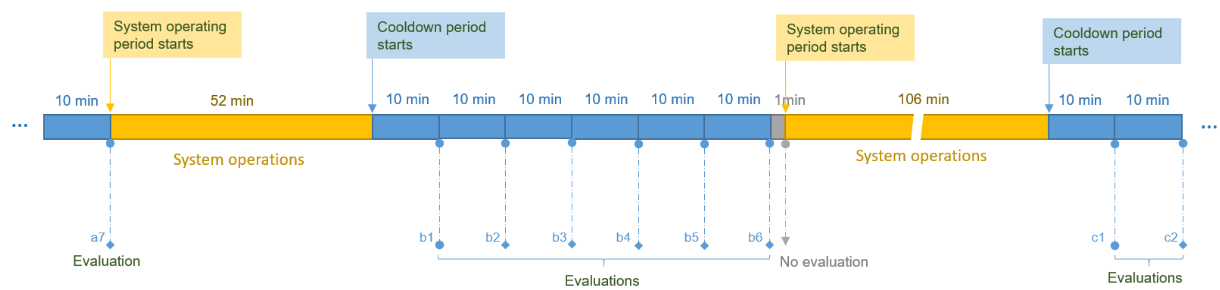

Figure 2. Example of evaluation checkpoints labelling for holistic evaluation

Causality Analysis

Causal impact is a statistical method that quantifies the effect (i.e., the impact) of a one-time event on a variable that is observed over time. The observations prior to the event comprise the pre-period, while those after the event comprise the post-period. Causal impact tries to determine how much the mean of the variable changes immediately after the event, and whether or not this change is statistically significant.

In this analysis, the events of interest are compressor maintenance, as hydrogen compression is the key process of hydrogen mass transfer within the system from the low-pressure storage to the high-pressure storage, during which hydrogen leakage may occur. At HRSs in BC, station operators perform both preventative and corrective compressor maintenances. While these maintenance operations may result in hydrogen losses (venting and purging), it is safe to assume that, after a compressor maintenance, hydrogen leakage would be minimum during compression process. Thus, causal impact analysis is carried out to preliminarily analyse significance of compressor maintenance in reducing hydrogen losses at the stations.

Uncertainty Estimation

The total uncertainty of mass balance calculation using this holistic idle period evaluation method consists of the uncertainty of station mass output which originates from Coriolis flow meter readings, and the uncertainty of station mass input which originates from mass calculations of the hydrogen in the storages.

The uncertainty in the amount of hydrogen dispensed is the uncertainty of the Coriolis mass flow meter readings, which ranges from 0.1% to 0.5% based on manufacturer specifications, so station mass output's uncertainty is estimated to be no more than 0.5%.

Other considerations for the uncertainty of hydrogen mass estimation in the system include pressure and ambient temperature sensors accuracy and precision, assumption of ambient temperature representing the hydrogen temperature in low- and high-pressure storage systems and assumption of steady stat in a predefined idle interval (10 minutes) after operations. A recent study tested the refuelling of hydrogen tanks with a water volume of 320 liters [10]. It was found that the temperature gradient of the hydrogen gas was negligible 5 minutes after the refuelling event. At this time, it reached a steady state at 25 to 35 °C depending on the fuelling pressure ramp rate and the initial hydrogen gas temperature. It also found that the settling time of 5 minutes was unaffected by the ambient temperature which was tested between -15 to +35 °C

A typical hydrogen cylinder of high-pressure storage banks at the HRSs in investigation with a smaller water volume of 255 liters should reach its steady state in a slightly less or a similar timespan after station operations. However, no sensors were placed inside the tank to measure internal hydrogen temperatures, and so ambient temperature measured at the dispenser were used to estimate the temperature of the hydrogen in the banks during standby state. More sensors can be installed to collect more temperature data to improve accuracy of the calculations. In this report, we assume the maximum uncertainty due to temperature difference (~10°C in difference in the first holistic idle period evaluation) in mass calculation to be around 3%.

In the most complicated hydrogen delivery scenario where system operations include low-pressure storage system refill, hydrogen compression and high-pressure storage system refill, and hydrogen dispensing events. The mass input evaluation of such a system operating period can be estimated to be 4.5%, from hydrogen storage container deformation under different high pressures and the difference between storage internal hydrogen temperature and the ambient temperature hydrogen. Thus, the total uncertainty of mass balance calculation is estimated in Eq (5).

$$\frac{\delta me}{me} \approx \frac{\delta m_{output}}{m_{output}} + \frac{\delta m_{input}}{m_{input}}$$

$$\approx \frac{\delta m_{output}}{m_{output}} + \frac{1}{m_{input}} \sqrt{\left(\frac{\partial m_{input}}{\partial T} \delta T\right)^2 + \left(\frac{\partial m_{input}}{\partial V} \delta V\right)^2} \approx 5.0\% \qquad \text{- (5) -}$$

Results and Discussion

Station Mass Balance

The station mass output is mainly monitored by CMFMs and recorded by the data acquisition system. Aggregating CMFM end-time readings of fuelling events at the stations yields a total amount of station mass output ($\sum m_{dispensed}$ in Eq (4)). Applying holistic evaluation method that ensures accurate calculations of mass change in the storage systems, hydrogen deliveries to the stations can be detected with pressure bumping up trends in operating periods and the station mass input can thus be computed ($\sum m_{delivery} - \Delta m_{storage}$ in Eq (4)).

Figure 3 shows the year-round mass balance of BC stations in fiscal year 2023 (April 2022 – March 2023). HRS01 is the most utilized station yielding a year-round mass balance of 95.2% (±4.8%). Hydrogen delivery to HRS01 is twice to thrice more frequent than HRS03 and HRS04 stations. From the comparison of mass balance summary of BC stations in FY23, HRS01 outperforms other stations significantly. With the known sources of hydrogen loss, station performance in terms of mass balance at different stations is analysed in later sections.

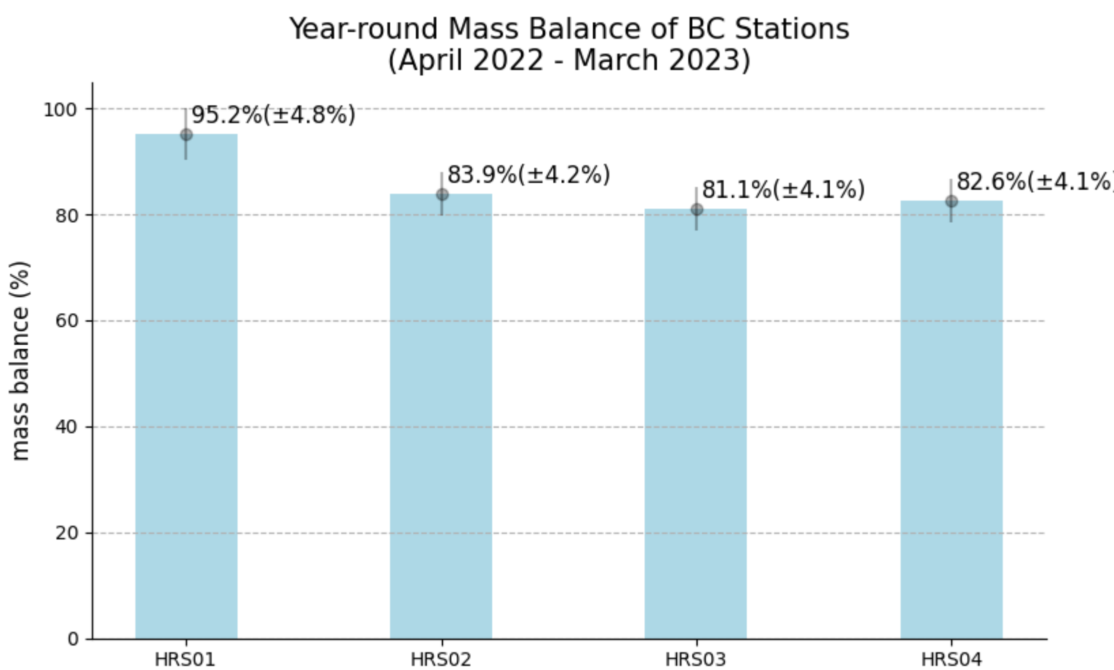

Figure 3. Recent one year (FY23) mass balance of BC stations

Figure 4 – Figure 7 summarise the mass balance of four BC stations using available data from the stations before April 2023. Hydrogen supply (station mass input), demand (station mass output), and hydrogen losses are also plotted.

Comparing the mass balance of the four stations in BC, it's distinguishable that HRS01 station outperformed all other 3 station consistently from the mass balance analysis on all available historical data. In the past fiscal year, April 2022 to March 2023, the mass balance of HRS01 station was well above 90% and the highest monthly mass balance, 99.3% (±5.0%), was observed in December 2022.

Only HRS02 station had comparative hydrogen demand to HRS01 station. However, its monthly mass balance was on average around 85% in the past one year. A peak mass balance of HRS02 appears in February 2023, at 92.6% (±4.6%). It can be an excellent case study during that time-period at HRS02 station to investigate the irregular improvement.

Hydrogen demand at HRS03 and HRS04 stations happened to be significantly less than HRS01 and HRS02 stations. In recent months, demand at HRS04 declined. Assuming that the hydrogen loss at standby state is constant, this hydrogen loss will have a higher impact on the hydrogen mass balance relative to the station supply. HRS03 station was able to maintain mass balance above 80% steadily as the supply/demand stayed relatively steady.

A mass margin variable, describing a minor contributor to hydrogen losses, was introduced to monitor the small mass changes in the storage system during station standby periods. Interestingly, a comparison of the mass margin at different stations during standby periods (see Table 4 in Annex section) indicates that hydrogen losses during station standby periods at HRS03 and HRS04 are less than at HRS01 station, rather than having a comparably larger hydrogen loss at standby state due to their lower mass balances. This implies that most hydrogen losses at all the stations occur during non-standby periods (i.e., station maintenance or system operating periods), although hydrogen leaks during station standby periods still contribute non-negligibly to the overall total hydrogen losses.

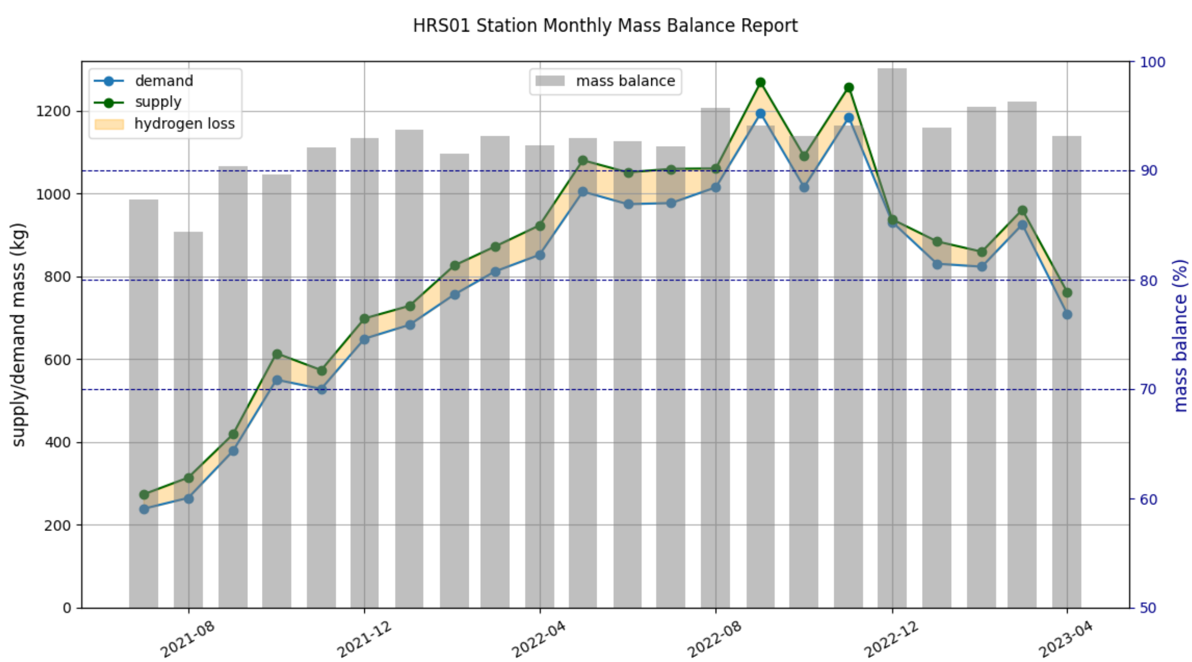

Figure 4. HRS01 monthly mass balance summary

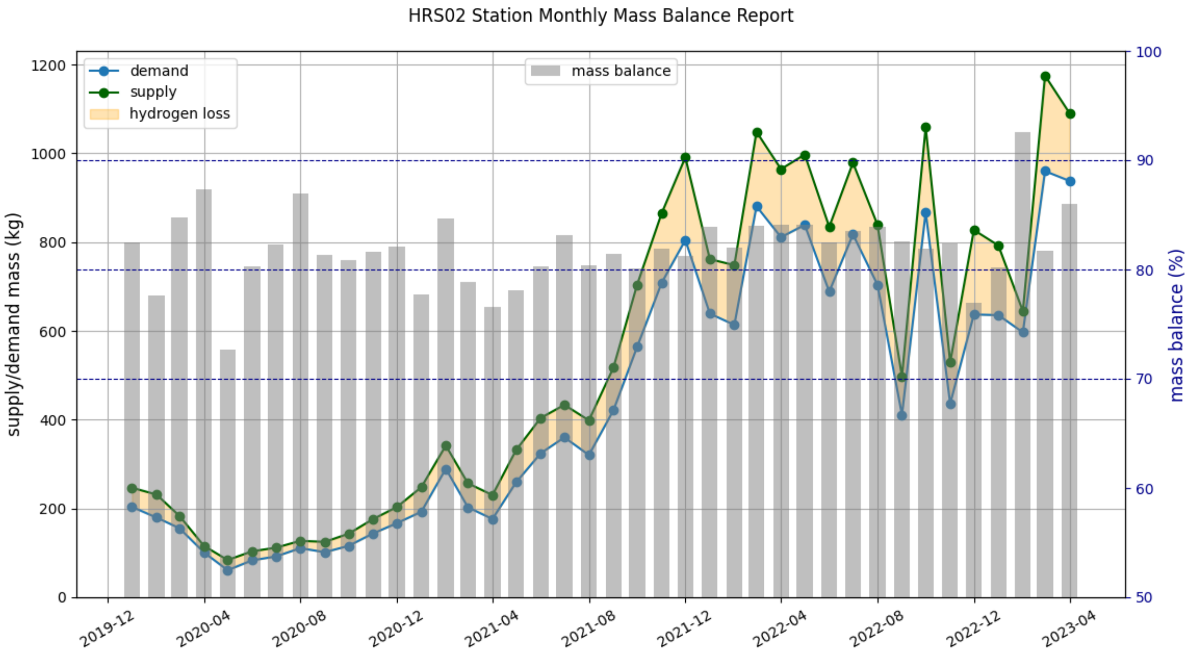

Figure 5. HRS02 monthly mass balance summary

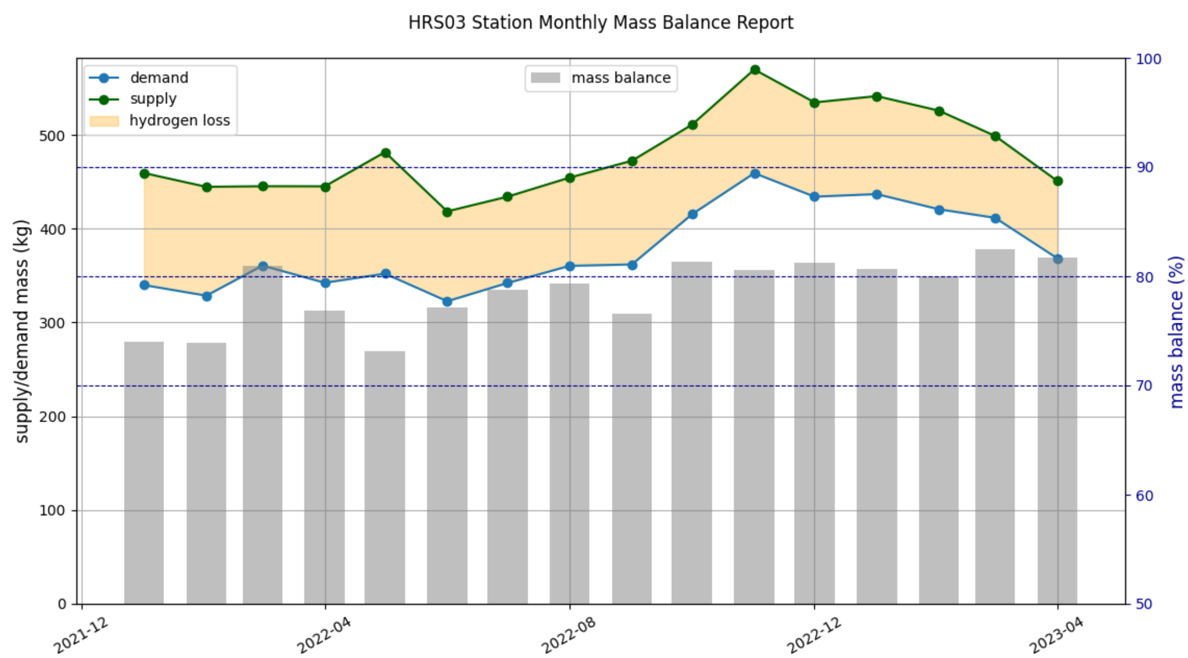

Figure 6. HRS03 monthly mass balance summary

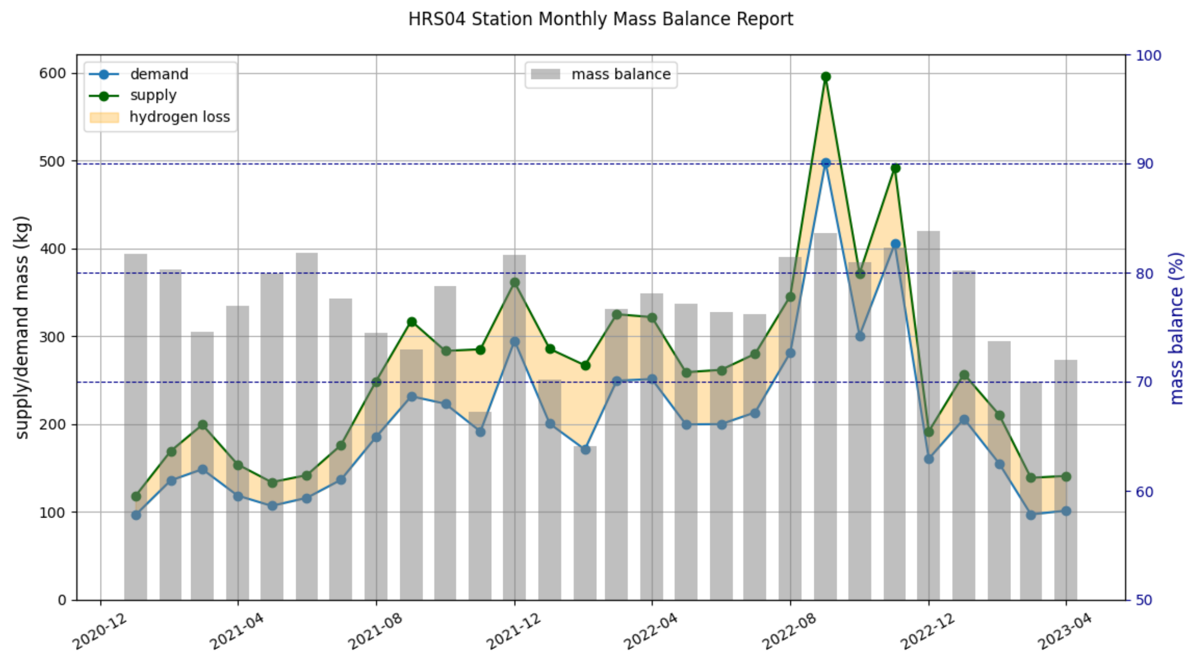

Figure 7. HRS04 monthly mass balance summary

Hydrogen Losses from Known Sources

To ensure the purity of the hydrogen delivered to the customer vehicles and operational safety of the dispenser, an HRS usually vents hydrogen in the dispenser hose after fuelling or during long standby periods. An occurrence of hydrogen venting in a 700 bars dispenser hose results in around 18 grams of hydrogen loss at the station if fully vented.

Figure 8 to Figure 11 summarize dispenser hydrogen hose venting at the HRSs. All four stations have close relative percentages of H_2 vented amount in hose to the total station supply. The vented amount in dispenser hose of the most utilized station, HRS01, was at an average of 0.71% to the total station supply, that of HRS02 and HRS03 were at an average of 0.68% and an average of 0.67% to their total station supply, whereas the vented amount at HRS04 was the lowest at an average of 0.55% of its total station supply.

Despite that the average percentage of total station supply used for purging processes at the stations were similar, the amount of hydrogen vented in hose at HRS01 contributes to 14.8% of the total station hydrogen loss, as shown in Table 1, while the amount of hydrogen vented in hose at other three stations contribute to less than 5% of the total station hydrogen loss. This correlates well with the higher utilisation of HRS01 in comparison to the other stations. Therefore, it implies that a substantial portion of the hydrogen loss at HRS01 was related to the operational need in hydrogen venting process to remove impurity and ensure operational safety. In comparison, only a small portion of the hydrogen was used for the venting process at HRS02, HRS03 and HRS04.

From Figure 3, HRS02, HRS03 and HRS04 had considerably lower mass balanced compared to HRS01. Thus, a majority of hydrogen losses at HRS02, HRS03 and HRS04 were from other sources, such as hydrogen leakage from the manifold fittings and hydrogen vented from pressure relief valves. The primary source of hydrogen losses, which may vary from station to station, requires further investigation.

Table 1. Station hydrogen loss and hydrogen vented in hose

Station	Station hydrogen loss average	H_2 vented in hose rel. to total supply average	H_2 vented in hose rel. to total H_2 loss
HRS01	4.8%	0.71%	14.8%
HRS02	16.1%	0.68%	4.2%
HRS03	18.1%	0.67%	3.7%
HRS04	17.4%	0.55%	3.2%

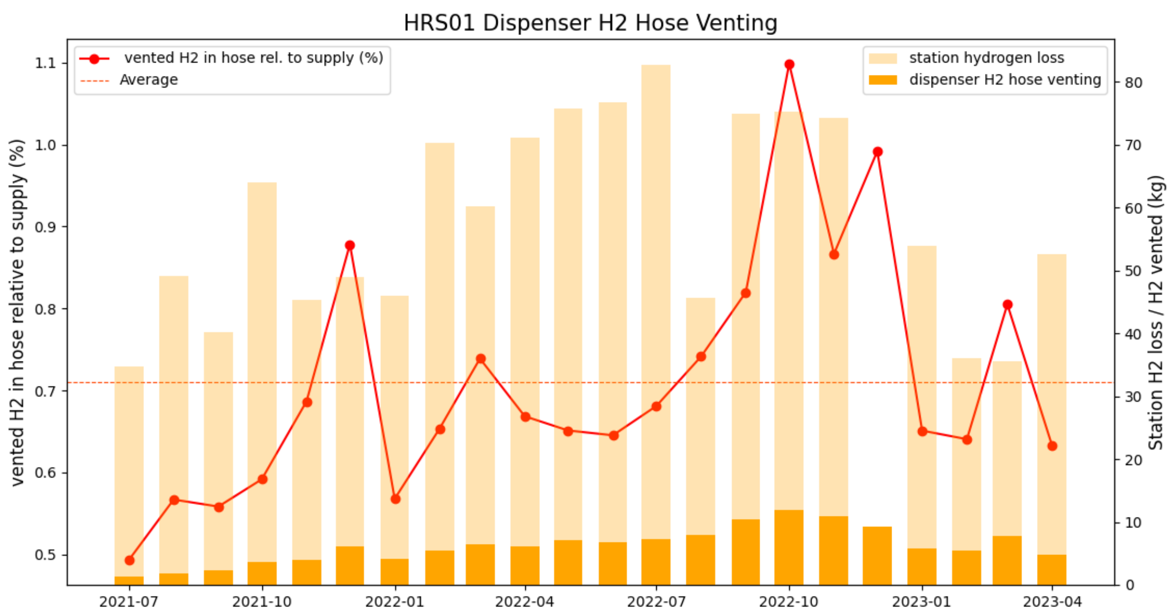

Figure 8. HRS01 dispenser H_2 hose venting summary

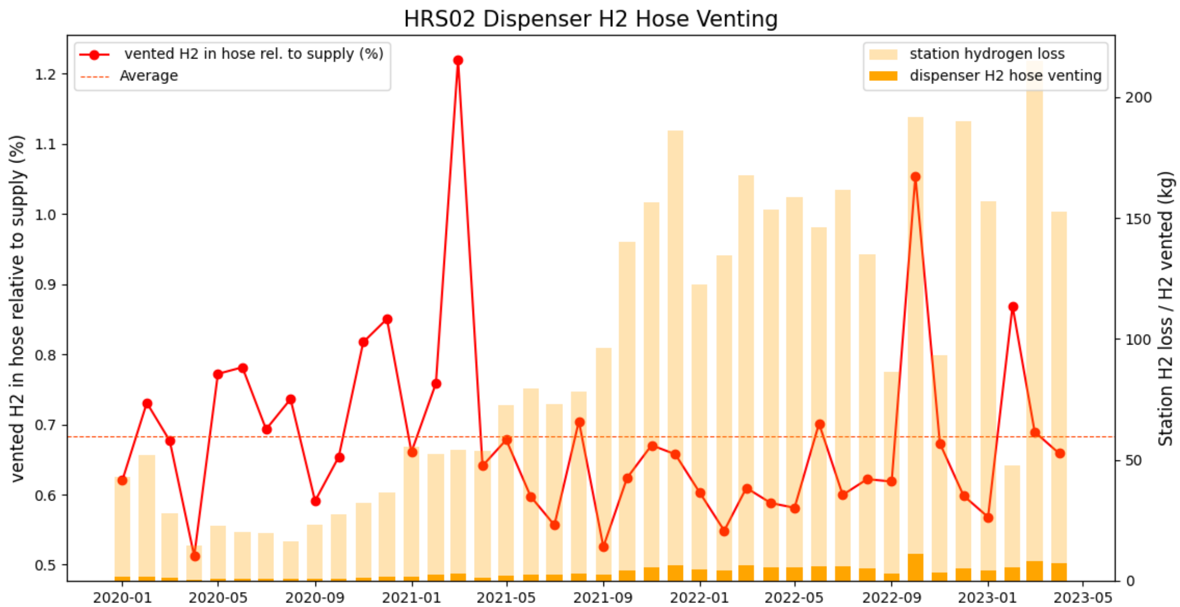

Figure 9. HRS02 dispenser H_2 hose venting summary

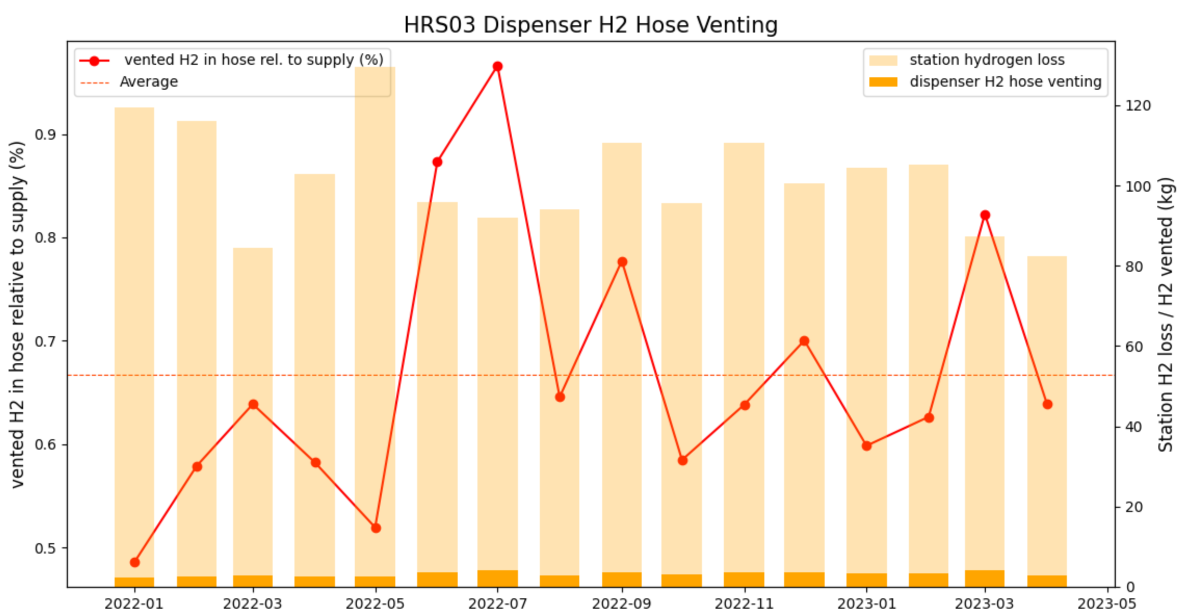

Figure 10. HRS03 dispenser H_2 hose venting summary

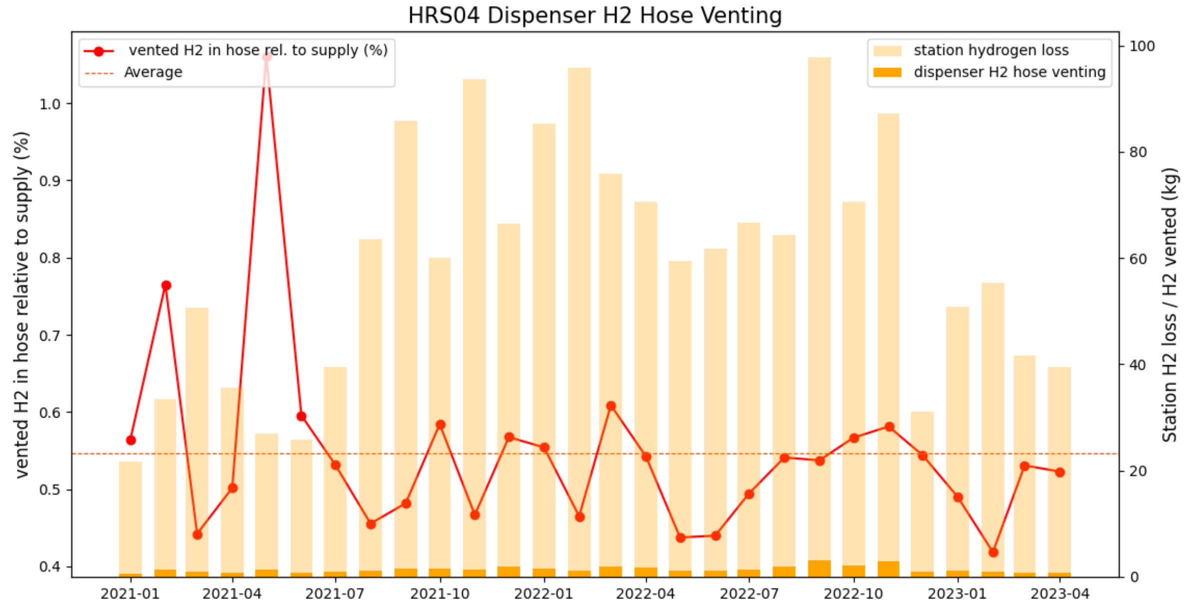

Figure 11. HRS04 dispenser H_2 hose venting summary

The operator company has installed a hydrogen Lower Flammable Limit (LFL) detector in the compressor room of each HRS to monitor hydrogen concentration and raise alarm when it exceeds the set limit. Generally, LFL of hydrogen is considered to be 4% by volume. LFL triggers at 10% and 5% represent alarm levels of a low concentration (0.4% by volume) and a relatively low concentration (0.2% by volume) of hydrogen detected in the compartment where the detector is installed to monitor possible hydrogen leakage. Table 2 summarizes occurrences of LFL triggers at 5% and 10%, listing event counts and total durations of LFL measurements over 5% and over 10%. Compressor maintenance counts was also listed to find possible correlation.

In year 2022, HRS01 was the station with the lowest LFL 5% trigger count and LFL 10% trigger count, with durations of 48.2 minutes and 28.4 minutes, respectively. These numbers were significantly less for the other three stations. Therefore, with the calculation of mass balance in the previous section that HRS01 dominates, a relatively large portion of hydrogen losses of HRS02, HRS03 and HRS04 are possibly from the hydrogen leakage in the compressor room. As the first established station in BC, HRS01 has been tested and improved on many aspects for years to reduce hydrogen leaks, such as manifold fittings and piping system adjustments. It’s suggested to perform similar leak tests and parts adjustments in the newer stations to achieve desirable station performance.

From the summary table below, on the compressor maintenance day, there was no strong correlation found between compressor maintenance events and LFL trigger occurrences. Only a few LFL triggers occurred on the maintenance day, mainly at HRS01 and HRS02.

However, the total duration of these LFL events seems to correlate well with the hydrogen mass balance of the stations for the year 2022. HRS01 with the highest mass balance has the lowest cumulated duration of LFL events as less than 80 minutes per year. The other stations have much higher cumulated duration, from 250 minutes for HRS 03 to 580 minutes for HRS02.

Table 2. LFL event summary at HRSs in BC

Station	Data date range	LFL 5% trigger count (duration in minutes)	LFL 10% trigger count (duration in minutes)	Compressor maintenance count (maintenance day with LFL 10% trigger)
HRS01	Year 2022	25 (48.2)	18 (28.4)	3 (1)
	Year 2023 (January to April)	3 (3.0)	2 (1.7)	0 (-)
HRS02	Year 2022	466 (465.6)	218 (114.9)	9 (3)
	Year 2023 (January to April)	4 (7.6)	4 (7.3)	2 (0)
HRS03	Year 2022	34 (202.5)	20 (43.0)	3 (0)
	Year 2023 (January to April)	16 (92.3)	6 (3.5)	1 (0)
HRS04	Year 2022	60 (429.0)	32 (71.1)	2 (1)
	Year 2023 (January to April)	0 (-)	0 (-)	0 (-)

Causal Impact of Compressor Maintenance

Along the hydrogen delivery pathway, one potential point of leakage is at the compressor. Compressor maintenance events include two major types: (i) check valve replacement, (ii) piston seal replacement. During a typical compressor maintenance, an HRS operator may perform replacements for check valve, piston seal or both, depending on the wear condition of compressor parts.

Causal impact analysis was carried out on the weekly mass balance dataset labelled with compressor maintenance records. Table 3 lists the results generated from causal impact analysis on mass balance of BC stations using compressor maintenances as interventions. Maintenance type column shows what compressor parts were replaced on the maintenance date. Posterior actual weekly average mass balance indicates the weekly average mass balance over four weeks after the maintenance, while the posterior predicted weekly average mass balance is the predicted mass balance at the station assuming the maintenance did not happen. In a general sense, if those two values were far apart then causality due to a compressor maintenance likely revealed.

Among BC stations, only 4 out of 15 instances of compressor maintenances, two at HRS01 and another two at HRS02, appeared to be the case where the causal effect can be considered statistically significant to mass balance of the stations.

At HRS01 station, a positive effect was observed during an intervention on a piston seal replacement in November 2021: the actual mass balance was considerably higher than the predicted mass balance with 97.6% probability of causal impact. Another intervention on a check valve replacement in February 2022: the actual mass balance was considerably higher than predicted with a 99.1% probability of causal impact.

At HRS02 station, a positive effect was observed during an intervention on a piston seal replacement in May 2021: the actual mass balance was considerably higher than the predicted mass balance with 100% probability of causal impact. Surprisingly, a negative effect was observed during an intervention on a check valve replacement in March 2021: the actual mass balance was significantly *lower* than the predicted value with 100% probability of causal impact.

From an engineering perspective, the wear of piston seals or compressor check valves usually leads to internal hydrogen leakage inside the compartments of the hydraulic cylinder that possibly causes low compression efficiency, instead of a noticeable amount of hydrogen losses to the atmosphere. In contrast, the wear of manifold connection fittings may likely result in hydrogen losses to the atmosphere from the system.

The causal impact of check valve and piston seal replacements explains the change in mass balance trend before and after maintenance periods, but it does not explain engineering fundamentals very well, which in turn implies that the hydrogen losses due to the compressor parts, check valves and piston seals, may not be the contributors to the overall station hydrogen losses. However, a small amount of hydrogen retained in the compressor vented to the atmosphere during a compressor maintenance and the amount of hydrogen needed to purify compartments in the compressor after a compressor maintenance contribute to the station hydrogen losses.

Table 3. Results of causal impact analysis

Station	Maintenance date	Maintenance type	Posterior actual weekly average mass balance	Posterior predicted weekly average mass balance with 95% confidence interval	Probability of causal impact
HRS01	**2021-11-11**	**Piston seal**	**93.2%**	**87.08% [81.4%, 93.1%]**	**97.60%**
	2022-02-16	**Check valve**	**94.2%**	**86.2% [79.7%, 92.9%]**	**99.10%**
	2022-03-29	Check valve, piston seal	93.2%	93.07% [90.5%, 95.7%]	53.95%
HRS02	2020-10-07	Piston seal	82.5%	84.8% [80.5%, 89.2%]	84.52%
	2021-03-08	**Check valve**	**75.7%**	**82.8% [79.6%, 86.0%]**	**100%**
	2021-05-19	**Piston seal**	**83.9%**	**74.8% [69.0%, 80.5%]**	**100%**
	2021-08-26	Check valve, piston seal	83.1%	82.5% [78.8%, 68.2%]	62.84%
	2022-03-01	Check valve, piston seal	83.9%	82.1% [79.6%, 84.5%]	93.91%
	2022-05-24	Check valve, piston seal	83.5%	84.3% [81.9%, 86.9%]	74.13%
HRS03	2022-02-02	Check valve, piston seal	78.3%	81.7% [73.7%, 89.6%]	79.22%
	2022-05-04	Check valve	70.3%	72.2% [62.4%, 81.9%]	63.84%
HRS04	2021-02-21	Check valve	82.9%	77.6 [70.5%, 84.5%]	92.71%
	2021-09-06	Piston seal	74.0%	75.2% [71.9%, 78.5%]	76.32%
	2022-02-08	Check valve, piston seal	70.5%	75.9% [67.1%, 84.6%]	90.11%
	2022-05-25	Check valve	77.4%	77.1% [72.2% 81.8%]	52.75%

Conclusion

Hydrogen losses vary across stations, with HRS01 outperforming HRS2, HRS03 and HRS04. The study conducted by Genovese et al. [4] on hydrogen leakage rates in real operation gives a range of 2-10% (±5%) as the commonly observed leakage amount at an HRS. Of the four stations in this analysis, only HRS01 comes close to this level of performance. The mass balance of HRS02 and HRS03 stations are well above 80% in most of the recent months. HRS04, however, is the station of the lowest utilization and its mass balance appeared to be lower than 80% in the most recent months.

Operational venting is performed to remove impurity and ensure operational safety after refuelling. The busiest station with the highest mass balance, HRS01, has the highest ratio of the amount of hydrogen used for operational venting to station mass total input compared to other stations. Hydrogen vented for operational need at HRS02, HRS03 and HRS04 is only a minor contributor for the station hydrogen losses. On the other hand, LFL trigger events at those three stations show that hydrogen leakage is more often detected in their compressor rooms than HRS01. Hence, hydrogen leakage from the manifold fittings and piping systems inside the compressor rooms at HRS02, HRS03 and HRS04 may be the largest factor of hydrogen losses.

In addition to estimating station mass balance itself, we have attempted to identify compressor maintenance on check valve replacement and piston seal replacement as a contributing factor to the improvement of mass balance. The causal impact analysis on the weekly mass balance dataset with interventions of such compressor maintenances implies that compressor maintenance overall across the four stations has no clear or consistent impact on the improvement of mass balance, so that the wear of the piston seals and the check valves of a hydrogen compressor is not a clear contributor to hydrogen losses at the stations.

Based on the mass balance analysis and preliminary hydrogen leak analysis in the current project work, the newer stations with low mass balances will be our primary focus in future work to collaborate with the operator company, including variations of hydrogen losses, manifold leak condition in the compressor rooms, and correlations between hydrogen venting in hose and station mass balances.

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Annex

Table 4. Mass margin of BC stations in standby periods

	Evaluation Count	Mean (kg)	Min (kg)	Median (kg)	Max (kg)
HRS01	32920	**-0.009679**	-0.188471	**-0.009043**	0.168789
HRS02	33262	**-0.005871**	-0.161206	**-0.003975**	0.146794
HRS03	38650	**-0.002060**	-0.252363	**-0.000499**	0.245488
HRS04	39344	**-0.004573**	-0.331684	**-0.006182**	0.320906

Note: holistic evaluations are done every 10 minutes during station standby periods