PNGRB ROADMAP ON HYDROGEN TRANSPORTATION THROUGH PIPELINES AND BLENDING WITH NATURAL GAS

SEPTEMBER 2025

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PETROLEUM AND NATURAL GAS REGULATORY BOARD (PNGRB)

SUBMITTED BY:

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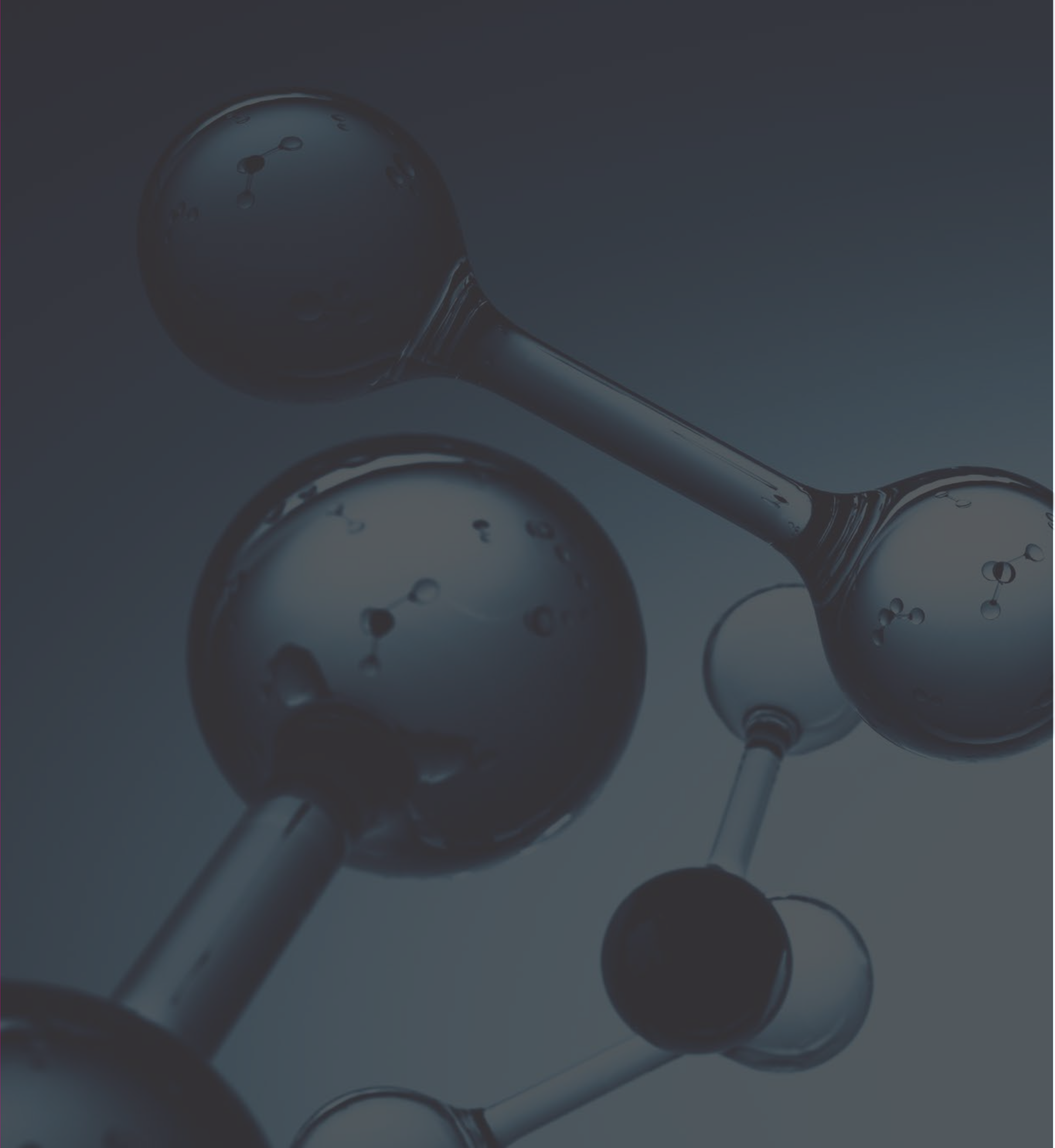

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Foreword

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FOREWORD

The National Green Hydrogen Mission represents a strategic initiative to enable the safe and regulated integration of hydrogen into India's energy infrastructure, supporting a sustainable and resilient energy transition. The Government's directive under the National Green Hydrogen Mission entrusts PNGRB with the responsibility to regulate the transportation of both 100% hydrogen and blended gas, a mandate that underscores the strategic importance of hydrogen in India's future. The pipeline network has to be 'hydrogen ready' so as to send a clear signal to the industry that this future fuel can be transported to market.

This roadmap is a testament to PNGRB's commitment to proactively shaping the future of India's gas infrastructure in alignment with the National Green Hydrogen Mission. Our vision through this roadmap is to ensure that India's pipeline network is prepared for the opportunities and challenges of hydrogen integration. This document sets out a clear direction for the sector: to adopt forward-looking standards, prioritize safety and reliability, and foster innovation across all stages of hydrogen transportation. The roadmap provides a structured framework for readiness assessment, pilot implementation, and long-term planning, with a strong emphasis on indigenous capability and regulatory clarity.

PNGRB recognizes the importance of collaboration among industry, government, and research institutions in realizing the full potential of hydrogen. By establishing robust regulatory foundations and encouraging stakeholder engagement, we aim to create an enabling environment for technology adoption and sustainable growth.

I extend my appreciation to all contributors and partners who have supported this initiative. I am confident that this roadmap will serve as a guiding document for the sector, supporting India's ambition to become a global leader in hydrogen and ensuring that our energy transition is both secure and sustainable.

(Dr. Anil Kumar Jain)
17-9-2025

Foreword

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MESSAGE

India stands at a pivotal moment in its energy transition, with hydrogen emerging as a key enabler for decarbonization and energy security. The development of a robust hydrogen ecosystem presents both significant opportunities and complex technical challenges for our nation. As the global hydrogen economy accelerates, it is essential that India proactively addresses the unique requirements of our domestic pipeline network and regulatory environment.

In this context, the comprehensive roadmap for hydrogen transportation developed by PNGRB demonstrates a forward-looking approach by integrating technical rigor, regulatory foresight, and institutional frameworks. Aligned with the Atmanirbhar Bharat mission, this roadmap emphasizes indigenous capability development, making India self-reliant in hydrogen technologies. The detailed work presented in this report serves as a critical guide for practical implementation, fostering a regulatory environment that supports innovation while safeguarding public and industrial interests.

A holistically designed hydrogen ecosystem must place safety, reliability, and indigenous capability at its core. PNGRB's active role across the hydrogen value chain is essential, not only in regulating infrastructure, but also in fostering innovation, standards development, and stakeholder engagement. Above all, I wish to emphasize the critical importance of developing technical standards that are specifically tailored to Indian conditions. Our unique operating environments, material profiles, and safety requirements demand standards that reflect domestic realities rather than relying solely on international templates. This approach will ensure that our hydrogen infrastructure is both world-class and contextually relevant, supporting the vision of Atmanirbhar Bharat.

I commend the efforts of PNGRB in crafting a strategic and actionable blueprint. This initiative not only positions India as a global leader in hydrogen integration but also ensures that the energy transition is safe, efficient, and sustainable. Let us work together to build a resilient, world-class hydrogen infrastructure that will power India's sustainable growth and global leadership in the hydrogen economy.

(Dr. V. K. Saraswat)

New Delhi
18.09.2025

स्वच्छ भारत
एक कदम स्वच्छता की ओर

Foreword

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The transition to a hydrogen-powered future is not just an aspiration, it is a strategic imperative for India's energy security, industrial competitiveness, and climate commitments. The "PNGRB Roadmap on Hydrogen Transportation through Pipelines and Blending with Natural Gas" marks a pivotal step in this journey, providing a comprehensive blueprint for integrating hydrogen into our nation's gas infrastructure.

This report, prepared by ICF Consulting India in close collaboration with the Petroleum and Natural Gas Regulatory Board (PNGRB), addresses the technical, regulatory, and economic challenges of hydrogen blending and dedicated pipeline deployment. By leveraging global best practices and India-specific pilot experiences, the roadmap offers actionable guidance and steps for safe, scalable, and cost-effective hydrogen transport.

Through rigorous analysis spanning pipeline readiness, regulatory frameworks, testbed layouts, and capacity building requirements, the report lays out a phased approach for mainstreaming hydrogen in both city gas distribution and transmission networks. Its recommendations are designed to support policymakers, industry leaders, and investors to make informed decisions, accelerate pilot projects, and foster innovation across the hydrogen value chain.

I commend the collaborative efforts of all stakeholders involved in this landmark initiative and trust that the roadmap will catalyse progress toward India's leadership in the global hydrogen economy.

Mr. Gurpreet Chugh

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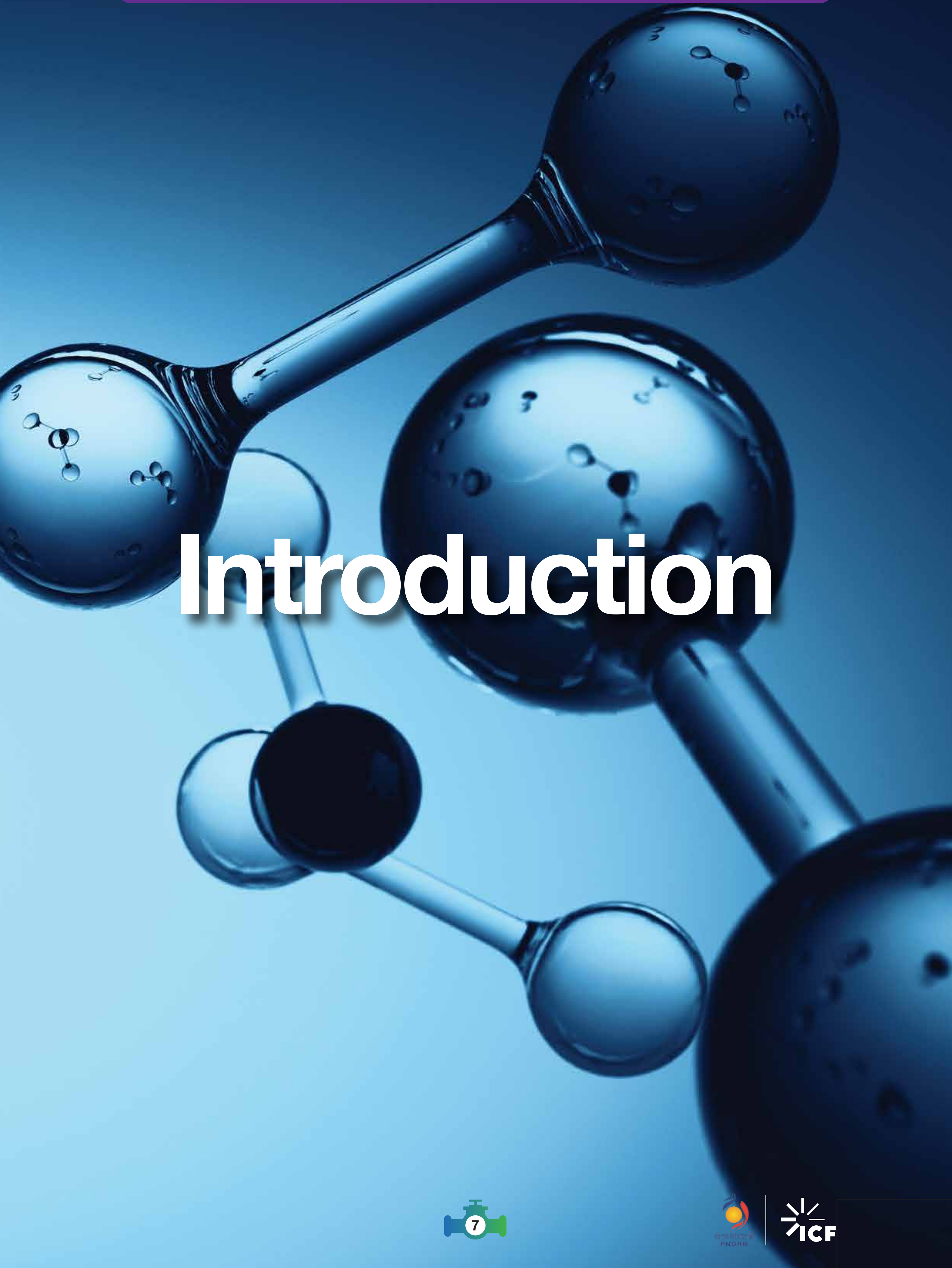
Glossary

Abbreviation	Full Form / Description	Abbreviation	Full Form / Description
API	American Petroleum Institute	H2RegNet	PNGRB Hydrogen Portal and Data Repository
APR	Annual Performance Review	H2	Hydrogen
ASME	American Society of Mechanical Engineers	HAZ	Heat Affected Zone
BG	Blended Gas (Service Class)	HIF	Hydrogen Innovation Fund
BIS	Bureau of Indian Standards	HSE	Health and Safety Executive (UK context)
CAPA	Corrective and Preventive Action	HIC	Hydrogen Induced Cracking
CAPEX	Capital Expenditure	HVAC	Heating, Ventilation, Air Conditioning
CEA	Central Electricity Authority	HAZOP/HAZID	Hazard and Operability Study / Hazard Identification
CGA	Compressed Gas Association	HCI	Hydrogen Compatibility Index (BIS, proposed)
CGD	City Gas Distribution	ILI	In line Inspection
CHP	Combined Heat and Power	IMS	Integrity Management System
CP	Cathodic Protection	ISO	International Organization for Standardization
CVCF	Composition/Calorific Value Correction Factor	IT	Information Technology
DCS	Distributed Control System	J–R curve	J integral Resistance Curve (fracture mechanics)
DNV	Det Norske Veritas (now DNV)	KPI	Key Performance Indicator
EIA	Environmental Impact Assessment	KIH	Threshold Stress Intensity for Hydrogen (cracking)
EIGA	European Industrial Gases Association	LCF/HCF	Low/High Cycle Fatigue
EMAT	Electro Magnetic Acoustic Transducer	LHV/HHV	Lower/ Higher Heating Value
EPC	Engineering, Procurement, Construction	LNG	Liquefied Natural Gas
EPDM	Ethylene Propylene Diene Monomer (elastomer)	MAOP	Maximum Allowable Operating Pressure
ESD	Emergency Shutdown	MDB	Multilateral Development Bank
FAT/SAT	Factory Acceptance Test / Site Acceptance Test	MDPE/HDPE	Medium/High Density Polyethylene
FCGR	Fatigue Crack Growth Rate	MIE	Minimum Ignition Energy
FEED	Front End Engineering Design	MOC	Management of Change
FKM	Fluoroelastomer (e.g., Viton)	MoP/MNRE/	Ministry of Power / Ministry of New & Renewable Energy
GC	Gas Chromatograph	MPI	Magnetic Particle Inspection

Glossary

Abbreviation	Full Form / Description	Abbreviation	Full Form / Description
GCR	Gas Cylinder Rules	**MTTR/MTTD**	Mean Time To Repair / Detect
NACE	National Association of Corrosion Engineers (now AMPP)	**PSA**	Pressure Swing Adsorption
NGHM	National Green Hydrogen Mission	**PQR**	Procedure Qualification Record
NGPL	Natural Gas Pipeline (Transmission) Network	**QA/QC**	Quality Assurance / Quality Control
NHTF	National Hydrogen Training Framework	**RTR**	Residual Thickness Ratio
NDT	Non Destructive Testing	**SCADA/RTU**	Supervisory Control And Data Acquisition / Remote Terminal Unit
NOx/CO	Nitrogen Oxides / Carbon Monoxide Gas Recirculation	**SCR/EGR**	Selective Catalytic Reduction / Exhaust
O&M	Operations & Maintenance	**SMYS**	Specified Minimum Yield Strength
OEM	Original Equipment Manufacturer	**SOP**	Standard Operating Procedure
OHSAS	Occupational Health and Safety Assessment Series	**SSRT**	Slow Strain Rate Test
PAUT/UT/RT	Phased Array Ultrasonic Testing / Ultrasonic Testing / Radiographic Testing	**T4S**	Technical Standards and Specifications including safety standards (PNGRB)
PAT	Perform, Achieve and Trade (energy efficiency scheme)	**THT**	Tetrahydrothiophene (odorant)
PDMS	Polydimethylsiloxane (membrane material)	**TPD**	Tons per day
PED	Pressure Equipment Directive	**TRIR**	Total Recordable Incident Rate
PE80/PE100	Polyethylene grades	**UAV**	Unmanned Aerial Vehicle (drone)
PESO	Petroleum & Explosives Safety Organisation	**UT gauging**	Ultrasonic Thickness gauging
PLC	Programmable Logic Controller	**VGF**	Viability Gap Funding
PNGRB	Petroleum and Natural Gas Regulatory Board	**Viton A**	Common FKM elastomer grade
PRS/PRSO	Pressure Reducing Station/with Odorization	**WI**	Wobbe Index
PRV	Pressure Relief Valve		



Introduction

A.1 Executive Summary

India's surging energy demand and its commitment to achieving net-zero emissions by 2070 have elevated hydrogen (H2) to a central position in its clean energy transition scheme. Recognising the strategic role that hydrogen will play in this transition, the **Petroleum and Natural Gas Regulatory Board (PNGRB)** has initiated the development of a National Hydrogen Roadmap focused on facilitating both **hydrogen blending into natural gas pipelines,** along with the eventual deployment of **dedicated hydrogen transport infrastructure.**

The study conducted for setting this roadmap outlines technical, regulatory, economic, and institutional strategies across nine interrelated modules. The report is designed to leverage the ongoing pilot initiatives, upgrade existing infrastructure, and guide long-term policy adjustments in alignment with the National Green Hydrogen Mission.

The flow of the roadmap will be in line with the following -

- Begin by identifying **potential pipeline routes and infrastructure** needs.
- Establish the **necessary regulatory framework** to support hydrogen infrastructure development.
- Set up a **controlled environment to test and validate** hydrogen processes and technologies.
- Simultaneously align **the end-user's module and deblending module,** all under a unified capacity building module.

The roadmap is further backed by two financial models:

- A **Testbed Costing Model** estimating capital expenses (cost of testing equipment, loop facility, process and sample analysis equipment, hydrocarbon analysis equipment, mechanical workshop and non-destructive testing equipment), and annual O&M (manpower, consumables, contingency and travel related costs).
- A **Cost Comparison Model** analysing the tariff implications of hydrogen blending, benchmarked against conventional natural gas prices.

Phased outcomes

- **Phase I (2025–2028):** Phase 1 focuses on building foundational capabilities required for hydrogen blending and infrastructure readiness. It includes establishing the Hydrogen Cell, developing the digital registry platform (H2RegNet), finalising regulatory baselines, conducting materials and system testing at the national testbed, and initiating pilot projects for both transmission and blending. **Key outputs would include updated standards, refined component compatibility lists, early operational rulebooks, and site-specific deblending recommendations.**
- **Phase II (2029–2033):** Phase 2 transitions from pilot activities to large-scale implementation. It emphasises mainstreaming early blending pilots into routine operations, with integrated deblending guidance, and initiating staged commissioning of pure hydrogen corridors. This phase also establishes institutional practices, such as annual standards updates, H2RegNet benchmarking dashboards, and deblending guidance for operational use, thereby supporting steady-state blended hydrogen operations. **Expected outcomes would include steady-state operation of blended hydrogen networks across city gas distribution (CGD) network and standardisation of transmission pipelines supported by mature regulatory frameworks, operational metrology, and industry best practices, thereby enabling safe, efficient, and large-scale deployment of hydrogen in India.**

The Module Interconnectedness has been shown in the diagram below.

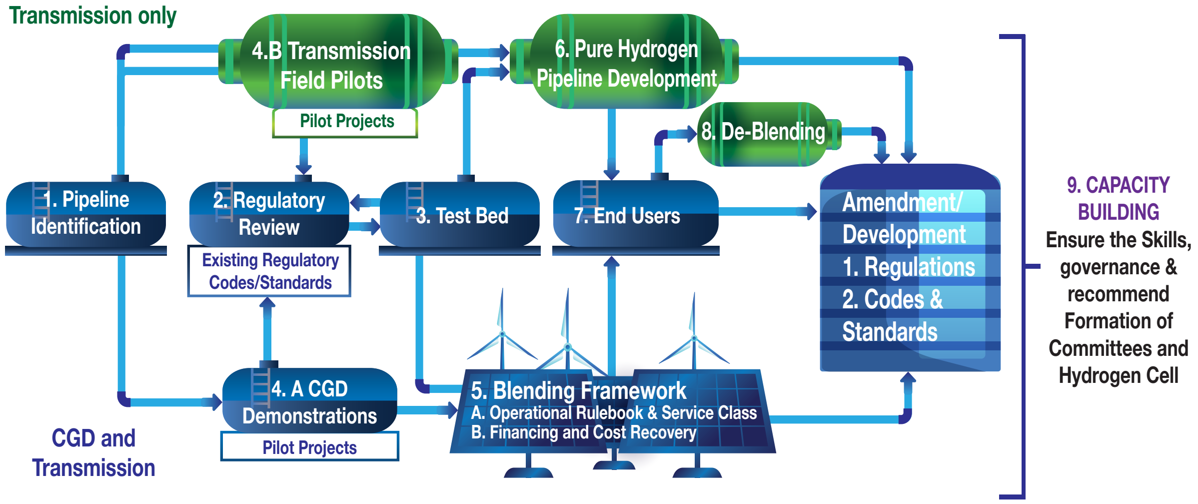


Figure 1. Modules Interconnectedness Flowchart

Table 1: Module-Wise Summary and Recommendations

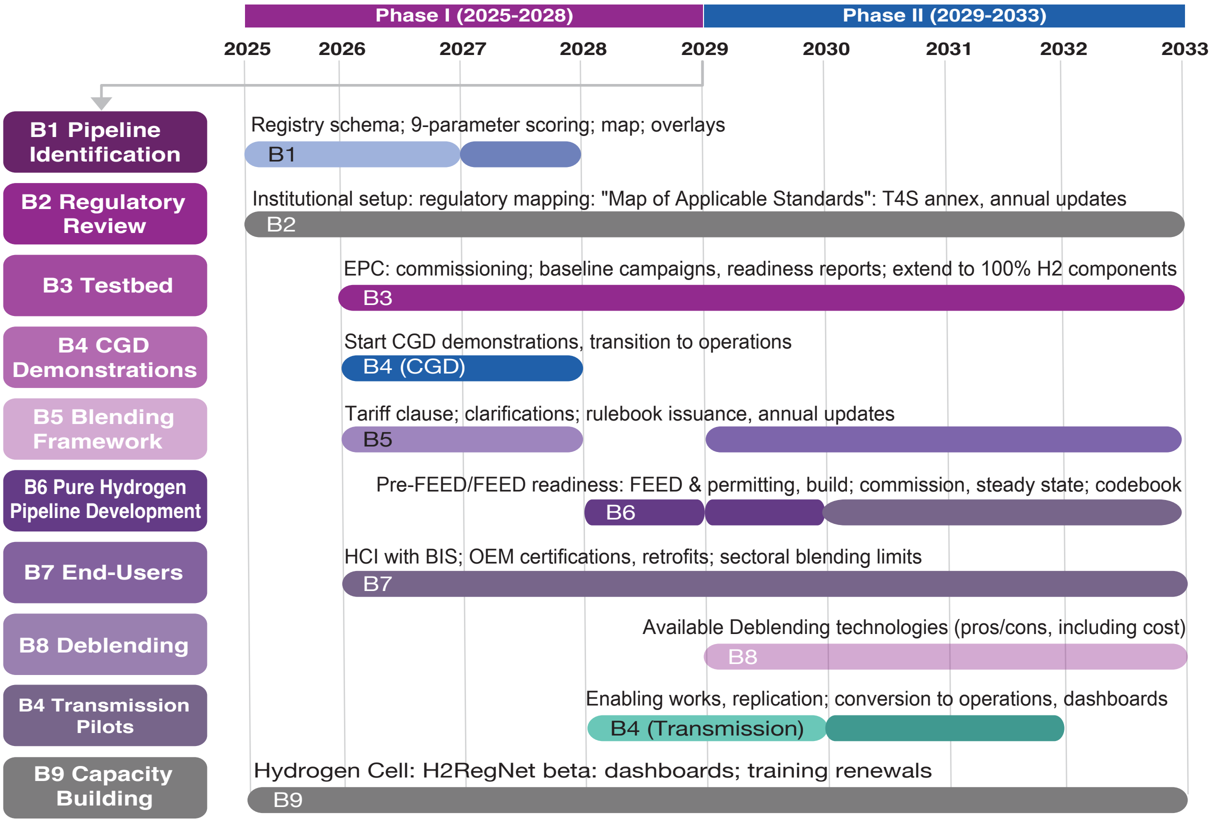
S. No.	Title	Description	Actionable Recommendations
1	Pipeline Identification	A nine-parameter scoring framework has been developed to assess existing pipelines for hydrogen blending readiness: ■ Material compatibility (14%) ■ Weld integrity (14%) ■ Component readiness (12%) ■ End-use compatibility (12%) ■ Age of pipelines (12%) ■ Gas losses (10%) ■ Class of location (10%) ■ Corrosion resistance (8%) ■ Capacity utilisation and MAOP (8%) Pipelines have been rated from "Excellent" to "Poor" to guide prioritisation of upgrades and blending rollout (Minimum 4 is mandatory in each parameter out of 5).	■ PNGRB to operationalise the nine-parameter screening framework to assess pipeline readiness, ensuring a minimum score of 4 in each parameter. ■ A national Installed-Base Readiness Registry should be developed cataloguing compressors, valves, meters, and seals with OEM-certified hydrogen blend limits. ■ Pipeline segments rated "Excellent" or "Good" should be prioritised for pilot blending without retrofitting, while "Fair" and "Marginal" segments should undergo targeted upgrades.
2	Regulatory Review	■ Gaps in India's current regulatory framework have been identified, particularly in the Gas Cylinder Rules. ■ Recommendations include the development of hydrogen transport codes aligned with ASME B31.12 and EIGA guidelines. ■ A bid evaluation framework for regulatory consultants has been proposed (60% technical, 40% financial) to select a regulatory partner. ■ Compliance templates and safety protocols have been drafted. ■ Coordination among BIS, PESO, MNRE, and CGDs has been planned for regulatory alignment.	■ Based on the identified regulatory gaps, PNGRB may initiate a dedicated plan to address hydrogen-specific codes, with particular focus on the Gas Cylinder Rules and the T4S framework. ■ A Hydrogen Regulatory Cell should be constituted within PNGRB to oversee certification, safety standards, and inter-agency coordination. ■ PNGRB should lead the development of a "Map of Applicable Standards" integrating ASME B31.12, EN 16726, and ISO 19880-1, tailored to Indian conditions.

<table>
<tr><th>S. No.</th><th>Title</th><th>Description</th><th>Actionable Recommendations</th></tr>
<tr><td>3</td><td>Testbed</td><td>A hydrogen testing facility has been proposed to assess the behaviour of infrastructure components under hydrogen blending. Facility includes:
■ Storage Zone with hydrogen and natural gas cascades and/or tube trailers.
■ Loop Area with two test loops replicating high-pressure transmission and low-pressure distribution pipelines.
■ Testing Area with facility to conduct 15+ tests, including tensile strength, fatigue, embrittlement, flammability, and cracking, among others.
■ Control Room for real-time monitoring and data acquisition.
■ EPC partner selection to be based on criteria prioritisation, hydrogen systems expertise, and financial solvency.</td><td>■ PNGRB should facilitate a national hydrogen testbed for transmission pipeline with modular zones for testing, and loop simulation, anchored by an EPC-led consortium.
■ The testbed must also include a dedicated testing and research facility to conduct India-specific studies on material compatibility, safety, and performance of gas infrastructure under hydrogen service.
■ A minimum test program should be established covering: SSRT in high-pressure H_2, K_IH threshold testing, fatigue crack growth, permeation rates, weld HAZ toughness, coating disbondment, elastomer compatibility (EPDM, NBR, FKM, PTFE), compressor surge maps, turbine derates, meter bias, and PRV/regulator response.
■ Annual “State of Hydrogen Readiness” reports should be published based on testbed findings to inform regulatory updates and pilot planning.</td></tr>
<tr><td>4</td><td>Pilot Projects
A CGD Demonstration:
B Transmission Pilots:</td><td>Pilot projects validate the feasibility, safety, and operational readiness of hydrogen blending in pipelines -
Technical Activities:
■ Material compatibility (tensile, fatigue, HE, HIC, impact, polymer tests)
■ NDT (PAUT, UT, MPI, RT, visual)
■ Gas quality (stratification, odorant, Wobbe Index)
■ Metering impact
■ Risk assessment (leakage, flammability)
■ Environmental & consumer impact (CO_2 reduction, appliance testing)
A CGD Demonstration - Focus on MDPE pipelines, appliance compatibility, live dashboards, and explicit exit to operations after pilot objectives are met.
B Transmission Pilots - Focus on steel pipelines, monthly technical reports, and national reference standards.</td><td>■ Each pilot must operate under an approved safety case.
■ Minimum test program as per technical assessments.
■ Energy-based billing for fairness.
■ Target 95% uptime, operating system-based tracking.
■ CGD pilots: time-bound, with exit to operations after objectives are met.
■ Transmission pilots: inform national standards and readiness.</td></tr>
<tr><td>5</td><td>Blending Framework</td><td>A Operational Rulebook and Service Class (Standards Map)
■ An operational rulebook is established to codify consistent SOPs, audit checklists, and reporting requirements for all operators handling hydrogen blends, aligned to regulatory baselines for both transmission and CGD.
■ Defines a standardised “Blended Gas” service class for billing and regulatory purposes, thus ensuring traceability of blend ratios, calorific value, and Wobbe Index.
■ A consolidated “Standards Map” is developed and maintained, integrating ASME B31.8, EN 16726, ISO 19880-1,</td><td>■ PNGRB is recommended to introduce a hydrogen infrastructure clause in CGD tariff orders to allow recovery of CAPEX for blending skids, sensors, and safety systems.
■ HIF should be institutionalised with contributions from PAT savings, CSR allocations, and MNRE viability gap funding.
■ PNGRB may consider a 1% Pipeline Tariff Cess to create a non-lapsable fund for hydrogen R&D and pilot support.</td></tr>
</table>

S. No.	Title	Description	Actionable Recommendations
		and component/elastomer specifications, tailored to Indian conditions. ■ Includes requirements for safety, operations, metrology, quality control, incident reporting, and periodic audits. **B Tariff and Finance Mechanism** ■ A structured hydrogen blending mechanism has been proposed based on international experience. ■ Creation of a Hydrogen Innovation Fund (HIF) has been recommended, with funding sources, including profit-after-tax (PAT) contributions from oil and gas companies, CSR allocations, and MNRE viability gap funding. ■ A tariff surcharge of ₹0.39–0.48 per standard cubic metre has been suggested to recover blending costs from industrial and commercial consumers.	
6	Pure Hydrogen Pipeline Development [T]	■ Comprehensive review of ASME B31.12 and EIGA guidelines. ■ A comprehensive EPC scope for design, installation, and validation has been prepared based on learnings from ASME B31.12 and EIGA codes.	■ Amend the PNGRB Act, 2006 to explicitly include "hydrogen pipelines" within its ambit, thus enabling PNGRB to oversee authorisation, tariff-setting, and safety compliance in alignment with ASME B31.12 standards for dedicated hydrogen networks. ■ PNGRB should adopt ASME B31.12 and EIGA guidelines for pure hydrogen pipeline design, with adaptations for Indian terrain and safety conditions. ■ EPC contracts should include mandatory pneumatic testing, dew point verification, and hydrogen flow trials before commissioning. ■ A national hydrogen pipeline code should be developed and notified, covering routing, welding, leak detection, and SCADA integration.
7	End Users	■ The impact of hydrogen blends on domestic and industrial appliances has been assessed. ■ Risks, such as NOx formation, flashback, blow-off, pressure drops, and material degradation have been considered. ■ Equipment categories evaluated include burners, boilers, compressors, CNG tanks, reformers, and turbines.	■ BIS may develop a Hydrogen Compatibility Index (HCI) for domestic and industrial appliances, supported by standardised testing protocols. ■ PNGRB is advised to mandate blend-specific appliance certification, and publish sector-wise blending limits based on testbed and pilot data. ■ OEMs can be engaged to retrofit legacy systems and design hydrogen-tolerant equipment, with incentives linked to HCI compliance.

S. No.	Title	Description	Actionable Recommendations
8	Deblending [T]	Three technologies for hydrogen extraction from blended gas have been evaluated: ▪ Pressure Swing Adsorption (PSA) providing >99.9% purity, but less effective below 5% blends. ▪ Cryogenic Separation, which is suitable for 5–100% blends with up to 95% recovery. ▪ Hybrid deblending units have been recommended for flexible deployment. ▪ Cost-benefit analysis indicates payback within 4–7 years, depending on scale and recovery rates.	▪ Modular deblending systems using membrane + PSA hybrids is suggested to be promoted for deployment across CGD zones and industrial hubs. ▪ Technology selection should be based on blend concentration, scale, and purity requirements, with CAPEX and payback benchmarks defined. ▪ Residual hydrogen in reinjected natural gas should be capped at <2%, and reuse pathways for recovered hydrogen should be standardised. ▪ Technology selection should be guided by inlet hydrogen concentration, scale of operation, and sector-specific purity requirements, thus ensuring alignment with ISO 14687 and ISO 11120 standards.
9	Capacity Building	▪ Roles and governance structures for all stakeholders in hydrogen value chain have been defined. ▪ Formation of a Hydrogen Cell within PNGRB with technical and regulatory powers has been recommended. ▪ A three-tier governance system comprising Apex Board, Scientific Advisory Committee, and Industry Committees has been proposed. ▪ The Hydrogen Portal (H2RegNet) has been planned for real-time blend monitoring, appliance compatibility tracking, and incident logging.	▪ Institutionalize the Hydrogen Cell (Division) with four verticals—Technical Standards, Regulatory Approvals, Digital Integration, and International Collaboration is recommended. ▪ The Hydrogen Portal (H2RegNet) should be launched to enable real-time blend monitoring, incident reporting, and certified equipment tracking. ▪ A National Hydrogen Training Framework (NHTF) should be rolled out with IITs, CSIR, GERMI, etc. as partners, targeting 80% stakeholder awareness by 2027.

PNGRB Hydrogen Roadmap — Consolidated Timeline (2025–2033)



The following table outlines the key modules of the Hydrogen Blending Roadmap, detailing the implementation timeline, primary deliverables, responsible owners, and supporting stakeholders.

Module	Window	Key Deliverables	Primary Owners	Support
B1 Pipeline Identification	2025–2028	Installed-Base Readiness Registry; 9-parameter scoring and “Excellent/Good/Fair/Marginal” map; Overlays and early interfaces	PNGRB; NGPL/CGD Entities	EPC/Testbed Consortium; OEMs
B2 Regulatory Review	2025–2033	Institutional set-up; Regulatory mapping and gap identification; “Map of Applicable Standards”; T4S hydrogen annex (Edition 1); annual updates	PNGRB	BIS; PESO; MNRE/Relevant Ministries
B3 Testbed	2026–2033	EPC award; Commissioning; Baseline campaigns; State of Hydrogen Readiness — India (Year 1, Year 2, Year 3); Extend to 100% H_2 components and compressor/turbine derates	EPC/Testbed Consortium	PNGRB; NGPL/CGD Entities; OEMs
B4 CGD Demonstrations	2026–2027	Start CGD demonstrations with energy-based billing; Completion and transition to operations	CGD Entities	PNGRB
B4 Transmission Pilots	2028–2031	Enabling works; Replication across zones; Conversion to operations; Dashboards via H_2RegNet	NGPL/Transmission Entities	PNGRB

Module	Window	Key Deliverables	Primary Owners	Support
B5 Blending Framework	2026–2027 2029–2033	Tariff clause; Clarifications on ramp rates, stop rules, metering QA; Annual standards updates and Rulebook issuance; Tariff differentiation	PNGRB	CGD/NGPL Entities
B6 Pure Hydrogen Pipeline Development	2028–2033	Pre-FEED/FEED readiness; FEED and permitting; Long-lead planning; Custody transfer metrology; Build and commissioning; Steady-state operations; National codebook	NGPL/Transmission Entities	PNGRB; EPC/Testbed Consortium
B7 End-Users	2026–2033	HCI with BIS; OEM certifications; Targeted retrofits; Sectoral blending limits by equipment class	BIS; OEMs	PNGRB; CGD Entities
B8 Deblending	2029–2033	Guidelines on available deblending technologies with pros/cons (including cost)	CGD/NGPL Entities; OEMs	PNGRB
B9 Capacity Building	2025–2033	PNGRB Hydrogen Cell; H_2RegNet beta; National dashboards; Training renewal cycles	PNGRB	CGD/NGPL Entities; EPC/Testbed Consortium; BIS; PESO

Conclusion

Commissioned by the **Petroleum and Natural Gas Regulatory Board (PNGRB)** and prepared by **ICF Consulting India Pvt. Ltd.**, this report lays a robust foundation for hydrogen integration into India's energy infrastructure. By following the recommended multi-phase approach, addressing technical and regulatory challenges, and harnessing collaborative stakeholder engagement, India can accelerate its transition to a sustainable hydrogen economy.

The framework not only prepares the nation to safely blend hydrogen into its natural gas networks, but also sets the stage for laying pure hydrogen pipelines in the future—thus propelling India toward a low-carbon, resilient energy future and supporting India's Panchamrit pledge, and help cut emissions intensity by 45% by 2030 and reach net zero by 2070.

Project Background, Purpose and Scope of Work

A.2 Project Background

The transition to green hydrogen is a critical pillar of India's broader decarbonisation strategy, with hydrogen expected to play a key role in the clean energy mix, particularly across hard-to-abate sectors. Given the significant opportunity to leverage the existing natural gas infrastructure for early-stage hydrogen uptake, the Petroleum and Natural Gas Regulatory Board (PNGRB) has initiated efforts to assess and enable hydrogen blending and transportation through pipelines.

Clause 6.4 of the National Green Hydrogen Mission (NGHM)

"MoPNG will support the uptake of green hydrogen in the refinery and city gas distribution sectors, both through Public Sector Enterprises and private sector entities. MoPNG will also enable development and facilitation of regulations for hydrogen blending with natural gas and its transport through pipelines through the Petroleum and Natural Gas Regulatory Board (PNGRB)"

In fulfilment of this mandate, PNGRB is leading the development of a regulatory and technical roadmap to facilitate hydrogen readiness of India's gas infrastructure, including pipelines, compressor stations, and end-user networks. This roadmap aims to provide a structured pathway for safe, scalable, and feasible hydrogen blending, and transport in near-to-medium term.

International experience (such as, HyDeploy, H100 Fife, TransHyDE, and FutureGrid) offers useful methods and datasets; however, India specific evidence is needed to calibrate standards to Indian grades, environments, and operating practices. In tandem, CGD companies have also initiated pilot projects.

This roadmap explains how to document those efforts consistently, strengthen safety and metrology practices, and capture lessons to inform standards and operating procedures. For transmission, field pilots have been defined to validate safe operating envelopes and metering reconciliation, as well as to guide dedicated corridor development where demand anchors exist.

The background to this report lies in a multi-agency effort to determine how existing natural gas infrastructure—pipelines, metering stations, appliances—can be repurposed or augmented to carry hydrogen blends in the near term, and pure hydrogen in the long term.

A.3 Objective and Scope of Work

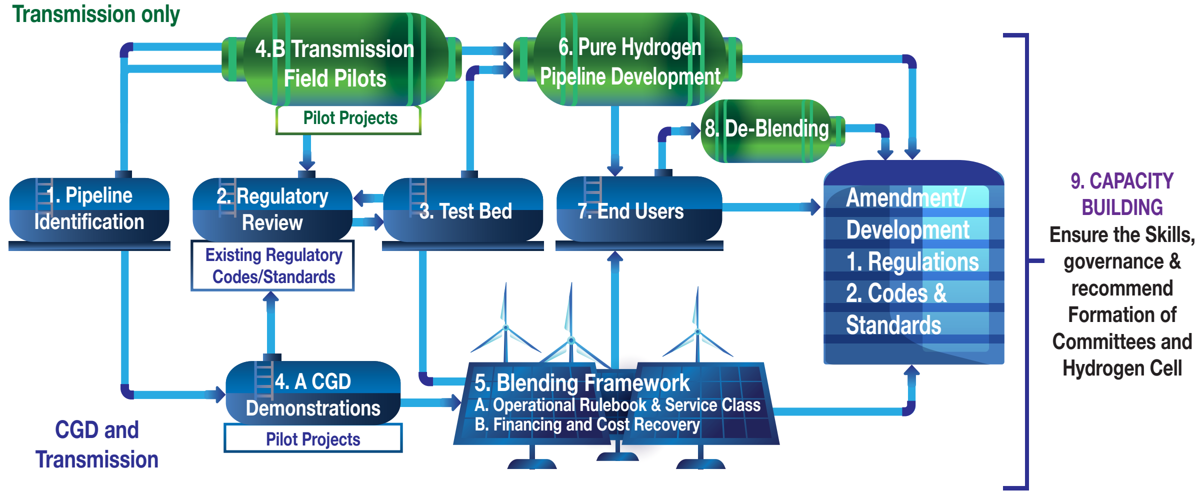
The objective is to develop a comprehensive, evidence-based roadmap for the transportation of hydrogen through Natural Gas Pipeline (NGPL) and CGD networks. The objective of this roadmap is to provide implementation steps and recommendations for:

1. **Establishing a robust regulatory and technical framework** for safe hydrogen blending and pure hydrogen transport in India's natural gas and CGD pipelines.
2. **Implementing national-scale pilots and testbeds** to generate India-specific data on material compatibility, safety, and operational performance for hydrogen infrastructure.
3. **Developing and adopting comprehensive codes, standards, and certification protocols** aligned with global best practices, and tailored to Indian conditions.
4. **Enabling sustainable financing and cost recovery mechanisms** through tariff reforms along with the creation of an HIF to support pilot projects, research and development (R&D), and infrastructure upgrades.
5. **Phasing the transition from hydrogen blending to dedicated pure hydrogen pipelines,** including the development of standards, pilot corridors, and regulatory oversight for future large-scale hydrogen transport.
6. **Building institutional capacity and digital platforms** for real-time monitoring, stakeholder training, and continuous knowledge sharing across the hydrogen value chain.

This report provides a comprehensive roadmap for hydrogen transportation through pipelines across NGPL and CGD -

- NGPL (Transmission) - *Denoted by [T] across the modules*
  - Establish the technical and procedural basis for operating hydrogen blends in steel pipelines, including materials qualification, fracture control, compressor and valve compatibility, leak detection, and emergency response.
  - Design field pilots to generate India-specific evidence and provide a pathway to dedicated hydrogen corridors, where justified by demand and standards.
- Other Shared Modules (Transmission + CGD)
  - Outline a national testbed program to close critical gaps (materials, metering, odorisation, safety, flow), where value adding.
  - Establish standards governance, training, and a data portal (H2RegNet) for transparent reporting.
  - Describe financing approaches to support prudent cost recovery and targeted innovation, including deblending for purity critical nodes and reinjection quality control.

Nine Modules of the Report



A summary of the main purpose and scope for each of the nine modules in this report is provided below:

Table 2: Purpose and Scope of Work for Each Module

Module	Purpose of Work	Scope of Work
B.1 Pipeline Identification	**Screening and Registry** - Prioritise NGPL segments and CGD zones using a geospatial registry and nine-parameter scoring to identify transmission pilot candidates, CGD documentation zones, candidate deblending offshoot nodes, and corridor interfaces.	Materials and weld integrity, component readiness, end-use overlays, leakage, location class, corrosion, capacity and/or MAOP headroom, OEM admissibility records, and outputs pack for downstream modules.
B.2 – Regulatory Review	Define India-specific annexed guidance aligned to international codes for the safe operation of hydrogen-natural gas blends in both steel transmission pipelines, stations, and CGD networks. This serves to establish a robust design basis for pilot projects, corridors, and auditable operational practices in systems currently piloting or planning to pilot hydrogen blending.	Materials and integrity (qualification and inspection), stations/components (compressors, valves, regulators, dryers), operations and safety (purging, blowdown, dispersion, ER plans), metrology (GC, sampling, reconciliation), documentation and training. Safety case templates, leak surveillance and odorisation verification, metering and energy reconciliation (where billing applies), consumer communications, and interfaces for deblending and reinjection.

Module	Purpose of Work	Scope of Work
B.3 Testbed (National Hydrogen Testing and Validation)	**Testbed** - Produce India-specific materials, metrology, odorisation, safety/dispersion, component, and flow evidence to calibrate B.2 and enable B.4 pilots, strengthen CGD operations, and inform B.6 pure hydrogen pipeline development and B.8 deblending.	Steel and weld behaviour, polymers/elastomers, station/component envelopes, meter bias and uncertainty, odorisation dose/verification, dispersion and emergency doctrine, flow dynamics; and annual state of hydrogen readiness in — India.
B.4 Pilot Projects A Transmission Field Pilots (NGPL) B CGD Demonstrations	A Validate safe operating envelopes, metering reconciliation, integrity monitoring, and emergency doctrine for blends in representative NGPL segments. B **Pilot Documentation, Evaluation, and Transition to Operations**: Document and assess CGD hydrogen blending pilots, harmonise operational practices and enable a structured transition to regular operations based on safety, compatibility, and performance outcomes.	A Pilot selection and configuration, instrumentation and data schema, operating envelopes, inspection cadence, reporting and acceptance criteria, and lessons-learned to standards. B Zone selection, data fields and KPIs, audit templates, outcomes review, and SOP consolidation as practices mature
B.5 Blending Framework A Operational Rulebook and Service Class B Financing and Cost Recovery	A **Standardisation:** Codify consistent SOPs, audit checklists, and reporting for operators handling hydrogen blends, aligned to B2 outputs. B **Tariff and Innovation fund:** Enable prudent cost recovery for justified upgrades and create an HIF for targeted trials (e.g., deblending, metrology).	A Safety, operations, metrology, quality control, incident reporting, and training requirements; defines a standardised "Blended Gas" service class where billing applies. B Tariff clause architecture, prudence criteria, ring-fenced innovation co-funding, reporting, and sunset/roll-in rules.
B.6 Pure Hydrogen Pipeline Development	**Dedicated Hydrogen Corridors:** Provide a feed-ready pathway to plan, design, and deliver pure hydrogen corridors where demand anchors and standards justify new assets or conversion.	Corridor selection, materials and welding procedures, compression and purification strategy, custody transfer metrology for H_2, QA/QC and commissioning, phased delivery
B.7 End Use	**Compatibility and Sector Guidance**: Map blend tolerances and compatibility considerations across key sectors.	Industry segments (industrial heat, CHP, mobility, sensitive users, such as hospitals, food/pharma), appliance considerations, and local envelope adjustments.
B.8 Deblending	**Technology Feasibility and Guidance for Transmission Offshoots:** Assess feasibility of separating hydrogen from blended transmission streams at purity-critical offshoot nodes, through literature and OEM data; provide best-practice guidance.	Comparative review of PSA, cryogenic, and hybrid systems; evaluation parameters (recovery, specific energy, CAPEX intensity, output quality, reliability, turndown); siting/integration practices; measurement and verification; recommendations mapped to industrial clusters. CGD household use is out of scope.
B.9 Capacity Building	**Governance, Data, Standards and training:** Ensure transparency, accountability, training, and continuous standards updates across NGPL and CGDs.	PNGRB Hydrogen Cell mandate, H2RegNet data model and publication rules, training and certification pathways, Standards Map (living document), stakeholder engagement.

A.4 Methodology

The methodology employed in this report was designed to produce an integrated assessment of hydrogen blending and infrastructure readiness in India. It is aligned with the nine modules that structure the report and focuses on data-backed technical evaluation, financial analysis, safety readiness, and institutional implementation. Each step in the methodology reflects the sequence of practical tasks and planning decisions needed to assess and operationalise hydrogen integration across pilot and national scales.

Table 4: Module-Wise Methodology Overview

Module	Methodology
1. Pipeline Identification	This module initiates the roadmap by identifying pipeline segments suitable for hydrogen blending or future conversion to pure hydrogen service. The approach involved:• Utilise pipeline data on pipeline grade and age provided by PNGRB to conduct a preliminary assessment of hydrogen blending suitability, applying 10 years as the threshold for pipeline vintage and X52 as threshold for pipeline grade.• Based on literature insights, propose a scoring matrix incorporating criteria, such as material compatibility, weld integrity, component readiness, end-use compatibility, pipeline age, gas losses, class location, corrosion, capacity utilisation, and MAOP to assess hydrogen blending suitability of pipeline section
2. Regulatory Review	Establishing a robust regulatory foundation was critical to govern both blending and pure hydrogen pipelines. This module included:• Review standards related to hydrogen pipeline transportation and identify gaps and missing links in the regulatory framework.• Examine Gas Cylinder Rules (GCR) to uncover additional regulatory deficiencies relevant to hydrogen handling and pipeline safety.
3. Testbed	A hydrogen testbed was conceptualised to validate material compatibility, system integrity, and safety protocols under controlled conditions:• Reviewed global testbed cases, such as Future Grid Phase-1, TransHyDE (GET H_2), and H_2-20 (DVGW) to define relevant test objectives, testing types, and infrastructure needs.• Defined testbed purpose and outcomes, including validation of material compatibility, safety, etc.• Designed test facility with 4 zones: Storage (tube trailers, cascades), Loop Area (2 test loops for NGPL and CGD), Testing Area (mechanical/fatigue machines), and Control Room (data acquisition, monitoring).• Identified key testing protocols covering mechanical, leakage, safety, and flow dynamics simulations under blended gas conditions.
4. Pilot Project **A. CGD Demonstrations** **B. Transmission Pilots**	A. CGD Demonstrations: Pilot design for CGD demonstrations is based on international and Indian pilots, focusing on MDPE pipelines and end-use appliances with hydrogen blending. The scope includes technical assessments (material compatibility, NDT, appliance testing), risk evaluation, environmental and consumer impact, safety and compliance planning, and training. Satisfaction criteria are tailored for MDPE pipelines. Each pilot is time-bound and includes an explicit exit strategy to transition to operations once the objectives are met. B. Transmission Pilots: Transmission pilot design draws on global experience, focusing on steel pipelines. The scope covers technical assessments (tensile, fatigue, HE, HIC, impact, polymer testing), NDT, gas quality, risk evaluation, and compliance with international standards. Satisfaction criteria are set for steel pipelines. Pilots include detailed cost estimation, phased implementation, and serve as national references for standards and operational readiness.
5. Blending Framework **A Operational Rulebook and Service Class**	A. Operational Rulebook and Service Class: It defines standardised practices for planning, approval, pre-injection readiness, normal operations, integrity management, emergency response, and reporting, ensuring safe, auditable, and efficient blending operations aligned with PNGRB regulations and international standards.

Module	Methodology
B Financing and Cost Recovery	B. Financing and Cost Recovery- The blending framework suggests ways to secure funding: • Reviewed international hydrogen funding models from the US, the UK, Germany, and Australia to understand public and private financing approaches. • Proposed creation of an HIF supported by PAT contributions and CSR allocations. • Recommended introduction of a tariff mechanism to recover costs by charging industrial and commercial consumers
6. End User	Understanding downstream impacts of hydrogen-blended gas was essential to protect consumers and ensure safety:• Review scope: • Domestic: Burners, ovens, furnaces and water heaters • Industrial: burners, boilers, turbines, compressor, CNG steel tank, gas engines, steam methane reformer• Assessed: • NOx formation under different blend ratios • Flashback, blow-off, and pressure fluctuation tolerance • Appliance material degradation and seal integrity • Output: appliance compatibility map for each blend ratio
7. Deblending	This module assessed the feasibility of separating hydrogen from blended streams from literature reviews: • Compared PSA, cryogenic, and hybrid (PSA + membrane) systems• Evaluated parameters: • Recovery rate • Energy consumption • Output gas quality and reliability • Recommendations mapped to industrial clusters where deblending is critical
8. Pure Hydrogen Pipeline Development	For long-term planning, dedicated hydrogen pipelines codes were evaluated: Evaluation of ASME B31.12 and EIGA codes• Preparation of scope of work for pure hydrogen pipeline (based on ASME B31.12).
9. Capacity Building	Capacity building was positioned as an enabler to all modules: Hydrogen cell within PNGRB along with various committees: • Responsible for testbed oversight, pilot approvals, and regulatory updates• Role of various stakeholders: • Mapping role of each stakeholder in the hydrogen value chain

Modules Description

B.1 Pipeline Identification

MODULE AT A GLANCE

SCOPE

Develop 9 parameter screening + national Installed Base Readiness Registry to rank segments and CGD zones for blending pilots or upgrades.

KEY RESULTS

Weighted 9-parameter screening criteria for pipeline identification for NGPL and CGD. Early candidate indicative segments identified (API 5L X42–X52, ≤10 years)

INTER MODULE LINKAGES

Inputs B4 (pilot selection), B2 (standards for acceptance), B3 (test matrices to reduce uncertainty), B5 (operational rulebook thresholds), B6 (corridor interface points), B8 (offshoot nodes for deblending).

SNAPSHOT ITEMS

- Decision Gate: Proceed only if each parameter ≥4/5.
- Red Flags: High-strength steels (X70+), poor weld data, high gas loss, HCA exposure (Class 3–4), corrosion RPR <0.9.
- Quick Data Pack: Material grade/age, weld integrity, components OEM limits, gas loss %, class location mix, corrosion rate/RTR, capacity/MAOP.

Identifying suitable pipeline segments for hydrogen blending trials is critical to ensuring safety, operational stability, and scalability. Hydrogen's physical and chemical characteristics introduce unique challenges, especially related to material integrity, leakage, and combustion dynamics. Therefore, pipeline segments must be screened rigorously using a multi-criteria assessment framework to identify viable candidates for phased blending initiatives.

Selection Criteria

A technical evaluation of pipeline infrastructure begins with understanding its core design, operational history, and material resilience. The following parameters form the basis of the selection framework:

1. Material Compatibility (Weight: 14%)

Description:

This parameter evaluates whether the material used in the pipeline is inherently resistant to hydrogen-induced damage. Certain materials, such as lower-grade carbon steels (e.g., API X42–X52) and high-density polyethylene (PE100), have better resistance to hydrogen embrittlement and gas permeation.

Rationale:

Hydrogen embrittlement can compromise the structural integrity of pipelines, particularly in high-strength steels. Materials that exhibit lower susceptibility are preferred for safe blending operations.

Tables below present the scoring matrix for material compatibility

Table 4: Score Based on Steel Grade

Steel Grade	Score (1-5)	Rationale
API 5L X42-X52 (below X52)	5	Excellent resistance to hydrogen embrittlement due to low yield strength and high fracture toughness.[1]
API 5L X52-X60	4	Good resistance; slightly higher susceptibility than X42 but acceptable with monitoring.
API 5L X60-X70	3	Moderate resistance; requires monitoring under higher hydrogen partial pressures (>50 bar).
API 5L X70-X80	2	High-strength steel; prone to embrittlement; requires mitigation measures.
API 5L X80 and higher	1	Very high-strength steel; highly susceptible to embrittlement; not recommended without retrofitting.

Table 5: Score Based on Plastic Grade

PE Grade	Score (1-5)	Rationale
PE100	5	High-density polyethylene with excellent resistance to hydrogen permeation and cracking.[2]
PE80	4	Moderate-density polyethylene; higher permeability but acceptable for low blends (<10% H_2).
PE63	2	Low-density polyethylene; not recommended for hydrogen blending due to high permeability.

2. Weld Integrity (Weight: 14%)

Description:

Welded sections of the pipeline are evaluated for hardness and the presence of flaws such as cracks, lack of fusion, or porosity. These areas are particularly vulnerable to hydrogen-induced cracking. Weld integrity scoring focuses on girth welds, which are most critical for hydrogen-induced cracking

Rationale:

Weld zones represent structural weak points where hydrogen exposure may lead to failure due to high residual stress, hardness, or inherent flaws. Monitoring weld quality is essential for long-term safety.

Key Sub-Parameters:

- Weld Hardness:
  - Measured using the Vickers Hardness Test.[3]
  - Hardness values exceeding 250 HV are more susceptible to embrittlement.

[1] https://www.sciencedirect.com/science/article/pii/S0360319925000382
[2] https://link.springer.com/article/10.1007/s43621-025-01007-0
[3] https://www.hse.gov.uk/pubns/books/l82.htm

- Weld Flaw Density:
  - Measured using Phased Array Ultrasonic Testing (PAUT).
  - Represents the proportion of weld circumference containing detectable flaws.

Exceptional cases where individual weld traceability data is unavailable—particularly for legacy pipelines—operators may adopt alternative scoring methods. These include:

- Using weld acceptance codes (e.g., ASME B31.8, API 1104) to assess compliance with minimum quality standards.
- Conducting representative Non-Destructive Testing (NDT) sampling across pipeline segments, including ultrasonic testing (UT), magnetic particle testing (MPT), or radiographic testing (RT) to establish weld integrity trends.
- Documenting historical repair records and hydrotest outcomes as supplementary evidence of weld reliability.

Weld Integrity Score Formula:

Weld Integrity Score = (Hardness Score × 0.6) + (Flaw Density Score × 0.4)

Scoring matrix for hardness score and flaw density score is presented below.

Table 6: Score Based on Hardness

Hardness Range (HV)	Score (1-5)
≤200	5
201–230	4
231–250	3
251–280	2
>280	1

Table 7: Score based on flaw density

Flaw Density (%)	Score (1-5)
≤1	5
>1–2	4
>2–3	3
>3–5	2
>5	1

ALTERNATE WELD INTEGRITY SCORE FORMULA FOR CASES WHERE INDIVIDUAL WELD TRACEABILITY DATA IS UNAVAILABLE

Weld Integrity Score (Alternate) = (Acceptance Code Score × 0.5) + (NDT Sampling Score × 0.5)

Scoring Matrix A: Acceptance Code Score

Scoring Matrix A: Acceptance Code Score

Compliance Level (Code-Based)	Score (1–5)
Fully compliant with ASME/API standards	5
Minor deviations, documented repairs	4
Compliant with legacy codes, no recent validation	3
Partial compliance, limited documentation	2
Non-compliant or undocumented	1

Scoring Matrix B: NDT Sampling Score

Defect Rate in Sampled Welds (%)	Score (1–5)
≤1%	5
>1–2%	4
>2–3%	3
>3–5%	2
>5%	1

3. Component Readiness (Weight: 12%)

Description:

This parameter examines the readiness of critical pipeline components—such as valves and compressors—for hydrogen service. Hydrogen's unique physical properties can affect seals, internal surfaces, and operating mechanisms.

Rationale:

Components not originally designed for hydrogen may degrade faster, leak, or underperform, thereby compromising the entire pipeline system. Operators must obtain OEM certification for hydrogen blend compatibility of compressors, valves, and metering systems

Key Considerations:

- Valves: Evaluated for sealing performance and hydrogen resistance. (For valves, 2 parameters have been considered viz. Material of body and valve age)
- Compressors: Assessed for compatibility with hydrogen compression requirements. (For compressor, key parameters are hydrogen blending limit (as approved by OEM) and compressor age)

Component Readiness Score:

The final score is taken as the minimum of all individual valves or component scores, as the least compatible element limits overall readiness.

Scoring criteria for key parameters are presented below.

Table 8: Score Based on Valve Body

Material Type (Body)	Compatibility with Hydrogen	Valve Rating
Austenitic Stainless Steel (e.g., 316L)	High compatibility, resistant to hydrogen embrittlement[4]	5
Duplex Stainless Steel	Moderate compatibility may require testing	3
Carbon Steel and Aluminum Alloys	Low or limited compatibility	1

[4] *https://www.sciencedirect.com/science/article/pii/S0360319925000382*

Table 9: Score Based on Valve Age

Valve Age (Years)	Valve Rating
Less than 5 years	5
5-10 years	4
10-15 years	3
15-20 years	2
More than 20 years	1

Table 10: Score Based on Blending % Allowed

Hydrogen Blend Percentage	Compressor Rating
Up to 2%	1
2% - 5%	2
5% - 10%	3
10% - 15%	4
15% - 20%	5

Table 11: Score Based on Compressor Age

Compressor Age (Years)	Compressor Rating
Less than 5 years	5
5-10 years	4
10-15 years	3
15-20 years	2
More than 20 years	1

4. End-Use Compatibility (Weight: 12%)

Description:

This parameter measures whether downstream equipment—such as industrial burners, turbines, or residential appliances—is capable of operating with hydrogen-natural gas blends without loss of performance or safety risks.

Rationale:

Even if upstream pipelines are ready for hydrogen blending, end-use failure or inefficiency can negate the benefits. Ensuring compatibility across the value chain is essential.

End-Use Compatibility Score:

The final score is determined by the minimum of all downstream equipment scores, as the least tolerant device sets the system limit.

The scoring matrix for end-use compatibility is presented below.

Table 12: Score for End-use Compatibility

Blend Limit (%)	Score (1-5)
Up to 1%	1
Up to 3%	2
3%–5%	3
5%–10%	4
More than 10%	5

5. Age of Pipelines (Weight: 12%)

Description:

The operational age of the pipeline system is evaluated as an indirect indicator of wear and potential degradation mechanisms such as fatigue, corrosion, and mechanical damage.

Rationale:

Older pipelines are more likely to exhibit microstructural defects, corrosion, or outdated specifications, making them more vulnerable to hydrogen-induced damage.

Scoring matrix for pipeline

Table 13: Score Based on Age

Age (Years)	Score (1-5)
<10	5
10-20	4
20-30	3
30-40	2
>40	1

6. Gas Losses (Weight: 10%)

Description:

This parameter considers the extent of gas leakage along the pipeline, which becomes more significant when hydrogen is blended due to its small molecular size and high diffusivity.

Rationale:

Hydrogen is more prone to leakage than methane, which can result in safety hazards, economic losses, and reduced environmental performance. Reducing gas loss is therefore a critical factor for successful hydrogen blending.

Table 14: Score Based on Gas Loss%

Gas Loss (Percentage)	Scoring	Practical Insights	Potential Causes
Less than 0.1%	5	Excellent performance; minimal leakage.	Properly maintained pipelines, effective seals, and good design[5].
0.1% - 0.4%	4	Very good performance; minor leakage acceptable.	Minimal corrosion, well-maintained fittings, and good operational practices.
0.4% - 0.6%	3	Acceptable performance; moderate leakage requiring attention.	Some corrosion, aging seals, or minor operational issues.
0.6% - 1%	2	Below average performance; significant leakage requiring immediate action.	Significant corrosion, damaged seals, poor maintenance, or operational negligence.
More than 1%	1	Poor performance; unacceptable leakage indicating severe issues and potential hazards.	Severe corrosion, major structural damage, significant operational negligence, or inadequate maintenance.

7. Class of the Location (Weight: 10%)

Description:

The location class assesses the level of human and infrastructure exposure in the event of a pipeline failure, focusing on High Consequence Areas (HCA). Field validation of location class may be required prior to pilot approval, especially in mixed-use zones where population density and land use may have changed since initial classification.

[5] *https://www.nature.com/articles/s44284-024-00178-7*

Rationale:

Areas with higher population density or sensitive infrastructure require stricter safety margins. The classification helps prioritize safety upgrades and monitoring in populated zones.[6]

Table 15: Score Based on Location

Class	Brief Description	Score
1	Rural areas with very low population density; minimal structures intended for human occupancy; Primarily agricultural or undeveloped land.	5
2	Suburban areas with moderate population density; scattered residences and small businesses; Mixture of residential, commercial, and agricultural land use.	3
3	Urban areas with high population density, numerous residences, businesses, and public facilities; Predominantly residential and commercial land use.	2
4	High-consequence areas (HCAs), areas near critical infrastructure (hospitals, schools) or sensitive environmental resources (water sources); critical infrastructure or environmental resources nearby.	1

Since pipeline sections may pass through various areas with vary in classes so to arrive at exact score, weighted average is required.

The weighted average score (S_{avg}) is:

$$(S_{avg}) = \frac{(L_1 \text{ x } 5) + (L_2 \text{ x } 3) + (L_3 \text{ x } 2) + (L_4 \text{ x } 1)}{x}$$

Where,

L1 = length (meters) in Class 1 (score 5)

L2 = length (meters) in Class 2 (score 3)

L3 = length (meters) in Class 3 (score 2)

L4 = length (meters) in Class 4 (score 1)

x=L1+L2+L3+L4= total length (meters)

8. Corrosion (Weight: 8%)

Description:

This parameter measures the rate of material degradation in the pipeline due to chemical interaction with transported gases or the external environment. Corrosion is typically expressed in millimeters per year (mm/year)[7].

Rationale:

Hydrogen can affect corrosion rates and accelerate material failure. Maintaining corrosion rates within acceptable limits is vital for long-term structural integrity.

Scoring Approach:

Corrosion evaluation is based on two equally weighted sub-parameters:

- Corrosion rate
- Residual thickness ratio

Table 16: Score Based on Corrosion

Corrosion Rate (mm/year)	Score (1-5)
0.1%-0.2%	**5**
0.2%-0.4%	**4**
0.4%-0.6%	**3**
0.6%-1%	**2**
More than 1%	**1**

[6] *https://puc.sd.gov/commission/PSOT/Presentation/classlocations.pdf*
[7] *https://www.hse.gov.uk/pubns/books/l82.htm*

Table 17: Score Based on Residual Thickness Ratio

Residual Thickness Ratio	Score	Rationale
Greater than 0.95	**5**	Excellent condition; minimal thickness loss, indicating high structural integrity and effective corrosion control.
0.90 to 0.95	**4**	Good condition: slight thickness loss, suggesting minor corrosion that requires monitoring and potentially minor maintenance.
0.80 to 0.90	**3**	Moderate condition; noticeable thickness loss, requiring more frequent inspections and potentially enhanced corrosion mitigation strategies to prevent further degradation.
0.70 to 0.80	**2**	Poor condition: significant thickness loss, indicating a need for immediate assessment and corrective actions to ensure structural integrity and prevent potential failures.
Less than 0.70	**1**	Severely degraded; substantial thickness loss indicating a need for immediate shutdown, comprehensive evaluation, and potential replacement of the affected section to prevent catastrophic failure.

Scoring is based on uniform thickness loss (general corrosion); pitting corrosion can be separately assessed where data is available.

9. Capacity Utilization and MAOP (Weight: 8%)

Description:

This parameter evaluates operational flexibility and safety margins based on pipeline pressure and unused capacity.

Rationale:

- Capacity Utilization: Pipelines operating below their maximum flow rate offer greater flexibility for introducing hydrogen.
- Operating Pressure vs. MAOP: Operating well below the Maximum Allowable Operating Pressure (MAOP) provides a safety margin, which is important since hydrogen increases internal stress.

Scoring is equally divided between:

- Reserve capacity
- Pressure buffer below MAOP

Table 18: Score Based on Capacity Utilization

Capacity Utilization (%)	Score
> 98.5%	1
96.5% - 98.5%	2
93% - 96.5%	3
90% - 93%	4
87%-90%	5
Operating Pressure (% of MAOP)	**Score**
> 90%	1
70% - 90%	2
50% - 70%	3
30% - 50%	4
< 30%	5

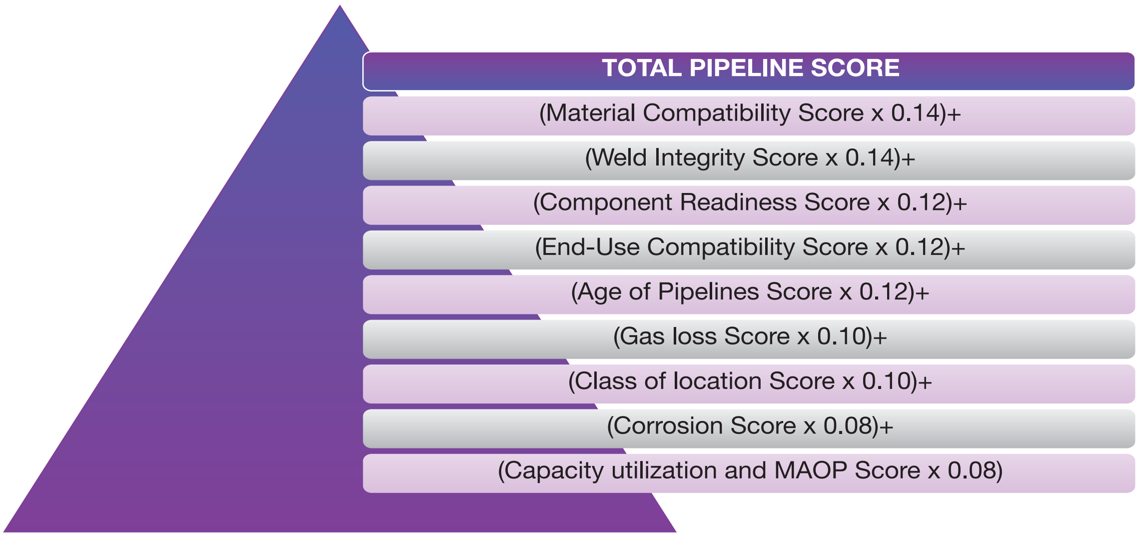
9-Parameter Screening Methodology

A weighted screening framework was developed to score pipeline segments on technical feasibility, blending safety, and operational reliability. Segments were divided into 1–5 km sections and scored using this matrix:

Table 19: 9 Parameter Score Methodology

Parameter	Weightage (%)	Rationale
Material Compatibility	14	Mitigates hydrogen embrittlement and cracking, ensuring structural longevity.
Weld Integrity	14	Prevents leaks by ensuring welds withstand hydrogen effects and operational pressures.
Component Readiness	12	Ensures existing components can be adapted without prohibitive costs or complex modifications.
End-Use Compatibility	12	Guarantees the hydrogen blend meets the specific requirements of downstream applications or equipment.
Age of Pipelines	12	Accounts for existing material degradation and potential for corrosion from long-term use.
Gas Losses	10	Minimizes fugitive emissions, maximizing economic efficiency and reducing environmental impact.
Class of the location	10	Reduces the impact of a release.
Corrosion	8	Preserves pipeline wall thickness and prevents failures.
Capacity Utilization & MAOP	8	Provides operational flexibility for blending and maintains a safe operating margin.

Once score of a pipeline section is finalized in each parameter, cumulative score of pipeline section is calculated. Illustration for pipeline score is shown below.



Suitability for blending is decided on the score obtained as per the table below.

Table 20: Evaluation Table

Total Pipeline Score	Rating	Action
≥4.50	Excellent	Blending without retro fitment may be possible
4.40-4.50	Good	Blending possible with minor retro fitment
Between 4.20-4.40	Fair	Moderate retro fitment Required before blending
Between 4.00-4.20	Marginal	Extensive Mitigation Required Before blending
<4.00	Poor	Rejection for blending

Note- It is hereby specified that a minimum score of 4 requirements must be met individually for each parameter, not merely as an overall average. Furthermore, individual blending limits shall be strictly respected during all blending operations.

Prioritized Pipeline Segments (Based on preliminary data)

Following initial evaluation of public and stakeholder-provided data, the following segments are recommended for pilot consideration:

For a few pipeline operators, namely GSPC, Torrent Power, GAIL, and DNP Limited, preliminary data was available, allowing for an initial analysis based on material grade and pipeline age. The assessment was conducted using threshold criteria of material grade X52 or lower and pipeline age of 10 years or less.

Based on this preliminary evaluation, it was observed that Torrent Power and DNP Limited primarily operate pipelines with material grade X65, which indicates limited compatibility for hydrogen blending under the defined thresholds. However, certain sections of pipelines operated by GAIL and GSPC were identified where both the material grade and age meet the specified criteria, suggesting potential feasibility for hydrogen blending in those segments.

Table 21: GSPC Pipeline Sections

S.NO.	Section Name	Pipeline size (Inch)	Pipeline Grade	Length(km)	Age of Pipeline as on 31-12-2024
1	Spurline Connectivity to China Steel	6	API 5L Gr X52	4.46	10
2	Sanand GIDC Connectivity	4 or 6 or 8 or 12	API 5L Gr X52	21.7	10
3	Dahej PCPIR Spur	6	API 5L Gr X52	8.76	8
4	IRM Connectivity	6	API 5L Gr X52	0.03	8
5	Indian Peroxite Connectivity	6	API 5L Gr X52	1.7	6
6	GACL Spurline Connectivity	6	API 5L Gr X52	1.9	4
7	Maruti Connectivity Pipeline	6	API 5L Gr X52	15.5	8
8	Chromeni Spurline	6 or 8	API 5L Gr X52	1.28	6

Table 22: GAIL Pipeline Sections

S.NO.	Grade	Material Compatibility (Preliminary screening)
1	API 5L Gr. B	No
2	API 5L Gr.X42	Yes
3	API 5L Gr.X52	Yes
4	API 5L Gr.X56	No
5	API 5L Gr.X60	No
6	API 5L Gr.X65	No
7	API 5L Gr.X70	No
8	API 5L Gr.X70 and X80	No

Recommendations

- PNGRB to operationalize the 9-parameter screening framework to assess pipeline readiness, ensuring a minimum score of 4 in each parameter

- A national Installed-Base Readiness Registry should be developed cataloguing compressors, valves, meters, and seals with OEM-certified hydrogen blend limits.

- Pipeline segments rated "Excellent" or "Good" should be prioritized for pilot blending without retrofitting, while "Fair" and "Marginal" segments should undergo targeted upgrades.

B.2 Regulatory Review

Hydrogen blending into existing natural gas networks introduces a paradigm shift in the regulatory and safety environment of the Indian energy sector. As of 2025, there is no comprehensive, hydrogen-specific regulation governing pipelines, distribution networks, safety devices, metering systems, or end-use appliances. This section outlines the current regulatory landscape, identifies major gaps, scope of work for regulatory partner and criteria to select partner.

MODULE AT A GLANCE

SCOPE

Close regulatory gaps for blending and pure H_2 pipelines; align with ASME/EN/ISO; prepare "Standards Map."

KEY RESULTS

GCR gaps for network-scale H_2; B31.12 phase-out post-2026; alignment to B31.3/B31.8; Safety Case templates; bid criteria for regulatory partner.

INTER MODULE LINKAGES

B3 (testbed results • code updates), B4 (Safety Case), B5 (Rulebook/Service Classes), B6 (H_2 codebook), B8 (ISO 14687/11120 for purity).

SNAPSHOT ITEMS

- Priority Gaps: SCADA linked safety, odorization for H_2, analyzer QA/QC, hydrogen ready meters, emergency isolation.
- Timeline: Standards Map (2026), T4S annex v1 (2028), annual updates.

Current Indian Context

Table 23: Current Indian Context

Institution / Regulation	Current Role / Jurisdiction	Limitations in Context of Hydrogen
1. Petroleum and Natural Gas Regulatory Board (PNGRB)	Regulates authorization and technical compliance of natural gas pipelines and CGD networks under the PNGRB Act, 2006. Oversees Technical Standards and Specifications including safety standards (T4S), covering: – Material grades – MAOP limits – Corrosion protection – Metering, odorization, and incident management	T4S developed primarily for methane: – Lack hydrogen embrittlement screening – No permissible blending ratios by material class – No specifications for chromatographic blending skids, flame arrestors, or hydrogen-specific leak-detection thresholds

Institution / Regulation	Current Role / Jurisdiction	Limitations in Context of Hydrogen
2. Petroleum and Explosives Safety Organization (PESO)	Enforces safety regulations for flammable gas storage and handling under the Explosives Act, 1884 and Gas Cylinder Rules, 2016. Oversees hydrogen cylinders in industrial use.	Does not cover: – Network-scale hydrogen blending – Hydrogen injection stations – SCADA-linked safety systems for gas grids
3. Gas Cylinder Rules (GCR) (under PESO)	Regulates fabrication, approval, and testing of gas cylinders including hydrogen.	Focused on captive hydrogen use only. Does not include: – Injection into public pipeline infrastructure – Blend station design – Sensor calibration – Online gas monitoring
4. Additional Institutional Overlaps	BIS standards (e.g., API 5L + ASME B31.8, IS 14885 for MDPE) exist for materials used in pipelines. Central Electricity Authority (CEA) and Ministry of Power (MoP) are addressing green hydrogen in RE integration.	BIS standards not developed for hydrogen: – Missing standards for sealant aging, fatigue behavior, and hydrogen permeation CEA and MoP lack coordination with MoPNG or PNGRB on gas blending No centralized framework for: – Hydrogen-ready meters – Odorant handling – Emergency isolation in mixed-gas networks

Table 24: Missing Links in Pure Hydrogen Standards

	Components	International Standards	Indian Standards	Gaps if any	Recommendations
TRANSPORTATION	Requirements for pipelines in gaseous hydrogen service	ASME B31.12 Hydrogen piping and pipelines	-	No IS	Adopt as it is or modify and adopt[8]
END USE	Requirements for piping in gaseous	ASME B31.12 Hydrogen piping and pipelines	-	No IS	Adopt as it is or modify and adopt[8]

While ASME B31.12 has been widely referenced, it is scheduled for withdrawal after 2026. India should therefore align its testing and qualification framework with the upcoming revisions of ASME B31.3 and ASME B31.8, which are expected to integrate hydrogen-specific provisions.

A consolidated "Map of Applicable Standards" should be prepared by PNGRB and BIS, identifying immediate adoptions and India-specific supplements. This should include ASME B31.8 (with ASME B31.12 to be phased out by 2026), a gas quality framework aligned to EN 16726 revisions (covering hydrogen content and Wobbe Index), and specifications for components, valves, and elastomers.

Review of GCR Rules and Identified Gaps and Limitations

The current Indian regulatory system is not adequately designed to address the material behaviour, system dynamics, or safety protocols required for hydrogen blending.

The Gas Cylinder Rules (GCR) have recently been updated to accommodate the growing relevance of hydrogen as a clean energy vector. While these updates represent a positive step toward incorporating hydrogen-specific considerations into the regulatory ecosystem, a comprehensive review reveals several critical gaps that warrant further attention. Below is a summary of key changes introduced, observed gaps, and a recommendation for a dedicated study to support regulatory strengthening

[8] *https://www.hse.gov.uk/pubns/books/l82.htm*

Key changes introduced

Table 25: Key Changes Introduced

Category	Details
1. Introduction of Hydrogen-Specific Definitions	Bulk Hydrogen Systems: Defined as systems with storage capacities exceeding 5,000 cubic feet, typically used in industrial applications and fueling stations. Green Hydrogen: Recognized as hydrogen produced via renewable sources (e.g., solar, wind) with carbon intensity ≤ 2 kg CO_2/kg H_2. Hydrogen Fuel Station Types: – Mother Stations: On-site production (e.g., solar-based electrolysis). – Daughter Stations: Supplied via mobile hydrogen transport. – Online Stations: Connected to hydrogen pipeline networks.
2. Enhanced Safety Provisions	Cylinders Tracking: Mandatory barcoding or RFID tagging; refilling of untagged cylinders prohibited. Electrical Safety: Compliance with IEC 60079 to prevent ignition hazards. Regular Testing: – Composite cylinders: Tested every 3 years. – Lifespan: 15 years (vehicular), 20 years (stationary).
3. Licensing Framework for Hydrogen Stations	Introduction of Form H License: – Requires risk assessments, ISO 14001-aligned emergency plans, and auto leak detectors. Entire licensing process must be conducted through a digital portal.
4. Adoption of Global Standards	ISO Standards (e.g., ISO 11623) adopted for equipment testing. NFPA-2 implemented for fire safety in hydrogen fueling stations (aligned with U.S. norms).

Identified Gaps in the Current Regulatory Framework

Table 26: Gaps in Current Framework

Gap	Issue	Recommendation
1. Undefined Penalties	No penalties for violations such as untagged cylinders.	Define punitive measures. Create a centralized compliance database.
2. Inadequate Worker Training Provisions	Training mandates apply only to testing personnel.	Make safety training mandatory for all hydrogen facility staff. Include modules on leak handling and emergency response.
3. No Real-Time Leak Detection Mandate	No requirement for 24x7 leak detection systems.	Mandate IoT-based sensors, auto shut-off valves, and continuous monitoring.
4. No Grievance Mechanism	No public/industry feedback platform post-rule implementation.	Create a multi-stakeholder review committee including regulators and industry.
5. No Guidance on Retrofitting Infrastructure	No technical protocols for adapting existing pipelines/assets.	Develop retrofit protocols covering – Material compatibility (embrittlement risks) – Pressure limits – Integrity testing – Preventive maintenance
6. Cybersecurity Gaps	No mention of cybersecurity safeguards in digital platforms.	Introduce norms to protect sensitive data and ensure system integrity.

Need for a Dedicated Regulatory Study

Table 27: Need for Study

Objective	Description
Clarify Regulatory Gaps	Identify missing provisions for pure hydrogen: pipeline codes, storage protocols, material standards.
Eliminate Overlaps	Harmonize or remove conflicting rules to simplify developer/operator compliance.
Align with Global Best Practices	Benchmark with ASME B31.12, ISO 19880 series, and NFPA 2.
Strengthen Safety Provisions	Establish enforceable safety standards across the hydrogen value chain.
Enable Technological Innovation	Streamline regulatory approvals for new hydrogen technologies.
Support National Hydrogen Goals	Ensure regulatory readiness for achieving the 2030 target of 5 MMT of green hydrogen production.

Conclusion and Recommendation

While the updated GCR rules mark important progress, the existing framework remains fragmented and lacks the depth needed to support large-scale hydrogen deployment. Therefore, it is strongly recommended that a dedicated regulatory study be undertaken in collaboration with a specialized regulatory partner. This initiative would serve as a foundation for drafting a comprehensive, future-ready hydrogen regulatory regime that is safe, streamlined, and globally aligned.

Ensure a Dedicated Team for Regulatory Standards: A committee to be constituted in the short term to begin drafting regulatory standards and safety protocols under PNGRB as well as revising existing ones set up by bodies such as PESO.

Responsibilities of this Committee could include:

- Draft Indian regulatory standards and safety protocols for hydrogen transportation and blending.
- Integrate global best practices with findings from Indian R&D and pilot studies to ensure **context-specific applicability.**

International Benchmarks for pure H_2 pipeline:

To establish a future-ready regulatory ecosystem for hydrogen blending and transmission, India must align its technical and safety frameworks with globally recognized standards. The following international codes and pilot examples provide relevant models for adaptation:

1. **ASME B31.12 – Hydrogen Piping and Pipelines[9]**
    - Comprehensive design code for hydrogen pipelines and components.
    - Covers material selection, fabrication, pressure classification, welding, and fracture control.
    - Provides stress intensification factors and leak prevention strategies specifically for hydrogen's small molecule behaviour.
2. **EIGA Guidelines (European Industrial Gases Association)[10]**
    - Provides practical safety and operational guidance on:
        - Hydrogen production and purification.
        - Bulk distribution, odorant handling, and pressure control.
        - Fire suppression systems and hazardous area classification.
    - Used extensively by EU regulators as a reference for national hydrogen codes.

[9] *ttps://www.asme.ozblications/eiga-documents/hydrogen/*
[10] *https://www.eiga.eu/publications/eiga-documents/hydrogen/*

Draft Evaluation Criteria and Scope of Work

India's transition to hydrogen-integrated gas networks requires an overhaul of its current regulatory frameworks. With the increasing relevance of hydrogen in India's energy transition, the role of a qualified regulatory partner becomes crucial to ensure that hydrogen infrastructure is developed in alignment with domestic regulations and international best practices. The selected regulatory partner must demonstrate deep domain knowledge, proven experience, and methodological rigor in areas such as flammable gas safety, pipeline standards, regulatory gap analysis, and testbed oversight.

Below table outlines the Pre-Qualification (PQ) Criteria that must be fulfilled by potential regulatory partners prior to their participation in the technical and financial evaluation stages.

Table 28: Pre-qualification Criteria

Criterion	Requirement	Verification Method	Consequence if Not Met
Research Publications	At least 3 peer-reviewed publications in reputable, indexed academic journals (e.g., Scopus, IEEE Xplore, Web of Science) within the past 5 years. Content Requirement: Publications must focus on topics related to flammable gas systems/petroleum and mineral pipelines (e.g., system safety design, gas leak detection, hazard analysis, or risk management).	Submit copies or reference numbers; evaluators verify via established databases.	Disqualification
Team Experience	Key technical personnel must have an average of at least 5 years of hands-on experience in flammable gas system/petroleum and mineral pipeline projects.	Detailed CVs, employment records, and project histories.	Disqualification
Domestic Regulatory Compliance	Completed 2 or more projects in India addressing flammable gas regulations/petroleum and mineral pipeline regulations with documented formal engagement (e.g., letters, workshop records) with agencies such as PESO, PNGRB, BIS etc.	Regulatory certificates, official letters, and joint reports.	Disqualification
International Standards	Completed 2 or more projects in India addressing international flammable gas regulations/petroleum and mineral pipeline regulations with documented formal engagement (e.g., letters, workshop records).	Regulatory certificates, official letters, and joint reports.	Disqualification
Regulatory Gap Analysis	Provide evidence of 1 significant project that includes a detailed gap analysis comparing local regulatory requirements with international best practices.	Detailed project reports with data comparisons and explanations.	Disqualification
Testing & Validation Oversight	Provide evidence of 1 major project. The focus is on how testbed data were reviewed and analyzed by qualified experts, resulting in practical, documented regulatory recommendations.	Process flowcharts, digital testbed logs, and detailed expert reports with recommendations.	Disqualification
Note- Only bidders who meet all the Pre-Qualification criteria will proceed to the Technical and Financial evaluations.			

Technical and Financial criterion

The evaluation is divided into two main categories: Technical Criteria (60 Marks Total) and Financial Criteria (40 Marks Total). The technical evaluation assesses expertise, experience, proposed methodology, and international regulation alignment, while the financial evaluation focuses on cost-effectiveness. The detailed criteria and awarded marks are presented below to ensure a transparent and structured selection process.

Technical Criteria Evaluation (60 Marks Total)

A. Expertise & Experience – 10 Marks Total

Research Publications (Max: 5 Marks)

The table for Research Publications evaluates the bidder's academic output relevant to the project. A rating of 0 indicates no relevant publications, while a rating of 5 is awarded for 5 or more high-impact publications demonstrating robust research leadership directly related to flammable gas systems. The marks awarded reflect the quality and relevance of the publications, ranging from 0 to 5 based on the number and impact of peer-reviewed works.

Table 29: Research Publication Score

Rating Level	Description	Marks Awarded
0	No relevant publications submitted.	0
1	1 publication in a lower-impact or non-indexed venue with minimal relevance.	1
2	2 publications in peer-reviewed venues with some relevance to flammable gas systems/petroleum and mineral pipeline.	2
3	3 publications with at least one in a reputable, indexed journal addressing topics like gas detection or risk analysis.	3
4	4 publications from reputable sources clearly addressing system safety or hazard analysis.	4
5	5 or more high-impact publications demonstrate robust research leadership and technical contributions directly related to flammable gas systems.	5

Team Experience (Max: 5 Marks)

The Team Experience table assesses the collective expertise of the bidder's team. A rating of 0 is given for teams with less than 3 years of average experience, while a rating of 5 is awarded for teams exceeding 10 years with recognized leadership and extensive hands-on expertise. The marks awarded, ranging from 0 to 5, reflect the depth and relevance of the team's project experience, particularly in flammable gas systems and pipelines.

Table 30: Team Experience Score

Rating Level	Description	Marks Awarded
0	Average team experience is below 3 years.	0
1	Average experience between 3–4 years with very limited project exposure.	1
2	Average experience between 5–6 years (meeting the minimum requirement).	2
3	Average experience between 7–8 years with documented involvement in significant flammable gas system projects//petroleum and mineral pipeline projects.	3
4	Average experience between 9–10 years with substantial and demonstrable contributions.	4
5	Average experience exceeds 10 years with recognized leadership and extensive hands-on expertise.	5

B. Proposed Methodology – 20 Marks Total

Regulatory Gap Analysis (Max: 5 Marks)

The Regulatory Gap Analysis table evaluates the bidder's ability to identify and address regulatory deficiencies. A rating of 0 is assigned if fewer than 5 gaps are identified without systematic analysis, while a rating of 5 is given for identifying 9 or more gaps with comprehensive root-cause analysis and benchmarking against 5+ international standards. The marks awarded, from 0 to 5, reflect the thoroughness and justification of the gap analysis.

Table 31: Regulatory gap analysis

Rating Level	Description	Marks Awarded
0	Identifies fewer than 5 regulatory gaps; lacks systematic data collection or benchmarking; analysis is absent.	**0**
1	Identifies 5 basic gaps using simple tools (e.g., spreadsheets) and benchmarks against 1 international standard with minimal justification.	**1**
2	Identifies 6 gaps with brief justifications; benchmarks against 2 international standards; presents a basic database.	**2**
3	Identifies 7 gaps with incident-based evidence; benchmarks against 3 international standards; uses a validated analytical approach.	**3**
4	Identifies 8 gaps with integrated risk assessments and detailed justifications; proposes realistic adaptations; uses automated data tools for analysis.	**4**
5	Excellently identifies 9 or more gaps through comprehensive root-cause analysis; benchmarks against 5+ international standards; provides clear, actionable proposals.	**5**

Testing & Validation Oversight (Max: 5 Marks)

The Testing & Validation Oversight table measures the bidder's approach to analyzing testbed data and converting it into regulatory recommendations. A rating of 0 indicates no evidence of analysis, while a rating of 5 is awarded for a comprehensive analysis validated by subject-matter experts. The marks awarded, ranging from 0 to 5, assess the depth and practicality of the recommendations.

Table 32: Testing and oversight score

Rating Level	Description	Marks Awarded
0	No evidence of any analysis of testbed data or conversion into regulatory recommendations.	0
1	Provides a very basic review of testbed data with minimal commentary; regulatory recommendations are cursory and incomplete.	1
2	Presents a documented analysis of testbed data using manual review; provides preliminary, but not detailed, regulatory recommendations.	2
3	Provides a detailed manual analysis of testbed data, linking specific test results to practical regulatory recommendations with supporting explanations.	3
4	Offers an integrated analysis report where testbed data is thoroughly reviewed by experts and converted into detailed, practicable proposals for regulatory change.	4
5	Demonstrates an exceptional approach in which comprehensive testbed data are manually analyzed and synthesized into robust, actionable regulatory outcomes that have been validated by subject-matter experts.	5

Stakeholder Engagement (Max: 10 Marks)

The Stakeholder Engagement table evaluates the bidder's strategy for involving stakeholders. A rating of 0 is given for minimal engagement, while a rating of 5 is awarded for engaging 7 or more stake-holders with advanced techniques and fully documented workshops. The marks awarded, from 0 to 10, reflect the breadth and effectiveness of the engagement process.

Table 33: Stakeholder Engagement Score

Rating Level	Description	Marks Awarded
0	Identifies fewer than 3 stakeholders; no structured feedback mechanism; engagement strategy is absent.	**0**
1	Identifies 3 stakeholders (e.g., local industry representatives or regulatory bodies), conducts a basic survey (≈5 questions) and holds 1 introductory workshop.	**2**
2	Identifies 4 stakeholders (e.g., adds local fire departments); uses simple surveys with email feedback; holds 2 workshops with basic agendas.	**4**
3	Identifies 5 stakeholders (e.g., including environmental groups); conducts structured interviews (10+ questions) and holds 3 well-documented workshops with clear agendas.	**6**
4	Identifies 6 stakeholders (e.g., including academic experts); uses focus groups and online forums; holds 4 workshops with detailed documentation of feedback and follow-up actions.	**8**
5	Identifies 7 or more key stakeholders (e.g., including community representatives); employs advanced engagement techniques (e.g., Delphi method, role-playing simulations); conducts 5+ fully documented workshops with published minutes.	**10**

C. International Regulation Alignment – 30 Marks Total

Regulation Review, Changes & Improvement (Max: 30 Marks)

The Regulation Review, Changes & Improvement table assesses the bidder's experience and contribution to regulatory development. A rating of 0 indicates no involvement, while a rating of 6 is awarded for exceptional leadership with internationally adopted reforms. The marks awarded, ranging from 0 to 30, reflect the bidder's depth of engagement and impact on regulatory frameworks.

Table 34: Regulation Review Score

Rating Level	Description	Marks Awarded
0	No evidence of any regulatory review, recommendations, or involvement in regulatory development.	0
1	Minimal acknowledgment of international standards with only a cursory review; references one standard (e.g., ISO) without substantial proposals or participation in regulatory processes.	5
2	Some documented evidence of reviewing current regulations and providing limited initial proposals for improvement; minimal participation in regulatory workshops.	10
3	Adequate demonstration of active participation in regulatory review processes, including a comparative analysis of current Indian regulations versus international best practices, with clearly documented recommendations for improvement.	15
4	Extensive experience in regulatory review and active contribution to proposing regulatory changes; the bidder has participated in multiple development committees and submitted well-documented proposals for improvement, aligned with global best practices.	20
5	Outstanding performance with a strong track record in regulatory reform; the bidder is recognized by industry or regulatory bodies for significantly improving the national regulatory framework through proactive proposals and policy development.	25
6	Exceptional, industry-leading performance in regulatory review and development; the bidder has driven major amendments or reforms, provided comprehensive proposals that have been adopted, with international recognition as a regulatory leader.	30

Financial Criteria Evaluation (40 Marks Total)

The Financial Criteria table outlines the scoring methodology based on bid cost. The formula calculates the financial score as (Lowest Bid / Bidder's Bid) × 40, where the lowest bid receives the full 40 marks, and others are scaled proportionally. Bidders must provide a detailed cost breakdown (labor, travel, equipment, etc.) to ensure transparency and fairness in the evaluation.

Table 35: Financial Criteria

Component	Description
Formula:	Financial Score = (Lowest Bid / Bidder's Bid) × 40
Guidelines:	Bidders must submit a detailed cost breakdown (labor, travel, equipment, etc.). The bid with the lowest overall cost receives the full 40 marks; all other bids are scaled up proportionally.

Scope of work

Table A: Detailed Scope of Work

Table 36: Scope of Work

Section	Description
1. Introduction and Objectives	• Conduct a comprehensive regulatory assessment for India's hydrogen value chain. • Analyze Indian acts, rules, guidelines, standards, and codes for hydrogen production, storage, transport, and safety. • Identify gaps, overlaps, and benchmark with international best practices. • Oversee technical validation of testbed and pilot project data to generate evidence-based regulatory insights • Develop actionable proposals through amendment or creation of new instruments to support safe and efficient hydrogen deployment.
2. Scope of Work (Activities)	All tasks shall be implemented under a unified framework for end-to-end delivery of assessments and proposals.
2.1 Comprehensive Regulatory Analysis and Benchmarking	• Identify all relevant Indian regulatory instruments for hydrogen. • Categorize them by hydrogen value chain segments: production, storage, transport, and end-use. • Review each regulation for scope, enforcement, and practical utility. • Conduct a regulatory gap and overlap analysis. • Benchmark Indian framework against standards from Germany, Australia, Canada, Japan, USA, UK, and South Korea.
2.2 Oversight of Testbed and Pilot Project Data	• Review hydrogen testbed and pilot data covering safety, durability, material compatibility, and performance. Perform expert manual analysis of results. Translate insights into regulatory proposals by identifying deficiencies in existing codes or standards.
2.3 Development of Regulatory Recommendations and Stakeholder Engagement	• Draft proposals for amendments or new regulatory instruments based on analysis and test data. • Prioritize regulatory actions by their safety, innovation, and efficiency impact. • Engage stakeholders: ministries, regulatory bodies, industry, R&D institutions, and PSUs. • Integrate stakeholder feedback into final proposals. • Address critical focus areas such as: – Modernizing safety standards. – Single-window clearance for hydrogen projects.

Table B: Deliverables

Table 37: Deliverables

Category	Deliverables
1. Regulatory Analysis Deliverables	• *Regulatory Inventory Report:* All Indian acts, rules, codes, and standards relevant to hydrogen. • *Regulatory Review Report:* Details on scope, enforcement, and limitations of each regulatory tool. • *Gap Analysis and Benchmarking Report:* Highlights inconsistencies in India's regulatory framework and compares with international benchmarks (e.g., ASME B31.12, ISO, NFPA).
2. Testbed Data Analysis Deliverables	• *Test Data Analysis Report:* Expert interpretation of testbed and pilot data related to safety, performance, and durability. • *Regulatory Outcome Report:* Explains how test insights informed proposed regulatory updates.
3. Regulatory Recommendation and Development Deliverables	• *Draft Regulatory Proposals:* Amendments or new regulations with rationale, benefits, and international references. • *Prioritization and Implementation Roadmap:* Sequenced, time-bound action plan. • *Stakeholder Consultation Summary:* Details of all engagements (e.g., meetings, surveys), and incorporation of inputs into final recommendations.
4. Final Integrated Report	• *Final Comprehensive Report:* Consolidated output covering findings, regulatory gaps, benchmarking, testbed interpretation, proposals, feedback, and roadmap.

Recommendations

- Based on the identified regulatory gaps, PNGRB may initiate a dedicated plan to address hydrogen-specific codes, with particular focus on the Gas Cylinder Rules and the T4S framework.

- A Hydrogen Regulatory Cell should be constituted within PNGRB to oversee certification, safety standards, and inter-agency coordination.

- PNGRB should lead the development of a "Map of Applicable Standards" integrating ASME B31.12, EN 16726, and ISO 19880-1, tailored to Indian conditions.

B.3 Testbed

MODULE AT A GLANCE

SCOPE

National facility to validate materials, elastomers, welds, metrology, odorization, safety/dispersion, flow dynamics under H_2 blends.

KEY RESULTS

Minimum test matrix including SSRT, KIH, FCGR, permeation, HAZ toughness, elastomer suites, meter bias, WI stability. EPC-led consortium; annual State of Hydrogen Readiness report.

INTER MODULE LINKAGES

Calibrates B2 standards; de-risks B4 pilots; informs B6 designs; HCI for B7; selection criteria for B8; training for B9.

SNAPSHOT ITEMS

Loop designs for NGPL/CGD; analyzer uptime ≥98%; weld testing emphasis; compressor/turbine derates; odorant performance.

Test Facility-Broad Overview

A hydrogen blending testbed is a controlled experimental setup used to simulate and study the real-world implications of injecting hydrogen into natural gas infrastructure. It enables rigorous assessment of the physical, chemical, and operational challenges associated with hydrogen blends, especially under pressure and flow conditions that mimic actual transmission and distribution systems.

A National Hydrogen Pipeline & Blending Testbed should be launched from Q4-2025, anchored by a consortium of technical institutes and industry participants. The testbed should evaluate Indian steel grades (API 5L X42–X70), coatings, weld procedures, elastomer and seal families, and the pressure/temperature envelopes representative of CGD systems. Findings should be consolidated in an annual **State of Hydrogen Readiness Report.**

Purpose

- To analyze the performance of key natural gas infrastructure components when subjected to hydrogen blends.
- To verify safety, reliability, and material behavior under hydrogen-induced conditions.
- To support policy, design, and engineering standards with empirical data and scientific evidence.

Aims

- **Assess Material Compatibility:** Evaluate the effects of hydrogen on metallic and non-metallic materials (pipes, valves, compressors, etc.).

- **Evaluate Safety and Integrity:** Study leakage behavior, crack growth, and failure points under hydrogen exposure.
- **Optimize Equipment Performance:** Test whether current gas systems and metering equipment remain functional without modifications.

Intended Outcomes

- **Validation of Hydrogen Blending:** Establish technical viability of hydrogen integration in gas pipelines.
- **Infrastructure Adaptation:** Identify required upgrades in existing infrastructure for hydrogen readiness.
- **Regulatory Compliance Support:** Provide a data-backed foundation for policy formulation and revision.

Facility Configuration and Layout

The facility integrates a range of systems and subsystems required to perform in-depth testing of hydrogen-natural gas mixtures. These systems have been carefully selected to mimic actual pipeline and distribution conditions while ensuring safety and flexibility. Also, for test beds, multiple scenarios need to build up for various types of pipelines and infrastructure.

Key Components Include:

- **Hydrogen Production Units:** Small electrolyzers are installed to generate hydrogen on-site using renewable electricity. In addition, hydrogen can be supplied via external tube trailers and cascade systems.
- **Hydrogen Storage:** Storage is managed through high-pressure cascades and tube trailers, capable of storing hydrogen at pressures of 90 to 100 bar.
- **Piping and Fittings:** Piping systems, pipe spools, and fittings are constructed from materials tested for hydrogen compatibility. These connect various zones within the facility and allow controlled flow.
- **PRS and Valves:** A pressure reduction skid regulates hydrogen pressure for downstream testing. Ball, gate, check, and control valves are integrated to manage gas flow and simulate operational control.
- **Instrumentation:** Flow meters and pressure sensors are strategically placed to continuously monitor gas flow and system pressure. Hydrogen detectors ensure rapid identification of any leaks.
- **Ratio Controllers:** These devices regulate the hydrogen-to-natural gas blend ratio, enabling testing under different blending percentages.
- **Safety Systems:** Flame arrestors, leak detection units, and pressure relief valves are installed to meet high safety standards.
- **Data Acquisition Systems:** A central data control system records and analyzes data in real-time, ensuring reliable performance monitoring and immediate detection of anomalies.
- **Test Loops:** Two distinct loops are created, one simulating a high-pressure natural gas transmission pipeline and the other representing a lower-pressure distribution system.
- **Testing Laboratory:** A dedicated space for conducting preliminary mechanical and chemical analyses using equipment such as tensile, delta and fatigue testers.

The testbed will include testing of metallic and non-metallic components such as flanges, gaskets, valve seats, PRS assemblies, and safety devices under hydrogen exposure. Intrusive inspection tools such as MFL, EMAT, and UT ILI will be explored for weld and corrosion validation.

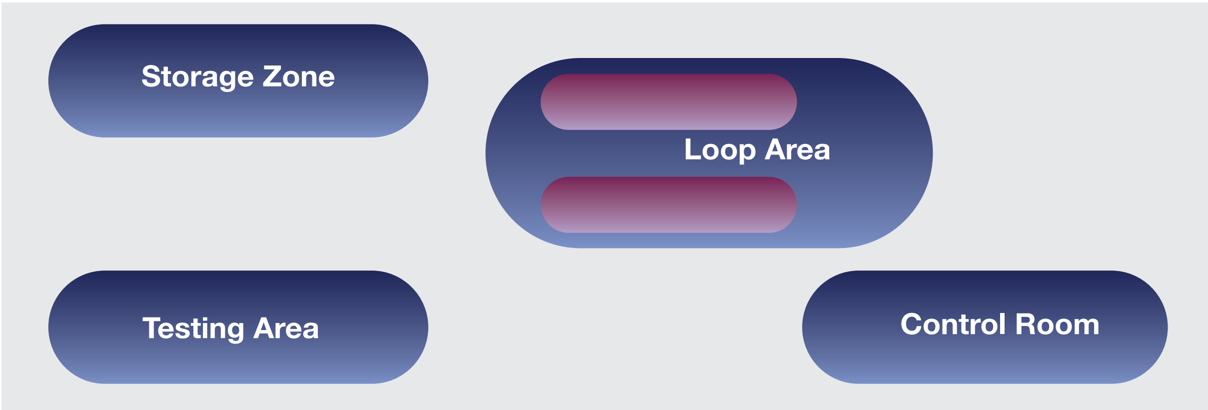
The testbed is laid out in functional zones to separate and streamline different operations:

- **Storage Zone:** This area is equipped with tube trailers and cascades for storing both hydrogen and natural gas safely. Gas sources are kept in secure enclosures to avoid cross-contamination and ensure operational flexibility.

- **Loop Area:** This section includes test loops constructed from hydrogen-compatible piping, valves, and fittings. Each loop is used to simulate hydrogen blending at various concentrations, testing mechanical resilience and flow behavior.
- **Testing Area:** Equipped with machines like tensile testers and fatigue testers, this area performs key material strength tests under hydrogen influence.
- **Control Room:** A centralized location from where all test operations is monitored and controlled. Data from sensors and equipment are visualized and analyzed here.

Note: Final loop design may be tailored based on site-specific conditions and the testing matrix required for each project.

Proposed layout has been shown below.



Types of Testing: Mechanical, Leakage, Flow Dynamics

A comprehensive suite of mechanical, safety, and flow-related tests is carried out to generate a complete dataset on hydrogen blending impact:

Table 38: Mechanical Testing

S.No.	Type of Test	Purpose	Objectives
1	**Tensile Testing**	Measure tensile strength and ductility of materials in hydrogen environments.	Assess if hydrogen exposure affects the tensile properties.
2	**Fatigue Testing**	Evaluate durability under cyclical loading.	Determine if hydrogen accelerates fatigue damage or reduces fatigue life.
3	**Crack Growth Testing**	Study crack propagation under hydrogen influence.	Understand hydrogen's role in accelerating crack growth.
4	**Toughness Testing (e.g., Izod Impact Test)**	Measure resistance to sudden impact or shock loading.	Identify if hydrogen reduces impact toughness.
5	**Hardness Testing**	Determine changes in material hardness after hydrogen exposure.	Assess material's resistance to wear and deformation.

Table 39: Leakage Testing

S.No.	Type of Test	Purpose	Objectives
1	**Material Permeation Testing**	Determine the extent to which hydrogen permeates through solid materials.	Assess potential material risks to the transmission system.
2	**Flange Testing**	Ensure that flanges continue to contain gas after transitioning to hydrogen.	Validate the suitability of seals for hydrogen service.

Table 40: Safety Testing

S.No.	Type of Test	Purpose	Objectives
1	**Explosion Risk and Fire Safety Testing**	Understand how hydrogen blends behave under fire or explosion conditions.	Ensure pipeline safety by understanding risks.
2	**Flammability Limits Testing**	Determine the concentration limits within which hydrogen blends are flammable.	Maintain safety during pipeline operations.
3	**Rupture Testing**	Assess risks associated with pipeline ruptures.	Incorporate findings into overall risk models.

For compressors and turbines, practical limitations must be recognized. International experience shows a typical blend cap of ~5% H_2 for many legacy compressors before requiring re-wheel or re-seal. In India, GAIL has reported successful turbine co-firing with 2–5% H_2 blends. As a forward action, all NGPL and CGD operators should catalogue OEM-stated admissibility levels for hydrogen blends in their installed compressors and turbines, to form the basis of phased integration planning.

Table 41: Flow Dynamics Testing

S.No.	Type of Test	Purpose	Objectives
1	**Flow Dynamics Simulations**	Test how hydrogen blends flow through pipeline systems and the resulting pressure losses.	Understand flow behavior and pressure dynamics.

Note- Apart from these tests, other tests e.g., Homogeneity testing of H_2-NG mixture, **impact of odorant** must also be tested.

A minimum test matrix for hydrogen service qualification should be adopted, consistent with international practice and upcoming ASME B31.3/B31.8 provisions. Recommended tests include:

- Slow Strain Rate Testing (SSRT) in high-pressure hydrogen environments;
- Fracture toughness threshold (K_IH) evaluation;
- Fatigue crack growth rate in H_2;
- Permeation studies;
- Slow cyclic loading assessments;
- Elastomer compatibility tests covering EPDM, NBR, FKM, and PTFE

Notably, IIT observations indicate a 30–35% drop in material toughness under slow strain testing. This underscores the importance of SSRT and threshold toughness evaluations, as conventional tensile tests may yield false negatives in detecting hydrogen embrittlement risk

Welding remains the critical node in hydrogen service, as highlighted by stakeholder inputs (e.g., Welspun). Pilot projects and future regulations should therefore mandate:

- Heat-Affected Zone (HAZ) toughness testing under representative blend pressures;
- Hydrogen cracking resistance tests for weldments;
- Procedure Qualification Records (PQRs) specifically qualified for H_2 service conditions.

An **installed-base readiness registry** should be established, cataloguing compressors, meters, regulators, valves, and seals. OEMs should verify blend admissibility classes (≤5%, ≤10%, ≤20%) and identify required modifications. This registry will provide operators with a transparent reference when designing and scaling pilots.

Global Studies Referred

The testbed design and methodology are informed by the following global benchmark studies:

1. **Future Grid Phase-1:** Conducted tests at 2%, 5%, and 10% hydrogen blending. Results showed no notable changes in performance, noise, leakage, or mechanical integrity. Even at 10%, the equipment functioned normally.
2. **TransHyDE (GET H_2):** Focused on hydrogen pipeline transport in Germany. Key outcomes included validation of leak detection methods, compressor design, and feasibility of long-distance hydrogen transport.
3. **H_2-20 DVGW:** Evaluated up to 20% hydrogen blending in domestic gas grids. Results confirmed that most household appliances functioned safely. The study supported updating Germany's hydrogen blending regulations.

DNV Study

Table 42: Results of DNV Study[11]

S.NO.	Blending %	Major Results
1	**2%**	• Testing showed minimal deviation from the 100% natural gas baseline. • Mechanical assets operated without changes. • No significant changes in noise or vibration levels. • No detectable hydrogen permeation through the pipelines.
2	**5%**	• Aligned with EU decarbonized gas package requirements. • Similar findings to 2% blend with no significant operational changes compared to natural gas baseline. • Mechanical assets operated without changes. • No changes in sealing integrity for isolation ball valves and other components.
3	**20%**	• Considered the limit of hydrogen blending without affecting gas supply. • No significant changes in operational performance or mechanical assets behavior. • Accurate gas analysis maintained throughout the testing period. • No noticeable differences in flow rates measured by the meters. • No significant changes in noise or vibration levels emitted during venting operations.
4	**100% (Pure Hydrogen)**	• Critical for assessing interaction with existing assets for future hydrogen infrastructure. • All mechanical assets continued to function and control gas flows around the facility. • Shorter operations of gas chromatographs provided accurate hydrogen content measurement; longer operations faced sample failures. • Temperature change through pressure reduction was measured to be as modelled, removing the requirement for pre-heat. • Noise levels increased during venting operations, but vibration impacts were minimal. • Hydrogen flux testing showed no detectable permeation through the pipelines.

[11]https://www.nationalgas.com/sites/default/files/documents/FutureGrid%20Phase%201%20Closure%20Report%20July%202024.pdf

Other Studies

Table 43: Comparative Analysis[12][13]

Aspect	TransHyDE (GET H_2)	H_2-20 DVGW
Lead Organization	Consortium including RWE, OGE, DVGW Research Center at KIT, Nowega, Rosen, Evonik, University of Potsdam	DVGW (German Technical and Scientific Association for Gas and Water), Avacon, E. ON, research partners
Funding	German Federal Ministry of Education and Research (BMBF), approx. €11.63 million	Industry and DVGW funded
Major Objectives	– Develop and operate a test environment for hydrogen transport pipelines – Measure hydrogen quality and quantity – Test material compatibility with hydrogen – Develop leak detection and pipeline inspection methods – Optimize compressor concepts for hydrogen transport	– Inject up to 20% hydrogen by volume into an existing gas distribution grid – Test appliance and infrastructure safety and compatibility – Collect operational and user data under real conditions – Develop recommendations for hydrogen blending in gas grids and update technical rules
What Was Done	– Established a demonstration test pipeline at RWE power plant site in Lingen – Conducted metrological and material testing – Developed remote hydrogen leak detection and intelligent pigging – Validated compressor and transport concepts under real conditions	– Conducted field tests injecting 20% hydrogen blend into a distribution grid serving ~400 customers – Monitored appliance performance and safety – Gathered user behavior data – Developed guidelines for hydrogen blending in gas grids
Key Conclusions	– Demonstrated feasibility of long-distance hydrogen pipelines – Validated measurement and safety technologies – Provided data supporting future hydrogen infrastructure rollout in Germany	– Confirmed safe operation of most domestic gas appliances with up to 20% hydrogen blend – Established groundwork for regulatory updates and broader hydrogen blending – Showed existing grids can accommodate hydrogen blending with minimal modifications
Project Duration	Started ~2020, ongoing with results expected by 2025	Field tests completed by 2022-2023, ongoing integration into standards
Strategic Importance	Lays foundation for Germany's hydrogen backbone pipeline infrastructure enabling large-scale hydrogen transport	Supports Germany's energy transition by enabling hydrogen blending in existing gas distribution networks

Models for setting up testbed and scope of work and evaluation criteria for selecting testbed partner

Various implementation models are considered:

- **Single-Firm Model:** One vendor manages construction and O&M, partnering with a research institution for scientific guidance.
- **Multi-Party Model:** Different entities handle construction, O&M, and testing separately.
- **Industry Collaboration:** Involves cooperation among multiple gas PSUs and PNGRB.
- **EPC Turnkey Model:** A full-scope EPC contractor manages everything from design to operation, in collaboration with academia.

Preferred Model: Collaborative Approach — This allows shared technical responsibility, academic insight, and long-term sustainability of operations.

Table below shows the comparison of various models.

[12] *https://www.get-h2.de/en/geth2-transhyde/*
[13] *https://www.dvgw.de/themen/forschung-und-innovation/forschungsprojekte/dvgw-forschungsprojekt-h2-20*

Table 44: Comparison of Various Models

S.NO.	Parameters	Single Firm Setup	Multiple Parties Setup	Industry Collaborations	EPC Turnkey
1	**Description**	One Firm is responsible for both construction and O&M. (need to partner with a research institution)	Different entities handle construction, O&M, and test conduction.	Multiple Gas PSUs collaborate with PNGRB to set up and manage the testbed.	An EPC turnkey contractor handles the entire setup, including construction and initial O&M, partners with a research institution.
2	**Construction**	Firm	Firm 1	Firm (Joint funding from all PSUs)	Firm
3	**O&M**	Firm	Firm 2	PSUs	Firm
4	**Tests and Results**	Research Institution/Firm	Research Institution/Firm 1 or 2	Research Institutions/PSUs	Research Institution (Partnered with Firm)

However, preferred set-up is shown in the table below.

Table 45: Finalized Model

Stage	Lead / Model	Objective / Description
Project Planning & Design	EPC Contractor	Define scope, technical specifications, and project requirements
Construction	EPC Contractor	Responsible for engineering, procurement, construction, and commissioning of testbed
Commissioning	EPC Contractor	Build and deliver fully functional testbed, ready for operational use
Performing tests	PSU / Stakeholders	Testbed handed over, ready for testing and validation and carrying out the testing.
Result dissemination	PSU / Stakeholders	Joint testing, data analysis, and dissemination of results

The estimated costing for the testbed setup has been shared with PNGRB for their reference and further decision-making.

Scope of work

Table 46: Testbed Set-up Scope

Section	Details
Overall Objective	Establish a state-of-the-art hydrogen testbed for evaluating hydrogen production, storage, compression, transport, and utilization technologies. The facility will validate blending of hydrogen with natural gas and assess safety, leakage, and performance under realistic conditions.
Zonal Layout	The testbed will be developed in four major zones: **Production and Compression Zone Storage Zone Testing Area Loop Simulation Area**
Production and Compression Zone	• **Hydrogen Production:** On-site electrolyzers powered by renewable energy. • **Alternative Supply:** Provision for hydrogen supply via tube trailers or cascade systems. • Compression: High-pressure hydrogen compressors (up to 70 bar), equipped with variable speed drives and safety interlocks for feeding hydrogen into storage and simulation systems.
Storage Zone	• High-pressure storage tanks or cryogenic units compliant with ASME standards. • Integrated with pressure monitoring, venting, and isolation valves to prevent over-pressurization or leakage.

Section	Details
Testing Area	**Mechanical Testing:** – Tensile Testing Machines – LCF/HCF Autoclaves **Leakage Testing:** – Material Permeation Testers – High-Pressure Flange Test Benches **Safety Testing:** – Burst Test Rigs – Explosion Chambers **Flow & Pressure Testing:** – Flow loops with pressure sensors to simulate pipeline conditions
Loop Simulation Area	● Replicates CGD and high-pressure transmission pipeline systems. Equipped with standard pipes, valves, fittings, flow meters, pressure transducers, and control valves. Simulates actual field conditions to monitor the impact of hydrogen on pressure stability and flow behavior.
Installation Requirements & Vendor Responsibilities	● **Site Preparation:** Foundation, utility connections (electricity, water, gas), and safety compliance. ● **Equipment Installation:** In accordance with OEM standards for all devices. ● **Calibration & Interlocks:** All instruments calibrated, and safety systems validated. ● **Documentation:** Submission of HAZOP studies and FAT reports.
Training & Capacity Building	● **Operational Training:** Practical training for operating all equipment, including troubleshooting. ● **Safety Training:** Emergency handling, shutdown procedures, gas venting, and leak management. ● **Data Training:** SCADA/DCS training for real-time monitoring, alarm handling, and data logging.

Draft Bidder Evaluation Criteria

Table 47: Financial Criteria for Bidder Qualification[14]

Parameter	Requirement (Single Bidder)	Requirement (Joint Venture)	Remarks
Bank Solvency	≥ 40% of total project cost	Lead Partner: ≥ 20% Other JV Partners: ≥ 10%	Demonstrates liquidity and financial health
Annual Turnover (Average of last 3 years)	≥ 30% of project cost	Lead Partner: ≥ 15% Other JV Partners: ≥ 7.5%	Ensures bidders have adequate business scale
Net Worth Erosion	≤ 30% erosion over the past 3 years	≤ 30% erosion over the past 3 years	Prevents selection of financially declining firms

Table 48: Technical Criteria for Bidder Qualification

Parameter	Requirement	Remarks
Similar Work Experience	Must have completed: – 3 projects of ≥ 40% of project cost each OR– 2 projects of ≥ 60% each OR– 1 project of ≥ 80% of project cost	Validates project execution experience and scale
Hydrogen Sector Capabilities	Experience in hydrogen infrastructure including: – Testbed construction– Lab fabrication– Commissioning– Component testing	Sector-specific technical competency
Laboratory Design & Execution	Experience in lab design for hydrogen/high-pressure systems, with focus on: – Safety compliance– ASME/ISO adherence– Automated data systems	Critical for safe and advanced testing operations
Performance Records	Submission of: – Completion certificates– Quality audit reports– Client performance ratings	Used for assessing execution quality and reliability

[14] https://drdo.gov.in/drdo/sites/default/files/procurement-manuals-document/PM-2020.pdf

Table 49: Evaluation and Scoring System

Category	Sub-Criteria	Marks
Financial Capability (Total: 30 Marks)	Bank Solvency – 10 Marks Turnover – 10 Marks Net Worth Stability – 10 Marks	30
Technical Capability (Total: 70 Marks)	Similar Work Experience – 30 Marks Sector-Specific Capabilities (Hydrogen, Labs, Project Execution) – 40 Marks	70
Total Score	**100**	
Qualification Requirement	Bidders must secure qualifying marks in both Financial and Technical sections	To be considered for final selection

A Minimum Test Program should be established to generate India-specific data for hydrogen blending. The program should include:

- **Materials & welds:** SSRT in high-pressure H_2 (varied fugacity's), J–R curves/CTOD, K_IH threshold testing, fatigue crack growth in H_2, permeation rates, weld HAZ toughness, PWHT variables, and coating disbondment under H_2 exposure.
- **Elastomers & polymers:** Compatibility testing (permeation, swelling, embrittlement) for EPDM, NBR, FKM, PTFE, and PA11/12 used in meters, regulators, and seals.
- **Equipment performance:** Compressor surge maps with H_2 blends, seal leakage, bearing loads; turbine derates; meter bias vs. blend composition; PRV/regulator dynamic response.
- **Gas quality & combustion:** Wobbe stability across blend ramps, flame speed effects in typical domestic burners and IC engines, NOx emission measurements, and appliance interchangeability windows aligned with gas quality specifications.

Recommendations

- PNGRB should facilitate a national hydrogen testbed for transmission pipeline with modular zones for testing, and loop simulation, anchored by an EPC-led consortium.

- The testbed must also include a dedicated testing and research facility to conduct India-specific studies on material compatibility, safety, and performance of gas infrastructure under hydrogen service.

- A minimum test program should be established covering: SSRT in high-pressure H_2, K_IH threshold testing, fatigue crack growth, permeation rates, weld HAZ toughness, coating disbondment, elastomer compatibility (EPDM, NBR, FKM, PTFE), compressor surge maps, turbine derates, meter bias, and PRV/regulator response.

- Annual "State of Hydrogen Readiness" reports should be published based on testbed findings to inform regulatory updates and pilot planning.

B.4 Pilot Project

MODULE AT A GLANCE

SCOPE

Validate feasibility/safety/metrology in CGD (MDPE) and NGPL (steel) pilots; Safety Case–based operations; time-bound with explicit exit.

KEY RESULTS

Acceptance criteria for MDPE/steel; energy-based billing; stop rules; live dashboards; monthly reporting.

INTER MODULE LINKAGES

B1 screens; B2 Safety Case; B3 test references; B5 Rulebook; B7 appliance testing; B8 deblending at purity nodes.

SNAPSHOT ITEMS

Ramp ≤1%/hr; hold points (2%,3%,5%); analyzer redundancy; leak survey cadence; Odor QA; KPIs: ≥95% uptime, zero Tier-2/3 incidents, fair billing

Pilot Project General Scope

This section outlines the general scope, technical activities, risk evaluations, and performance expectations associated with pilot-scale hydrogen blending into existing natural gas pipelines. The scope of the report is applicable for both ongoing and upcoming pilot initiatives intended to evaluate compatibility, safety, operational reliability, and environmental impact.

Project Intent

Objective

To validate the technical feasibility, operational safety, and material compatibility of blending hydrogen (H_2) into natural gas (NG) pipelines across both transmission and distribution systems.

Key Goals

- Assess the compatibility of pipelines, valves, fittings, and appliances with hydrogen exposure.
- Evaluate critical risks such as leakage, stratification, flammability, and fatigue.
- Ensure full compliance with international standards such as ASME, ISO, ASTM, and NACE.

Details of Technical Assessments

Material Compatibility Testing

Material behavior under hydrogen service will be evaluated using the following test methods:

- Tensile Testing
- Hydrogen Embrittlement (HE) Testing
- Impact Testing
- Fatigue Testing
- Hydrogen-Induced Cracking (HIC) Assessment
- Polymer Testing

Table 51: Various Types of Mechanical Testing

Test Type	Purpose	Standard
Tensile Testing	Measure ultimate tensile strength (UTS) and ductility (Reduction of Area (RA%), elongation).	ASTM E8/E8M (Standard Test Methods for Tension Testing of Metallic Materials)
Fatigue Testing	Assess crack initiation/propagation under cyclic pressure stress.	ASTM E466 (Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests).
Hydrogen Embrittlement (HE)	Measure susceptibility to hydrogen-assisted cracking.	NACE TM0284 (Evaluation of Pipeline and Pressure Vessel Steels for Resistance to Hydrogen-Induced Cracking)
Hydrogen-Induced Cracking (HIC)	Detect subsurface cracks in steel.	NACE TM0284 (Method A)
Impact Testing	Assess fracture toughness under H_2 exposure.	ASTM E23 (Standard Test Methods for Notched Bar Impact Testing).
Polymer Testing	Measure H_2 diffusion through PE.	ISO 15105-1 (Plastics – Film and Sheeting – Determination of Gas Transmission Rate).

Non-Destructive Testing (NDT)

To ensure structural soundness and detect flaws, the following NDT techniques will be applied:

- Phased Array Ultrasonic Testing (PAUT)
- Ultrasonic Thickness (UT) Gauging
- Magnetic Particle Inspection (MPI)
- Radiographic Testing (RT)
- Visual Inspection

Table 52: NDT Tests

Test Type	Purpose	Standard
Phased Array Ultrasonic Testing (PAUT)	Identify cracks in welds/bends.	ASME Boiler and Pressure Vessel Code (BPVC) Section V (Non-Destructive Examination).
Ultrasonic Thickness (UT) Gauging	Monitor wall thinning due to corrosion/erosion.	ASME B31.12 (Hydrogen Piping and Pipelines).
Magnetic Particle Inspection (MPI)	Detect surface cracks in steel.	ASTM E709 (Standard Guide for Magnetic Particle Testing).
Radiographic Testing (RT)	Assess internal defects (porosity, inclusions).	ASME BPVC Section V.
Visual Inspection	Check for corrosion, weld integrity, and surface defects.	ASME B31.12.

Gas Behavior and Quality Monitoring

- Stratification/Segregation Analysis to assess uniform mixing of hydrogen in gas flow.
- Odorant Testing to evaluate the detectability of leaks post-hydrogen blending.
- Pilot design will include stratification and homogeneity testing under static and no-flow conditions, especially in vertical risers.

Table 53: Gas Behaviour Analysis

Test Type	Purpose	Standard
Stratification/Segregation Analysis	Validate uniform mixing of H_2 and NG.	Any relevant standard.
Odorant Testing	Ensure detectability of odorants in H_2 blends.	ASTM D6273-20.

Metering and regulation systems are also impacted by hydrogen blending. Composition and density variations alter meter error curves across turbine, rotary, diaphragm, and ultrasonic meters. It is therefore recommended that a metering impact assessment be included in all pilot projects. Additionally, pilot billing systems should deploy on-site energy conversion (CVCF-based correction) to ensure consumer fairness when calorific value fluctuates. Blended gas quality will comply with Appendix-II of the Petroleum and Natural Gas Regulatory Board (Authorizing Entities to Lay, Build, Operate or Expand Natural Gas Pipelines) Regulations, 2008, which define permissible limits for key components such as H_2S, CO_2, moisture, total sulfur, and calorific value. These parameters ensure safe operation, appliance compatibility, and regulatory compliance across CGD networks.

Risk Assessment

- **Purpose:** To identify and mitigate potential operational and safety risks associated with hydrogen blending.
- **Key Risk Areas**
  - Leakage Risk
  - Flammability Risk

Table 54: Risk Assessment

Test Type	Purpose	Standard
Leakage Risk	Identify H_2 diffusion through seals/flanges.	ISO 20485:2017 (techniques for leak detection using a tracer gas).
Flammability Risk	Ensure safe operation within H_2's flammability range (4–75% vol).	ISO 10156

Environmental and Consumer Impact

Key Activities

- Quantify **CO_2 reduction** from partial substitution of natural gas with hydrogen.
- Perform **appliance testing** to ensure end-use safety and functional compatibility.
- Analyze energy economics and appliance efficiency at blended hydrogen concentrations.

Table 55: Environmental and Consumer Impact Testing

Test/Assessment Type	Purpose	Standard
Co_2 Reduction	Quantify carbon emission reductions.	ISO 14044 (Life Cycle Assessment).
Appliance Testing	Residential: Validate flame stability and emissions	EU Eco-design Directive 2009/125/EC.
	Industrial: Ensure optimal turbine combustion efficiency.	CSA 6.26 (Combustion Performance of Gas-Fired Appliances).

To ensure fairness in consumer transactions during pilot operations, all pilot projects should adopt energy-based billing (₹/kWh or MJ) in place of volumetric billing (₹/SCM). This adjustment is necessary since hydrogen blending alters the calorific value per unit volume of the gas mixture. Incorporating energy-based billing will maintain consistency between energy delivered and consumer charges, thereby safeguarding consumer interests during pilot evaluations.

Commercial & Consumer Protection Measures should be embedded in pilot design to safeguard end-users. These include:

- **Energy-based billing:** Pilot bills to show energy units (kWh/MJ), with monthly average LHV and Wobbe Index published alongside the applied hydrogen blend percentage.
- **Price-cap guardrail:** If volumetric billing continues during transition, a compensation factor should be applied to reflect measured energy dilution relative to reference natural gas.
- **Metering & measurement code:** Update to require traceable CV/Wobbe measurement (e.g., gas chromatograph or equivalent) and verification of meter accuracy across composition ranges.

Safety and Regulatory Compliance

Focus Areas

- Adherence to national safety protocols and industry best practices.
- Establishment of **emergency procedures** and incident reporting mechanisms.
- Compliance monitoring against PNGRB guidelines and international hydrogen standards.

Table 56: Safety Compliance

Test Type	Purpose	Standard
Emergency Protocols	Identification of leaks	NFPA 2.
Incident Reporting	Document leaks, equipment failures, and near-misses.	OSHA 29 CFR 1910.119 (Process Safety Management).

Odorants and leak detection protocols require adaptation for hydrogen service. Compatibility checks should be carried out for conventional odorants such as tetrahydrothiophene (THT) and mercaptans, alongside evaluation of hydrogen-ready odorization options. To address hydrogen's higher diffusivity and lower ignition energy, pilot project safety cases should mandate portable H_2 sensors and enhanced leak survey frequency within pilot zones.

Each pilot project should operate under an approved Safety Case, incorporating hazard identification, MAOP review, venting and odorization arrangements, emergency response, public communication, training, leak detection planning, and change management. These Safety Cases should be reviewed and cleared by the PNGRB Safety and Scientific Committees.

Training and Capacity Building

Purpose

To develop technical and operational competencies among personnel responsible for hydrogen operations.

Activities

- Conduct hands-on and theoretical training on hydrogen properties, blending techniques, and safety protocols.
- Familiarize operational teams with testing methods and emergency response mechanisms.

Table 57: Training Requirements

Training Group	Purpose	Standard
Technical Staff	Train on H_2 safety, NDT methods, and leak response.	CGA H_2-1 (Hydrogen Safety Training Program).
First Responders	Conduct H_2 fire suppression and evacuation drills.	NFPA 2.

Reporting and Deliverables

A. Monthly Reports (To PNGRB)

- Hydrogen concentration data (by % volume).
- Leak log and resolution records.
- NDT and inspection results.
- Key performance indicators (e.g., leak count, downtime, blend ratio).

B. Final Technical Dossier

- Summary of all material test results (tensile, fatigue, HE/HIC, impact).
- Consolidated risk assessment and mitigation report.
- Environmental impact data (CO_2 reduction, appliance compatibility).

A CGD Demonstration (with Exit)

The CGD demonstration projects are designed to validate the feasibility and safety of hydrogen blending under real-world conditions in city gas distribution networks. These pilots focus on MDPE pipelines and end-use appliances.

Evaluation Areas:

- **Material Compatibility and Permeability:** Permeation testing, polymer degradation analysis, tensile testing.
- **Non-Destructive Testing (NDT):** Visual inspection, ultrasonic testing, and other suitable methods.
- **Safety and Risk Assessment:** Evaluation of leakage, flammability, stratification, and odorant response.
- **Gas Quality Monitoring:** Assessment using the Wobbe Index.
- **Environmental and Consumer Impact:** Quantification of CO_2 reduction and compatibility testing of appliances.

Table 58: Satisfaction Criterion: MDPE Pipelines

Category	Test/Assessment Type	Purpose	Standard
Material Compatibility and permeability	Tensile Testing	Evaluate ultimate tensile strength and ductility to ensure material integrity after hydrogen exposure.	ASTM E8/E8M
	Hydrogen Embrittlement (HE)	Assess susceptibility to hydrogen-assisted cracking, ensuring material withstands hydrogen exposure without degradation.	NACE TM0284
	Hydrogen-Induced Cracking (HIC)	Detect subsurface cracks in steel, focusing on identifying critical flaws that could lead to failure.	NACE TM0284
	Impact Testing	Evaluate fracture toughness under hydrogen exposure to ensure the material absorbs energy without fracturing.	ASTM E23
	Fatigue Testing	Assess crack initiation and propagation under cyclic pressure stress, ensuring endurance under operational loading.	ASTM E466
	Hardness Testing	Monitor for significant hardness changes to detect potential embrittlement or degradation.	ASTM E92
Non-Destructive Testing (NDT)	Phased Array Ultrasonic Testing (PAUT)	Identify cracks ≥2 mm in welds and bends.	ASME BPVC Section V
	Ultrasonic Thickness (UT) Gauging	Monitor wall thinning due to corrosion/erosion to maintain pipeline integrity.	ASME B31.12
	Magnetic Particle Inspection (MPI)	Detect surface cracks in steel to ensure safety of the pipeline.	ASTM E709
	Radiographic Testing (RT)	Assess internal defects such as porosity and inclusions.	ASME BPVC Section V

Category	Test/Assessment Type	Purpose	Standard
Safety and Risk Assessment	Leakage Risk	Identify H_2 diffusion through seals/flanges, ensuring effective sealing mechanisms are in place.	ISO 20485:2017
	Flammability Risk	Ensure safe operation within H_2's flammability range (4–75% vol), implementing safety measures to prevent ignition.	Any relevant standard
	Stratification Risk	Monitor for potential stratification of hydrogen within the pipeline system, ensuring uniform gas distribution.	Not specified
	Odorant Effectiveness	Ensure detectability of odorants in hydrogen blends, ensuring current odorants remain effective in blended gas.	ASTM D6273-20.
Gas Quality Analysis	Wobbe Index Monitoring	Maintain combustion stability for end-user appliances by ensuring gas quality remains suitable.	EN 16726
Environmental and Consumer Impact	CO_2 Reduction	Quantify carbon emission reductions through life cycle assessments, demonstrating environmental benefits.	ISO 14044
	Appliance Testing	Validate flame stability and emissions (NOx ≤40 mg/kWh) to ensure consumer safety.	EU Eco-design Directive
Note: All steel pipeline-associated components including fittings, valves, and appliances shall undergo integrated testing as per the general project scope. Additional corrosion analysis, re-testing, and advanced NDT methods may be deployed where necessary.			

Reporting and Deliverables

- Live monitoring dashboards for operational and consumer safety.
- Technical reports on appliance compatibility and consumer impact.
- Final assessment with recommendations for operational integration or exit.

Timeline

- 12-24 months: Site prep, installation, injection, monitoring, reporting, and explicit exit/transition to operations.

Exit Strategy

CGD demonstration pilots are to be strictly time-bound, with a defined period for data collection and evaluation. Upon achieving the pilot's objectives, such as validation of safety, compatibility, and operational protocols, the pilot should transition to regular operations or be scaled up, based on regulatory review and stakeholder consensus. The exit plan should include a final technical report, lessons learned, and recommendations for operational integration or further scale-up.

B Transmission Pilots

The transmission pilot projects are designed to validate the technical feasibility, operational safety, and material compatibility of hydrogen in natural gas transmission pipelines (NGPL). These pilots focus on steel pipelines (API 5L X42–X52, <10 years old).

Satisfaction Criteria for Steel Pipelines

Evaluation Areas:

- Material Compatibility: Tensile, impact, fatigue, hardness, HE, and HIC tests.
- Non-Destructive Testing (NDT): PAUT, UT gauging, MPI, RT.

- Safety and Risk Assessment: Leakage, flammability, stratification risks, odorant testing.
- Gas Quality: Continuous Wobbe Index monitoring.
- Environmental and Consumer Impact: Appliance testing and CO_2 reduction evaluation.

Table 59: Satisfaction Criteria for Steel Pipelines

Category	Test/Assessment Type	Purpose	Standard
Material Compatibility	Tensile Testing	Evaluate ultimate tensile strength and ductility to ensure material integrity after hydrogen exposure.	ASTM E8/E8M
	Hydrogen Embrittlement (HE)	Assess susceptibility to hydrogen-assisted cracking, ensuring material withstands hydrogen exposure without degradation.	NACE TM0284
	Hydrogen-Induced Cracking (HIC)	Detect subsurface cracks in steel, focusing on identifying critical flaws that could lead to failure.	NACE TM0284
	Impact Testing	Evaluate fracture toughness under hydrogen exposure to ensure the material absorbs energy without fracturing.	ASTM E23
	Fatigue Testing	Assess crack initiation and propagation under cyclic pressure stress, ensuring endurance under operational loading.	ASTM E466
	Hardness Testing	Monitor for significant hardness changes to detect potential embrittlement or degradation.	ASTM E92
Non-Destructive Testing (NDT)	Phased Array Ultrasonic Testing (PAUT)	Identify cracks ≥2 mm in welds and bends.	ASME BPVC Section V
	Ultrasonic Thickness (UT) Gauging	Monitor wall thinning due to corrosion/erosion to maintain pipeline integrity.	ASME B31.12
	Magnetic Particle Inspection (MPI)	Detect surface cracks in steel to ensure safety of the pipeline.	ASTM E709
	Radiographic Testing (RT)	Assess internal defects such as porosity and inclusions.	ASME BPVC Section V
Safety and Risk Assessment	Leakage Risk	Identify H_2 diffusion through seals/flanges, ensuring effective sealing mechanisms are in place.	ISO 20485:2017
	Flammability Risk	Ensure safe operation within H_2's flammability range (4–75% vol), implementing safety measures to prevent ignition.	Any relevant standard
	Stratification Risk	Monitor for potential stratification of hydrogen within the pipeline system, ensuring uniform gas distribution.	Not specified
	Odorant Effectiveness	Ensure detectability of odorants in hydrogen blends, ensuring current odorants remain effective in blended gas.	ASTM D6273-20.

Category	Test/Assessment Type	Purpose	Standard
Gas Quality Analysis	Wobbe Index Monitoring	Maintain combustion stability for end-user appliances by ensuring gas quality remains suitable.	EN 16726
Environmental and Consumer Impact	CO_2 Reduction	Quantify carbon emission reductions through life cycle assessments, demonstrating environmental benefits.	ISO 14044
	Appliance Testing	Validate flame stability and emissions (NOx ≤40 mg/kWh) to ensure consumer safety.	EU Eco-design Directive
Note: All steel pipeline-associated components including fittings, valves, and appliances shall undergo integrated testing as per the general project scope. Additional corrosion analysis, re-testing, and advanced NDT methods may be deployed where necessary.			

International pilots, notably the UK HyDeploy program, have demonstrated technical feasibility of hydrogen blending up to 20% H_2 by volume under controlled conditions, while also highlighting unresolved challenges around whole-system deployment and energy billing. For India, it was agreed during stakeholder discussions that blending should be limited to 5% H_2 by volume, in line with current PNGRB permissions. This cap should not be increased until specifically allowed by PNGRB. The 20% threshold is therefore noted only as an international benchmark.

Blending should be treated as a transitional decarbonization lever, with limited abatement potential. It should not be conflated with 100% hydrogen conversion, which requires segregated networks and appliance changeout, as demonstrated in the H100 Fife project.

Reporting and Deliverables

- Monthly technical reports to PNGRB (hydrogen concentration, leak logs, NDT results, KPIs).
- Final technical dossier with all test results and risk assessments.

Timeline

- 24-30 months: Feasibility, installation, injection, monitoring, reporting.

Indian Pilot Timelines

Project Duration: 9 to 12 months (divided into phases)

- **Phase 1 (Month 0–2):** Feasibility study, approvals, procurement planning
- **Phase 2 (Month 3–5):** Site prep, installation, and initial dry run
- **Phase 3 (Month 6–8):** Hydrogen injection, monitoring, and adjustment
- **Phase 4 (Month 9–12):** Reporting, debrief, and regulatory consultation

Progress reviews will be conducted bi-monthly with PNGRB and stakeholder representatives.

Deliverables from Pilot Cycle

- Live Monitoring Dashboards
- Mid-term and Final Technical Reports
- Updated Safety and Operating Protocols
- Cost-Benefit Learning Brief for Future Pilots
- Regulatory Whitepaper with Empirical Input

This pilot will serve as a national reference case, informing the development of India's hydrogen blending standards, operational readiness index, and future tariff frameworks.

Recommendations

- **Installed Safety Case:** Each pilot should operate under an approved Safety Case, including hazard identification, MAOP review, venting, odorization, emergency response, public communication, and change management.

- **Technical Testing Matrix:** PNGRB should require a minimum test program covering tensile, fatigue, HE/HIC, impact, polymer/permeation, PAUT, UT gauging, MPI, RT, stratification analysis, and odorant effectiveness.

- Energy-based billing (₹/kWh or MJ) should be adopted for pilot consumers to ensure fairness and transparency in hydrogen-blended gas transactions

- Pilot projects should target a minimum of 95% operational uptime with zero safety incidents, with an endeavour to link SCADA-based tracking and advanced leak detection systems.

B.5 Blending Framework

MODULE AT A GLANCE

SCOPE

Operational Rulebook + Service Classes ; tariff and finance mechanisms (tariff clause; HIF; optional cess).

KEY RESULTS

BG-class definitions; mandatory energy-based billing; analyzer QA/QC; audit checklists; tariff estimate for 5–10% blends.

INTER MODULE LINKAGES

B2 code annexes; B4 pilot KPIs feed rules; B7 HCI thresholds; B9 H2RegNet data schema.

SNAPSHOT ITEMS

A Governance: Operator-in-charge + Hydrogen Competent Person(certified); leak survey frequency by class; change control (MOC) requirements; cybersecurity guardrails.

B Financial Framework: Indicative blending tariffs (₹0.39–0.48/SCM); Hydrogen Innovation Fund (PAT, CSR, VGF, MDB); separate hydrogen tariff clause; Pipeline Tariff Cess proposal; funding for testbed, pilots, and appliance retrofits

A Operational Rulebook & Service Class

Purpose

- Establish uniform operating practices for hydrogen-natural gas blending across NGPL and CGD.
- Align with PNGRB's T4S updates, PESO GCR amendments, the Map of Applicable Standards (ASME B31.8 with hydrogen annexes, transitional use of ASME B31.12/EIGA guidance), EN 16726 gas quality alignment, and ISO 14687/ISO 11120 at hydrogen take-offs/deblending.

Scope and applicability

- Applies to: transmission (NGPL) and distribution (CGD) pipelines, blending stations, deblending stations, PRSs/PRSOs, metering assets, odorization systems, and connected end-use equipment within PNGRB-authorized systems.
- Out of scope: standalone, non-grid hydrogen users unless directly connected to a PNGRB-authorized pipeline.

Definitions (for clarity and consistent use across SOPs)

- Blended Gas: Natural gas containing hydrogen within an approved service class.
- Service Class: A PNGRB-approved operating envelope defining allowable H_2 vol%, prerequisites, metrology, safety, billing, and reporting.
- Safety Case: A PNGRB-reviewed document that demonstrates risks are understood and controlled for a defined pilot/operating zone.

- H2RegNet: PNGRB's digital portal for hydrogen data, approvals, monitoring, and incident reporting.

Service Classes (BG = Blended Gas)

- BG-1 (≤2% H_2 vol): Low-risk introductory operation.
  - Typical use: Early CGD zones, preliminary NGPL pilots; minimal asset changes; metrology check; volumetric billing allowed with compensation factor or shift to energy-based billing.
- BG-2 (≤5% H_2 vol): Early-scale pilots and narrow operational rollout.
  - Typical use: PNGRB-permitted cap; requires Safety Case approval; energy-based billing recommended; minimum instrumentation per this Rulebook.
- BG-3 (≤10% H_2 vol): Extended pilots/operations in qualified systems.
  - Typical use: Post-testbed evidence; OEM certifications catalogued; energy-based billing required; deblending guidance in place where purity-critical offshoots exist.
- BG-4 (≤20% H_2 vol): Advanced operation where pilots, testbed evidence, and end-use compatibility allow.
  - Typical use: Limited domains with certified appliance cohorts, enhanced safety and metrology; regulator-specific approvals; robust deblending scheme.

Note: All Service Class upgrades are subject to PNGRB Hydrogen Cell clearance, satisfying the 9-parameter screening minimum (≥4/5 per parameter) and end-use compatibility evidence. PNGRB retains the right to set lower caps for specific corridors or customers.

Quality and metrology requirements

- Gas quality envelope
  - Shall comply with PNGRB Appendix-II specifications and EN 16726 alignment for blended service; PNGRB Hydrogen Cell to publish hydrogen-specific annex (e.g., allowable H_2 range per class, Wobbe band maintenance method, max O_2/H_2O for integrity, odorant type/dose, and analyzer QA/QC).
  - Deblending and hydrogen off-takes: align end-use hydrogen purity to ISO 14687; reinjected NG stream residual H_2 <2% unless otherwise permitted by PNGRB.
- Measurement and billing
  - Energy-based billing:
    - ► Mandatory from BG-2 upward (recommended also for BG-1).
    - ► Implement CVCF-based correction using on-site gas composition analysis (GC or equivalent). Publish monthly average LHV, Wobbe Index, and applied conversion factors on bills.
  - Metering:
    - ► Class-specific meter verification across composition bands (turbine, diaphragm, rotary, ultrasonic).
    - ► Analyzer performance: daily auto-cal checks, monthly multi-point validation; retention of calibration records in H2RegNet.

Organizational roles and competencies

- Operator-in-charge: Single accountable person per zone responsible for Safety Case, SOP adherence, and reporting.
- Hydrogen Competent Person (HCP): Certified under the National Hydrogen Training Framework (NHTF) for hydrogen properties, hazards, metrology, and emergency response.
- Third-party inspectors: PNGRB empanelled for pre-commissioning and annual audits.
- Cybersecurity steward: Ensures SCADA/telemetry hardening for blend control, per PNGRB cybersecurity advisories.

Lifecycle SOPs (mandatory)

1. Planning and approval

- Run the 9-parameter screening (material, welds, components, end-use, age, gas loss, location class, corrosion, capacity/MAOP) and meet the ≥4/5 threshold on every parameter.
- Prepare a Safety Case:
  - Hazard ID (HAZID/HAZOP), consequence modeling (dispersion/ignition), MAOP review, blending control logic, purge/vent plans, odorization, ESD and blowdown, public communication, and emergency response.
- End-use mapping: catalogue critical/sensitive customers (hospitals, food/pharma) and apply tailored limits or deblending.
- Approvals: submit Safety Case + readiness checklist to PNGRB Hydrogen Cell through H2RegNet.

2. Pre-injection readiness

- Mechanical integrity:
  - NDT sampling per plan (PAUT/UT/MPI/RT where applicable); weld hardness mapping where at risk; CP system health verification; leak survey baseline.
- Instrumentation & controls:
  - GC/analyzers, blend ratio controllers, PRV/regulators, odorizer, H_2 detectors, ESD blocks; complete loop checks and FAT/SAT documentation.
- OEM admissibility registry:
  - Compressors, turbines, valves, seals, meters: record OEM blend limits (≤5%, ≤10%, ≤20%) and any derates/conditions.
- Purge and inerting plan:
  - Nitrogen purge sequences, chromatographic validation before first hydrogen.
- Training and drills:
  - Operators and first responders trained; conduct a simulated emergency drill; record learnings in H2RegNet.
- Consumer communication:
  - Issue public notice for pilot zone; set up helpline; share energy-billing explainer.

3. Injection and normal operations

- Start-up:
  - Ramp rates: ≤1% H_2 vol change per hour (or PNGRB-approved rate); hold points at 2%, 3%, 5% for checks.
  - Homogeneity checks at risers/low-flow legs; stratification assessments in dead-legs/verticals.
- Controls and limits:
  - Automatic clamps: halt blend increase on any out-of-band reading: WI band drift, analyzer failure, odorant low-flow, leak alarm, PRV chatter, compressor surge warning, or ESD trip.
- Routine surveillance:
  - Leak surveys increased frequency (BG-1: quarterly; BG-2: bi-monthly; BG-3/4: monthly or as PNGRB directs).
  - Odorization QA: daily dose verification and weekly odor intensity tests.
  - Metering QA: monthly bias check per meter class vs. composition.
- Data:
  - Stream to H2RegNet: hourly composition, LHV/WI, pressure/flow, alarms, odorant dose, leak logs, downtime; structured per PNGRB data schema.

4. Maintenance and integrity management

- Integrity:
  - Annual integrity review: CP data, wall loss trends, girth-weld indications, coating holidays; targeted ILI (MFL/UT/EMAT) on risk segments.

- Components:
  - Elastomer/seal change-out intervals set by BG class; odorizer maintenance; regulator/PRV stroke tests quarterly.
- Calibration:
  - Analyzer calibration per OEM; inter-lab proficiency once a year; backup analyzer availability.

5. Emergency response and incident management

- Classify incidents (Tier 1 minor leak; Tier 2 controlled release; Tier 3 significant release/ignition).
- Immediate actions:
  - Isolate via ESD, depressurize/blowdown as per Safety Case, muster and cordon; notify authorities/PNGRB within mandated timelines (e.g., Tier 3 within 1 hour).
- Investigation:
  - Root cause analysis; corrective and preventive actions; restart only after PNGRB clearance for Tier 2/3.
- Public communications:
  - Incident advisories; resolution summary posted on H2RegNet and operator website.

6. Change management (MOC)

- Required for: blend percentage change, equipment change, control logic or analyzer swap, odorant change, or significant operating envelope changes.
- Documented risk review and PNGRB notification; approval required for Service Class upgrade.

Audit checklists (excerpts)

- Pre-commissioning (sample)
  - 9-parameter screen ≥4/5 in each parameter; evidence uploaded.
  - Approved Safety Case; emergency drill completed; public notice issued.
  - Analyzer FAT/SAT; dual-power/UPS for critical instruments; cybersecurity review passed.
  - Odorizer performance test; PRV/regulator response test; nitrogen purging plan and records.
  - OEM admissibility registry complete for compressors, valves, meters.
- Operations (sample)
  - Hourly data streaming to H2RegNet; alarms reviewed daily; deviations actioned within SLA.
  - Leak survey completion within class-based frequency; repairs closed with verification.
  - Energy-based billing implemented (BG-2+); monthly published LHV/WI values.
  - Consumer complaints logged and resolved; end-use site audits for sensitive customers.
- Safety and incidents (sample)
  - Detector maintenance/calibration records; ESD test records; Tiered incident reporting on time.
  - CAPA closure rate >95% within due dates; lessons-learned integrated into SOPs.
- Metrology (sample)
  - Meter bias checks completed; analyzer drift within limits; calibration certificates valid.
  - Wobbe/LHV traceability to standards; reference gas certificates current.

Reporting and KPIs

- Monthly to PNGRB via H2RegNet
  - Blend % time series; LHV/WI; alarm/ESD events; leak count and MTTD/MTTR; analyzer uptime (%); odorizer uptime; metering deviations; consumer safety complaints; downtime and availability; CO_2 abatement estimate.
- Annual State of Hydrogen Readiness — India (testbed-led)

- Consolidate field and lab findings; recommend standards updates; update Service Class annexes.

- Core KPIs
  - Safety: TRIR; Tier-2/3 incidents; emergency response time.
  - Integrity: leaks per km; corrosion growth rates; weld indications trend.
  - Metrology: analyzer uptime >98%; meter error within class limits.
  - Customer: complaint closure time; billing accuracy; outage minutes.
  - Availability: ≥95% system uptime for pilots.

Data and cybersecurity

- Secure telemetry to H2RegNet; role-based access; tamper-evident logs; annual cyber audit per PNGRB advisory; backup data retention ≥5 years.

Document control

- Controlled distribution of SOPs; versioning; 24/7 access for control room; archival per PNGRB retention norms.

B Tariff and Finance Mechanism

To support large-scale hydrogen blending into India's gas infrastructure, a comprehensive financial framework has been developed. This framework incorporates various financing mechanism to obtain funding for testbed and pilots.

Analysis of overseas countries

This report provides an updated overview of the financing sources and programs dedicated to advancing hydrogen technology and infrastructure across four key countries: the United States, the United Kingdom, Germany, and Australia. These investments support research, development, and deployment of clean hydrogen solutions to meet environmental and industrial goals, with a focus on public funding, public-private partnerships (PPPs), and green bonds.

Table 60 : USA Funding Overview [15]

Category	Details
Total Investment	\$21.81 billion (DOE + State Programs)
Key Programs	H_2Hubs Program: \$7 billion – Regional clean hydrogen hubs for production, delivery, and use
	Hydrogen & Fuel Cell Technologies Office (HFTO): \$0.43 billion – Supports R&D and deployment of hydrogen technologies
	Clean Hydrogen Electrolysis Program: \$1 billion – Target to reduce cost to \$2/kg H_2 by 2026
	California ARCHES Program: \$11.2 billion (DOE + private funds) – Largest hydrogen corridor; aims to reduce emissions by 2 MMTPA and create 220,000 jobs
Public-Private Partnerships (PPPs)	$MACH_2$ Hub (Mid-Atlantic): \$3.62 billion – Delaware, New Jersey, Pennsylvania; 600,000 tons/year hydrogen production for renewable and industrial decarbonization
	HyVelocity (Gulf Coast): \$1.2 billion – DOE + ExxonMobil; supports blue and green hydrogen for industrial use and export
Green Bonds	Air Products: \$1.34 billion – Supports blue and green hydrogen production; targets 1.5 GW electrolyzer capacity by 2027
	Plug Power: \$1.6 billion (2023) – Expands green hydrogen infrastructure; plans to set up 500+ hydrogen stations by 2025

[15] *https://www.hydrogen.energy.gov/library/funding-opportunities*

Table 61: UK Funding Overview [16]

Category	Details
Total Investment	$3.25 billion
Key Programs	Green Hydrogen Subsidy Program: €3.2 billion – Supports renewable hydrogen production facilities
Key Programs	Net Zero Hydrogen Fund: €0.244 billion – Supports low-carbon hydrogen capacity across the UK
Key Programs	University of Glasgow Hydrogen Innovation Centre: €0.00133 billion – Green hydrogen PoC to prototype facility
Public-Private Partnerships (PPPs)	HyNet Project (Northwest England): €3 billion – 5,000 construction jobs, 1,000 permanent jobs; low-carbon hydrogen + CCUS
Public-Private Partnerships (PPPs)	East Coast Cluster: €1+ billion – 50% decarbonization of UK industrial emissions by 2030 with offshore wind integration
Green Bonds	BP: €700 million – Blue and green hydrogen; 1 GW target capacity by 2030
Green Bonds	ScottishPower: €500 million – Offshore wind-based green hydrogen for industry and transport

Table 62: Germany Funding Overview [17]

Category	Details
Total Investment	€10.5 billion under National Hydrogen Strategy
Key Programs	IPCEI Hydrogen Program: €7 billion – Large-scale EU hydrogen projects with German leadership
Key Programs	H_2Global Foundation: €3.5 billion – Supports domestic hydrogen production and imports through auctions and subsidies
Public-Private Partnerships (PPPs)	GET H_2 Project (Lower Saxony): €1.2 billion – Hydrogen network for industrial use; 300,000 tons/year
Public-Private Partnerships (PPPs)	NOW (Norddeutscher Wasserstoff-Verbund): €0.8 billion – Green hydrogen for northern Germany industrial clusters
Green Bonds	Siemens Energy: €600 million – Electrolyzer manufacturing and hydrogen infrastructure funding
Green Bonds	Thyssenkrupp: €400 million – Green hydrogen for steel sector; targets carbon neutrality by 2035

Table 63: Australia Funding Overview [18]

Category	Details
Total Investment	Over 900 million AUD (National Hydrogen Strategy)
Key Programs	Hydrogen HeadStart Program: $2.64 billion USD – Competitive revenue support for large-scale hydrogen projects
Public-Private Partnerships (PPPs)	Asian Renewable Energy Hub – Green hydrogen using solar and wind for export to Asia; strong govt + private support
Public-Private Partnerships (PPPs)	Port Bonython Hydrogen Hub – Co-hosting hydrogen producers, users, and exporters in South Australia
Green Bonds	Hysata: 15 million AUD (CEFC) – Efficient electrolyzer technology
Green Bonds	LAVO: Private investments – Metal hydride storage; enhances hydrogen generation/storage

[16] *https://assets.publishing.service.gov.uk/media/65ddc51dcf7eb10015f57f9b/hydrogen-net-zero-investment-roadmap.pdf*
[17] *https://www.dfg.de/en/research-funding/funding-opportunities/programmes*
[18] *https://www.dcceew.gov.au/energy/publications/australias-national-hydrogen-strategy*

Indian Context

In addition to international case studies, the indicative impact of hydrogen blending on the volumetric energy content of natural gas should be explicitly recognized. Computed on a lower heating value (LHV) basis, energy dilution is approximately ~3–4% for 5% H_2 by volume, ~7–8% for 10% H_2, and ~14–16% for 20% H_2 blends. The implications of this reduction must be factored into tariff design, metering practices, and consumer communication to ensure transparency and fairness during rollout.

In Indian context, there can be various ways to fund the testbed and pilots. Few suggestions are mentioned below.

Table 64: Tariffs

Section	Section
Tariff Modeling Parameters	• Hydrogen Cost: ₹300–₹500/kg (green hydrogen via electrolysis from renewable energy sources) • Blend Ratio: 5–10% H_2 by volume in CGD pipelines • Energy Equivalence Adjustments: Calorific value adjusted due to H_2 blending
Cost Head Components (per SCM)	• Blending station CAPEX amortization: ₹0.08–₹0.12 • O&M including sensor calibration, gas analysis: ₹0.05–₹0.07 • Leak detection and safety interlocks: ₹0.03–₹0.05 • Gas shrinkage compensation and QA/QC: ₹0.02–₹0.03
Indicative Tariff Range	₹0.39 to ₹0.48 per standard cubic meter (SCM) for 5–10% hydrogen blending
Recommendations for PNGRB and CGDs	• Incorporate hydrogen infrastructure cost recovery within regulated CGD tariffs under a separate hydrogen tariff clause • Allow tariff revisions in Annual Performance Review (APR) filings when blend ratios exceed 5% • Introduce a framework for tariff differentiation among: – Blend consumers (standard safety upgrade) – De-blend consumers (higher quality control, recovery overheads) – Pure hydrogen users (direct pipeline or industrial feed) • Can alternatively introduce Pipeline Tariff Cess : A specific proposal can be made to add a 1% cess on the natural gas pipeline tariff. This could generate an estimated ₹1,000-2,000 crore annually, which could be ring-fenced in a non-lapsable fund dedicated solely to hydrogen R&D.

Table 65: Hydrogen Innovation Fund

Section	Details
Purpose	To support early-stage R&D, pilot implementation, and OEM certification related to hydrogen infrastructure and safety
Sources of Capital	• PAT Scheme Contributions: Up to 0.3% of annual net profits from major pipeline operators • CSR Contributions: 1% of the 2% mandatory CSR allocation under Section 135 of the Companies Act, 2013 from CGD and NGPL entities • Viability Gap Funding (VGF): From MNRE's Green Hydrogen Mission for demonstration projects like mobile testbeds and SCADA systems • Climate Finance & MDB Participation: Funding from ADB, World Bank, and GCF for testbed R&D and infrastructure expansion
Fund Application Areas	• National testbed and mobile lab infrastructure • Field pilots in urban and industrial CGD zones • Subsidy for hydrogen appliance retrofits • Certification labs for pipeline materials and consumer equipment • Integration of hydrogen-compatible digital twins, SCADA tools, and AI-based leak prediction platforms
Disbursement Mechanism	• Competitive project-based funding • Performance-linked tranches based on blend ratio, safety KPIs, and coverage • Annual monitoring and impact audit by an independent agency

Recommendations

- PNGRB is recommended to introduce a hydrogen infrastructure clause in CGD tariff orders to allow recovery of CAPEX for blending skids, sensors, and safety systems.

- A Hydrogen Innovation Fund (HIF) should be institutionalized with contributions from PAT savings, CSR allocations, and MNRE viability gap funding.

- PNGRB may consider a 1% Pipeline Tariff Cess to create a non-lapsable fund for hydrogen R&D and pilot support.

B.6 Pure Hydrogen Pipeline Development

MODULE AT A GLANCE

SCOPE

FEED-ready pathway for dedicated H_2 corridors; EPC scope; commissioning/testing; national codebook development

KEY RESULTS

Design factors (wall thickness, design factor ≤0.4 Class 2+); pneumatic/hydro test rules; dew-point <-60°C; helium sniffer; ESD spacing; crack arrestors.

INTER MODULE LINKAGES

B2 codebook; B3 100% H_2 component validations; B5 custody transfer metrology; B9 training for H_2 O&M.

SNAPSHOT ITEMS

FEED artifacts; routing/HCA avoidance; leak detection (fixed + fiber-optic + UAV); flare/vent design; operating system integration.

Developing and operating pure hydrogen pipelines represents a new frontier in India's energy infrastructure. Unlike natural gas, hydrogen's low molecular weight, high diffusivity, and unique combustion properties necessitate a holistic rethinking of pipeline engineering, safety, and maintenance protocols. This section presents an expanded and detailed framework for the planning, construction, commissioning, and regulation of pure hydrogen pipelines aligned with global best practices and Indian deployment needs.

EPC Scope of Work

A comprehensive EPC (Engineering, Procurement, Construction) package for hydrogen pipeline projects must address technical precision, material compatibility, and multi-agency regulatory compliance.

Table 66: EPC Scope of Work

Category	Sub-Category	Key Requirements / Activities
1. Engineering and Design	**a) Pipeline Routing and Alignment**	Conduct geotechnical surveys for seismic, water table, and soil stability Mandated Environmental Impact Assessments (EIA) for sensitive zones Submit alignment sheets with elevation and crossing permits (highways, rivers) Secure Right-of-Way (ROW) via stakeholder consultation and legal mapping
	b) Stress Analysis and Support Design	Apply Finite Element Analysis (FEA) for thermal and dynamic stress Design anchors to ASME B31.3 compliance
	c) Hydraulic and CFD Modeling	Simulate hydrogen dispersion under leak scenarios using CFD Conduct hydraulic studies for pressure drop, pulsation, and energy loss optimization
2. Procurement	**a) Pipe Procurement**	Select seamless or ERW API 5L X52–X70 grade steel Pipes must be heat-treated for hydrogen embrittlement resistance
	b) Component Sourcing	Procure hydrogen-rated regulators, valves, rupture disks, and sealants Components must meet ASTM and ISO standards
	c) Instrumentation	Install redundant chromatographs, pressure transmitters, ultrasonic flow meters Ensure SCADA compatibility with RTUs
3. Construction	**a) ROW Acquisition and Clearing**	Follow legal mapping and engage stakeholders to clear and secure ROW
	b) Trenching and Bedding	Implement cathodic protection (CP) and mitigate thermal expansion effects
	c) Field Joint Coating	Use heat-shrink sleeves or fusion-bonded epoxy for corrosion protection
4. Testing and Commissioning	**a) Leak and Strength Testing**	Conduct pneumatic testing with dry nitrogen at 1.25–1.5x design pressure
	b) Drying and Dew Point Verification	Ensure dew point < -60°C before hydrogen introduction
	c) Trial Operation	Conduct 48–72 hours of hydrogen flow trial with full safety system validation

Design and Materials per ASME B31.12 [19]

The ASME B31.12 standard provides the foundational design and construction code for hydrogen pipeline systems and has been widely adopted in global hydrogen projects. It addresses all critical parameters—pressure handling, material resilience, and joint integrity—tailored to hydrogen's unique physical and chemical behaviours.

[19] *https://haisms.ir/images/iso/638477715664883795ASME%20B31.12-2023.pdf*

Table 67: ASME B31.12 Overview

Main Category	Sub-Category	Specifications / Requirements
1. Design Fundamentals	Design Pressure	Must accommodate MAOP + surge allowance. Derating of 30–50% recommended from methane MAOP for hydrogen A 7–10% margin between MOP and MAOP/design pressure to be maintained for greenfield hydrogen pipelines
	Wall Thickness	Must factor hydrogen's low molecular weight & high diffusivity; requires thicker walls or lower hoop stress.
	Design Factor	≤ 0.4 in Class 2+ zones to improve fatigue resistance.
2. Material Selection	Transmission Pipelines	API 5L X42–X60 carbon steels with low S/P content; ASTM A333 allowed in cold climates.
	Distribution Pipelines	Use lined carbon steel or flexible metallic hoses in low-pressure, high-bending zones.
	Fittings & Components	Forged stainless steel (304L/316L); Inconel 625 for high-pressure zones.
	Gaskets & O-Rings	PTFE, Viton A, perfluoroelastomers as per ASTM F2476 (2,000 psi, 1,000 hr. endurance).
3. Compatibility & Durability Enhancements	Cathodic Protection	Impressed current or sacrificial anode systems; dual-potential monitoring.
	Internal Coatings	Epoxy linings to prevent wall absorption and microbial corrosion.
	Fracture Control Plans (FCP)	Crack arrestors, welded sleeves, ≤22 HRC hardness zones to resist propagation.
4. Routing	Routing Strategy	Avoid schools/hospitals/high-rises; co-locate with other utilities; avoid pooling zones by considering elevation/drainage.
5. Welding & joining	Weld Processes	SAW for longitudinal; GMAW for circumferential welds.
	Welder Certification	Must comply with ASME Sec IX and use hydrogen-specific test coupons.
	Post-Weld Inspections	100% Radiographic Testing (RT), Magnetic Particle Inspection (MPI), and hardness mapping.
6. Testing Protocols	Pneumatic Pressure Testing	1.5x design pressure using nitrogen, monitored ≥12 hours. Hydro testing will be used where pipeline stress exceeds 30% of the Specified Minimum Yield Strength (SMYS), as pneumatic testing is not permissible under such conditions due to safety risks.
	Helium Sniffer Tests	Applied to welds, flanges, fittings for micro-leak detection.
	Inertization & Pre-Flushing	Multi-pass nitrogen purge, chromatographic validation.
7. Commissioning	Sensor Calibration	Leak, flow, and pressure sensors must be calibrated.
	Hydrogen Admittance	Gradual in 5% steps to reach 100% in 12–24 hours.
	Trial Run	ESD simulation, valve actuation checks, end-user flow control validation.

Main Category	Sub-Category	Specifications / Requirements
8. Safety Systems	Leak Detection	Fixed electrochemical & IR H□ sensors; fiber-optic DTS; UAV/sniffer-based mobile units.
	Emergency Shutdown (ESD)	Pneumatic fail-safe valves with battery backup; <5 km ESD blocks; SCADA-aligned visual & audible alarms.
	Ventilation & Relief	Flame arrestors at high-point vents; staged flare stacks with ignition sensors; explosion-proof enclosures. Design of vents and blowdown lines to be PESO-approved configurations.
9. Operations, O&M	Preventive Maintenance	Leak walkdowns, gasket cycles, corrosion mapping. A comprehensive Integrity Management System (IMS) will be developed to address hydrogen-specific threats."
	Real-Time Telemetry	Continuous gas quality, pressure, and temperature monitoring.
	Alarm Handling	Predefined thresholds, escalation matrix, SOP-based actioning.
10. Predictive Analytics	Digital Twin	AI/ML tools for anomaly detection; digital twin overlaid with historical NDT and logs.
11. Quality Control	QA/QC Norms	Conform to ISO 29001, API Spec Q1.
	Welding Book & Traceability	Each weld mapped to welder ID and quality/test record.
	Commissioning Report Validation	By internal O&M and independent third-party teams.

Reference may be made to the H100 Fife project in Scotland, which is demonstrating 100% hydrogen delivery on a dedicated new network. This case illustrates that a transition to full-hydrogen service requires segregated infrastructure and end-use appliance conversion, and cannot be achieved through blending approaches.

Draft Bidder Evaluation and Compliance

1. Prequalification Criteria
   - Proven experience in hydrogen or high-pressure gas pipelines >50 km.
   - ASME B31.12, API 5L, PED, and OHSAS 18001 compliance.
   - In-house welding school and NDT capability.
2. Technical Evaluation
   - Blending station design expertise.
   - Control logic and SCADA integration strength.
   - Risk management and asset lifecycle strategy.
3. Commercial and ESG Review
   - Financial liquidity, work-in-hand analysis.
   - ESG compliance, EIA clearance, and CSR contributions.

Recommendations

- Amend the PNGRB Act, 2006 to explicitly include "hydrogen pipelines" within its ambit, enabling PNGRB to oversee authorization, tariff-setting, and safety compliance in alignment with ASME B31.12 standards for dedicated hydrogen networks.

- PNGRB should adopt ASME B31.12 and EIGA guidelines for pure hydrogen pipeline design, with adaptations for Indian terrain and safety conditions.

- EPC contracts should include mandatory pneumatic testing, dew point verification, and hydrogen flow trials before commissioning.

- A national hydrogen pipeline code should be developed and notified, covering routing, welding, leak detection, and SCADA integration.

B.7 End-Users

MODULE AT A GLANCE

SCOPE

Appliance/equipment compatibility, NOx/flashback risks, HCI with BIS, sectoral limits and retrofit programs.

KEY RESULTS

Up to 10% blends: largely OK; 10–20% needs calibration/retrofits; BIS HCI launch; OEM certification cohorts; NOx management guidance.

INTER MODULE LINKAGES

B3 combustion/metrology evidence; B5 Service Classes; B4 appliance tests; B8 purity requirements.

SNAPSHOT ITEMS

Priority segments: hospitals, food/pharma, CHP/turbines; publish sectoral blending limits; retrofit kits; NOx guards; flashback arrestors where needed.

Hydrogen blending introduces significant shifts in combustion behaviour, requiring thorough evaluation of appliances to ensure consumer safety, performance stability, and emission compliance. Key parameters tested include flashback risk, NOx emissions, sealant degradation, and device compatibility across residential and industrial settings.

Residential and Industrial equipment testing protocols

- Testing has been performed on boilers, cooktops, space heaters, commercial burners, and industrial process equipment across pilots such as THyGA (EU), HyDeploy (UK), and HyP SA (Australia).
- More than 100 appliances were tested in Europe alone (THyGA) to benchmark flame stability, emissions, and mechanical tolerance under hydrogen blends up to 60% (lab-only).
- Testing was conducted under both steady-state and transient conditions, including ignition cycles, burner turndown ratios, and valve actuation frequencies.

Flashback Risk, NOx Emissions, and Sealant Integrity

A. Flashback Risk:

- Increased significantly above **30% hydrogen by volume**, due to elevated combustion velocity.

- No critical flashback was observed at blends up to **19% H_2**, with initial occurrences noted at **20%** and consistently observed beyond **50%** in older or narrow-port burner designs.
- Findings from 14 technical studies confirm the onset of flashback at higher blends, emphasizing the need for **burner redesigns or flashback arrestors** for higher concentrations.

B. NOx Emissions:

- NOx levels were shown to **increase with higher hydrogen content** due to elevated flame temperatures.
- Appliance modification or **flame cooling technologies** (e.g., staged air/fuel mixing) may be necessary beyond 10% blends to remain within emission thresholds.

C. Sealant Integrity:

- Elastomeric components (EPDM, Viton, NBR) were tested for hydrogen compatibility under thermal cycling and exposure conditions.
- **Swelling, cracking, and permeability** were observed in some seals, suggesting that blend-tolerant materials need to be adopted or rated as per ISO 11114-4.

Blend-Specific Appliance Compatibility Findings and Various Equipment in Detail

A. Up to 10% Hydrogen:

- Most modern appliances performed reliably without modification.
- No observed changes in ignition, combustion stability, or thermal output.

B. 10–20% Hydrogen:

- Select appliances required **recalibration** of flame sensors and **software updates** to maintain safety and efficiency.
- Older equipment (pre-2005) showed higher failure rates and poor flame detection.

C. Beyond 20%:

- Recommended only for **hydrogen-dedicated networks** or where **OEM-certified appliances** are deployed.
- Appliance testing revealed significant design limits related to quenching distance and thermal stress

Impact of hydrogen blending on equipment [20 21 22]

Table 68: Impact of Hydrogen Blending on Equipment

Component	Aspect	Details
Turbine	NOx Formation	NOx formation increases due to high flame temperatures (>1500°C); prompt NOx from fuel-bound nitrogen is not a concern with hydrogen.
	H_2 Combustion	Hydrogen burns 7x faster than methane, causing pressure instabilities and hotspots; require advanced NOx control strategies.
	Blending Limits	Traditional turbines can't handle >5% H_2 without retrofits.
	Advanced Strategies	Techniques include optimized injectors, staged combustion, e.g., Siemens SGT-600 handles 60% H_2 syngas.
	Material Consideration	Hydrogen embrittlement threatens turbine components.
Compressor	Adiabatic Efficiency	Drops 8% per 10% H_2 blend; higher specific heat ratio increases friction and energy losses.
	Discharge Temperature	Increases 15–25°C per 20% blend; risks overheating and valve failures.
	Compression Ratio	Increases 10–15% per 20% H_2; causes mechanical stress and leakage.
	Power Consumption	Rises 6–12% per 20% H_2 due to low mass flow efficiency.
	Volumetric Flow Rate	Increases with H_2 due to low density, causing bottlenecks and leaks.
	Gas Density	Drops 50–70% at 30% H_2; increases surge risk.
	CAPEX	20–30% higher for H_2-ready systems due to material and cooling needs.
	Mitigation	Use VSDs, intercooling, anti-surge systems, H_2-resistant materials.
	Material Consideration	Hydrogen embrittlement is a concern in all major parts.
CNG Steel Tank	Hydrogen Embrittlement	Atomic H reduces ductility and fracture toughness, leading to failure.
	High-Strength Steel	Higher risk of embrittlement even at 2–5% H_2 due to microstructure.
	Regulatory Limits	UNECE R110 limits H_2 <2% in uncertified steel tanks.
	Cyclic Loading Failure	Accelerates fatigue and failure, especially under repeated pressurization.
	Temperature Sensitivity	Embrittlement worsens at -40°C to +85°C.
	Mitigation	Use tempered steels, nickel coatings, redesign, switch to composites for >5% H_2.
Gas Engines	Flame Speed & Pressure	H_2 causes faster combustion, higher pressure, and wear.
	Methane Number (MN)	MN decreases, leading to increased knocking risk.

[20] *https://docs.nrel.gov/docs/fy23osti/81704.pdf*

[21] *https://www.aga.org/wp-content/uploads/2023/08/Impacts-of-Hydrogen-Blending-on-Gas-Piping-Ma_.pdf*

[22] *https://www.mdpi.com/2075-5309/14/8/2284*

Component	Aspect	Details
	Engine Knock	Occurs at lower loads can cause piston/cylinder damage.
	NOx Emissions	Increases 10–30% due to higher adiabatic temperature.
	Wear	Higher thermal stress increases component wear.
	Cylinder Pressure	Peak pressures rise by 10–20%, shortening engine life.
	Mitigation	Use knock sensors, SCR/EGR, reinforce internals, advanced coatings.
	Material Consideration	Hydrogen embrittlement also affects engine parts.
Steam Methane Reformer (SMR)	Equilibrium Shift	H_2 in feed gas shifts reaction backward, reducing CH_4 conversion.
	Catalyst Coking	Lower conversion promotes carbon deposition on catalysts.
	Methane Slip	3–5% CH_4 loss from unconverted feed.
	Energy Penalty	5–8% more fuel needed due to reduced efficiency.
	Syngas Quality	H_2 dilution lowers syngas purity by 10–15%.
	Mitigation	Cap $H_2 \leq 2\%$; optimize catalysts and recycle CH_4; improve purification.
Boilers	Heat Output	Reduced due to H_2's low energy density (12.75 MJ/m³ vs. 37.8 MJ/m³ for CH_4).
	NOx Emissions	Increases due to higher flame temperatures.
	CO Variability	Fast flames may lead to incomplete combustion.
	Material Degradation	Embrittlement of piping and heat exchangers causes leaks.
	Condensate Corrosion	Acidic moisture corrodes flues and vents.
	Flashback	Flame can burn backwards into the burner.
	Mitigation	Resize burners, use corrosion-resistant alloys, flame arrestors.
	Material Consideration	Hydrogen embrittlement must be addressed.
Domestic Gas Burner	Heat Output	Reduced Wobbe Index reduces heating performance.
	Flashback	Hydrogen's high flame speed causes flashback.
	Flame Lift-Off	Flame detaches due to low H_2 density, risking shutoff.
	Material Degradation	Hydrogen leaks are possible due to valve/pipe weakening.
	Mitigation	Retrofit ports, optimize flow rate, use stainless components.

Recommendations

- BIS may develop a Hydrogen Compatibility Index (HCI) for domestic and industrial appliances, supported by standardized testing protocols.

- PNGRB is advised to mandate blend-specific appliance certification and publish sector-wise blending limits based on testbed and pilot data.

- OEMs can be engaged to retrofit legacy systems and design hydrogen-tolerant equipment, with incentives linked to HCI compliance

B.8 Hydrogen Deblending

MODULE AT A GLANCE

SCOPE

PSA, Cryogenic, Hybrid (Membrane+PSA) technology selection; residual limits; CAPEX benchmarks; operational fit.

KEY RESULTS

Guidance like Selection matrix: <5% (membrane/cryo scaled); 5–20% (hybrid); >20% (PSA/cryo); residual H_2 in reinjected NG <2%; purity to ISO 14687/11120.

INTER MODULE LINKAGES

B5 Rulebook; B4 pilot offshoots; B6 custody transfer; B7 sectoral purity needs; B3 validation tests.

SNAPSHOT ITEMS

Indicative CAPEX ranges (PSA 10 TPD ₹40–60 Cr; Cryo 20 TPD ₹100–120 Cr; Hybrid 5 TPD ₹25–35 Cr); O&M skills; space/electricity needs.

As hydrogen blending into natural gas pipelines gains momentum, the ability to separate hydrogen at downstream points becomes essential—especially where pure hydrogen is required for industrial feedstocks, fuel cell applications, or storage. Deblending technologies enable recovery of hydrogen from blended gas streams, allowing dual utility of a shared pipeline infrastructure. This section elaborates the primary technologies used for deblending, their capabilities, constraints, and economic feasibility.

Pressure Swing Adsorption (PSA) [23]

Pressure Swing Adsorption (PSA) is a well-established gas separation technology used for purifying hydrogen from hydrogen-methane blends. It leverages the selective adsorption characteristics of gases under varying pressure conditions, making it viable for mid-to-high concentration hydrogen deblending.

Process Overview

- The hydrogen-natural gas mixture is passed through fixed beds containing adsorbents such as zeolites, activated carbon, or alumina.
- At high pressure, the heavier components like methane (CH_4), carbon dioxide (CO_2), and other impurities preferentially adhere to the adsorbent surface.

[23] *https://www.sciencedirect.com/topics/engineering/pressure-swing-adsorption*

- Hydrogen, which exhibits minimal adsorption, continues through the bed as purified product gas.
- Once the bed reaches saturation, it is depressurized to release the adsorbed gases in a regeneration phase.
- The process cycles between adsorption and desorption using multiple beds in parallel for continuous operation.

Performance Parameters

- **Purity Achievable:** Up to 99.999% hydrogen purity.
- **Recovery Efficiency:** Approximately **60–70%** when operated at low hydrogen concentrations (below 20% H_2 in blend).
- **Optimal Operating Range:** Best suited when the incoming hydrogen content exceeds 10% by volume.
- **Residual Target:** For compliance, residual hydrogen post-deblending must be <2% in the natural gas stream.

Advantages

- **Scalability:** Modular setups allow deployment for small, medium, and large deblending units.
- **Mature Commercial Availability:** Widely used across refineries, hydrogen fuelling stations, and ammonia plants.
- **Synergy with Hybrid Systems:** When used in tandem with membrane separation, PSA enhances overall system efficiency by polishing the partially enriched hydrogen stream.

Limitations

- **Lower Efficiency at Low H_2 Concentrations:** PSA is less effective for blends below 5% hydrogen, where recovery rates fall significantly.
- **High O&M Costs:** Mechanical wear due to frequent valve actuation, high compression demands, and adsorbent replacement increase operational expenses.
- **Footprint and Complexity:** Multiple synchronized beds, gas switching manifolds, and purge lines require significant space and automation infrastructure.

Technology Integration

- **Membrane + PSA Hybrid Model:**
  - Stage 1: Membrane separation increases H_2 purity from 20–40% to ~70–90%.
  - Stage 2: PSA performs final polishing to >99% H_2 purity.
  - This approach reduces PSA load, extends adsorbent life, and improves cost-efficiency.

Cryogenic Separation [24]

Cryogenic separation is highlighted in the presentation as the most suitable method for achieving ultra-high hydrogen purity when separating hydrogen from natural gas blends, especially in low to mid-percentage hydrogen scenarios (5–20%).

Process Description:

- **Feed gas mixture** (hydrogen and methane) is introduced into a **cryogenic system,** where it undergoes staged cooling.

[24] *https://www.sciencedirect.com/topics/engineering/cryogenic-separationCryogenic Separation - an overview | ScienceDirect Topics*

- Hydrogen and methane are separated based on their **boiling points** (hydrogen: –252.87°C; methane: –161.5°C).
- **Methane condenses** into a liquid phase, while **hydrogen remains gaseous** and is withdrawn.
- Hydrogen is purified further using **controlled temperature-pressure distillation columns and flash separators.**

Technical Specifications:

- **Hydrogen Purity:** Achievable up to 99.999%
- **Recovery Efficiency:** ~90–95% (best among all compared technologies)
- **Blend Concentration Range:** Efficient from 5% to 100% hydrogen blends
- **Cooling Requirements:** Sub –160°C; typically requires staged refrigeration using liquid nitrogen or closed-loop helium cycles

Advantages:

- **Highly efficient for both low and high H_2 concentrations**
- **Dual output utility:** Produces pure hydrogen and liquefied methane (LNG), enhancing commercial viability
- **Meets residual hydrogen threshold** (below 2%) in the processed natural gas stream as per pipeline reinjection limits

Limitations:

- **High energy consumption** due to intense refrigeration demand
- **Large footprint and capital cost,** making it economically feasible only for large-scale operations
- **Requires advanced insulation and cold-resistant construction materials**

Commercial Feasibility:

- Suggested for **hub-level or centralized deblending** where gas volumes justify scale
- Can be **co-located with LNG terminals** to optimize cost via shared infrastructure

Membrane + PSA Hybrid Systems [25]

Hybrid hydrogen separation systems, combining membrane-based pre-concentration with Pressure Swing Adsorption (PSA) polishing, offer an optimized route for deblending hydrogen from natural gas streams, particularly at medium hydrogen blend concentrations.

Process Description:

- **Stage 1: Membrane Separation**
  - The gas mixture is passed through **polymeric or composite membranes** (e.g., polyimide, PDMS, palladium-alloy).
  - Hydrogen, having higher permeability, diffuses through the membrane while methane and other components are retained.
  - The **hydrogen-rich permeate** (70–90% H_2) significantly reduces the burden on downstream PSA units.

[25] *https://www.sciencedirect.com/science/article/abs/pii/S1385894719301494*

- **Stage 2: PSA Purification**
  - The enriched hydrogen stream enters PSA units where residual gases like CH_4, CO, N_2, and moisture are adsorbed.
  - Final output purity exceeds 99%, aligning with fuel-grade or industrial-grade hydrogen quality requirements.

Key Features:

- **Optimized Efficiency:**
  - Bulk removal of impurities by membranes improves PSA performance and extends its adsorbent life.
- **Material Synergy:**
  - Membranes can remove corrosive impurities (like H_2S) before they reach the PSA beds.
- **Energy and Cost Savings:**
  - PSA units operate on lower cycle time due to pre-enrichment, lowering compressor duty and valve switching frequency.
- **Field Deployability:**
  - The hybrid design supports **compact, skid-mounted units** suitable for CGD/NGPL installations and pilot deblending stations.

Limitations:

- **Membrane Sensitivity:**
  - Membranes may degrade under exposure to **moisture, Sulphur compounds,** or particulates without proper pre-treatment.
- **Residual Methane:**
  - Methane in tail gas may require reuse or flaring unless economically recycled.
- **Multi-Stage Compression:**
  - Both membrane and PSA stages need moderate to high feed pressures (typically >10 bar), requiring energy-intensive compressors.

Performance Metrics:

- **Hydrogen Recovery Efficiency:** ~75–80%
- **Residual H_2 in CH_4 stream:** <2% (achieves regulatory deblending thresholds)
- **Capital Viability:** Suitable alternative for projects where cryogenic separation is economically infeasible

Technology Comparison and Residual Limits

Table 69: Impact of Hydrogen Blending on Equipment

Parameter	PSA	Cryogenic Separation	Membrane + PSA Hybrid
Hydrogen Purity	Up to 99.999%	98–99.99%	97–99.9%
Minimum H_2 Blend for Recovery	>10%	>5%	>7%
Energy Consumption	Moderate	High	Moderate
Footprint	Medium	Large	Compact
Modularity	High	Low	High
Capex	High	Very High	Medium
Operational Complexity	Medium	High	Medium
Residual Methane in H_2	<10 ppm	<100 ppm	50–500 ppm

Selection and Cost-Benefit Analysis

Selecting the most suitable hydrogen deblending technology depends on a combination of gas composition, throughput requirements, site constraints, and end-use purity demands. The following comparative framework guides decision-making for CGD zones, industrial clusters, and centralized hydrogen hubs.

1. Hydrogen Concentration at Inlet

- Cryogenic systems show stable performance even at 5% hydrogen due to differential condensation.
- PSA is economically feasible only above ~10% hydrogen content, where recovery exceeds 70%.

Table 70: Technology Selection by Hydrogen Concentration

H_2 Volume Fraction	Recommended Technology	Justification
<5%	Membrane or Cryogenic (if scaled)	PSA becomes inefficient at low H_2 concentrations; membranes can act as pre-filters
5–20%	Membrane + PSA Hybrid	Pre-concentration via membrane improves PSA cycle performance
>20%	PSA or Cryogenic	Both technologies efficient; selection depends on scale and output quality

2. Scale of Operation

- Decentralized applications such as CGD blending terminals prefer **hybrids or PSA-only units.**
- Cryogenic systems are viable **only with constant feed volume and power availability.**

Table 71: Technology Fit Based on Operational Scale

Deployment Scale	Best Fit Technology	Rationale
Small (2–5 TPD)	Membrane + PSA Hybrid	Modular, skid-mounted, easily operated by CGD networks
Medium (5–15 TPD)	PSA Standalone or Hybrid	Balance between cost and purity
Large (>20 TPD)	Cryogenic	Justifies high CAPEX, suitable for hydrogen parks or export zones

3. Purity Requirements by Sector

Hydrogen quality must align with ISO 14687 standards for fuel cells and ISO 11120 for industrial gas cylinders.

Table 72: Technology Fit Based on End-Use Purity Requirement

Application	Required H_2 Purity	Suitable Technologies
Fuel cells, mobility, refineries	>99.99%	PSA or Cryogenic
Industrial burners, heat treatment	90–95%	Membrane + PSA
Ammonia, methanol synthesis	>99.9%	PSA, Cryogenic

4. Capital Expenditure (CAPEX) Estimates [26]

These costs assume industrial-quality fabrication and Indian EPC rates, excluding land and civil works.

Table 73: Estimated CAPEX for Key Deblending Technologies

Technology	Typical Capacity	Estimated CAPEX (INR)	Notes
PSA	10 TPD	₹40–60 Cr	Depends on degree of automation and materials
Cryogenic	20 TPD	₹100–120 Cr	Includes cold box, turbo-expanders, insulation
Membrane + PSA	5 TPD	₹25–35 Cr	Compact, ideal for CGD field deployment

5. Operational Considerations

Table 74: Operational Feasibility Factors by Technology

Parameter	Impact on Technology Feasibility
Electricity Access	Critical for cryogenic and PSA compressors
Manpower Skills	Cryogenic requires higher O&M training; hybrids manageable at CGD scale
Purge Gas Availability	PSA needs nitrogen or hydrogen sweep gas for regeneration cycles
Space Constraints	Membrane and hybrid systems have smallest footprint

[26] *https://www.mdpi.com/1996-1073/18/10/2440*

Recommendations

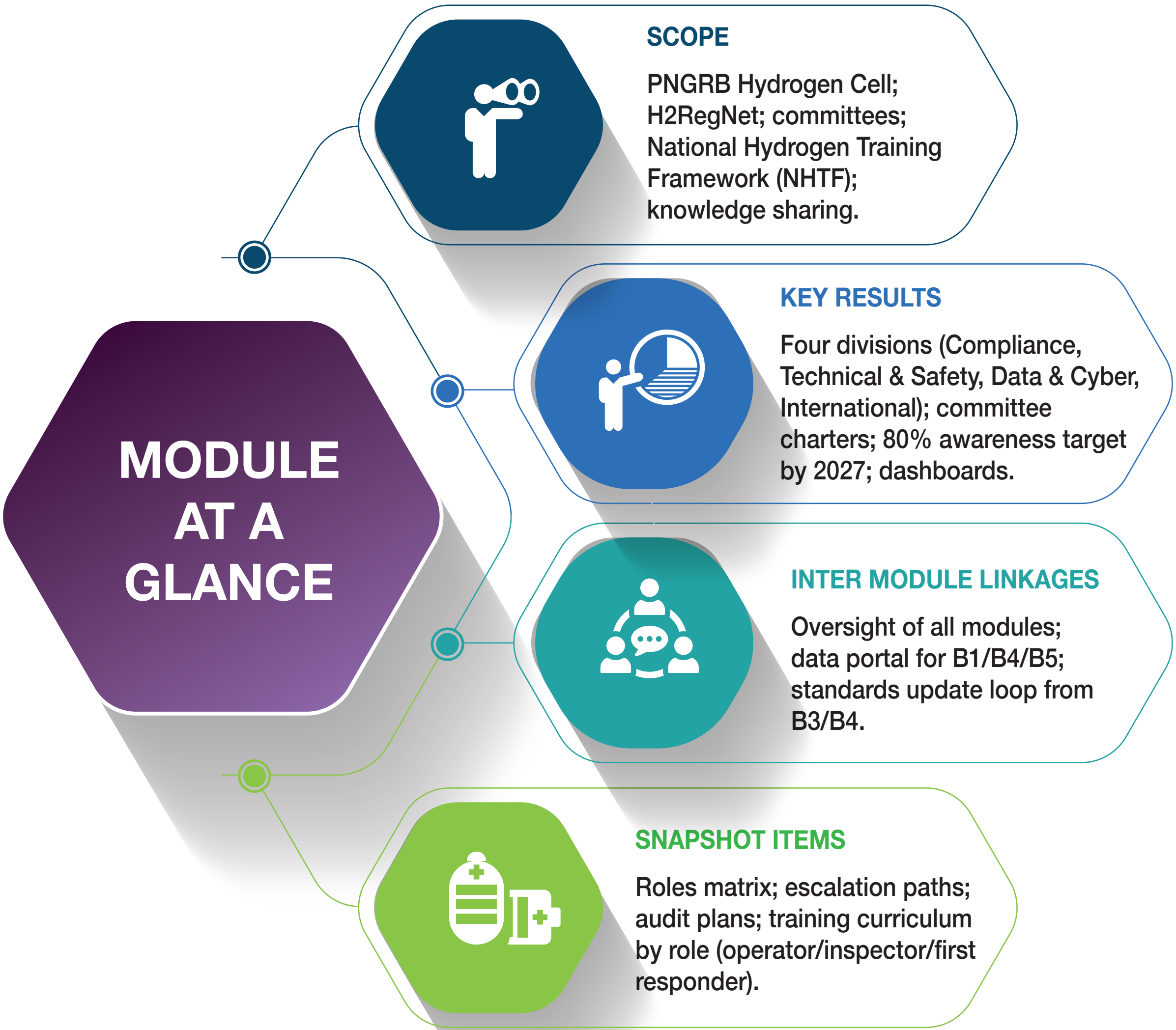
- Modular deblending systems using membrane + PSA hybrids is suggested to be promoted for deployment across CGD zones and industrial hubs.

- Technology selection should be based on blend concentration, scale, and purity requirements, with CAPEX and payback benchmarks defined

- Residual hydrogen in reinjected natural gas should be capped at <2%, and reuse pathways for recovered hydrogen should be standardized

- Technology selection should be guided by inlet hydrogen concentration, scale of operation, and sector-specific purity requirements, ensuring alignment with ISO 14687 and ISO 11120 standards.

B.9 Capacity Building



The integration of hydrogen into India's energy ecosystem will require not only physical infrastructure, but also a resilient institutional framework and a trained, forward-looking workforce. Given the novelty and cross-disciplinary nature of hydrogen deployment, institutional readiness must include regulation, safety, education, data transparency, and inter-agency coordination. This section presents a comprehensive institutional design with functional mandates, stakeholder responsibilities, and workforce development strategies to support India's National Green Hydrogen Mission.

PNGRB Hydrogen Cell

PNGRB has established the Hydrogen Cell, which assures long-term regulatory readiness for hydrogen blending and pure hydrogen infrastructure. This unit acts as the central authority for hydrogen regulation, standardization, pilot oversight, and sectoral engagement, including coordination with international agencies.

A. Mandate and Functional Scope:

1. Regulatory Development and Technical Oversight:

- Draft new hydrogen-specific chapters under PNGRB's Technical Standards and Specifications including safety standards(T4S).
- Periodically update safety and material compatibility protocols based on pilot findings and international standards like ASME B31.12, ISO TC197, and EIGA guidelines.
- Certify hydrogen blending and deblending proposals submitted by CGD entities through a structured material risk evaluation and leak testing framework.

2. **Hydrogen Asset Registry Management:**
   - Maintain a national digital repository of hydrogen-related infrastructure:
     - Pipeline segments approved for blending
     - Injection skids and hydrogen metering stations
     - Incident and maintenance logs
3. **Cross-Sectoral and International Liaison:**
   - Represent India in bodies such as:
     - ISO/TC 197 – Hydrogen Technologies
     - ASME – International Hydrogen Pipeline Codes
     - EIGA – European safety practices for gas systems
   - Collaborate with MNRE, MoPNG, and PESO to harmonize storage, dispensing, and emergency standards.
4. **Interface with H2RegNet Portal and Digital Ecosystem:**
   - Link the national hydrogen testbeds and CGD pilot data to H2REGNET, PNGRB's supervisory and analytics platform.
   - Standardize SCADA data exchange for real-time monitoring of hydrogen blends, Wobbe Index variations, and appliance impacts

B. Proposed Organizational Structure

- **Chief Hydrogen Regulator:** Equivalent to Director-level, reporting to PNGRB Chairperson.
- **Four Specialized Divisions:**
  1. **Regulatory Compliance & Certification**
     - Processes CGD applications, monitors testing labs, approves new blending percentages.
  2. **Technical & Safety Standards**
     - Updates pipeline integrity protocols, ensures leak/flashback thresholds, supervises emergency drills.
  3. **Data Systems and Cybersecurity**
     - Operates the SCADA data node, flagging anomalies in hydrogen transport parameters.
  4. **International Coordination & Industry Engagement**
     - Hosts workshop oversees MOUs with EIGA, ASME, and global hydrogen innovation hubs.

PNGRB Committees

Table 75: PNGRB Committee Hierarchy

Level	Committee Name	Key Role / Responsibility
1	Apex Board	Overall strategic oversight and final policy decision-making for hydrogen blending across CGD and NGPL sectors.
2	Scientific Advisory Committee	R&D, technical innovation, and drafting regulatory standards , safety assessments and codes.
3	Industry Committee 1 (NGPL)	Evaluation of commercial and technical feasibility, challenges, and operational issues related to hydrogen blending in natural gas transmission pipelines (NGPL).
4	Industry Committee 2 (CGD)	Evaluation of technical and commercial aspects, challenges, and stakeholder engagement related to hydrogen blending in city gas distribution (CGD) networks.

Table 76: Details of Committees

S. No	Committee Name	No. of Members	Chairperson	Convenor	Composition	Meeting Frequency	Key Functions
1	Scientific Advisory Committee	8	ED (Executive director) from regulated entities – R&D/Technical (NGPL) (focused on hydrogen and related areas)	PNGRB Officer	• 1 Chairperson (ED with specialization in Hydrogen and related areas) • 1 PNGRB Officer (Convenor) • 3 ED/CGM representatives from regulated entities • 2 experts from institutions like BIS/PESO for standards and safety assessments. • 1 Academia (Professor in Hydrogen Technology, Materials Science, or Pipeline Integrity from reputed institutions like IIT, NIT, or another eminent person) • Chairpersons of industry committee 1 and committee 2	Once in 3 months	Develop a comprehensive R&D Framework Define core research themes (e.g., material compatibility, blending ratios, deblending methods and challenges such as hydrogen embrittlement and sensor integration). Engage technical institutions like IITs and labs for targeted, non-overlapping studies. Prioritize indigenous solutions tailored to Indian infrastructure, safety, and cost conditions. Propose and monitor pilot projects/testbeds to refine technical solutions for NGPL and CGD. Drafting Regulatory Standards: Drafting Indian regulatory standards and safety protocols for hydrogen transportation and blending. Integrate global literature with outcomes from Indian R&D and pilot studies. Safety Assessment: Examine safety risks across the hydrogen value chain (production, transport, blending, end-use). Develop India-specific safety codes and protocols, especially for high-pressure blending and residential use Review global and academic safety literature to ensure thorough risk mitigation.
2	Industry Committee 1-NGPL	6	ED/CGM from regulated entity (in Hydrogen and related areas)	PNGRB Officer	• 1 Chairperson (ED/CGM specialized in Hydrogen and related areas) • 1 PNGRB Officer (Convenor) • 3 ED/CGM representatives from regulated entities • 1 Academia (Professor in hydrogen and related areas from reputed institutions like IIT, NIT, or another eminent person)	Once in 2 months	Collect and benchmark industry feedback on NGPL-specific issues (e.g., retrofitting, maintenance, cost integration). Evaluate the commercial and technical feasibility of hydrogen blending in NGPL systems. Recommend retrofit and risk-mitigation strategies based on global best practices and local conditions.

S. No	Committee Name	No. of Members	Chairperson	Convenor	Composition	Meeting Frequency	Key Functions
3	Industry Committee 2-CGD	6	ED/CGM from regulated entity (in Hydrogen and related areas)	PNGRB Officer	• 1 Chairperson (ED/CGM with expertise in CGDs commercial & technical issues) • 1 PNGRB Officer (Convenor) • 3 ED/CGM representatives from regulated entities • 1 Academia (Professor in hydrogen and related areas from reputed institutions like IIT, NIT, or another eminent person)	Once in 2 months	Gather feedback on the operational challenges and commercial readiness for hydrogen blending in CGDs. Recommend strategies for safely integrating hydrogen into CGDs, considering higher allowable blending limits. Ensure system integrity and consumer safety through technical evaluations and continuous monitoring.

Hydrogen Portal (H2RegNet) and Data Repository

A comprehensive Hydrogen Portal (H2RegNet) should function as the digital backbone of India's hydrogen integration framework.

Features and Capabilities

- **Live Dashboard:** Real-time map of blending activity by CGD zone, blend ratio, and pipeline status.
- **Application Interface:** Allows CGDs and EPCs to upload project proposals, safety protocols, and QA/QC reports.
- **Incident Reporting:** Portal for near-miss reports, safety violations, and remedial actions.
- **Standard Repository:** Downloadable codes, testing procedures, and regulatory circulars.
- **User-Specific Access:** Tiered access for regulators, operators, auditors, researchers, and OEMs.

Interoperability and Governance

- Integrated with PNGRB's existing e-Governance platform.
- Linked to MNRE and MoPNG databases for cross-sector policy alignment.
- Monitored and updated quarterly by a joint committee (PNGRB, BIS, PESO).
- Hazardous area classification will be conducted per PESO and IEC 60079 standards for all hydrogen installations.

Roles of CGDs, Transmission companies, MNRE, PESO, and BIS

1. City Gas Distribution (CGD) Companies

Few CGDs have been assessed for material compatibility for hydrogen blending based on steel grade (e.g., X65 limitations) and weld readiness.

2. Transmission companies

Responsibilities include long-distance hydrogen pipeline development, particularly in relation to pure hydrogen corridor planning, as well as internal hydrogen integration for refineries and transport fuel supply.

3. MNRE

MNRE is the principal policy and funding entity via the Green Hydrogen Mission. It was proposed to lead the Hydrogen Innovation Fund (HIF) supported by CSR and PAT contributions.

4. **PESO**

PESO's role in updating the Gas Cylinder Rules (2024 Draft) and safety protocols for hydrogen injection, storage, and deblending facilities is highlighted. Coordination with PNGRB is recommended.

5. **BIS (Bureau of Indian Standards)**

BIS is actively developing Bharat H_2 standards and harmonizing Indian standards with ISO (e.g., IS/ISO 11114-1/2 for material compatibility with hydrogen).

Training, Site Visits, Knowledge Sharing

1. Training Programs and Capacity Development
    - Launch of **National Hydrogen Training Framework (NHTF**) with modular learning for:
        - Field Operators: Leak detection, material identification, safety drills.
        - Engineers and Designers: Blend ratio modelling, PSA and membrane technologies.
        - Regulatory Officers: Site inspection, NDT record review, SOP evaluation.
    - Partner institutions:
        - **IIT Bombay, IISc Bangalore, IIP Dehradun, GERMI, and CSIR Labs.**
        - Support from international agencies like GIZ, IEA, and Mission Innovation.
2. **Site Demonstrations and Facility Walkthroughs**
    - Annual visits to:
        - Hydrogen blending stations in pilot cities.
        - Electrolyser farms and hydrogen compressors.
        - PSA deblending units and appliance test labs.
    - Shadowing opportunities with PESO-certified inspectors and hydrogen safety engineers.
3. **Knowledge Exchange Platforms**
    - India Hydrogen Forum: Annual national conference hosted by PNGRB and MNRE.
    - Online library of technical papers, case studies, and international whitepapers.
    - Public webinar series with industry leaders and safety experts.

Recommendations

- Institutionalize the Hydrogen Cell (Division) with four verticals—Technical Standards, Regulatory Approvals, Digital Integration, and International Collaboration is recommended.
- The Hydrogen Portal (H2RegNet) should be launched to enable real-time blend monitoring, incident reporting, and certified equipment tracking.
- A National Hydrogen Training Framework (NHTF) should be rolled out with IITs, CSIR, GERMI, etc. as partners, targeting 80% stakeholder awareness by 2027.

Way Forward

C.1 Detailed Project Implementation Plan - for Each Module

This section outlines the next steps and action items across all modules of the hydrogen roadmap along with the roles and responsibilities of PNGRB, ministry, selected vendors, CGD entities, and other institutional partners.

B1 Pipeline Identification

Implementation Steps	Key Activities	Timeline	Deliverables
Define Registry	Build installed-base readiness registry schema; Data model	2025	Registry Schema
Ingest and Score	Ingest initial pipeline data; 9-parameter screening; Generate scores	2025–2026	First-Wave 9-Parameter Scores
Publish Readiness	Publish “Excellent/Good/Fair/Marginal” map; Pilot gating advisories	2026–2027	Readiness Map; Advisories
Overlay/Use Cases	End-use overlays; Nominate early interfaces to future corridors	2027–2028	Overlay Pack; Interface List

B2 Regulatory Review

Implementation Steps	Key Activities	Timeline	Deliverables
Set-up and Plan	Institutional set-up and partner on-boarding; Planning and framework finalisation	2025	Set-up Note
Map and Identify Gaps	Regulatory mapping and gap identification; Draft recommendations	2026	Gap Analysis
Publish Standards Map	“Map of Applicable Standards” (ASME B31.8 with hydrogen annex, transitional B31.12/EIGA; EN 16726 alignment)	2026	Standards Map
Notify Annex	T4S hydrogen annex (Edition 1); Safety case guidance; Skids/analyser specs	2028	T4S Annex; Guidance
Annual Updates	Standards and rulebook updates aligned with lessons and EN 16726	2029–2033	Annual Update Circulars

B3 Testbed

Implementation Steps	Key Activities	Timeline	Deliverables
Design & Award	Finalise concept; EPC tender; Award EPC	2026	EPC Award
Commission	Commission loops and labs; Start baseline campaigns (materials, metrology, odorisation, dispersion)	2026–2028	Commissioning Records; Baseline Datasets
Report & Expand	State of Hydrogen Readiness — India (Year 1, Year 2); extend to 100% H_2 components and compressor/turbine derates; Year 3	2027–2030	Annual Reports; Extended Scope Outputs

B4.a. CGD Demonstrations

Implementation Steps	Key Activities	Timeline	Deliverables
Start Demos	Start CGD demonstrations with energy-based billing	2026	Pilot Start Reports
Transition	Complete CGD pilots; Transition to operations; Publish dashboard entries	2027	Completion Dossier; Dashboard Entries

B4.b. Transmission Pilots

Implementation Steps	Key Activities	Timeline	Deliverables
Prepare	Commission transmission pilot enabling works (NDT, analyser installs)	2027–2028	Enabling Works Pack
Run	Begin transmission pilots under Safety Cases; Monthly technical reporting	2028–2030	Monthly Pilot Reports
Replicate/Convert	Replicate across zones; Convert suitable pilots to operations; Dashboards	2029–2031	Conversion Dossiers; Dashboard

B5 Blending Framework

Implementation Steps	Key Activities	Timeline	Deliverables
Notify Finance	Notify tariff clause for prudent cost recovery; Seed HIF	2026	Tariff Clause; HIF Note
Clarify	Clarifications on ramp rates, stop rules, metering QA; Tariff refinement from pilots	2027	Clarification Circular
Update & Issue	Annual standards updates and Rulebook issuance; Tariff differentiation	2029–2033	Annual Rulebook/Standard Updates

B6 Pure Hydrogen Pipeline Development

Implementation Steps	Key Activities	Timeline	Deliverables
Pre-FEED/FEED readiness	Corridor screening; demand anchors; preliminary route selection; QA/QC strategy	2028	Readiness Pack
FEED & permitting	FEED; Permitting; Long-lead procurement planning; Custody transfer metrology	2029–2030	FEED; Permits; Metrology Plan
Build & Commission	Phased construction; Commissioning; Steady-state ops; Codebook	2030–2033	Commissioning Dossiers; National Codebook

B7 End Users

Implementation Steps	Key Activities	Timeline	Deliverables
HCI & Testing	Launch appliance compatibility program with BIS (HCI design); Lab-testing priority appliances	2026–2027	HCI
Retrofits	Launch targeted retrofit schemes for legacy appliances	2028	Retrofit Program
Sectoral Limits	OEM certification scale-up; Publish sectoral blending limits by equipment class based on domestic data	2030	Sectoral Limits Note

B8 Deblending

Implementation Steps	Key Activities	Timeline	Deliverables
Guidance Consolidation	Guidelines on available deblending technologies (pros/cons, including cost) for market participants to read and use	2026–2029	Deblending Guidelines Set

B9 Capacity Building

Implementation Steps	Key Activities	Timeline	Deliverables
Institutionalize Cell	Institute PNGRB Hydrogen Cell; Publish governance and committee charters	2025	Governance Pack
Platform Beta	Launch H2RegNet beta version (data model, pilot intake)	2026	H2RegNet beta
National Hydrogen Training Framework (NHTF)	Design National Hydrogen Training Framework (NHTF) covering OEMs, operators, and regulators	2027–2033	Training Structure; Schedule; and Curriculum Outline

C.2 PNGRB Hydrogen Roadmap — Consolidated Timeline (2025–2033)

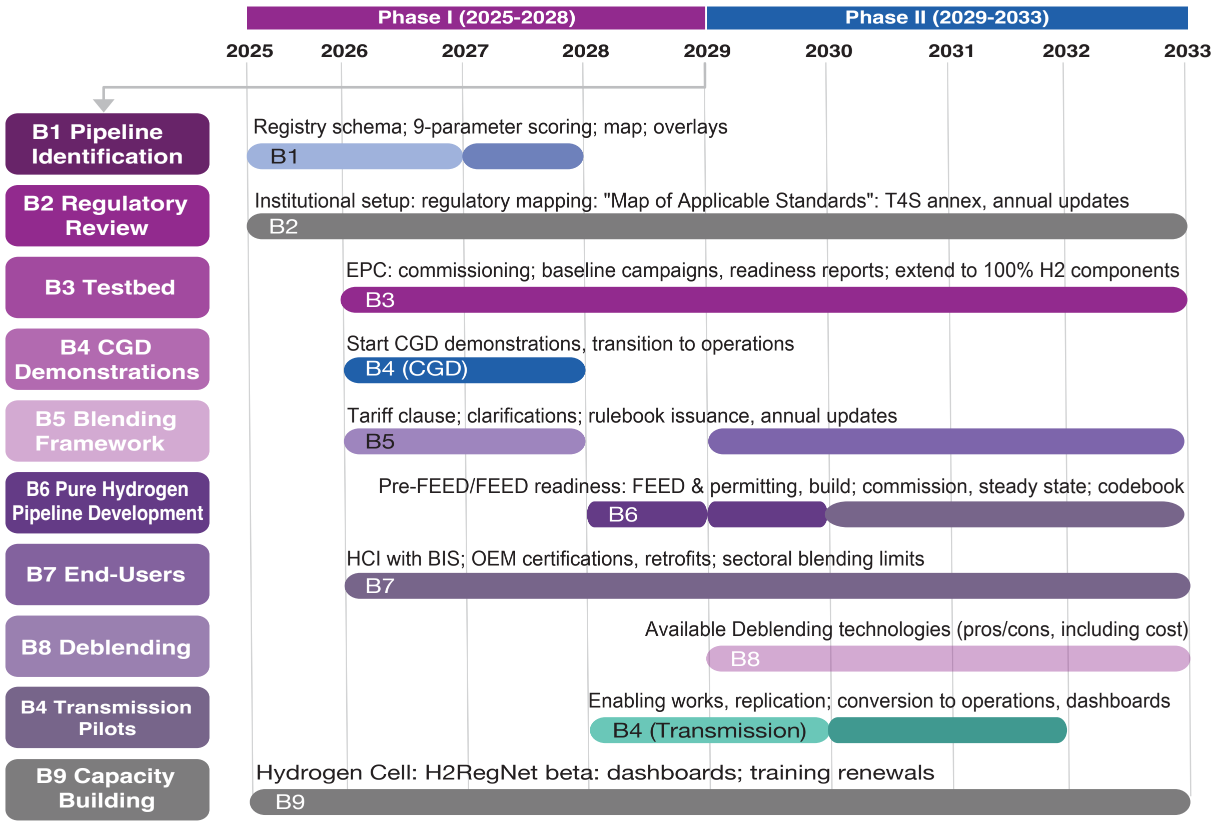


Figure 3: Consolidated Modules Map as per Roadmap Timeline

Implementation steps for each year of the roadmap are given in detail below –

2025

- B1: Build Installed-Base Readiness Registry Schema; Ingest Initial Pipeline Data for 9-Parameter Screening.
- B2: Institutional Set-up and Partner Onboarding, Planning and Framework Finalisation
- B9: Institute PNGRB Hydrogen Cell; Publish Governance, Committee Charters;

2026

- B1: Complete First Wave of 9-Parameter Scoring; Publish "Excellent/Good/Fair/Marginal" Map; Issue Pilot Gating Advisories.
- B2: Regulatory Mapping and Gap Identification of Existing Standards, Drafting Recommendations and Publish "Map of Applicable Standards" (ASME B31.8 with Hydrogen Annex, Transitional B31.12/EIGA References; EN 16726 Alignment Note).
- B3: Finalise Testbed Concept and EPC Tender; Freeze Minimum India-Specific Test Matrix (SSRT, KIH, FCGR, Permeation, Elastomer Suite). Award EPC; Commission Core Loops and Labs; Start Baseline Campaigns (Materials, Metrology, Odorisation, Dispersion).
- B4: Start CGD Demonstrations with Energy-Based Billing.
- B5: Notify Tariff Clause for Prudent Cost Recovery; Seed HIF.
- B7: Launch Appliance Compatibility Program with BIS (HCI Design); Start Lab-Testing Priority Appliances.
- B9: Launch H2RegNet Beta Version (Data Model, Pilot Intake).

2027

- B1: Update Registry with End-Use Overlays; Nominate Early Interfaces to Future H_2 Corridors.
- B3: Publish State of Hydrogen Readiness — India (Year 1); Finalize India-Specific Component Envelopes (Valves, Seals, Meters).
- B4: CGD Pilots Complete; Transition to Operations Where Criteria Met; Commission Transmission Pilot-Enabling Works (NDT, Analyser installations).
- B5: Clarifications on Ramp Rates, Stop Rules, Metering QA; Tariff Refinement from Pilots.
- B7: BIS Issues Hydrogen Compatibility Index (HCI) v1.0; OEMs Start Certification for Key Appliances/Equipment.

2028

- B2: Notify T4S Hydrogen Annex (Edition 1); Issue Guidance on Safety Case Content; Approve Standard Blending Skids and Analyser Specs; Incorporate Testbed Lessons, Odorisation and WI Controls, Emergency Doctrine Updates.
- B3: State of Readiness — Year 2; Publish Weld-HAZ Toughness Norms; Elastomer Replacement Intervals.
- B4: Begin Transmission Pilots Under Approved Safety Cases; Monthly Technical Reporting to PNGRB.
- B5: Appliance Cohorts; Critical Customer Rules; Cyber Hardening.
- B6: Initiate Pre-FEED/FEED Readiness: Corridor Screening, Demand Anchors, Preliminary Route Selection, QA/QC Strategy for H_2 Networks.
- B7: Launch Targeted Retrofit Schemes for Legacy Appliances in Selected Zones.

2029

- B4: Scale-up Replication in Additional CGD/NGPL Zones Using Matured SOPs; Integrate Learnings In To T4S and Rulebook.
- B2/B5: Annual Standards Updates and Rulebook Issuance; Align with EN 16726 Revisions; Expand Tariff Differentiation (Blend/Deblended/Pure H_2).
- B6: FEED and permitting for First Dedicated H_2 Corridor; Start Long-Lead Procurement Planning; Define Custody Transfer Metrology for H_2.

2030

- B3: Extend Testbed Scope to 100% H_2 Pipeline Components and Compressor/Turbine Derates.
- B6: Begin Phased Construction of Pure H_2 Corridor (Priority Segment); Set Up Commissioning Plan: Pneumatic Tests, Dew Point Control, Helium Sniffer Tests, Staged Admission.
- B7: OEM Certification Scale-Up; Publish Sectoral Blending Limits by Equipment Class Based on Domestic Data.

2031

- B6: Commission First Corridor Segment; Complete Hydrogen Custody Transfer Stations and SCADA Integration; Initiate Operational Trials.
- B4: Convert Suitable Pilots to Permanent Operations; Publish National Performance Dashboard through H2RegNet.

2032

- B6: Extend Corridor to Additional Nodes; Integrate with Industrial Clusters and Mobility Hubs; Update National Code for H_2 Pipelines Based on Field Experience.
- B2/B5: Annual Code and Rulebook Refresh; Expand Cyber Standards for Hydrogen Skids and Analysers.

2033

- B6: Achieve Steady-State Operations on Multi-Segment H_2 Corridors; Publish National Hydrogen Pipeline Codebook (Routing, Welding, Leak Detection, SCADA).
- B3/B4/B5/B7/B8/B9: Mature Steady-State Regime — Annual Standards Updates, KPI Benchmarking Dashboards, OEM Certification Continuity, Training Renewal Cycles.

C.3 Decision Gates for the Roadmap

Interconnection of modules and gates

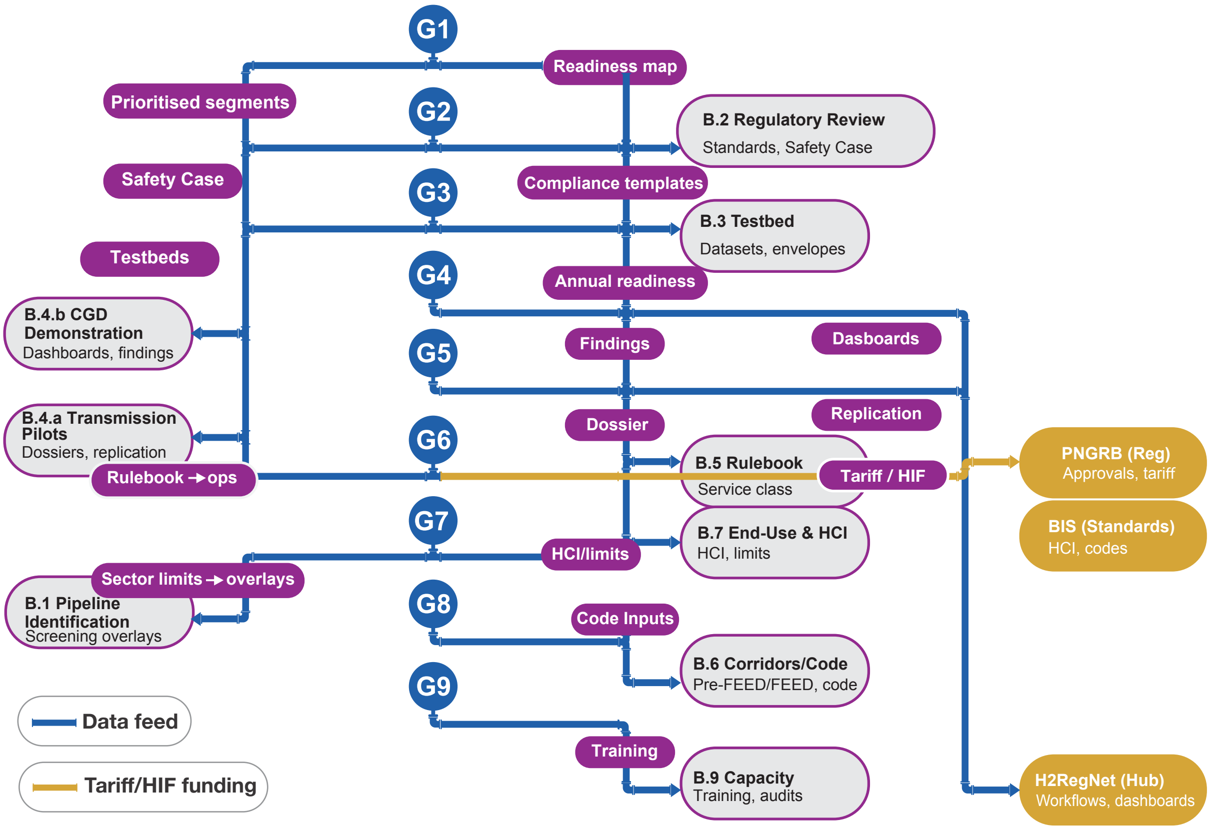


Figure 3. Interconnection Between Modules and Gates

DETAILS OF GATES

Gate 1 — Installed Base Readiness Registry (B.1)

Gate Criteria:

- Installed Base Readiness Registry schema defined, and initial pipeline data ingested.
- 9 parameter screening completed for candidate NGPL segments and CGD zones, with section wise scores.
- Minimum score of 4 met individually for each parameter.
- Prioritized pipeline segments list prepared (Excellent/Good/Fair/Marginal) and pilot gating advisories drafted.

Go/No Go Decision:

- Go: Section scores satisfy "minimum 4 in each parameter," and segments rated "Excellent"/"Good" (or "Fair" with defined targeted upgrades) are identified.
- No Go: Any parameter <4 or segments rated "Marginal/Poor" without defined mitigation.

Outputs on Go:

- Readiness map and prioritized pipeline segments (feeds B.3 Testbed sampling plan, B.4 Pilot Projects, B.5 Operational Rulebook planning).
- Overlay/end use interface pack (feeds B.7 End Users and B.6 corridor interfaces).

Outputs on No Go:

- Rework screening, gather additional weld integrity/NDT, corrosion, gas loss, or end use compatibility data; apply targeted upgrades; rescore.
- Escalate for advisory only if data gaps persist.

Gate 2 — Regulatory Baselines + Safety Case (B.2, B.5 prerequisites)

Gate Criteria:

- "Map of Applicable Standards" prepared (ASME B31.8 with hydrogen annex, transitional B31.12/EIGA references; EN 16726 alignment).
- T4S hydrogen annex draft/guidance elements identified (Safety Case content, skids/analyzer specs, odorization verification, metering and energy reconciliation—in line with report timelines).
- Pilot Safety Case documentation prepared for candidate zones/segments via H2RegNet.

Go/No Go Decision:

- Go: Safety Case complete and aligned with the published "Map of Applicable Standards" and hydrogen annex guidance; interfaces for deblending and reinjection documented where applicable.
- No Go: Missing Safety Case elements (hazard ID, dispersion, MAOP review, purge/venting, odorization, ESD/blowdown, metrology, consumer communications), or misalignment with standards map.

Outputs on Go:

- Approved Safety Case (feeds B.4 CGD Demonstrations, B.4 Transmission Pilots).
- Compliance templates and audit checklists pack (feeds B.5 Operational Rulebook).
- Hydrogen Regulatory Cell workflows initiation (feeds B.9 Capacity Building, H2RegNet).

Outputs on No Go:

- Rework Safety Case; add missing analyses (e.g., odorization verification, metering reconciliation, leak surveillance).
- Hold pilots until annex and standards alignment achieved.

Gate 3 — Testbed Commissioning and Minimum Test Program Results (B.3)

Gate Criteria:

- EPC award for testbed; commissioning records for Loop Area (NGPL/CGD loops), Testing Area, and Control Room.
- Minimum test matrix executed (SSRT in high pressure H_2, KIH threshold, fatigue crack growth in H_2, permeation, weld HAZ toughness, coating disbondment, elastomer compatibility). Baseline datasets generated.
- State of Hydrogen Readiness — India (Year 1/Year 2 as applicable) issued or equivalent baseline outputs.

Go/No Go Decision:

- Go: Commissioned loops and labs with baseline datasets covering materials, metrology, odorization, dispersion, and component envelopes as specified.
- No Go: Testbed zones not commissioned, or minimum test matrix not complete, or datasets insufficient to calibrate pilots and standards.

Outputs on Go:

- Component envelopes (valves, seals, meters), weld HAZ norms, elastomer replacement intervals (feed B.2 annex drafting, B.4 pilot acceptance criteria, B.5 Rulebook).
- Annual State of Hydrogen Readiness — India (feeds B.2 annual updates, B.5 annual Rulebook/standards updates, B.7 sector limits).
- Installed base admissibility registry inputs (feeds B.1/B.4 planning).

Outputs on No Go:

- Re test or expand test scope; complete commissioning punch list; delay pilot approvals until datasets are available.

Gate 4 — CGD Demonstrations (with Exit) Acceptance (B.4.b)

Gate Criteria:

- Pilot design meets "CGD Demonstration" scope: materials/permeation tests (ISO 15105 1), NDT plan, safety/risk (leakage, flammability, stratification), odorant effectiveness (ASTM D6273 20), Wobbe Index monitoring (EN 16726), and energy based billing.
- Live dashboards and reporting cadence prepared; explicit exit strategy defined.

Go/No Go Decision:

- Go: Safety Case approved; instrumentation installed; metrology set; consumer communication prepared; pilot is time bound with explicit exit to operations after objectives are met.
- No Go: Missing instrumentation, Safety Case, or energy based billing plan, or unsatisfied satisfaction criteria for MDPE pipelines.

Outputs on Go:

- Pilot start reports; live dashboards; monthly reports to PNGRB; Final assessment with recommendations for operational integration/scale up (feeds B.5 tariff refinements; B.2 annex updates; B.7 HCI inputs).
- Transition to operations where criteria met (feeds B.5 service class adoption in CGDs).

Outputs on No Go:

- Rework pilot readiness (install analyzers, odorization QA, detectors), extend NDT, add training; resubmit Safety Case.

Gate 5 — Transmission Pilots Readiness and Safety Case Approval (B.4.a)

Gate Criteria:

- Enabling works completed: NDT (PAUT/UT/MPI/RT), analyzer installs, Safety Case content per transmission scope (steel API 5L X42–X52, <10 years), Wobbe Index continuous monitoring, odorant effectiveness, leakage/flammability/stratification assessment.
- Satisfaction criteria for steel pipelines aligned to test protocols (ASTM/NACE references in the report).

Go/No Go Decision:

- Go: Safety Case cleared; instrumentation and monitoring in place; pilot operating envelopes and inspection cadence defined; monthly technical reporting committed.
- No Go: Missing enabling works, incomplete Safety Case, or unresolved integrity findings.

Outputs on Go:

- Pilot monthly reports; Final technical dossier; national reference standards inputs (feed B.2 T4S annex and standards updates, B.5 Rulebook, B.6 corridor readiness).
- Replication and conversion dossiers for steady state operations (feeds B.4 replication, H2RegNet dashboards).

Outputs on No Go:

- Targeted mitigations (integrity repairs, component upgrades), expanded testing; resubmission after closure of findings.

Gate 6 — Blending Framework Operationalization (Operational Rulebook + Service Class + Tariff/HIF) (B.5)

Gate Criteria:

- Operational Rulebook drafted: planning/approval, pre injection readiness, normal operations, integrity management, emergency response, reporting, and audit checklists; Service Classes defined; measurement and energy based billing provisions stated, H2RegNet data schema aligned.
- Tariff clause notified for prudent cost recovery; HIF seeded; clarifications on ramp rates, stop rules, metering QA issued.

Go/No Go Decision:

- Go: Rulebook components and Service Class envelopes approved; tariff clause and HIF mechanisms notified as per schedule.
- No Go: Rulebook elements incomplete; tariff clause or HIF not notified; metrology and billing not aligned.

Outputs on Go:

- Issued Rulebook and Standards Map references (feed B.4 pilots operations, B.1 screening enforcement, B.9 audits and training).
- Tariff clause and HIF operational (feed B.3 testbed funding, B.4 pilots).

Outputs on No Go:

- Hold on Service Class upgrades and tariff recovery; refine clauses using pilot data; re issue clarifications.

Gate 7 — End Use Compatibility and BIS Hydrogen Compatibility Index (HCI) Publication (B.7)

Gate Criteria:

- Appliance compatibility map and sectoral findings compiled from pilots/testbed; BIS Hydrogen Compatibility Index (HCI) v1.0 prepared; OEM engagement for certification and retrofits initiated.
- Sector wise blending limits draftable based on domestic data.

Go/No Go Decision:

- Go: BIS issues HCI; PNGRB mandates blend specific appliance certification and publishes sector wise blending limits when supported by data.
- No Go: Insufficient domestic data to finalize HCI and sector limits.

Outputs on Go:

- HCI publication; OEM certification scale up; retrofit programs (feed B.5 Rulebook updates; B.4 pilot acceptance; consumer protection measures).

- Sectoral blending limits note (feeds B.1 end use overlays; B.5 Service Class refinements).

Outputs on No Go:

- Continue appliance testing via testbed and CGD pilots; extend datasets; defer publication until evidence consolidated.

Gate 8 — Pure Hydrogen Pipeline Pre FEED/FEED Readiness (B.6)

Gate Criteria:

- Corridor screening with demand anchors; preliminary route selection; QA/QC and custody transfer metrology strategy; FEED and permitting plan; alignment to ASME B31.12/EIGA and forthcoming B31.3/31.8 provisions noted in the report.
- Draft EPC scope aligned to report's EPC table; welding, routing, leak detection, SCADA integration coverage in national hydrogen pipeline code draft.

Go/No Go Decision:

- Go: Pre FEED/FEED readiness pack complete; permitting path and long lead procurement planning in place.
- No Go: Demand anchors or routing unresolved; QA/QC or metrology strategy incomplete.

Outputs on Go:

- FEED package, permits, long lead plan; national code drafting inputs (feed B.2/B.5 annual updates, B.6 codebook).
- Procurement planning for sensors/SCADA/QA systems (feeds B.6).

Outputs on No Go:

- Re screen corridors; refine demand anchor analysis; complete missing studies; resubmit readiness pack.

Gate 9 — Pure Hydrogen Corridor Commissioning and Codebook (B.6)

Gate Criteria:

- Phased construction complete; commissioning plan executed: pneumatic tests, dew point < –60°C verification, helium sniffer tests, staged hydrogen admission; ESD and PRV/regulator response validated.
- Custody transfer stations and SCADA integration operational; trial run completed.

Go/No Go Decision:

- Go: Commissioning dossiers finalized; steady state operation achieved; national hydrogen pipeline codebook ready for publication.
- No Go: Commissioning tests not passed, or safety systems not validated.

Outputs on Go:

- Commissioning dossiers; steady state operations; national hydrogen pipeline codebook covering routing, welding, leak detection, and SCADA integration (feeds B.2 notifications/updates; B.9 training; H2RegNet benchmarks).
- Dashboard entries via H2RegNet (feeds B.9).

Outputs on No Go:

- Corrective actions on test failures; repeat commissioning steps; hold steady state declaration until compliance achieved.

Flow and primary outputs of gates

G1 — Installed-Base Readiness
9-param screen: min 4/parameter; segments prioritized.

Primary outputs

Readiness map - B.3/B.4/B.5

End-use overlays - B.7/B.6

G2 — Regulatory + Safety Case
Safety Case aligned to Standards Map & H_2 annex.

Primary outputs

Approved Safety Case - B.4

Compliance templates - B.5

G3 — Testbed Commissioned
Minimum test matrix complete; baseline datasets.

Primary outputs

Component envelopes - B.2/B.4/B.5

Annual readiness - B.2/B.5/B.7

G4 — CGD Demos Accepted
Safety Case; instrumentation; energy billing: exit defined.

Primary outputs

Dashboards - PNGRB

Findings - B.5/B.2/B.7

G5 — Transmission Pilots
Safety Case; monitoring: envelopes + inspection cadence..

Primary outputs

Dossier - B.2/B.5/B.6

Replication - H2RegNet

G6 — Blending Framework
Rulebook + Service Classes approved; tariff/HIF notified.

Primary outputs

Rulebook - B.4 ops/B.1/B.9

Tariff/HIF - fund B.3/B.4

G7 — End-Use + BIS HCI
BIS HCI v1.0 issued; sector limits when supported.

Primary outputs

HCI - B.5/B.4

Sector limits - B.1/B.5

G8 — Pure H_2 Pre-FEED/FEED
Readiness pack complete; permits + long-lead plan.

Primary outputs

FEED + permits - B.6

Code inputs - B.2/B.5

G9 — Corridor Commissioned
Commissioning passed; steady state; codebook ready.

Primary outputs

Codebook - B.2/B.9

Benchmarks - H2RegNet

C.4 INDICATIVE RISKS AND POTENTIAL RISK MITIGATION MATRIX

The table below summarizes the program-wide risks applicable across all modules, along with their mitigation measures, responsible owners, and key performance indicators (KPIs) to track risk management effectiveness throughout the hydrogen blending roadmap implementation.

Category	Risk	Mitigation Plan	Owner	KPI
Strategic	Fragmented standards (BIS/PESO/PNGRB) delay pilots and testbed commissioning.	Constitute PNGRB Hydrogen Cell (2025); publish "Map of Applicable Standards" (2026); notify T4S Hydrogen Annex v1 (2028); annual updates.	PNGRB Hydrogen Cell; BIS; PESO	Standards update cycle ≤12 months; % modules referencing same standards map.
	Public and stakeholder acceptance risk (blending in CGD zones).	H2RegNet public dashboards; early consumer communications; energy-based billing in pilots; incident transparency.	CGD entities; PNGRB Comms; State authorities	Consumer complaint closure time; acceptance rate >95%.
Technical	Hydrogen embrittlement in higher strength steels/weld HAZ.	9-parameter screen (Material, Weld Integrity); SSRT, KIH, FCGR at testbed; cap legacy compressors/turbines per OEM registry; limit early blends to BG-2 (≤5%) unless cleared.	Operators; Testbed Consortium; PNGRB Hydrogen Cell	Weld HAZ toughness compliance; Tier 2/3 incidents = 0 in pilots.
	Analyzer/odorant reliability and metrology bias.	Redundant analyzers; daily auto-checks; weekly odor QA tests; monthly meter bias checks across meter classes; energy-based billing.	Operators; Third-party metrology auditors	Analyzer uptime ≥98%; billing accuracy ≥ 99.5%.
Operational	Leak frequency increases due to hydrogen diffusivity.	Increased leak survey frequency by BG class; elastomer upgrade schedule; CP verification; ESD segmentation ≤5 km; portable H_2 sensors.	Operators	Leaks per km trending down; MTTD/MTTR targets met.
Regulatory/ Compliance	GCR gaps for grid-scale H_2 injection and operating system safety.	Regulatory partner to draft gap-closure proposals; integrate NFPA-2/ISO 19880/EN 16726 annexes; cybersecurity advisories for analyzers.	PNGRB Hydrogen Cell; PESO; BIS	Gap list closed per plan; cyber audit annual pass.
Financial/ Tariff	Cost recovery uncertainty and funding shortfalls.	Tariff clause (2026); Hydrogen Innovation Fund (PAT/CSR/VGF/MDB); optional 1% Pipeline Tariff Cess; APR-based refinements.	PNGRB; MNRE; Operators	Approved tariff line items; % capex recovered; HIF disbursals on performance.
Data/Cyber	Telemetry loss or tampering in H2RegNet feeds.	Secure telemetry; role-based access; tamper-evident logs; annual cyber audit; data retention ≥5 years.	Operators; PNGRB IT	Data completeness >99%; zero critical cyber incidents.

Annexures

This section presents detailed appendices referenced throughout the report. These annexures consolidate the technical evidence, cost models, equipment inventories, and pilot data analyses underpinning recommendations on hydrogen blending, infrastructure readiness, and testbed deployment.

Annexure A: Mechanical and Material Testing Protocols

Test Types and Methods:

Table 78 : Standardized Mechanical and Permeation Tests for Hydrogen Compatibility

Test Type	Description	Standard Reference
Tensile Strength Test	Measures ductility, yield strength under hydrogen exposure	ASTM E8, ASME B31.12
Slow Strain Rate Test (SSRT)	Detects hydrogen embrittlement in steel and alloys	ISO 7539-7, NACE TM0198
Fracture Toughness Test	Evaluates resistance to crack propagation under stress	ASTM E1820, API 579
High/Low Cycle Fatigue Test	Assesses cyclic stress endurance of pipes and welds	ASTM E466, ISO 12107
Permeation Testing (MDPE/HDPE)	Measures hydrogen diffusion through polymer pipelines	ISO 15105-1, ISO 11114-2

Annexure B: Safety System Specifications

Installed Equipment and Functions:

Table79: Hydrogen-Specific Safety Systems and Functional Integration

Safety Component	Function	Technical Specs / Notes
Infrared Hydrogen Leak Detector	Detects real-time hydrogen leaks in test loops	Response time < 2 seconds, 20m spacing
Pressure Relief Valves (PRVs)	Automatic pressure venting above threshold	Rated per ASME Sec. VIII Div. 1
Flame Arrestors	Prevents flame flashback from downstream combustion	Bidirectional, explosion-tested
Electrochemical H_2 Detectors	Fixed sensors at blending and PRS locations	Detection range: 0–4% H_2 in air
Fiber-optic DTS Cables	Leak localization via thermal anomaly detection	Accuracy: ±1°C over 1 km
Emergency Shutdown System (ESD)	Triggers shutdown based on SCADA alerts	Integrated with gas quality, flame, pressure

Annexure C: Appliance Compatibility Testing Setup

Test Rigs and Parameters

Table 80 : Appliance Testing Configurations for Hydrogen-Methane Blends

Appliance Type	Testing Focus	Parameters Measured
Residential Stoves	Flame behaviour, flashback	NOx emissions, ignition delay, flame speed
Industrial Burners	Blend stability, material stress	Combustion temperature, noise, flashback risk
Boilers and Heaters	Thermal output and back pressure	Flue gas composition, burner geometry response
Compressors and Valves	Seal integrity, lubrication issues	Internal leakage, wear rate, hydrogen friction

Annexure D: Testbed Equipment List

Equipment Categories

Table 81: Testbed Equipment List

Category	Equipment Examples
Mixing & Injection	Hydrogen injectors, chromatographs, blend controllers
Leak Detection	Electrochemical sensors, flame arrestors, isolation valves
Testing Equipment	Fatigue rigs, slow strain testers, ultrasonic & acoustic leak tools
Instrumentation	SCADA servers, telemetry dashboards, Wobbe index analyzers
Utilities & Support	Compressors, HVAC, fire suppression, power conditioning systems

Facility Layout Summary

Table 82 : Facility Layout Summary

Zone	Description
Storage Zone	H_2 tube trailers, cascade storage (90–100 bar)
Loop Area	NG/H_2 blend flow loops with manual & digital taps
Testing Zone	Controlled environment for leak, flow, flame tests
Control Room	SCADA terminals, digital twin monitoring

Annexure E: Hydrogen Blending Cost Comparison Model

This annexure presents a statistically driven summary of the Excel-based model used to evaluate the economic viability of hydrogen blending versus pure hydrogen transmission. The model simulates various input conditions and provides tariff outputs critical to CGD planning.

Input Assumptions and Variables:

Table 83 : Scenario-Based Economic Inputs for Hydrogen Blending Cost Estimation

Parameter	Unit	Scenario A	Scenario B	Scenario C
Hydrogen Price	₹/kg	150	180	220
Blend Ratio	% vol	5%	10%	10%
Calorific Correction Factor	%	5.2%	6.0%	6.8%
Blending Infrastructure CAPEX	₹Cr	6.5	7.2	8.0
Annual O&M Cost	₹Cr	0.45	0.53	0.61

Output Tariff Summary (₹/SCM):

Table 84 : Blended Hydrogen Tariff Components by Scenario (₹/SCM)

Cost Head	Scenario A	Scenario B	Scenario C
CAPEX Amortization	0.08	0.10	0.12
O&M Cost	0.05	0.06	0.07
Safety and Calibration	0.04	0.05	0.05
QA/QC, Shrinkage, Monitoring	0.03	0.03	0.04
Total Blended Tariff	0.40	0.44	0.48

Sensitivity Analysis:

- Every ₹10 increase in hydrogen price raises tariff by approx. ₹0.01–₹0.015/SCM.
- Increasing blend ratio from 5% to 10% raises cost by 7–10% but improves GHG offset potential by 2.1x.

This annexure provides a detailed breakdown of the Excel-based hydrogen blending cost comparison model referenced. The model is designed to analyse cost competitiveness between hydrogen blending and 100% hydrogen pipelines.

Model Input Parameters:

Parameter	Unit	Range / Default Value
Hydrogen Price	₹/kg	150 – 220
Blend Ratio	% by volume	2%, 5%, 10%
Calorific Correction Factor	%	Based on Wobbe Index
CGD Base CAPEX	₹ Cr	Project-specific
Annual O&M Cost (blending infra)	₹Cr/year	Estimated 5–8% of CAPEX

Calculated Cost Heads (`/SCM):

Cost Component	Estimated Range (`/SCM)
CAPEX Amortization	0.08 – 0.12
O&M + Calibration	0.05 – 0.07
Leak Detection + Safety	0.03 – 0.05
Gas Shrinkage / QA/QC Buffer	0.02 – 0.03
Indicative Blended Tariff	0.39 – 0.48

Outputs Generated:

- Tariff comparison for 5% and 10% blends
- Sensitivity matrix based on hydrogen cost variability
- Lifecycle cost visualization comparing blending vs pure hydrogen corridors

Model Components:

- **Input Parameters:**
  - Hydrogen procurement cost (₹/kg)
  - Target blending ratio (2%, 5%, 10%)
  - Energy equivalence corrections for H_2 vs CH_4
  - CGD operational cost base (CAPEX/OPEX)
- **Cost Heads Calculated:**
  - CAPEX amortization for blending infrastructure (skids, chromatographs, interlocks)
  - O&M costs: gas analysis, leak monitoring, and SCADA maintenance
  - Shrinkage and blending inefficiencies
- **Outputs Generated:**
  - Tariff estimates in ₹/SCM for different hydrogen price and blend scenarios
  - Lifecycle cost comparison between blending and pure hydrogen lines
  - Sensitivity charts for CAPEX vs hydrogen price assumptions

Use Cases:

- CGD operators preparing Annual Performance Review (APR) filings
- PNGRB tariff committee assessment of hydrogen clause addition
- Policymakers modelling impact of subsidy or VGF on end-user tariffs

Annexure F: International Pilot Case Studies

Hydrogen blending has been explored through a series of structured pilot projects globally, each contributing distinct insights based on their scale, blend ratios, regional regulations, and technical configurations. These pilots serve as precedents for India's emerging hydrogen integration strategy and are critical for benchmarking operational practices, safety norms, and customer engagement models. This section reviews five globally significant pilots and synthesizes their implications for India's hydrogen roadmap.

HyDeploy (United Kingdom)

Project Overview: HyDeploy was the United Kingdom's flagship hydrogen blending pilot, launched with the intent of evaluating the technical and regulatory readiness for low-level hydrogen blending in domestic gas networks. The project was delivered in three phases:

- HyDeploy 1: Conducted at Keele University, Staffordshire.
- HyDeploy 2: Expanded to a public network in Winlaton, Northeast England.
- HyDeploy 3: Aimed at integrating hydrogen across larger public infrastructure networks.

Primary Objectives:

- Demonstrate safe injection of up to 20% hydrogen by volume into the gas grid without modifying existing infrastructure.
- Confirm end-user appliance safety and combustion stability.
- Generate empirical evidence to support regulatory decisions by the UK Health and Safety Executive (HSE).

Technical Configuration:

- Blending skid with online chromatographic sensors and feedback-controlled valves.
- Supply network included 130 homes and university buildings.
- Testing of over 100 appliances: boilers, cooktops, space heaters, and water heaters.

Key Technical Outcomes:

- Blending at 20% did not require appliance replacements or safety system upgrades.
- No perceptible change in flame characteristics, heating efficiency, or gas odor.
- Leak frequency and pressure drop profiles remained unchanged.
- All materials tested (pipes, seals, gaskets) met safety thresholds.

Indian Relevance:

- Validates the feasibility of small-scale urban pilots.
- Suggests 20% blending can be achieved without retrofits under controlled conditions.
- Provides a replicable structure for stakeholder collaboration and regulator engagement.

THyGA (Europe)

Project Overview: The Testing Hydrogen Admixtures for Gas Appliances (THyGA) project is a pan-European collaboration focused on assessing the readiness of end-user appliances for hydrogen-natural gas blends. The project is funded under the European Union's Horizon 2020 framework.

Project Goals:

- Investigate operational safety and efficiency of residential and commercial appliances with hydrogen blends up to 60%.
- Classify appliances based on hydrogen tolerance levels.
- Recommend technical standards and redesign guidelines for OEMs.

Methodology:

- Over 100 appliances tested in certified laboratories across Europe.
- Evaluation parameters included:
  - Flashback susceptibility.
  - Combustion efficiency.
  - Carbon monoxide (CO) and nitrogen oxides (NOx) emissions.
  - Operational stability and thermal output.

Critical Insights:

- Most appliances performed reliably up to 20% blending.
- Beyond 30%, risk of flashback and sensor malfunction increased significantly.
- Some appliances required burner redesigns, sensor re-calibration, or software updates.

Indian Relevance:

- Highlights the risk of uncontrolled appliance deployment beyond 10% H_2 blending.
- Provides a robust database to initiate appliance certification protocols.
- Suggests consumer safety will require manufacturer compliance and targeted retrofitting.

H100 Fife (Scotland)

Project Overview: H100 Fife is the world's first full-scale demonstration of a **100% hydrogen gas**

network built from scratch for residential heating. The project is spearheaded by SGN (Scotia Gas Networks) with funding from the UK government and Ofgem.

Objectives:

- Demonstrate that residential heating systems can operate on 100% hydrogen.
- Ensure public safety through advanced appliance and infrastructure design.
- Evaluate long-term feasibility of hydrogen-exclusive networks.

System Design:

- Hydrogen generated via a multi-MW electrolyser powered by offshore wind.
- Dedicated polyethylene pipeline network to prevent material incompatibility.
- Serves up to 300 homes, with voluntary consumer participation.
- Installed hydrogen-compatible appliances: boilers, gas cooktops, meters.

Key Innovations:

- First-ever rollout of hydrogen-only meters and boilers.
- High focus on consumer awareness, safety training, and opt-in consent.
- Incorporated smart monitoring and fire detection tools.

Indian Relevance:

- Offers a model for exclusive hydrogen networks in new townships or SEZs.
- Reinforces the importance of purpose-built appliances and systems.
- Demonstrates the scale-up potential of electrolyser-based localized hydrogen grids.

HyP SA (Hydrogen Park South Australia)

Project Overview: HyP SA is a government-supported initiative launched by Australian Gas Networks to blend hydrogen into the natural gas supply of over 700 homes and businesses in the suburb of Mitchell Park.

Core Objectives:

- Deploy a 5% hydrogen blend safely and effectively within an existing residential network.
- Use the pilot to inform national blending standards and safety codes.
- Strengthen public trust through extensive communication and transparency.

System Architecture:

- Hydrogen generated via a 1.25 MW Proton Exchange Membrane (PEM) electrolyser.
- Blending managed through a central injection station with online monitoring.
- Public communication included door-to-door interactions, public forums, and Q&A sessions.

Outcomes:

- 99% consumer acceptance reported.
- No operational faults in consumer appliances.
- High data quality and system responsiveness confirmed by independent verification agencies.

Indian Relevance:

- Emphasizes the role of consumer engagement in de-risking hydrogen deployment.
- Suitable model for smaller city networks or gated communities.
- Demonstrates the effectiveness of integrating renewables with localized hydrogen supply.

Enbridge–Cummins (Canada)

Project Overview: Enbridge Gas, in partnership with Cummins, initiated a hydrogen blending pilot in Ontario to inject hydrogen into a mid-pressure distribution network serving a mix of institutional and commercial customers.

Technical Goals:

- Introduce a 2% hydrogen blend to test infrastructure response.
- Assess impact on pressure regulation, combustion efficiency, and system leak integrity.
- Establish operational baselines for future blend increases.

Key Technical Parameters:

- Used commercial grade electrolysers for onsite hydrogen production.
- Installed chromatographic analysers and programmable logic controllers (PLCs) for automated blending.
- System operated in a looped network configuration to simulate real-world demand patterns.

Results:

- No deviation in flame stability or heating rate.
- Pressure control systems operated within tolerance limits.
- No hydrogen-related incidents or alarms triggered during the trial.

Indian Relevance:

- Provides evidence for industrial park-scale pilots.
- Demonstrates the reliability of in-line blending for mid-pressure applications.
- Supports the case for distributed hydrogen generation within CGD infrastructure.

Summary of Learnings and Implications

Across all reviewed projects, the following critical learnings emerge:

1. Blending Feasibility:
    - Blending hydrogen up to 10–20% by volume is technically feasible in existing networks.
    - Requires minimal infrastructure retrofits if implemented below critical thresholds.
2. Appliance Compatibility:
    - Residential appliances must be tested and certified.
    - Older units, particularly pre-2005 models, are more prone to failure or instability.
3. Safety Infrastructure:
    - Leak detection systems, ESDs, and SCADA-based monitoring are vital.
    - Hydrogen requires specific flame arrestors and pressure relief devices.
4. Public Engagement:
    - Communication campaigns are essential for pilot success.
    - Informed consent and complaint redressal enhance public trust.
5. Policy and Regulation:
    - Each pilot was supported by clear regulatory frameworks.
    - Coordinated oversight across energy, safety, and metrology authorities is necessary.
6. Technical and Economic Scalability:
    - Electrolyser integration is feasible but requires grid synergies.
    - Decentralized production models can reduce transport risks.

Implications for India:

- Start with low-volume pilots (2–5%) in carefully selected CGD zones.
- Develop hydrogen appliance certification schemes.
- Build hydrogen cells in regulatory bodies for dedicated oversight.
- Prioritize public education, safety training, and multi-stakeholder participation.

Annexure G: Technical Feasibility of Hydrogen Blending

Material Compatibility and Embrittlement

Hydrogen has unique interactions with metallic and polymeric materials. Unlike methane, hydrogen can permeate materials more easily and induce damage mechanisms such as hydrogen embrittlement.

Key Observations:

- Hydrogen Embrittlement (HE):
  - Occurs when atomic hydrogen penetrates metal lattices, leading to loss of ductility, cracking, and brittle failure.
  - Affected materials include carbon steel, low alloy steels, and austenitic stainless steels.
  - Micro-cracks are more common in welds, elbows, and regions with high tensile stress.
- Polymeric Pipes (MDPE/HDPE):
  - While not prone to embrittlement, they are vulnerable to hydrogen permeation.
  - Long-term exposure can degrade mechanical properties under cyclic loading.
  - Field data shows that MDPE pipes tolerate up to 20% H_2 blends with enhanced joints and clamps.
- Elastomers and Seals:
  - Gasket and O-ring materials (EPDM, NBR, Viton) may swell, crack, or become brittle.
  - Compatibility testing under accelerated aging is necessary before deployment.

International References:

- ASME B31.12, ISO/TR 15916, and ISO 11114-4 provide hydrogen-specific guidelines for pipeline materials and testing protocols.

Indian Context:

- CGD networks in India predominantly use MDPE (PE80/PE100) for distribution and carbon steel for transmission.
- Pre-screening via SSRT, fracture mechanics testing, and NACE TM0177 is recommended.

Leakage Risks and Gas Behaviour

Hydrogen's molecular structure and physical properties increase its leakage potential compared to methane.

1. **Technical Characteristics:**
   - **Smaller Molecular Size:** Hydrogen (0.29 nm) can escape through micro-fissures and imperfect welds.
   - **Higher Diffusivity:** It has a diffusivity nearly three times greater than methane in most polymers.
   - **Low Viscosity:** This enhances the rate at which hydrogen escapes through porous or poorly joined materials.
   - **Wider Flammability Range:** 4–75% in air, compared to methane's 5–15%.

- **Lower Minimum Ignition Energy (MIE):** Only 0.02 mJ for hydrogen versus 0.29 mJ for methane.

2. **Testing & Monitoring:**
   - **Helium Leak Testing** (used as a surrogate for hydrogen) in high-precision systems.
   - **Soap Bubble and Pressure Decay Methods** in low-pressure pipeline joints.
   - **Electrochemical and IR Sensors** for continuous hydrogen detection.
3. **Preventive Engineering:**
   - Replace aging pipe segments, threaded connections, and legacy gaskets.
   - Use double-block and bleed systems, welded joints, and hydrogen-rated valves.

Wobbe Index, Density, Flame Speed

Hydrogen blending significantly changes the thermodynamic and combustion characteristics of the fuel gas mixture.

1. **Wobbe Index (WI):**
   - Defined as Higher Heating Value (HHV) / √ (gas density).
   - Natural gas WI: ~52–55 MJ/m³; Hydrogen: ~45 MJ/m³.
   - Blending hydrogen lowers WI, which can affect burner performance, heating efficiency, and appliance calibration.
2. **Gas Density:**
   - Hydrogen density at NTP: 0.0899 kg/m³ vs. methane at 0.717 kg/m³.
   - Lower density leads to reduced linepack (energy stored in the pipeline).
   - Affects metering and pressure regulation, especially in orifice-type flow meters.
3. **Flame Speed:**
   - Hydrogen: ~2.91 m/s (laminar); Methane: ~0.43 m/s.
   - Faster flame speeds increase the risk of flashback, burner instability, and premature ignition.
   - Design upgrades are needed for narrow-port burners and appliances with passive mixing.
4. **Design Implications:**
   - Validate combustion stability in appliances using Coanda effect burners, swirl stabilization, and dual fuel control.
   - Use automated blending skids with in-line chromatographs and calorimeters to ensure mixture uniformity.

End-Use Equipment and Appliance Compatibility

Appliances are typically optimized for methane's combustion properties. Hydrogen blends challenge these systems due to differences in flame temperature, quenching distance, and energy density.

1. **Residential Sector:**
   - Stoves, water heaters, space heaters: Most can tolerate up to 10% hydrogen without major changes.
   - Ignition Systems: May misfire or operate intermittently if not re-calibrated.
   - Flame Detectors: Some UV-based detectors may not recognize hydrogen flames.
2. **Commercial/Industrial Sector:**
   - Large-volume burners and furnaces: Performance affected at >20% H_2 due to flashback risks.
   - Process Heaters: Require redesign of burner heads, flame arrestors, and air-fuel mixing systems.

- Steam Boilers and CHP Units: OEM consultation needed to verify blend limits (typically up to 15%).

3. **International Benchmarks:**
   - THyGA project showed that newer condensing boilers handled up to 30% blends; older ones failed beyond 15%.
   - H100 and Enbridge pilots included hydrogen-specific appliances with optimized burners and sensors.

4. **Indian Recommendations:**
   - Develop a Hydrogen Appliance Certification Scheme (HACS) under BIS.
   - Mandate hydrogen blend readiness for new appliances by 2028.
   - Promote retrofitting kits with OEM warranty for older appliances.

Safe Blending Thresholds

Establishing safe hydrogen blending thresholds is a multidimensional exercise based on scientific evidence, international case studies, and domestic infrastructure testing.

1. **Key Thresholds:**
   - Up to 2%: Requires no appliance change; safe in all networks.
   - 2–5%: Suitable for early-phase pilots with monitoring.
   - 5–10%: Requires pre-approved materials and leak detection systems.
   - 10–20%: Needs certified appliances, SOPs, and risk mitigation.
   - Above 20%: Only feasible in new networks or after infrastructure adaptation.

2. **Blending Criteria:**
   - Pipeline Material: Confirm compatibility via screening matrix (see Annexure A).
   - Age and Condition: Older pipelines may need de-rating.
   - End-Use Sensitivity: Hospitals, food processing, and pharma require stricter controls.
   - Geographical Factors: Urban vs. rural network pressure, leak risk, and load profiles.

3. **Safety Protocols:**
   - Define Hydrogen Management Zones (HMZs) with real-time gas composition tracking.
   - Integrate hydrogen alarms and emergency interlocks into SCADA.
   - Periodic audits by PESO-certified agencies.

4. **Global Experience:**
   - HyDeploy: Validated 20% blending without appliance issues.
   - HyP SA: Operating safely at 5% with broad community acceptance.
   - THyGA: Recommended max blend of 20% for legacy appliance compatibility.

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