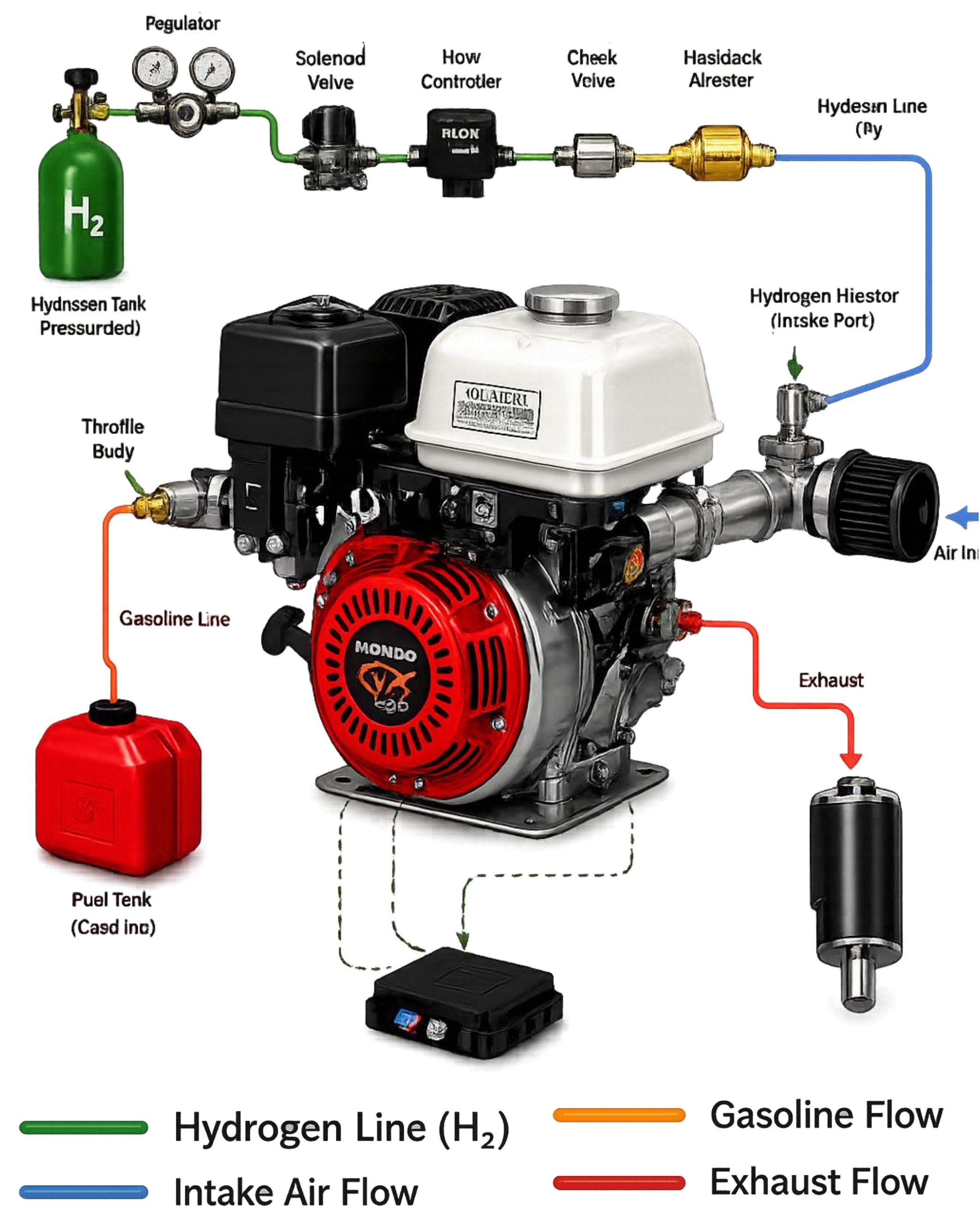


Objective

- To develop and optimize a hydrogen-assisted dual-fuel system for integration into existing internal combustion engines, using the Honda GX200 as a case study, to improve combustion efficiency, reduce harmful emissions, and ensure safe, reliable operation.

Proposed Initial Design



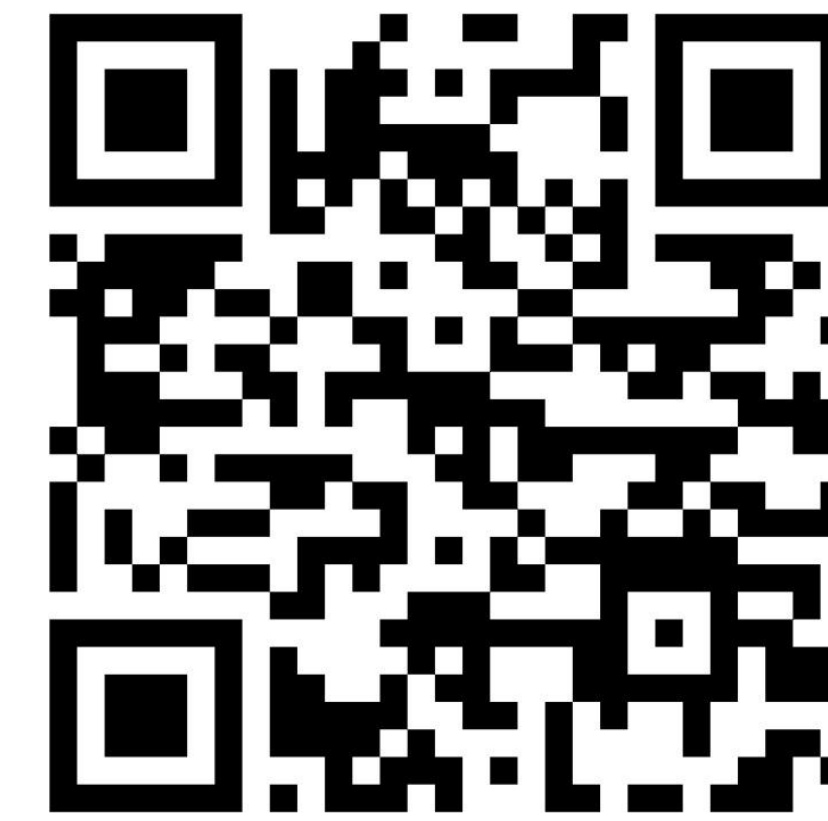
Prototype Development

Gasoline Baseline Testing

Scenario	RPM	Fuel Flow (kg/hr)	Fuel Power (kW)	Brake Power (kW)	Torque (Nm)
Min	1288	0.5	6.03	1.21	8.94
Mid	1484	0.5	6.03	1.21	7.76
Max	2118	0.5	6.03	1.21	5.44

Dual-Fuel Simulation

Baseline engine simulation results showing RPM, fuel flow, fuel power, brake power, and torque across minimum, mid, and maximum operating scenarios.

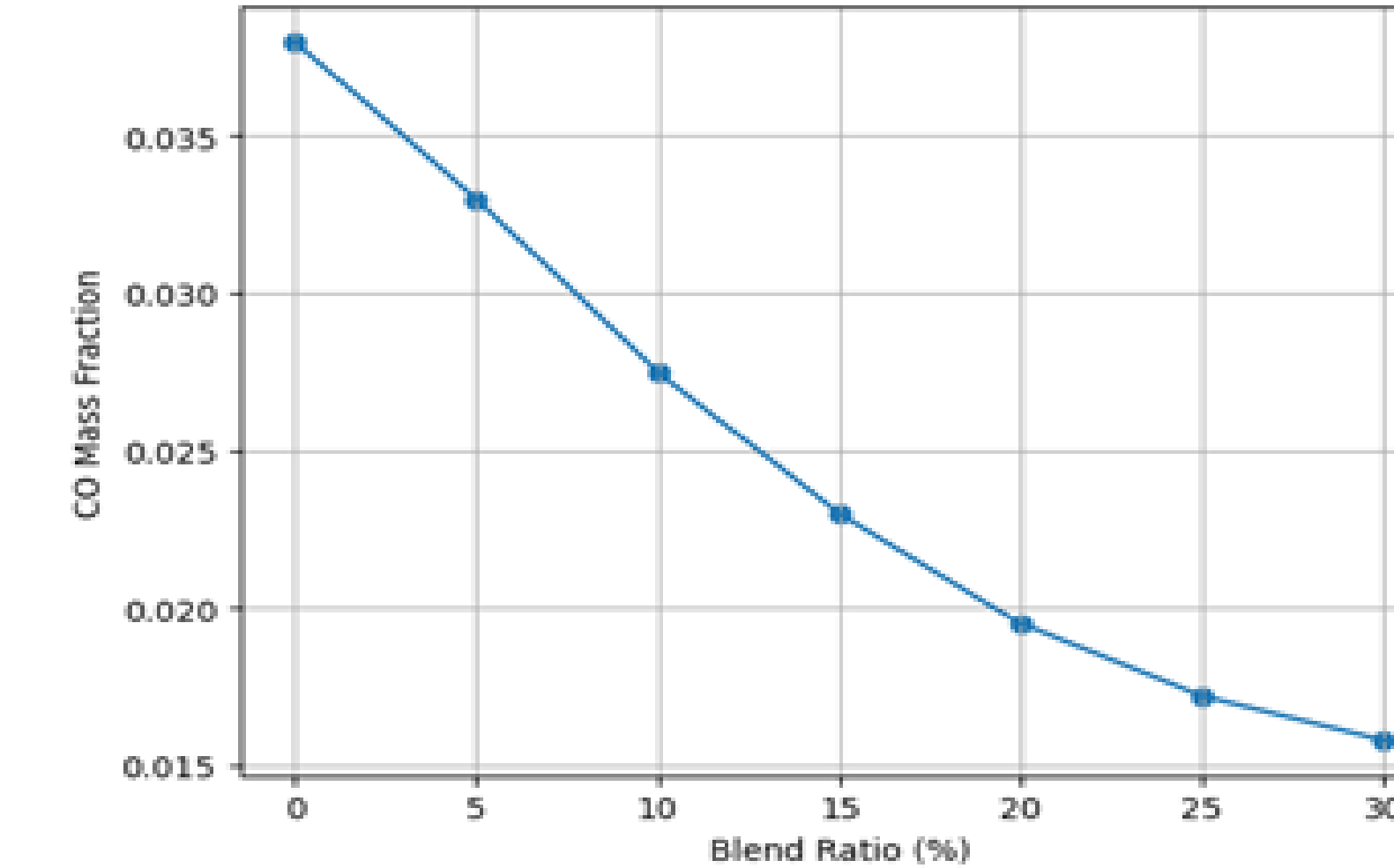


Constraints & Specifications

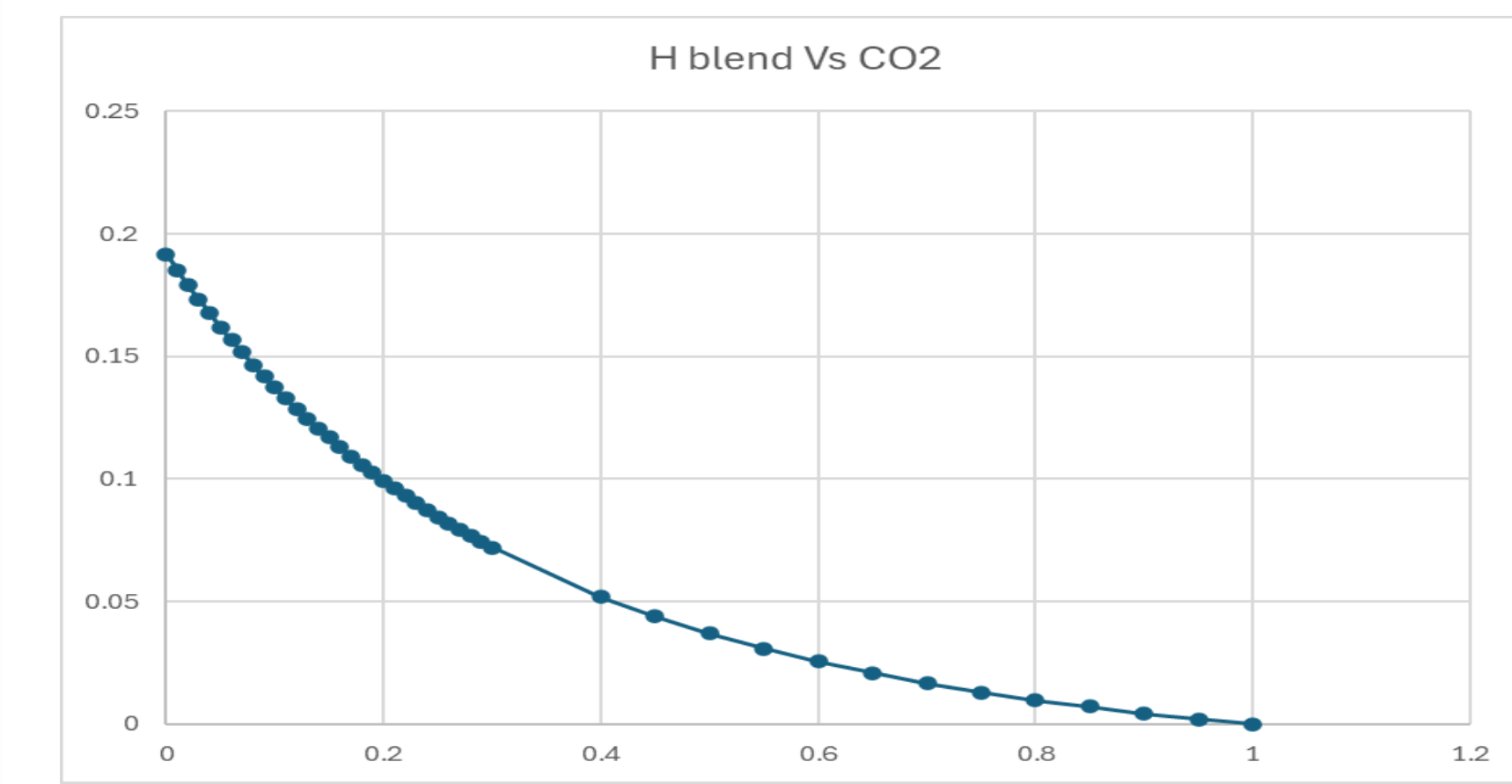
SPECIFICATIONS	CONSTRAINTS
H ₂ volumetric flow rate: 3.0-5.4 L/min	Ambient testing temperature: 18-25 °C
Hydrogen Injection geometry: <ul style="list-style-type: none"> Outer diameter: 3.5-4.2 mm Inner diameter: 2.0-2.8 mm 	Cylinder head pressure ≤ 15 bar
Unburned H ₂ ≤ 1%, CO mass fraction ≤ 2%	Cylinder head temperature < 200 °C during dual-fuel operation
Optimized hydrogen-gasoline volumetric ratio to minimize emissions	Hydrogen blending ratio ≤ 80% (by energy)
Torque sensor accuracy ± 0.5%	Hydrogen exit velocity ≤ 30 m/s
Carbon-equivalent emissions reduced by ≥ 10% vs. gasoline only operation, ensuring ≥ 75% system efficiency	Hydrogen injection tube wall thickness ≥ 0.5 mm
Correlations among torque, fuel efficiency, and CO _x emissions with an R ² value ≥ 0.85.	Hydrogen storage pressure ≤ 200 bar with dual safety valve
Obtain an optimization hydrogen blending ratio of 30% for safety.	-

Validation / Verification

CO Vs H2 blend



CO2 Vs H2 blend



Hydrogen Blending Optimization Model

$$\begin{aligned} \max Z &= \sum_{i \in I} r_i \cdot x_i \\ \sum_{i \in I} r_i \cdot x_i &\leq 30 \\ \sum_{i \in I} C R_i \cdot x_i &\geq 10 \\ \sum_{i \in I} \eta_i \cdot x_i &\geq 75 \\ 3.0 &\leq \sum_{i \in I} Q_{H_2,i} \cdot x_i \leq 5.4 \\ C R_i &= 100 \left(1 - \frac{\dot{m}_{C,i}}{\dot{m}_{C,0}} \right) \end{aligned}$$

Optimization Model (Tube Selection Model)

$$\begin{aligned} \text{Decision Variables} &: x_s = \begin{cases} 1, & \text{if tube option } s \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \quad \forall s \in S \\ \text{Objective Function} &: \min Z = \sum_{s \in S} \left(\frac{\pi}{4} (d_{out,s}^2 - d_{in,s}^2) \right) x_s \\ \text{Constraint} &: \sum_{s \in S} x_s = 1 \\ \frac{\pi}{4} d_{out,s}^2 &\leq a A_{in,max} + M(1 - x_s) \quad \forall s \in S \\ \frac{d_{out,s} - d_{in,s}}{2} &\geq t_{min} - M(1 - x_s) \quad \forall s \in S \\ Q_{H_2,s} &\leq v_{max} \cdot \frac{\pi}{4} d_{in,s}^2 + M(1 - x_s) \quad \forall s \in S \\ Q_{H_2,s} &\leq Q_{max} + M(1 - x_s) \quad \forall s \in S \\ Q_{H_2,s} &\geq Q_{min} - M(1 - x_s) \quad \forall s \in S \\ d_{in,s} &\leq 0.0028 + M(1 - x_s) \quad \forall s \in S \\ d_{in,s} &\geq 0.002 - M(1 - x_s) \quad \forall s \in S \\ d_{out} &\leq 0.0042 + M(1 - x_s) \quad \forall s \in S \\ d_{out} &\geq 0.0035 - M(1 - x_s) \quad \forall s \in S \\ x_s &\in \{0,1\} \quad \forall s \in S \\ d_{in}, d_{out} &\geq 0 \end{aligned}$$

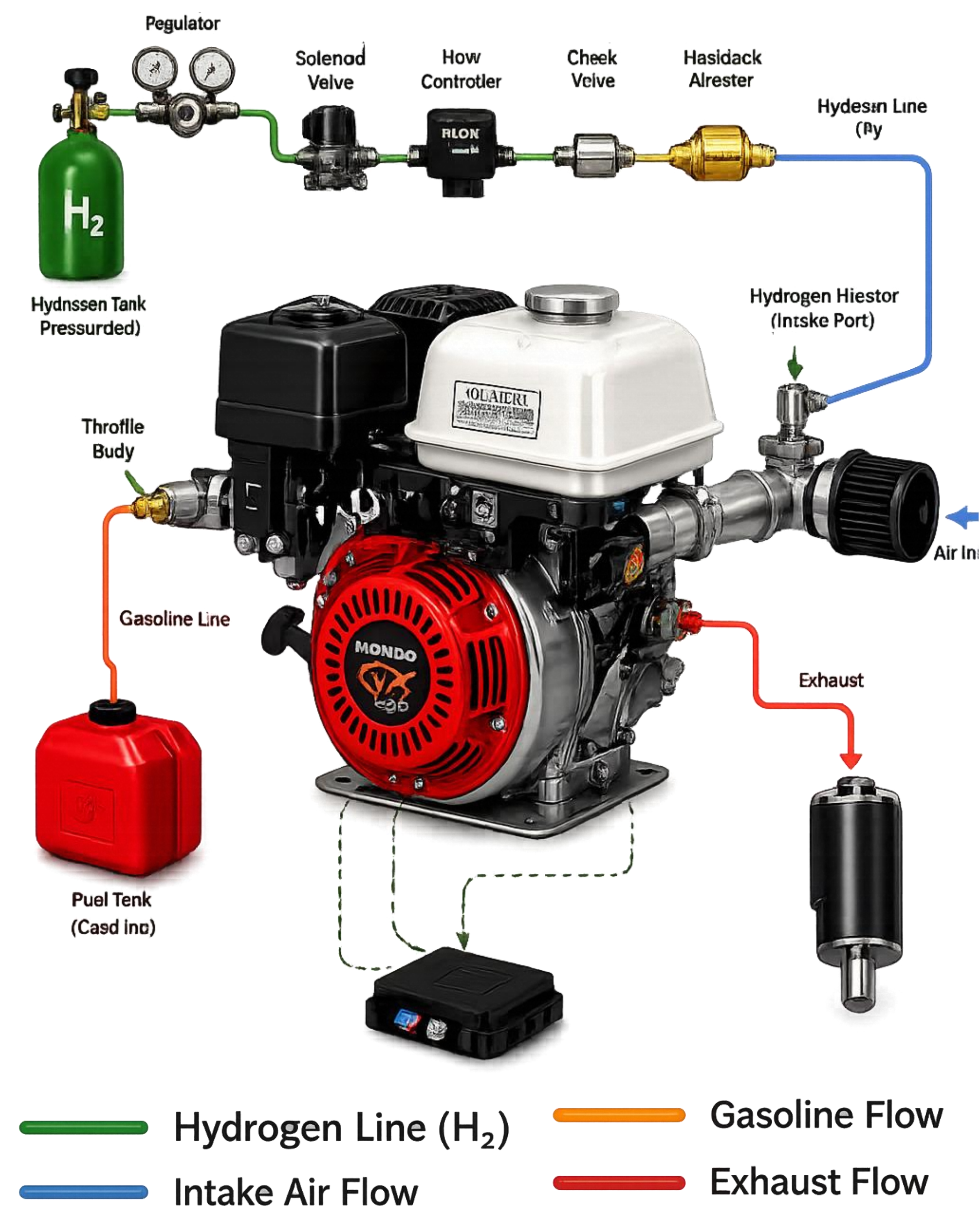
Conclusion

- The 10% H₂ blend is optimal, maintaining the lowest temperature (270 °C) and ensuring safe engine operation
- Dual-fuel operation maintains ~6.03 kW fuel input while reducing gasoline usage and potentially improving efficiency compared to gasoline-only (BTE ≈ 20%, 1.21 kW output).
- Optimization supported safe, efficient, and data-driven design selection

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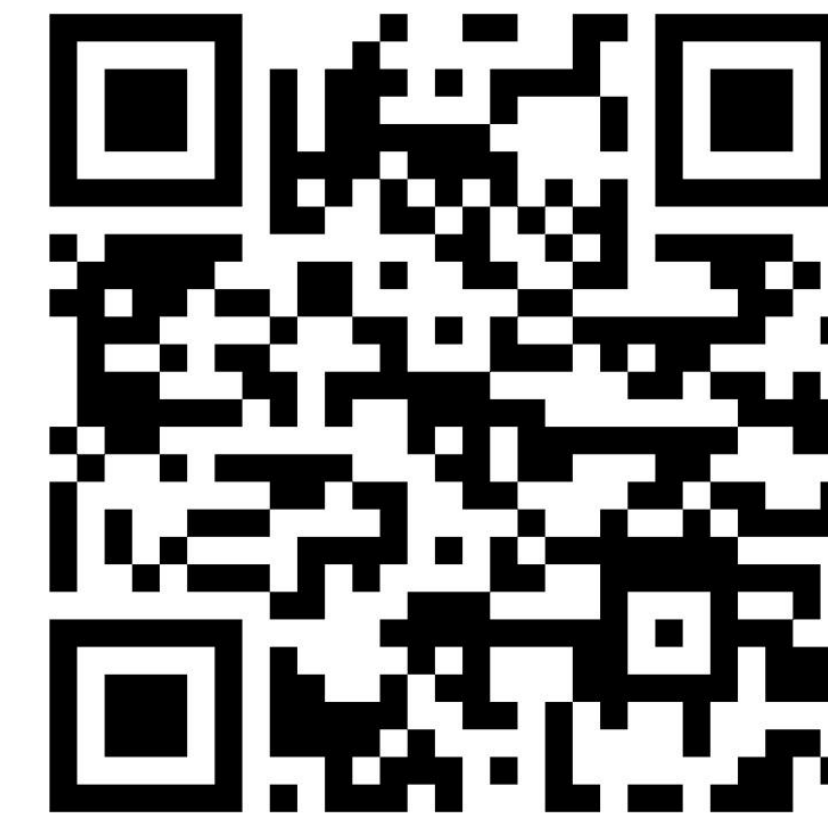
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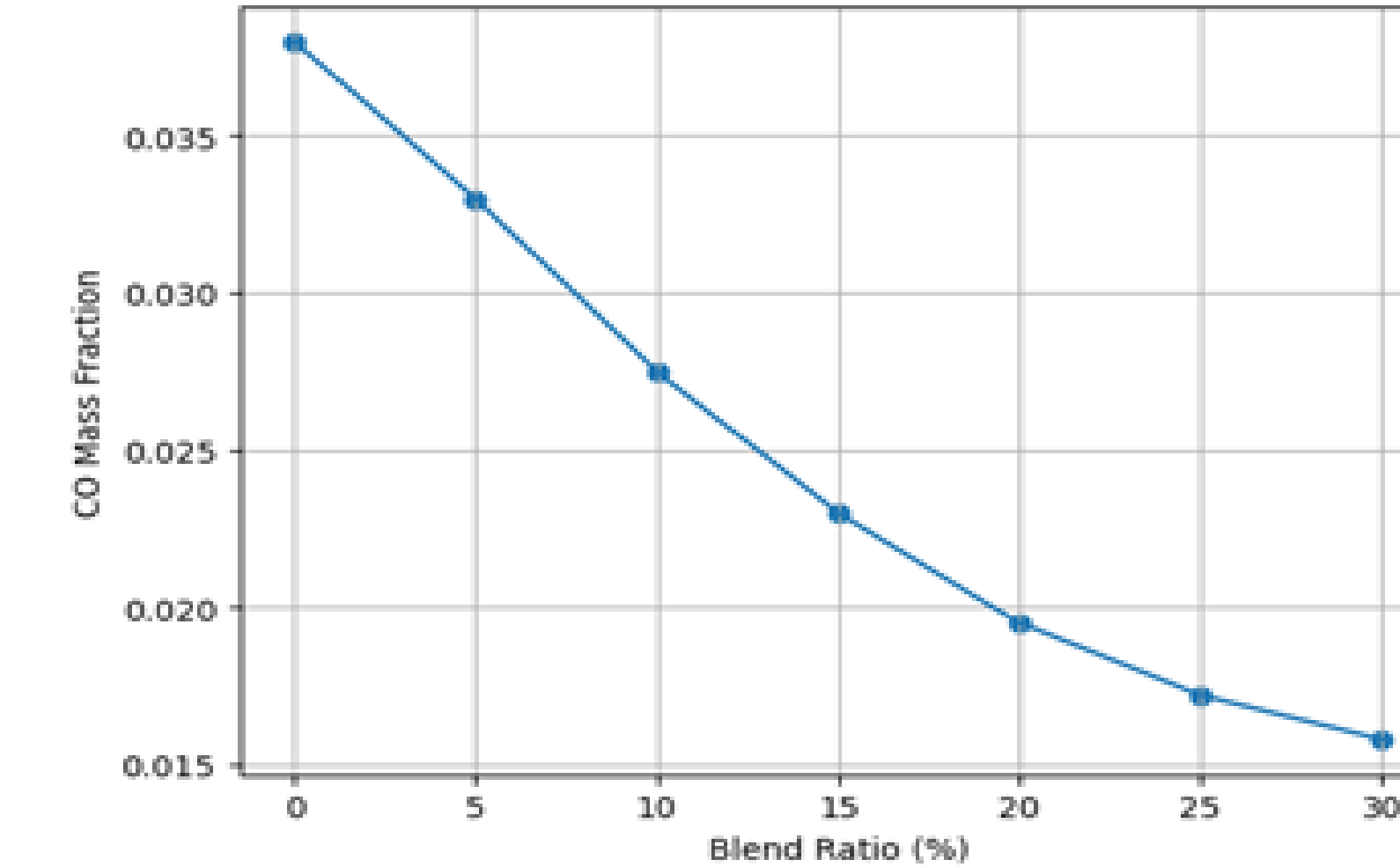


Constraints & Specifications

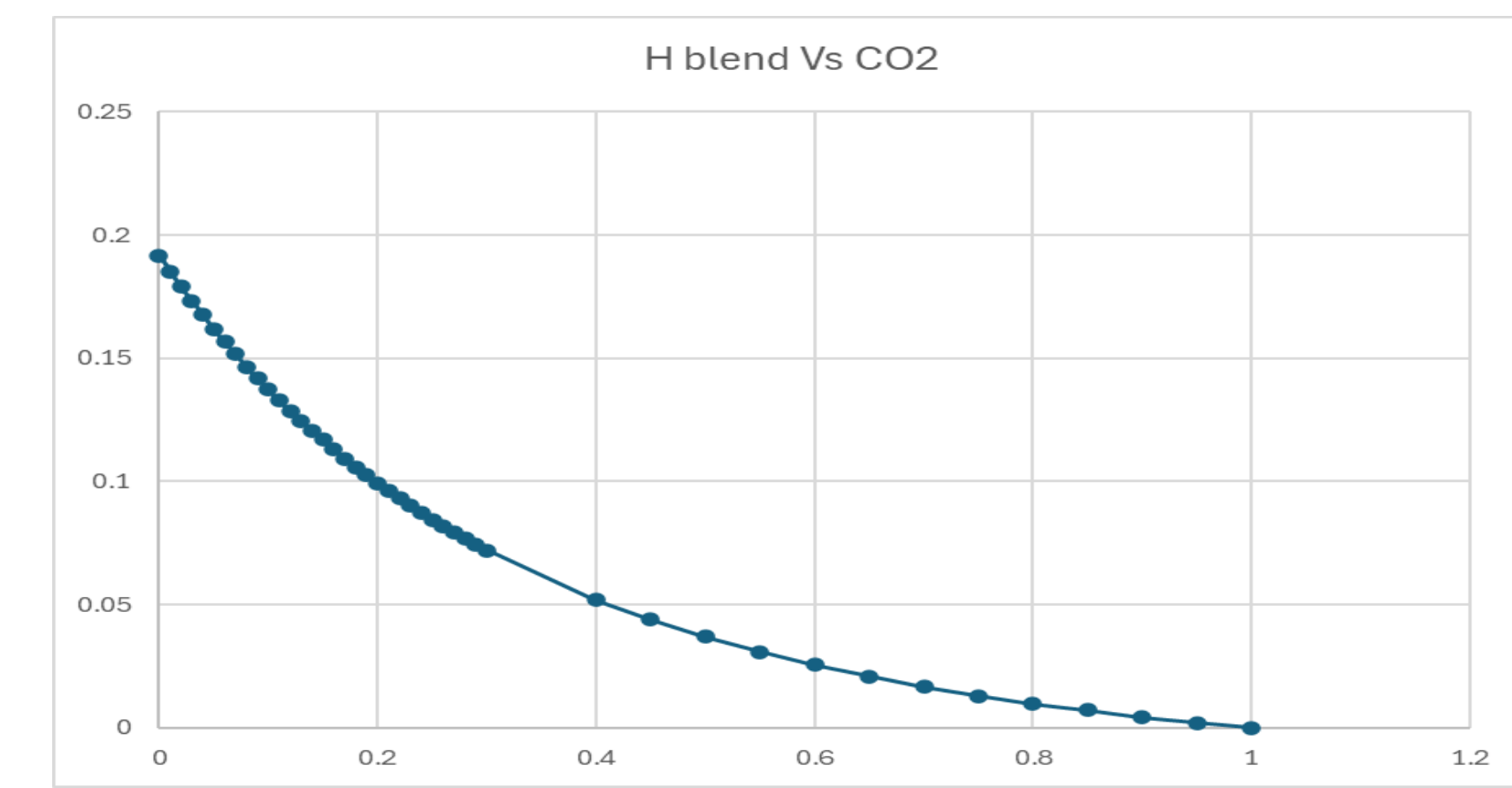
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Obtain an optimization hydrogen blending ratio of 30% for safety.	-

Validation / Verification

CO Vs H2 blend



CO2 Vs H2 blend



KEY ITEM	BLENDING MODEL	TUBE SELECTION MODEL
Objective	Maximize overall blending performance, $Z = \sum r_i x_i$	Minimize tube cross-sectional size, $Z = \sum [\pi/4 (d_{out,s}^2 - d_{in,s}^2)] x_s$
Decision variable	x_i = selected blend / operating case	$x_s \in \{0,1\}$; one tube option selected
Key limits	$\sum r_i x_i \leq 30$ $\sum CR_i x_i \geq 10$ $\sum \eta_i x_i \geq 75$	$\sum x_s = 1$ $QH_{2,s} \leq V_{max} \cdot (\pi/4) d_{in,s}^2$ $Q_{min} \leq QH_{2,s} \leq Q_{max}$
Design bounds	$3.0 \leq \sum QH_{2,i} x_i \leq 5.4$ L/min $CR_i = 100(1 - mC_i / mC_0)$	$0.002 \leq d_{in} \leq 0.0028$ m $0.0035 \leq d_{out} \leq 0.0042$ m t _{min} enforced by wall thickness
Practical output	Safe and efficient H ₂ blending window with reduced carbon emissions	Compact tube geometry that satisfies intake area, flow, and safety constraints

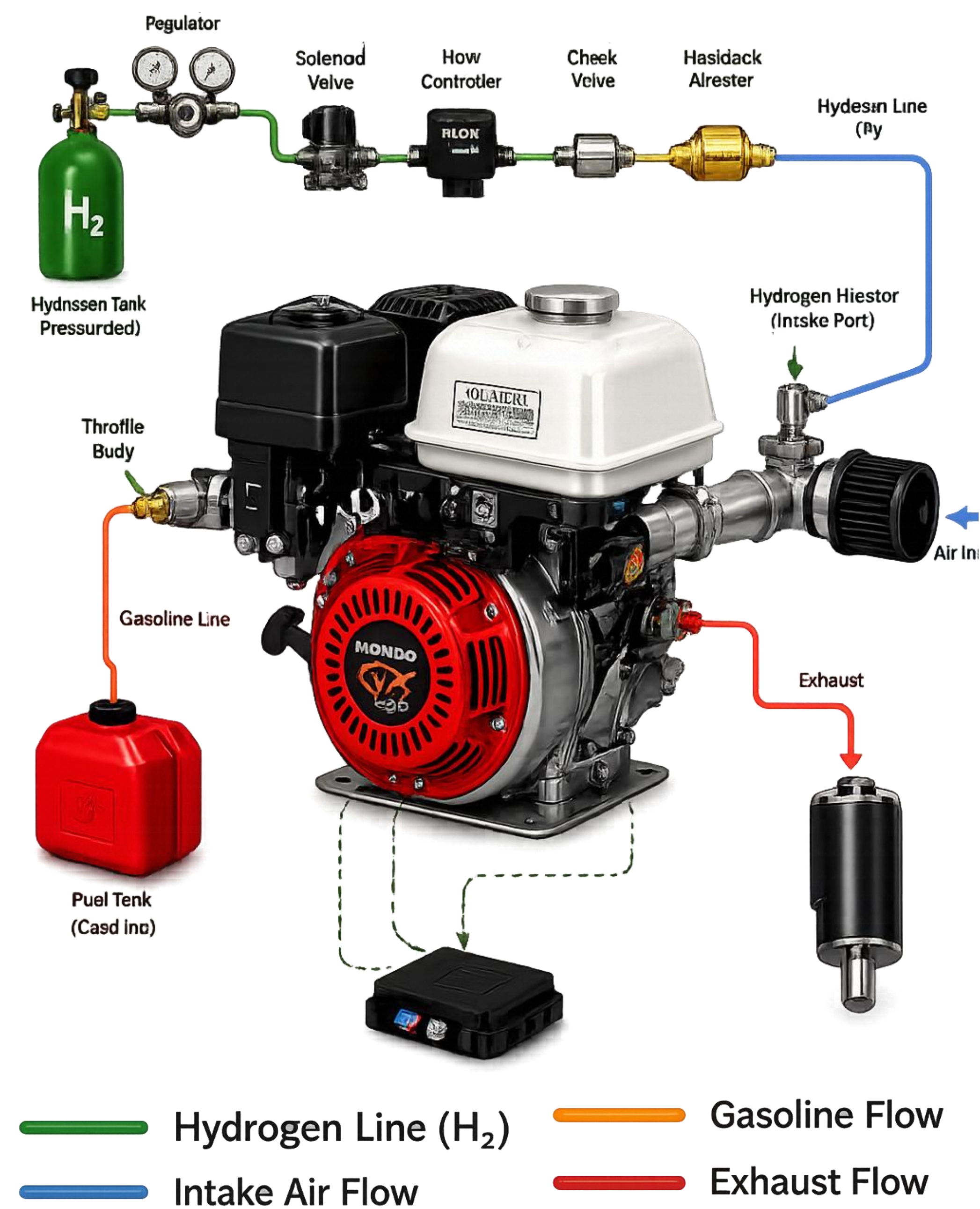
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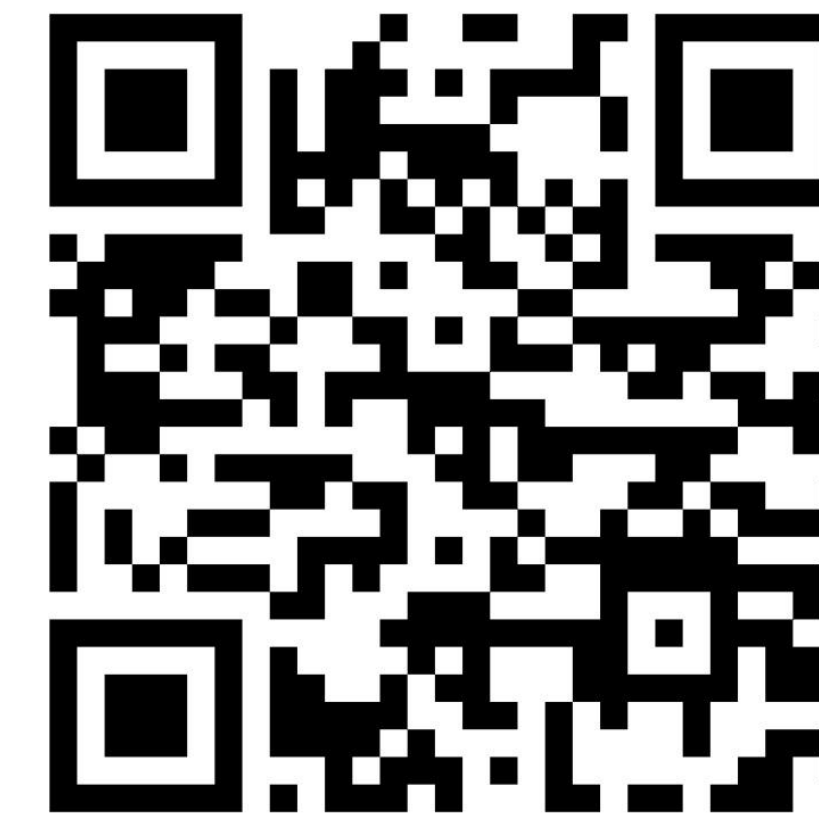
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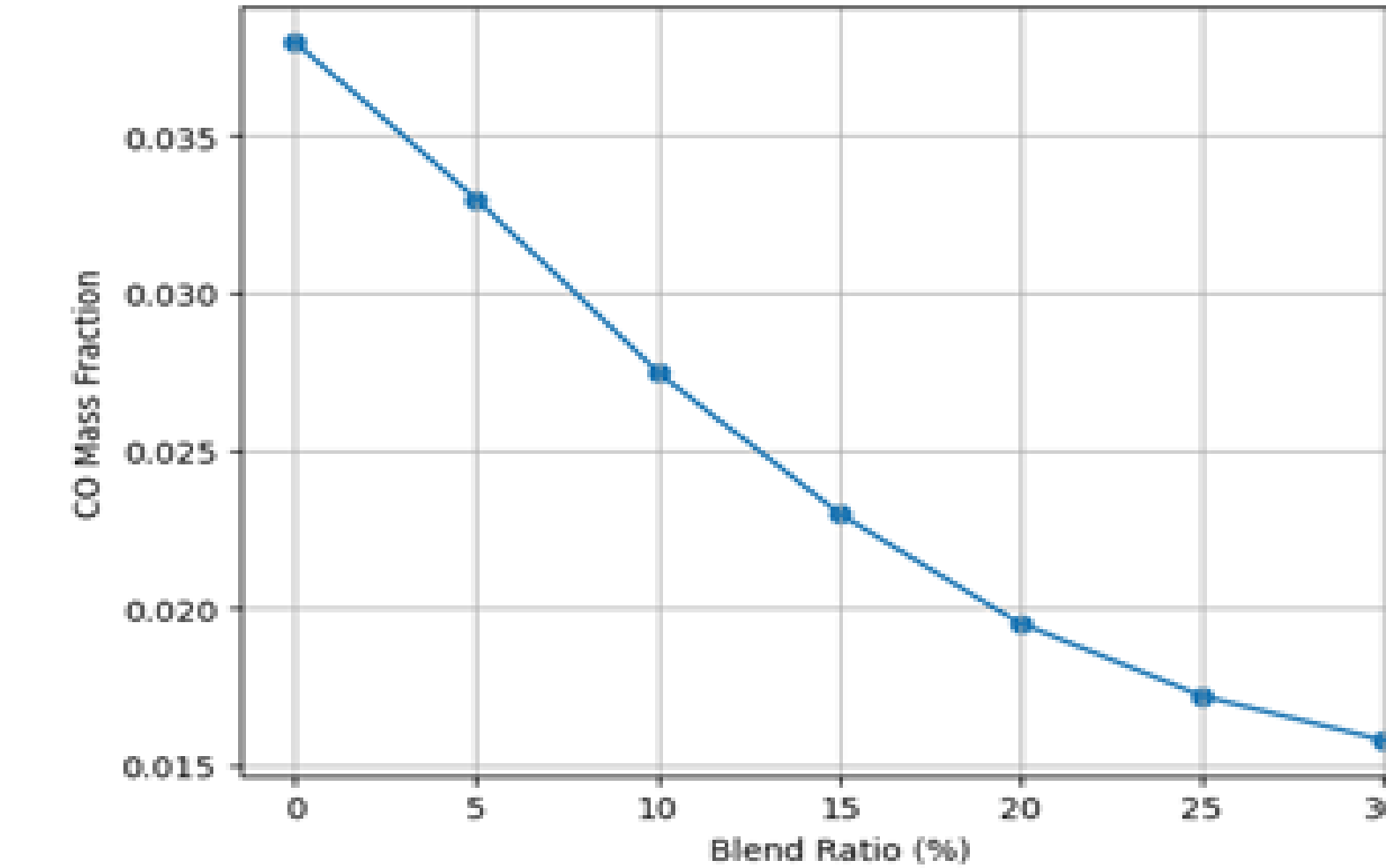


Constraints & Specifications

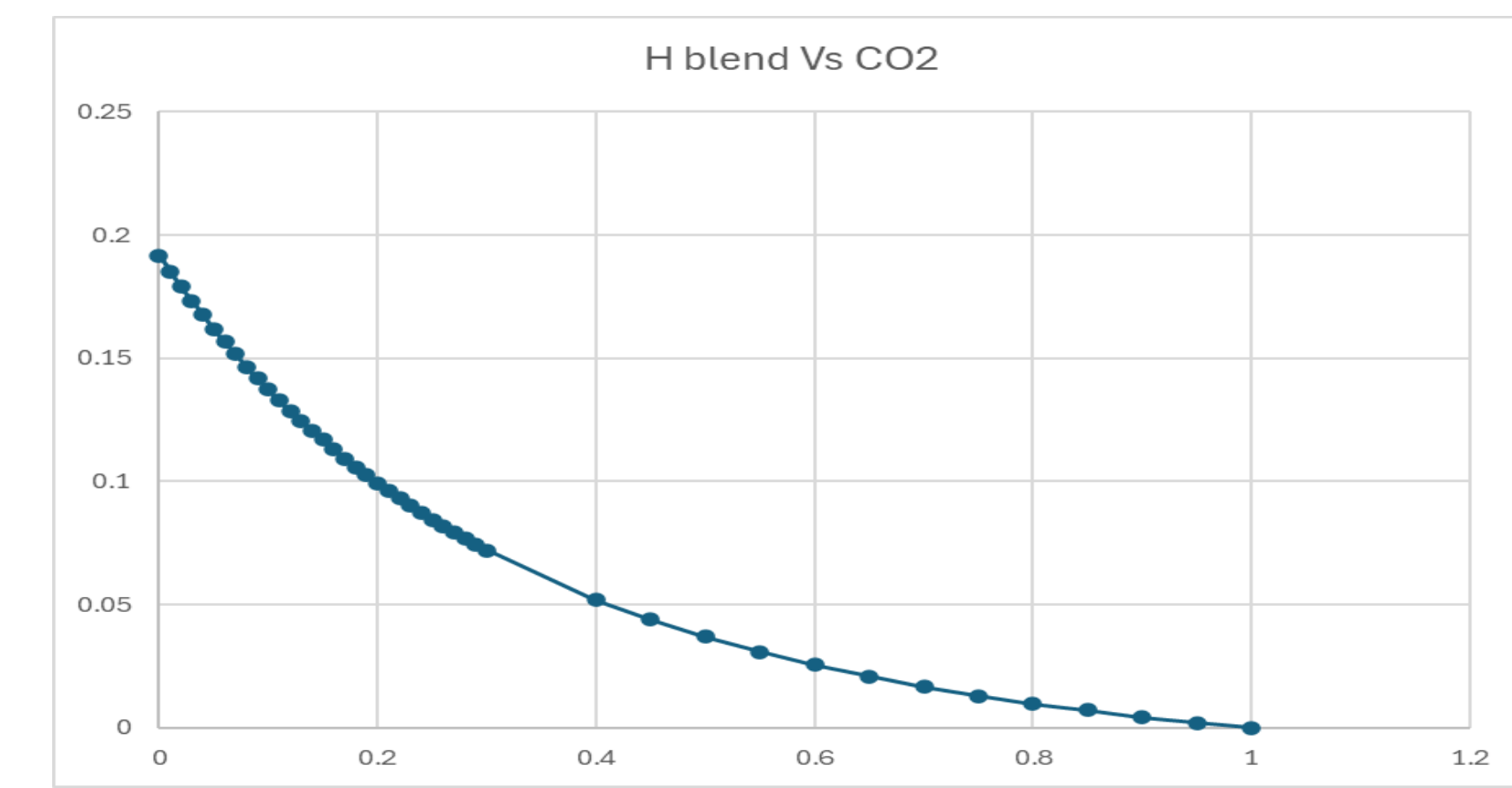
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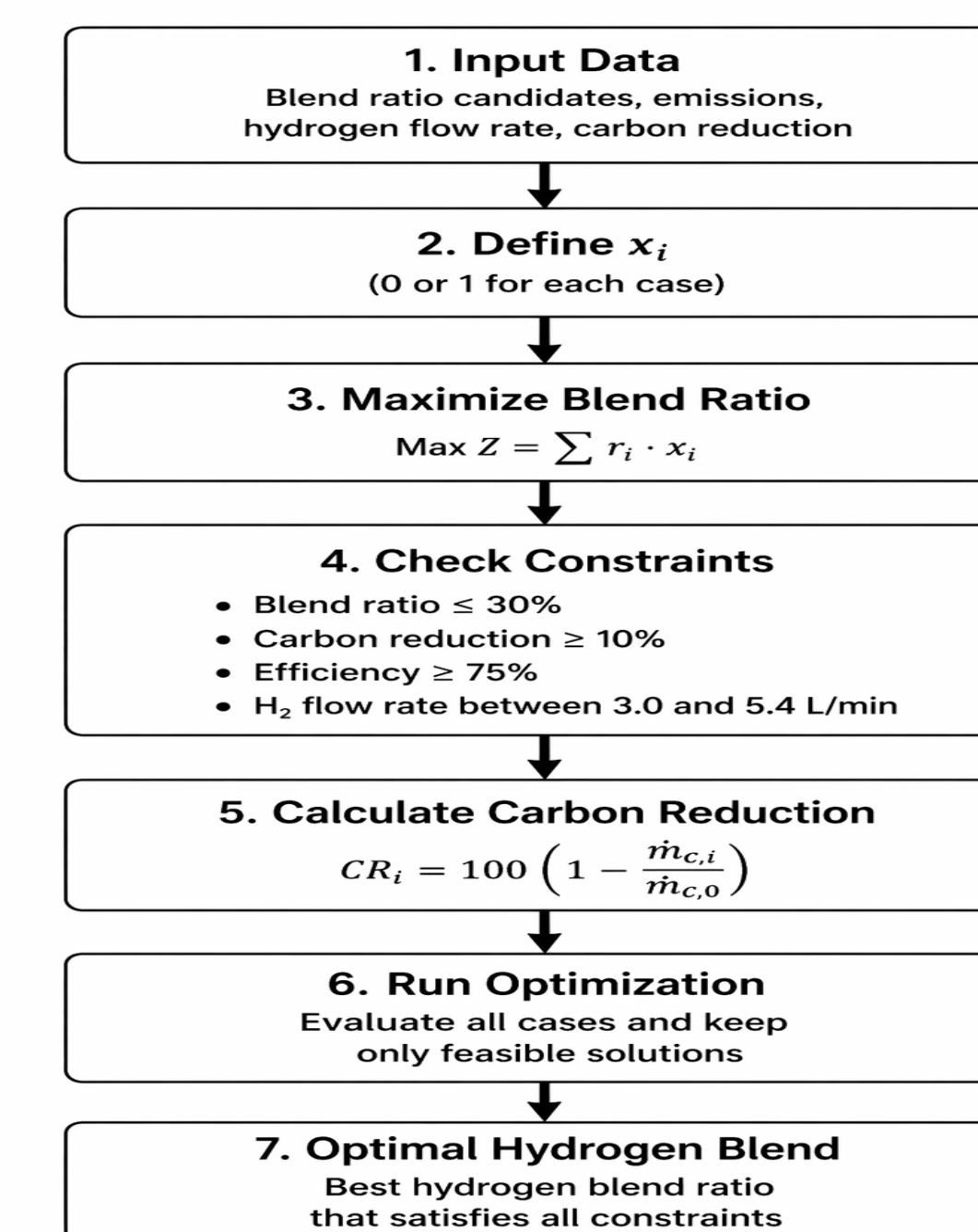
CO Vs H2 blend



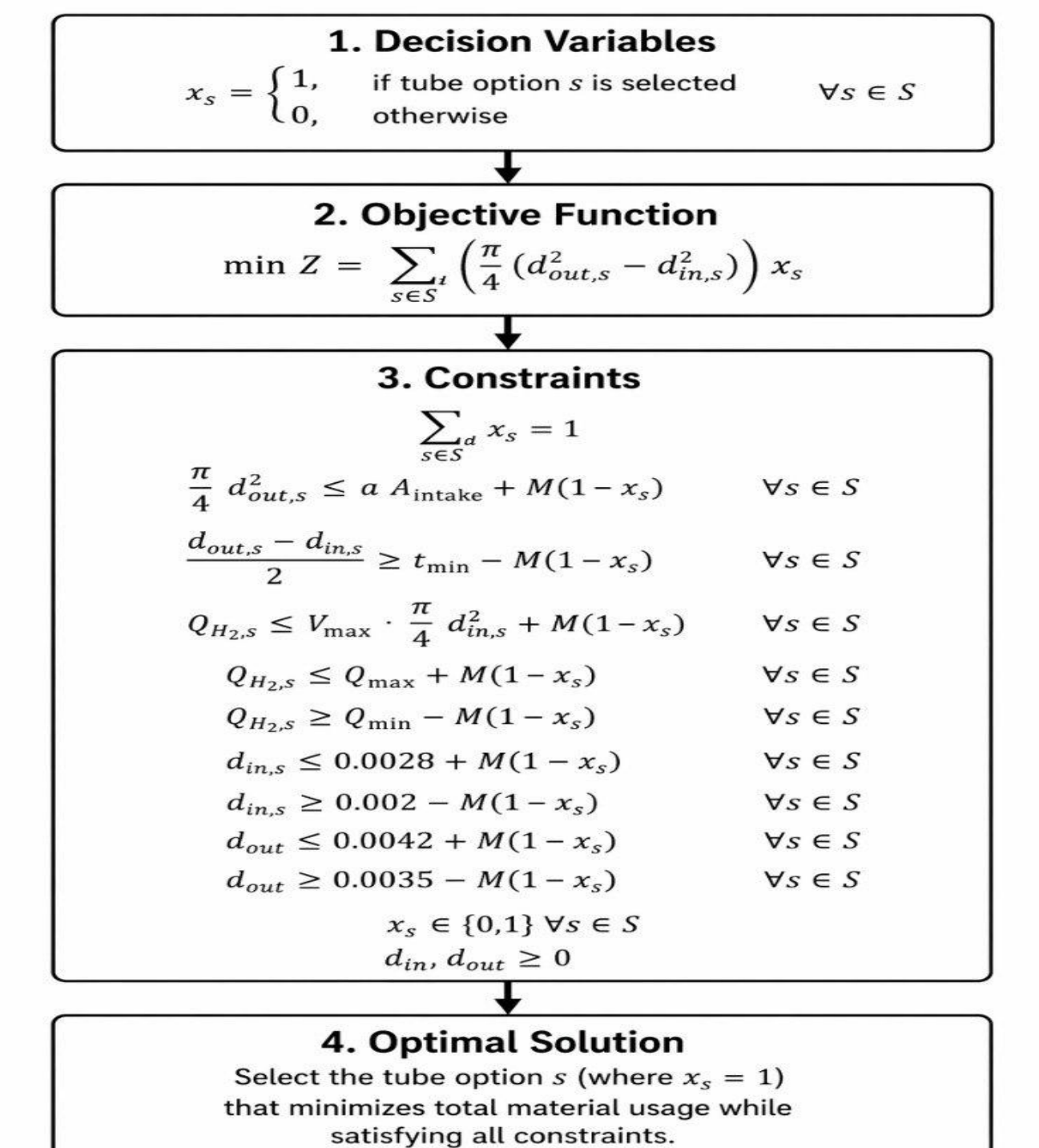
CO2 Vs H2 blend



Optimization Model Flowchart



Optimization Model (Tube Selection Model)



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