Comparative Evaluation of Hydrogen Emission Quantification Methods at the Component Level Using Controlled Releases

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Context

Hydrogen (H_2) is a key decarbonization vector for hard-to-electrify sectors [1].
Yet **fugitive and operational emissions** along the value chain contribute to climate change. Monitoring these emissions remains challenging, as H_2 properties severely constrain the available detection technologies [3].

GWP_{100} = 11.6 ± 2.8 [2]

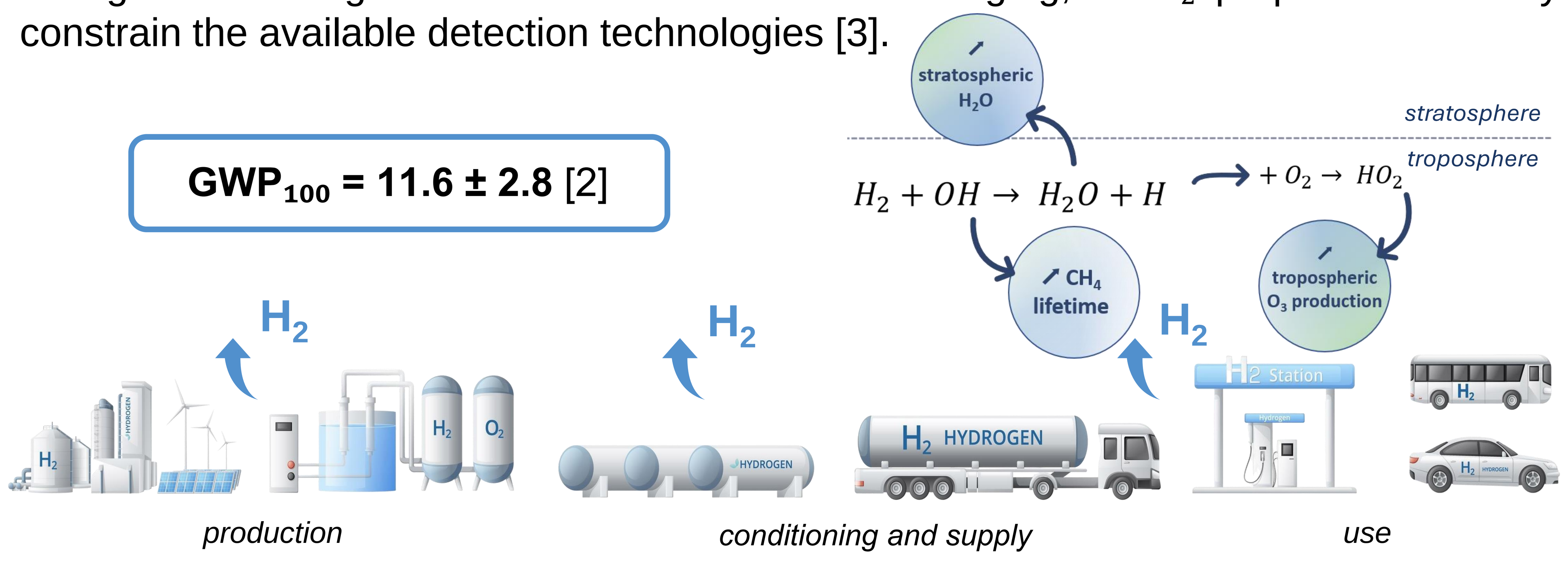

Fig. 1. Example of a hydrogen value chain

Objectives

- Provide an update on the different methods available to quantify H_2 emission at the component-level
- Investigate the performance of 7 of the most mature component-level methods using blind controlled release experiments and understand their capabilities on the quantification of different leaks
- Investigate the influence of the leaking component and leak size on the quantification estimates

Methods

- 7 methods compared:

Table 1. *Description of the different source-level quantification methods*

	4 acoustic cameras	2 high flow samplers (HFS)	1 bagging method
leak quantification method	conversion of sound levels from an array of microphones into volumetric flow	concentration measurement in high flow rate suction of the leaking gas	Leak enclosure with a controlled carrier gas flow and concentration measurement
time needed for measurement	5 min	10-15 min	40 min
safety measurement limit	no limitation	35 g·h⁻¹	216 g·h⁻¹

- 15 blind controlled releases from **0.11** to **240.69 g·h⁻¹**
- 3 typical leaking components in the H_2 industry
- Performance indicator used: Absolute Relative Error (ARE)

$$ARE = \frac{|E_{estimate} - E_{actual}|}{E_{actual}}$$

$E_{estimate}$: emission estimate
E_{actual}: actual emission

Fig. 2. *Controlled release facility at the Enagas Metrology & Innovation Center (Zaragoza, Spain)*

Results

- **Consistency:** R^2 values for HFS #1, #2 and bagging show that estimates increase consistently with actual release rates. Acoustic cameras exhibit substantially higher dispersion, indicating lower predictability.
- **Bias:** Systematic bias for acoustic cameras:
  - Cam #1: overestimation at low rates and underestimation at high rates
  - Cam #2 & #3: underestimation at low rates, overestimation at high rates
  - Cam #4: consistent underestimation
- **Accuracy:** HFS #1 and #2 achieve the lowest error rates (13% and 18%), while Bagging has a slightly higher error (25%) but covers a wider range of leak sizes. Acoustic cameras show higher error rates (62–107%).

Table 2. *Fractions of controlled releases quantified by methods*

methods	controlled releases involved	leaks successfully quantified	quantification rate (involved releases)	quantification rate (all releases)
acoustic cam #1	15	9	60%	60%
acoustic cam #2	15	10	67%	67%
acoustic cam #3	15	9	60%	60%
acoustic cam #4	15	8	53%	53%
HFS #1	9	9	100%	60%
HFS #2	9	6	67%	40%
Bagging	13	13	100%	87%

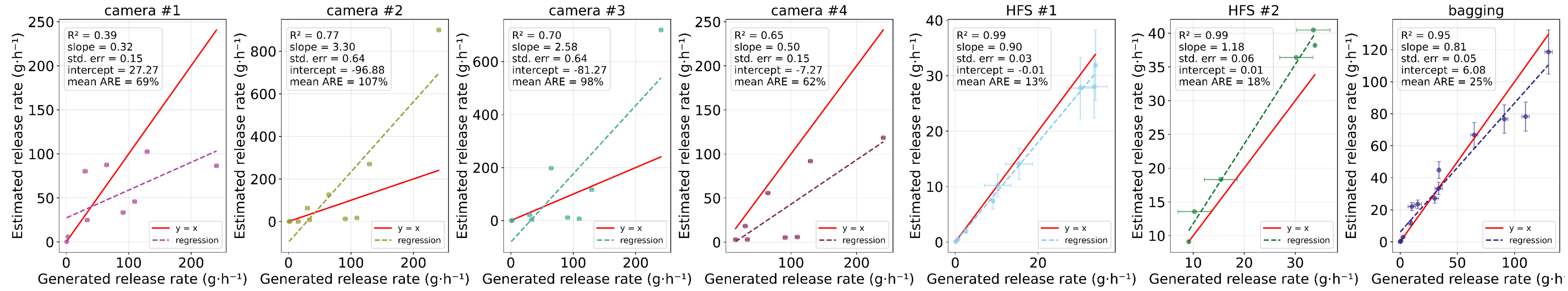

Fig. 4. *Estimated versus generated realease rates for each release and methodc*

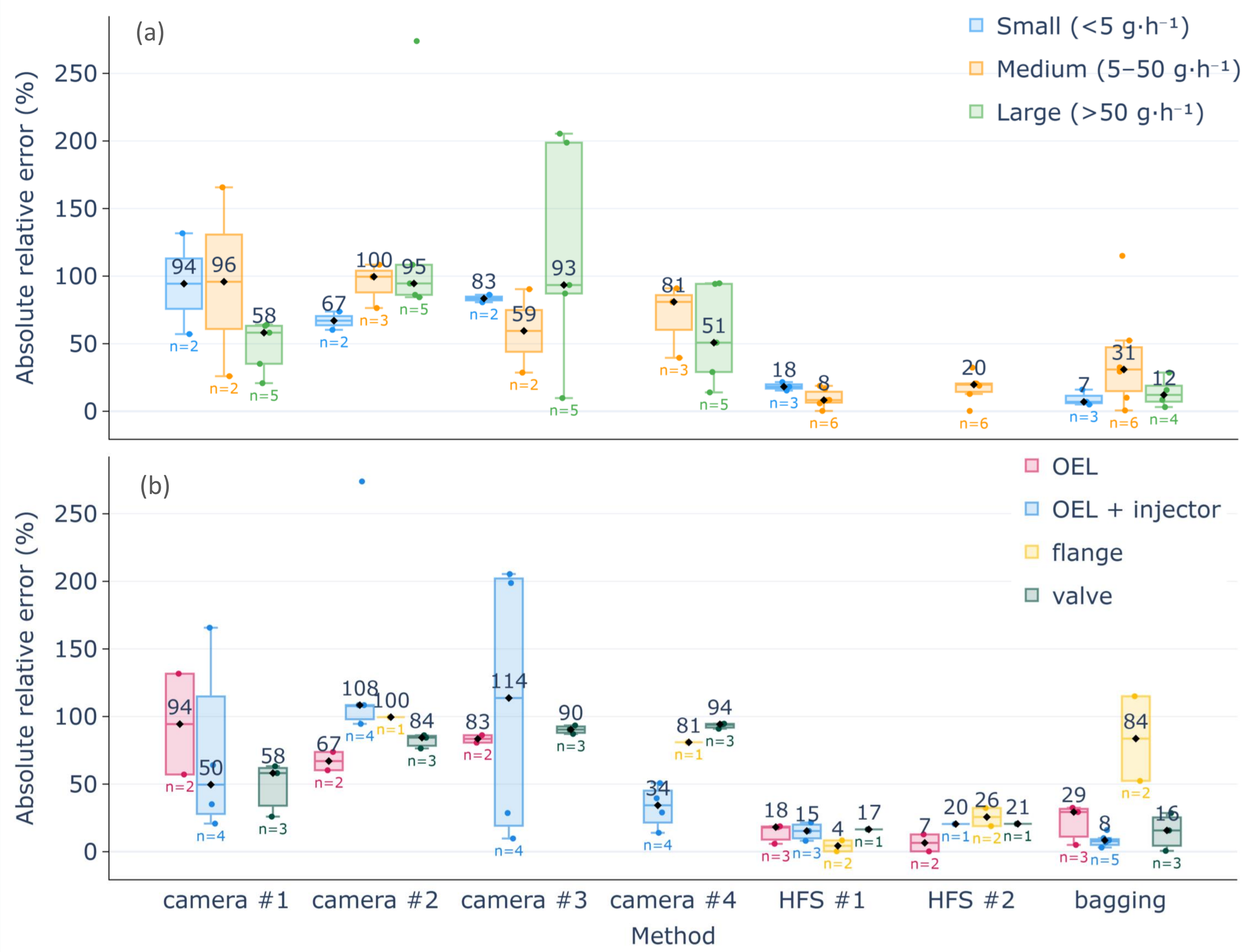

Fig. 5. *Boxplot of the absolute relative errors grouped by method and release size (a) or component (b). Black diamonds indicate the median value.*

- **Influence of release size on estimates:**
  - No consistent trend is observed
  - Bagging: higher error for medium releases
  - Acoustic cam #1, #4 and HFS #1: decreasing error with increasing release rate
  - Acoustic cam #2 and #3: lower error at smaller releases rates
  - HFS #2: provided estimates only for medium releases
- **Influence of components on estimates:**
  - Results are limited by the small sample size (n).
  - Bagging: higher errors on flanges, likely due to physical constraints that limit proper enclosure
  - Cam #1: performs worse on open-ended lines without injector
  - Cam #2 and HFS #2: performs better on the open-ended line
  - Cam #3: shows fairly consistent errors across all categories
  - Cam #4: performs best on open-ended lines with an injector
  - HFS #1: achieves lower errors on flanges

Conclusion

- The two HFS deliver the highest consistency, accuracy, and lowest bias (mean error 13–18%) with short measurement durations, though they were not evaluated above 35 g·h⁻¹ due to safety constraints. Bagging covers a wider range (0.11–216 g·h⁻¹) with a 25% mean error, but requires longer durations (~40 min per component) and is more challenging to install. Acoustic cameras enable rapid detection but show high errors (62–107%), limiting their reliability for quantification.
- These results demonstrate that source-level methods are available on the market to accurately quantify H_2 leaks with small and characterized uncertainties. They provide operators with a basis for selecting the most appropriate method for their field constraints.
- Complementing source-level quantification with site-level methods could improve and validate total site emission estimates, making a dedicated benchmark of site-level measurement methods for H_2 a valuable next step.

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