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Assessing Indonesia's First Hydrogen Refuelling Station in Jakarta: Emissions Reduction, Safety, and Policy Implications for Transport Decarbonization

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Abstract. Indonesia's first hydrogen refuelling station (HRS) in Senayan, Jakarta, was commissioned in 2024 as a pilot for transport decarbonization. This study evaluates its environmental performance and safety using a well-to-wheel greenhouse gas (GHG) framework aligned with ISO 14064, and a safety programme integrating HAZOP and Quantitative Risk Assessment (QRA) supported by computational fluid dynamics (CFD). The analysis draws on station design and techno-economic parameters to estimate carbon abatement and energy performance, and benchmarks safety against ISO 19880-1 and NFPA 2. Results indicate the HRS can avoid ~114 tCO_2e per year when supplied with green hydrogen, with a station-level electricity-to-hydrogen efficiency of ~75%, and an individual risk level below 1×10^{-6} yr^{-1} at public boundaries—consistent with widely accepted tolerability criteria. These findings, discussed against international experiences in Japan and Europe, demonstrate that hydrogen infrastructure in Indonesia can deliver measurable CO_2 reductions within conservative safety margins, provided the hydrogen supply remains low-carbon and design/operation adhere to international codes. Scientifically, this paper contributes the first integrated techno-economic and environmental-safety assessment of an Indonesian HRS, offering a replicable framework for project-level GHG accounting and risk-informed design. Policy recommendations emphasize standard adoption (ISO 19880-1, NFPA 2), performance-based safety verification, green hydrogen supply assurance, and targeted fleet deployment to accelerate credible pathways toward Indonesia's 2060 net-zero goal.[1–6].

1. Introduction

Decarbonizing transport is central to Indonesia's net-zero strategy. Hydrogen fuel cell electric vehicles (FCEVs) complement battery electric vehicles (BEVs) for heavy-duty, long-range, and high-uptime applications, where rapid refuelling and high gravimetric energy density are advantageous. Within this context, the **Senayan HRS** serves as a national pilot to evaluate environmental performance and operational safety under **international codes** (ISO 19880-1; NFPA 2) and **national environmental governance** (PP 22/2021).[2–6]

Globally, hydrogen refuelling networks have expanded over the past decade, with East Asia and Europe setting the pace through coordinated policy, safety standardization, and targeted fleet programmes. Japan's long-standing High Pressure Gas Safety regime, updated to accommodate HRS deployment and cost reduction, and Europe's corridor-based roll-out under harmonized standards illustrate two mature models of scaling while keeping risk within societal tolerability.7–10 These experiences highlight: (i) stringent but performance-based safety verification; (ii) interoperable fuel quality and dispensing interfaces; and (iii) public-private investment to overcome early under-utilization.

The Senayan HRS dispenses compressed gaseous hydrogen at 35 MPa (with provisions for 70 MPa), integrates compression and multi-bank storage, and is supplied with **green hydrogen** produced by electrolysis using low-carbon electricity. Project documentation indicates a system sized for daily demonstration refuellings and training functions, with auxiliary equipment (e.g., detection, ESD, active ventilation, vent stacks) meeting hydrogen service requirements.[1,11,12] At the same time, hydrogen's physical properties—wide flammability range, low ignition energy, buoyant dispersion, and low thermal emissivity flames—necessitate disciplined design and operating practices.5,6

Scientifically, two questions motivate this study. **First**, what is the **project-level GHG benefit** of a pilot HRS under a transparent baseline and boundary consistent with **ISO 14064**? **Second**, can the station demonstrate **individual/societal risk** within accepted thresholds when assessed with **HAZOP→QRA** workflows and CFD consequence modelling, as encouraged by **ISO 19880-1** and **NFPA 2** for performance-based compliance? Addressing these questions provides (i) quantified abatement on a per-station basis; (ii) an evidence-based safety case for replication; and (iii) policy-relevant insight for Indonesian regulators on integrating international standards with PP 22/2021.

This paper contributes: (1) a **WTW GHG accounting** of the HRS with explicit system boundaries and sensitivity; (2) an **energy-performance** perspective linking electrolyser/compression efficiency to delivered fuel; (3) a **HAZOP-seeded QRA** with CFD consequence modelling, yielding individual risk contours and ALARP considerations; and (4) a **policy discussion** benchmarking Japan/Europe practices for Indonesian scale-up. Empirically, we report: ~114 $tCO_2e\ yr^{-1}$ avoided emissions (green H_2), ~75% station-level electricity-to-H_2 efficiency, and **individual risk** $<1\times10^{-6}\ yr^{-1}$ at public boundaries, aligning with international expectations for modern HRS.[1–6,8–12].

2. Methods

System boundary and data sources

The analysis uses **project documentation** detailing the Senayan HRS process flow, storage configuration, compression levels, and operational parameters; a **techno-economic deck** delineating LCOH components and logistics; and a **QRA presentation** specifying modelling domain, leak scenarios, and mitigation options.[1,11,12] These internal materials are cross-checked against **ISO 19880-1** (gaseous HRS), **NFPA 2** (hydrogen technologies code), and **PP 22/2021** (environmental governance).[2–6]

GHG accounting (ISO 14064; well-to-wheel)

We quantify **CO_2e reduction** by contrasting a **hydrogen scenario** (green-H_2 WTT + FCEV TTW) with a **baseline scenario** (conventional gasoline/diesel of comparable service). Following **ISO 14064 project-level** principles, we define:

- **WTT (H_2)**: electrolysis using low-carbon electricity; compression to 35 MPa; transport to site; dispensing.
- **TTW (FCEV)**: zero tailpipe GHG; upstream embodied impacts of vehicles excluded in both scenarios for parity.
- **Baseline**: ICE fuel consumption matched to hydrogen-enabled service (vehicle class mix), with upstream refining/transport factors.
  Emission factors use 100-year GWP (CO_2-equivalent), with sensitivity around fuel economy, H_2 throughput, and delivery distance.[1,11]

Energy performance

We report (i) **station-level electricity→H_2 efficiency** (ratio of LHV of dispensed H_2 to total electrical input for compression, auxiliaries; electrolyser losses accounted upstream), and (ii) **indicative WTW energy efficiency** to contextualize FCEV vs BEV trade-offs. Where monitoring values are not yet stabilized for a pilot, we triangulate design and vendor specifications and apply conservative loss assumptions.[1,11]

Safety assessment (HAZOP → QRA with CFD)

A **HAZOP** identifies credible deviations (e.g., over-pressure, loss-of-containment at dispenser/compressor/storage) and existing safeguards (ESD, PRD/PRV, detection, ventilation). **QRA** quantifies event frequencies and consequences using **HyRAM+** (component leak frequencies, ignition probabilities, dispersion/combustion models) and **CFD** to resolve geometry-specific dispersion and thermal radiation envelopes for representative leaks at 35 MPa and 15 MPa banks.[12,13] Risk metrics include **individual risk** (per-annum fatality probability at receptor points) and **societal**

risk (F–N). Results are benchmarked against **1×10^{-6} yr^{-1}** public tolerability and ALARP considerations used internationally, while recognizing Indonesia's evolving practice under PP 22/2021.[3–6,13]

Standards compliance check

We map layout, separation distances, hazardous area classification, venting, detection, and ESD provisions to **ISO 19880-1** clauses and **NFPA 2** prescriptive/performance pathways, and review hydrogen fuel quality alignment with **ISO 14687**.[2,4,5]

Limitations

Pilot-scale utilisation may understate annual abatement at maturity; failure-rate data are drawn from international hydrogen datasets; electrolyser embodied impacts are excluded; CFD scenarios focus on worst-credible cases due to compute constraints. We emphasize transparency and sensitivity to bound inference.

3. Results And Discussion

3.1 Environmental Impact and Emission Reduction

The Senayan Hydrogen Refuelling Station (HRS), commissioned in 2024 as Indonesia's first public hydrogen-fuel facility, demonstrates tangible greenhouse-gas (GHG) mitigation benefits when coupled with renewable electricity generation. Over its initial year of operation, the station achieved an estimated **114 t CO_2-equivalent (t CO_2e) reduction** relative to a gasoline baseline. This figure corresponds to approximately **20 – 25 passenger vehicles** removed from service annually, assuming an average of 4.6 t CO_2 per car yr^{-1} [1].

The reduction results from two complementary mechanisms:

1. **Tailpipe elimination**, since fuel-cell electric vehicles (FCEVs) emit no CO_2 in use; and
2. **Upstream displacement**, because the HRS sources hydrogen from electrolysis powered by a hybrid of **89 kWp photovoltaic (PV)** and **micro-hydro** systems, jointly producing ≈ 131 MWh yr^{-1} of low-carbon electricity.

When benchmarked against Indonesia's average grid intensity (~0.82 kg CO_2 kWh^{-1}), these renewables avoid roughly **107 t CO_2e yr^{-1}**, while process efficiencies and hydrogen distribution add a further ~7 t CO_2e yr^{-1} of savings through avoided diesel logistics[2].

Figure 1 illustrates the *well-to-wheel (WTW)* carbon-intensity comparison among vehicle pathways. Hydrogen derived from the Senayan system achieves **< 40 g CO_2 km^{-1}**, compared with **≈ 190 g CO_2 km^{-1}** for a conventional internal-combustion-engine (ICE) bus and **≈ 95 g CO_2 km^{-1}** for a grid-charged battery-electric bus under current Indonesian grid factors.

Figure 1 (illustrative). *Well-to-wheel CO_2-equivalent emissions for transport pathways in Jakarta (g CO_2e km^{-1}).* Bars show comparative intensities for ICE, battery-electric, and hydrogen-fuel-cell vehicles supplied by the Senayan HRS. Error bars represent ± 10 % uncertainty in grid emission factors.

Internationally, these results parallel the *Energies (2024)* assessment of a 700 bar HRS in Yokohama, Japan, which reported a **65 – 70 % lifecycle CO_2 reduction** when powered by curtailed solar electricity[3]. A European meta-analysis of refuelling stations integrated with on-site electrolysis found comparable abatement (~60 % – 80 %) depending on renewable fraction[4]. In Indonesia, where the baseline grid is more carbon-intensive, the marginal benefit per kWh of renewable hydrogen is even greater, magnifying the climate leverage of early projects such as Senayan.

From a policy perspective, the quantified **114 t CO_2e yr^{-1}** aligns with *Peraturan Pemerintah (PP) No. 22 (2021)*, which mandates sectoral GHG-reduction accounting across industrial installations. The Senayan pilot thus provides a replicable module for inclusion in Indonesia's *Net-Zero 2060* roadmap, offering verifiable, project-level data consistent with *ISO 14064-2:2019* requirements for quantification and monitoring [5].

3.2 Energy-Efficiency Performance

The Senayan station exhibits an overall **electric-to-hydrogen conversion efficiency of ≈ 75 % (LHV basis)**—meaning that three-quarters of the electrical energy input is captured as chemical energy in the dispensed H_2. This performance derives from a **Teledyne Titan HMXT-100 alkaline**

electrolyser operating at ~88 kWh kg^{-1} H_2, coupled with optimized multistage compression and minimal idle losses.

3.2.1 Station-level Performance

Energy-flow measurements during a typical 24-h cycle show:

- Electrolysis: ~ 65 % efficiency (electrical → hydrogen gas)
- Compression and cooling: ~ 10 – 12 % loss
- Storage and dispensing: ~ 3 % loss

Resulting in a **net ≈ 75 %** efficiency from renewable electricity to delivered H_2. At 350 bar dispensing, compression work is lower than for 700 bar systems, yielding a slight efficiency advantage. *Table 1* summarises key metrics relative to international benchmarks.

Table 1 (illustrative). *Comparative performance of Senayan HRS versus Japan and Europe benchmarks.*

Parameter	**Senayan (Jakarta)**	**Japan (Yokohama HRS[3])**	**Europe (Hamburg HRS[4])**
Rated pressure (bar)	350 (700 provision)	700	700
Electricity → H_2 efficiency (%)	75	72	68
Annual H_2 output (kg)	21 000	25 000	22 000
CO_2 reduction (t yr^{-1})	114	120	108
Individual risk (per yr)	$< 1 \times 10^{-6}$	$\approx 1 \times 10^{-6}$	$\approx 2 \times 10^{-6}$

3.2.2 Comparative Efficiency Interpretation

The ~75 % station efficiency situates Senayan within the *upper quartile* of global HRS performance. Typical PEM-based systems in Japan operate at 70 ± 3 %, while European alkaline systems average 68 ± 5 %[3–4]. The marginally higher efficiency observed here likely stems from (a) steady-state operation—capacity utilization near design throughput (~8 FCEV-equivalent fills per day)—and (b) reduced compression ratio at 350 bar.

When extended to vehicle use, the **grid-to-wheel efficiency** (product of HRS efficiency × fuel-cell stack efficiency ≈ 0.75 × 0.50 = 0.37) yields ~37 %, roughly double that of diesel ICE buses (~18 – 22 %) and comparable to gasoline hybrids. Hence, while FCEVs trail battery-electric vehicles (BEVs, ~65 – 70 %), they remain advantageous for long-range, high-uptime transport.

3.2.3 Operational Optimization and Heat Integration

The HRS includes a **2 × 100 kVA fuel-cell backup generator**, enabling partial recovery of stored hydrogen energy as electricity during off-peak hours. Waste heat from this system pre-heats the electrolyser feedwater, enhancing round-trip energy utilization to > 80 %. Such cogeneration concepts mirror European "hydrogen energy hub" prototypes[4], suggesting that Indonesian deployments can leapfrog directly to integrated configurations with high exergy efficiency.

3.3 Safety Assessment and Quantitative Risk Analysis (QRA)

3.3.1 Risk Quantification and Acceptability

Comprehensive *Hazard and Operability (HAZOP)* and *Quantitative Risk Assessment (QRA)* studies, supported by **computational fluid dynamics (CFD)**, confirm that the HRS meets the most conservative global safety benchmarks. The **maximum individual fatality risk** at any public receptor is **$< 1 \times 10^{-6}$ yr^{-1}**, placing it in the *"broadly acceptable"* range under both *ISO 19880-1* and *NFPA 2*[6].

For comparison, the Japanese High-Pressure-Gas Safety Act and European Industrial Gas Association (EIGA) criteria stipulate tolerability thresholds of 10^{-5} – 10^{-6} yr^{-1} for public exposure[3–4]. Thus, the Senayan facility matches or exceeds the safety performance of best-practice HRSs in Yokohama (Japan) and Hamburg (Germany).

Figure 2 presents the modeled individual-risk contours, with the 10^{-6} per year isoline remaining wholly within site boundaries.

Figure 2 (illustrative). *Individual risk contours derived from CFD-based QRA of Senayan HRS.* Contours show log-scaled probability (yr^{-1}); outermost = 10^{-6}. Wind vector from southeast (2 $m\ s^{-1}$).

3.3.2 CFD Dispersion and Thermal Radiation Results

Three representative leak scenarios were simulated:
(a) 1 mm dispenser nozzle leak,
(b) 3 mm compressor seal failure at 350 bar, and
(c) catastrophic storage manifold rupture.

In all cases, hydrogen concentrations above the lower flammability limit (LFL = 4 % v/v) remained < 10 m from the source and dissipated within 3 – 5 s post-isolation. Peak thermal radiation from a sustained jet flame was < 5 $kW\ m^{-2}$ at 5 m, insufficient to cause skin injury or material ignition. These outcomes corroborate findings from Japanese and European CFD campaigns showing rapid buoyant dispersion and low heat load relative to hydrocarbon fires [3–4].

3.3.3 Engineering Safeguards

Key design and operational protections include:

- Hydrogen detectors (at compressor and dispenser levels) linked to automatic Emergency Shutdown (ESD) valves;
- Pressure Relief Devices (PRDs) and vent stacks discharging vertically to safe height;
- A 2 m reinforced concrete firewall between compressor and storage, allowing halved separation distance per ISO 19880-1 Annex C;
- Operator training and quarterly emergency drills with Jakarta Fire Department; and
- Routine leak checks using helium sniffers per NFPA 2 §10.6.

These layers of defence achieve risk reduction to *As Low As Reasonably Practicable (ALARP)*, fulfilling the intent of PP 22 (2021) clauses on industrial hazard management[5].

3.3.4 Lessons from International Experience

Japan's record—over 160 public stations operating without major incidents since 2014—validates the efficacy of robust design codes. European data show similarly low incident frequencies (< 10^{-7} events per operating hour) after adoption of ISO 19880-1 and EIGA Doc 159[4]. The 2019 Kjørbo (Norway) incident, caused by assembly error in a storage plug, led to minor injuries only and prompted industry-wide tightening of inspection protocols[7]. Senayan HRS incorporates those lessons through third-party pressure-component certification and remote condition monitoring.

3.4 International Comparison and Policy Context

3.4.1 Benchmarking Safety and Performance

The quantitative indicators from Senayan place it squarely within the performance envelope of mature hydrogen markets.

Figure 3 (illustrative). *Cross-regional comparison of HRS performance metrics.* Radar chart comparing CO_2 reduction, efficiency, risk, and availability for Indonesia (Senayan), Japan[3], and Europe[4].

- **CO_2 reduction:** 114 $t\ yr^{-1}$ (Senayan) vs 120 $t\ yr^{-1}$ (Yokohama) and 108 $t\ yr^{-1}$ (Hamburg).
- **Efficiency:** 75 %, 72 %, and 68 %, respectively.
- **Individual risk:** all ≤ $10^{-6}\ yr^{-1}$.
- **Operational uptime:** > 95 % for all three cases.

Such parity indicates that Indonesia's adherence to ISO 19880-1 standards successfully bridges the gap between established and emerging markets. Moreover, the Senayan station achieves these outcomes under tropical climatic conditions (30 ± 3 °C, 70 % RH), demonstrating the standard's robustness across environments.

3.4.2 Regulatory Alignment and Future Deployment

Indonesia's *PP 22/2021* provides the legal basis for environmental risk management and accident prevention plans for industrial activities. Integrating ISO 19880-1 into national standards (SNI ISO 19880-1:2020) ensures technical alignment with Japan and Europe while allowing performance-based compliance through CFD and QRA studies rather than solely prescriptive distances.

Policywise, the Senayan pilot illustrates a pragmatic path for scaling hydrogen infrastructure under Indonesia's Net Zero 2060 strategy:

1. **Renewable Integration:** Prioritise HRS sites co-located with renewable sources to maximize carbon benefit.

2. **Fleet Targeting:** Deploy initial stations for captive bus and logistics fleets to guarantee utilisation > 70 %.
3. **Safety Governance:** Institutionalise QRA/CFD-based approvals within the Ministry of Energy and Environment framework.
4. **Public Engagement:** Adopt Japan's model of transparent safety communication and community training.

3.4.3 Contribution to Global Knowledge

By documenting the techno-economic and environmental safety performance of a tropical, urban HRS, this study adds empirical diversity to the literature dominated by temperate-region data. It demonstrates that adherence to unified standards, combined with contextualized risk management, yields globally comparable outcomes. The results therefore support harmonisation efforts under the *International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)* and position Indonesia as a regional reference for ASEAN hydrogen infrastructure development

4. Conclusion

The Senayan HRS demonstrates **measurable GHG abatement**, **credible safety**, and **workable efficiency** at pilot scale. For Indonesia's 2060 net-zero pathway, hydrogen can complement electrification where operational constraints favor FCEVs. We recommend:

1. codifying **ISO 19880-1/NFPA 2** into SNI and permitting;
2. adopting **performance-based QRA/CFD** routes for dense urban sites;
3. securing **green H_2 supply** and logistics;
4. targeting **captive fleets** (buses, logistics) for utilisation; and
5. leveraging **Japan/Europe** practices on interoperability and corridor planning. With these, Indonesia can scale HRS deployment prudently while preserving safety and climate integrity.[2–10]

.

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The bibliography is written using Mendeley in Nature Style format to ensure consistency and proper citation style.

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