Bharat Cleantech Manufacturing Platform: Green Hydrogen Indigenisation Pathways

Accelerating an Aatmanirbhar, Green and Viksit Bharat

bharat CLIMATE FORUM

Council for International Economic Understanding

CEEW THE COUNCIL

Dalberg

As India rapidly moves towards meeting its NDCs, indigenisation of cleantech manufacturing is critical for an *Aatmanirbhar* and *Viksit Bharat*

India has national targets and projections across renewable energy and e-mobility for 2030…

300 GW Solar *installed capacity*[1]

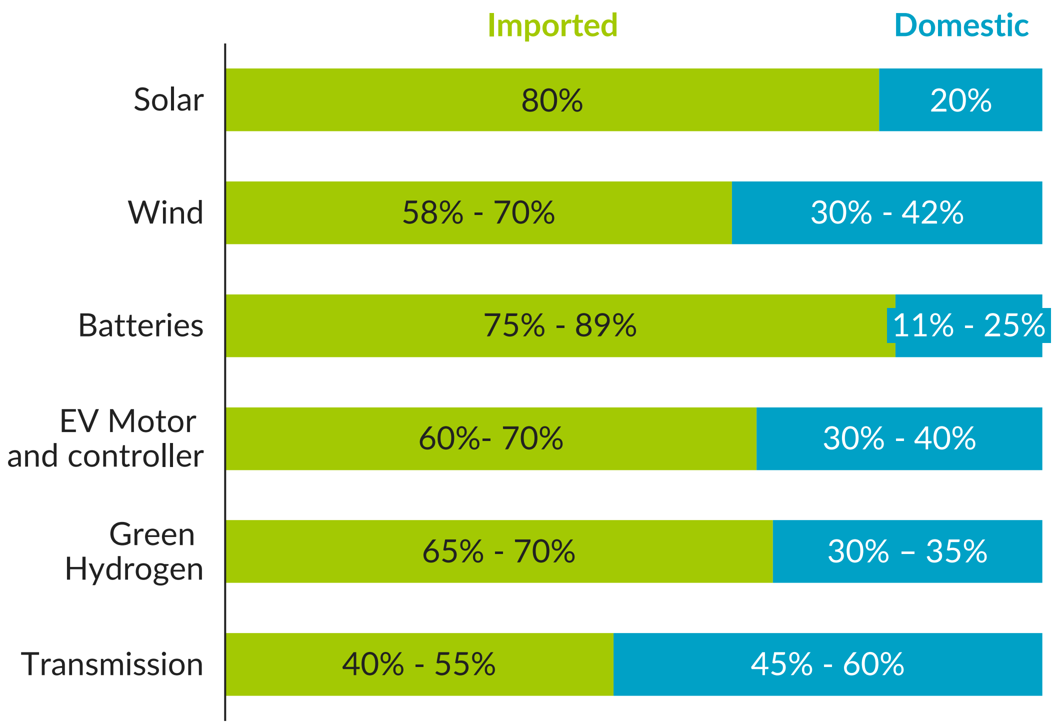
30% EV *sales penetration*[2]

100 GW Wind *installed capacity*[3]

5 MTPA Green Hydrogen *production*[4]

… but cleantech supply chains are heavily import-dependent and need to be indigenised for an Aatmanirbhar Bharat

Cleantech manufacturing import dependence across the value chain, 2023



Source: (1) MNRE; Solar capacity projection extrapolated from CEA's 2032 Solar capacity projections, assuming linear growth in capacity; (2) NITI Aayog ; (3) ET ; (4) MNRE - NGHM; MNRE, Ministry of Power; Economics Times; BNEF's installed and announced capacity; IEA, India – World Energy Investment 2024 – Analysis; NITI, India's Power Sector | Capacity & Generation Mix; PIB, India's Ethanol Push: A Path to Energy Security, CEEW, Strengthen India's Clean supply chain, 2024; Bain, India Electric Vehicle Report, 2023; Policy circle; Economist Impact, Scaling clean energy: financing and transition strategies for India's sustainable future

The Platform could support the National Manufacturing Mission to target at least 50% indigenisation of cleantech manufacturing value chains by 2030 enabling net-zero ambition with indigenous production

The Platform's potential to accelerate development of incremental indigenous capacity can be observed across sectors

Sector-wise goals

	Solar	Wind	BESS	E-mobility	Green Hydrogen	Transmission
Installed capacity						
2030 targets	300 GW[1]	100 GW[2]	230-240 GWh[3]	30@30[4]	5 MTPA[6]	648,190[7] ckm
% value chain indigenisation*						
Current levels (est.)	~20%	~35%	~20%	~35%[5]	~35%	~55%
2030 target (Proposed)	~50%	~60%	~45%	~50%	~60%	~70%

May decline due to shifting and unstable demand of domestic components amid intensified global competition

Note: *Indigenisation is domestic value contribution across cleantech value chain from raw materials to end production for all components; : (1) MNRE; (2) ET; (3) Estimated requirements under National Electricity Plan (NEP) 2023 of CEA; (4) NITI Aayog ; (5) For EV Motors and controllers; (6) MNRE - NGHM (7) 2032 target from National Electricity Plan Volume II – Transmission of CEA

Source: MNRE, Ministry of Power; Economics Times; BNEF's installed and announced capacity; IEA, India – World Energy Investment 2024 – Analysis; NITI, India's Power Sector | Capacity & Generation Mix; PIB, India's Ethanol Push: A Path to Energy Security, NEP 2023 of CEA; EV Reporter, India's electric vehicle supply chain landscape | An overview, 2024

A detailed strategy and action plan for the focus sectors would be developed to achieve these goals and objectives and build the cleantech indigenisation pathways for these sectors

Sector-wise gaps would be identified and addressed with all stakeholders across each cross-cutting theme in alignment with the National Manufacturing Mission

Enablers:
Policy recommendations; Trade partnerships; Public and private stakeholder recommendations; Demand and supply drivers; Leveraging AI for Climate and cleantech manufacturing

Sectors

Solar | Wind | BESS | E-mobility | Green Hydrogen | Transmission

Cross-cutting themes

Demand & Market Architecture	*Drive demand and adoption of output, incl.* ***Quality Control Orders (QCOs)***
R&D & Product Innovation	*Drive technology sharing, adoption and indigenous R&D*
Upstream Raw Materials & Critical Inputs	*Streamline raw material sourcing (e.g. critical rare earth elements; bio-energy feedstock etc.)*
Capital Equipment & Infrastructure	*Address machinery sourcing & infrastructure requirements (e.g., grid connectivity)*
Talent & Workforce	*Bridge skilling gaps for specialised and non-specialised workforce*
Financing & Taxation	*Identify financial instruments and mechanisms to reduce the funding gap* *Identify levers to improve* ***Ease of Doing Business*** *to attract investments*

TABLE OF

Contents

Council for International Economic Understanding

Dalberg

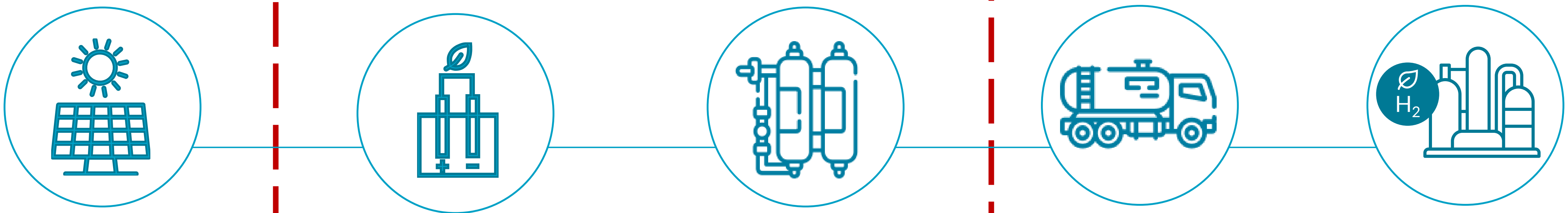
CEEW

SECTION ONE

CURRENT LANDSCAPE AND GREEN HYDROGEN INDIGENISATION PATHWAYS FOR INDIA

Green hydrogen value chain extends from renewable energy production and distribution to hydrogen storage and end-use; Our focus is on the electrolysis and green hydrogen production segments

Green Hydrogen Value Chain



Renewable Energy Production & Distribution

Solar, wind, or hydro power is generated and delivered to electrolysis systems (covered in solar and wind indigenisation presentations)

Electrolysis

Alkaline, PEM, AEM, or SOEC electrolysers convert demineralised water or steam into H_2 and O_2

Purification & Compression

Cleaning, and compression of raw hydrogen

Storage & Transport

Storage and transport of hydrogen as compressed gas, liquid hydrogen, or chemical carriers (i.e. ammonia, methanol, metal hydrides)

End-Use

Usage in sectors such as steel, refineries, fertilisers, mobility, city gas distribution, etc. replacing fossil fuels

Our current focus

India's focus has evolved from the early 2000's, moving from adoption of hydrogen as an alternative fuel for decarbonization to becoming a global hub for green hydrogen production by 2030

Evolution of focus on hydrogen in India

2003
Ministry of New and Renewable Energy (MNRE) set up the **National Hydrogen Energy Board (NHEB)** to identify pathways for adoption of hydrogen as an alternative fuel

2006
National Hydrogen Energy Roadmap (NHERM) launched to shape policy, financing, and infrastructure for bridging technological gaps across the hydrogen value chain by 2020

2016
Dept. of Science & Technology (DST) launched **Hydrogen & Fuel Cell Program** to fund R&D across production, storage, delivery, and fuel-cell end uses

2023
National Green Hydrogen Mission (NGHM) launched with an aim of making India a green hydrogen production hub and an outlay of **INR 19,744 crore** up to FY 29-30

2023
MNRE launched **Green Hydrogen R&D Roadmap** setting priority R&D themes for electrolysers, catalysts, membranes, system integration, storage, and transport

2024
Launched **Strategic Interventions for Green Hydrogen Transition (SIGHT)** with key supply-side incentives for electrolyser manufacturing and green hydrogen production

2025
SECI SIGHT program tenders auctioned 750 KTPA of green ammonia capacity at fixed prices using SIGHT incentives

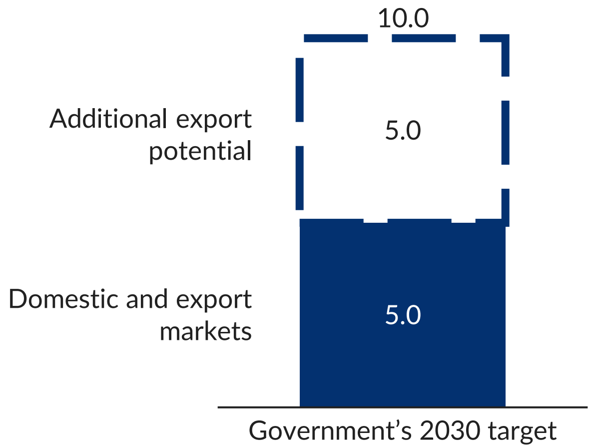
Overall hydrogen focus | Green hydrogen focus

Source: ADB Working Paper, India's Green Hydrogen Review & Perspective, 2025; MNRE, National Green Hydrogen Mission website, accessed 2025

India has set an ambitious target of producing 5-10 MTPA green hydrogen by 2030, but most green hydrogen projects are still to start construction

India has set bold 2030 targets and developed supportive policies to spur green hydrogen production capacity

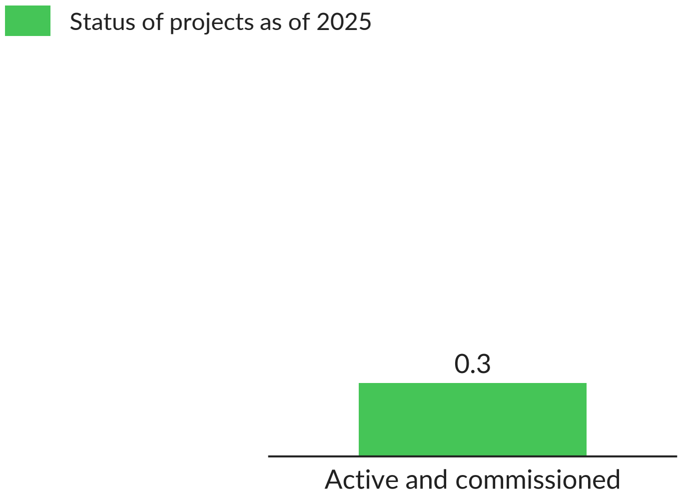
India's green hydrogen production capacity targets
Million tonnes per annum (MTPA), 2030



- **The above targets have been accompanied by government policies such as SIGHT:** Under the Strategic Interventions for Green Hydrogen Transition (SIGHT) scheme, the government has set aside **INR 13,050 Crores** for incentivising green hydrogen production

This has led to strong momentum in commitments, but only 0.3 MTPA is currently active

India's cumulative green hydrogen production capacity
Million tonnes per annum (MTPA), 2025-30

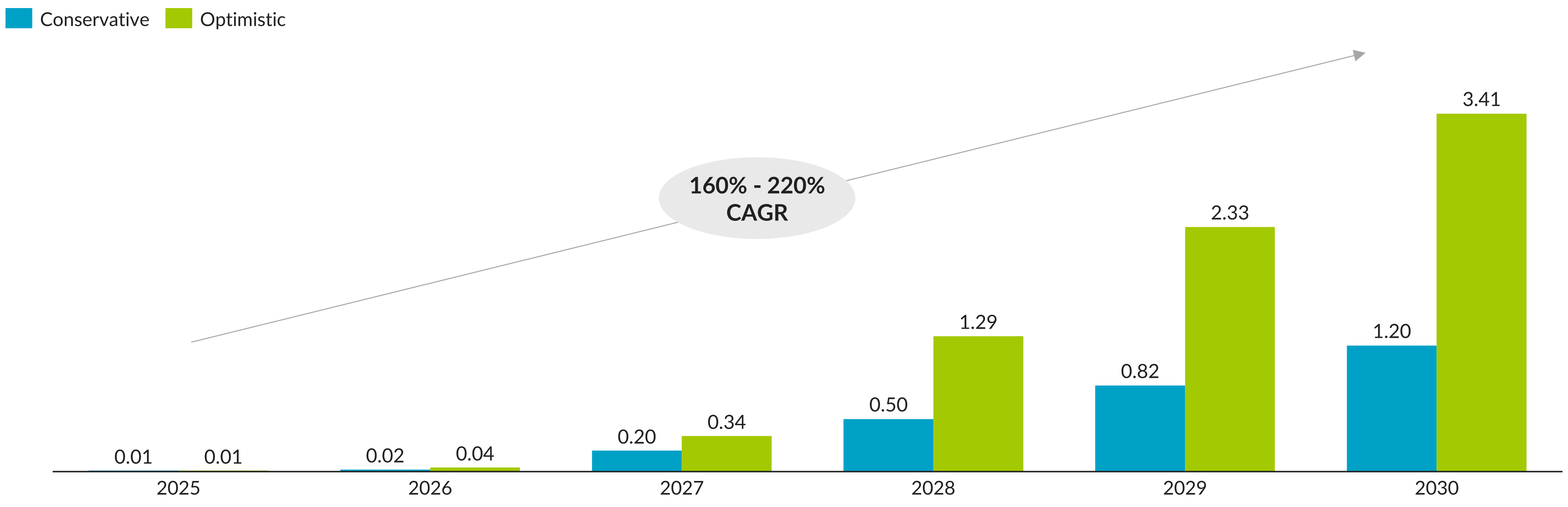


- Projects for another **0.4 MTPA** are planned and under construction, and **11.2 MTPA** are announced but yet to start construction
- Construction of this announced capacity will need to start at least by 2027 to be ready for 2030 as it takes ~3 years to commission a plant

Source: NGHM Project Database, accessed 2025; NGHM website, accessed 2025; Harnessing Green Hydrogem NITI Aayog, 2022; SECI, 2024; Dalberg analysis

This lag in pace is driven by insufficient demand from end-use industries; Our estimates suggest that total demand would reach only ~1.2-3.4 MTPA by 2030, including export markets

Green hydrogen total projected demand including domestic and exports – Conservative and optimistic scenarios
MTPA, 2025-2030



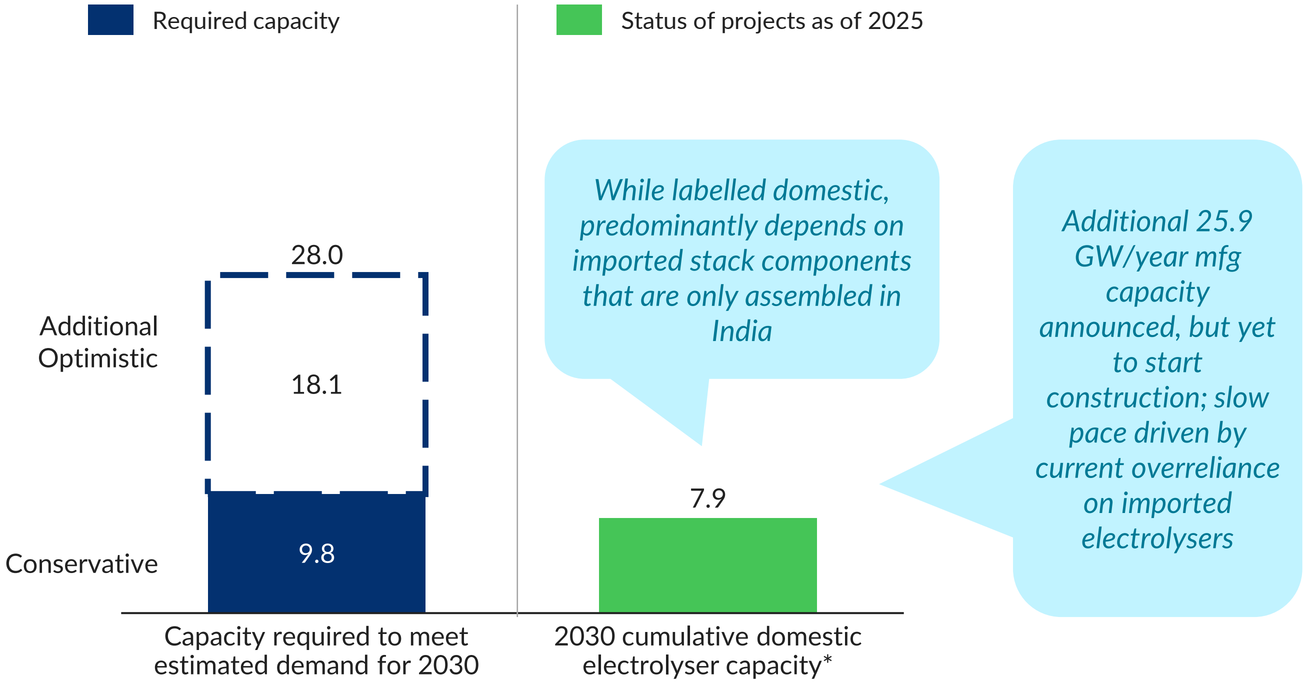
Projected demand for 2030 captures ongoing and planned projects within sub-sectors, as well as the result of proposed policy interventions to boost demand across these sub-sectors

Source: Harnessing Green Hydrogen, NITI Aayog, RMI, 2022; Financing Green Hydrogen in India, BNEF, CEEW, 2024; CEEW and Dalberg analysis

Achieving true domestic capacity for meeting 2030 demand will require policy interventions to boost domestic value addition in electrolysers manufactured in India

Domestic capacity to reach 7.9 GW cumulatively with many more projects announced; however, mostly anchor on assembled stacks

Required electrolyser capacity vs. India's cumulative domestic electrolyser capacity*
Gigawatts, 2030



Boosting true domestic electrolyser capacity by 2030 will require policy interventions

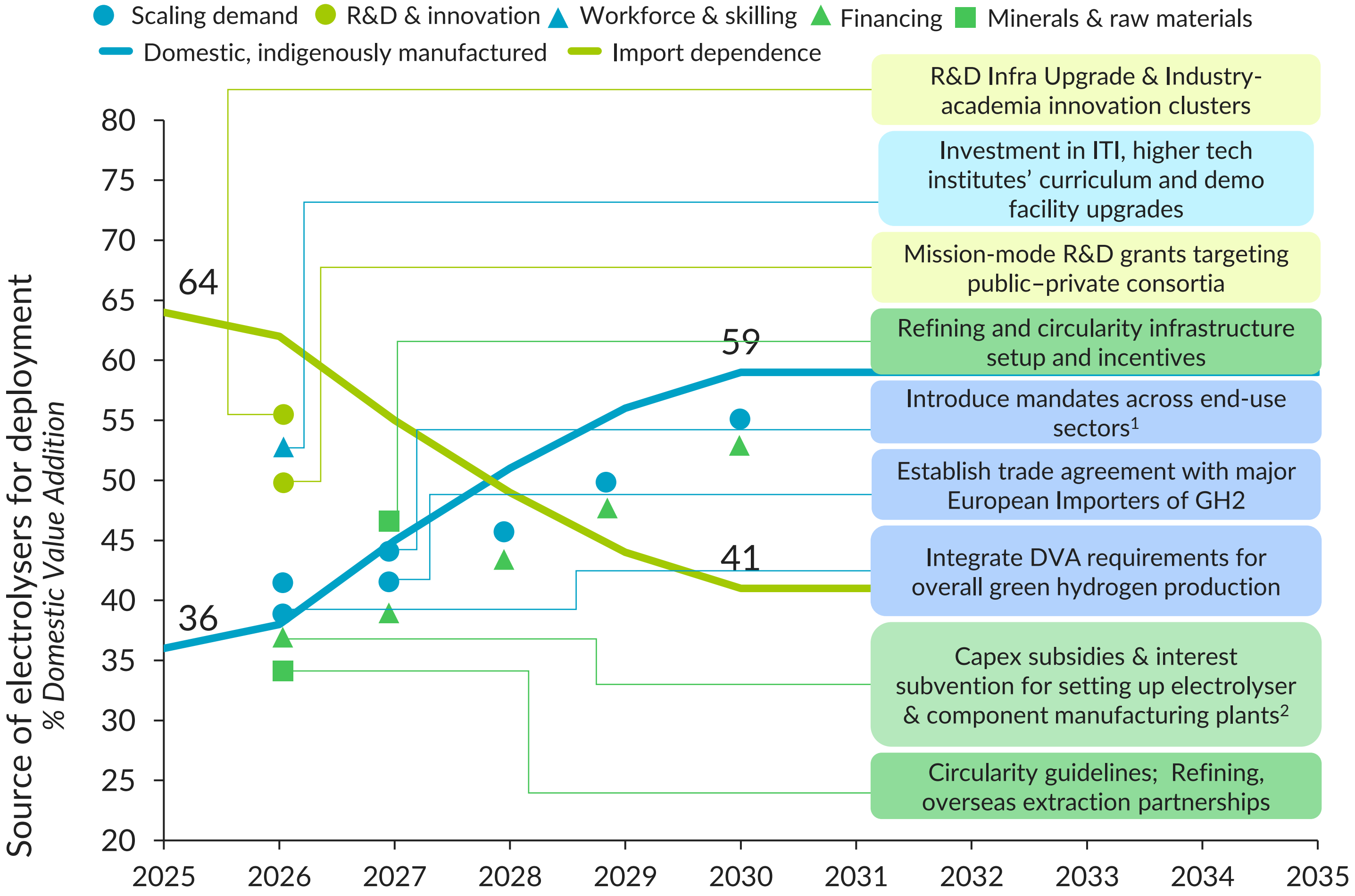
- Most green hydrogen projects in India currently rely on imported electrolysers, driving the slow pace of construction of domestic electrolyser capacity
- Currently, **domestic value addition (DVA) requirements are specified for electrolyser manufacturing incentives** under SIGHT Component I
- However, these **incentives are not differentiated** for **indigenously manufactured stack components** vs. those that are imported and **only assembled in India**
- There is a need for **policy support to boost DVA** within domestic electrolysers, as well as **greater usage of domestic electrolysers in green hydrogen production projects overall**

Note: Based on interviews with industry representatives, electrolyser components are still predominantly (~60–80%) imported and assembled domestically. Further indigenisation is possible and requires substantial investments in R&D and manufacturing, which are precluded by a lack of sufficient demand; 2030 cumulative domestic electrolyser capacity considers 75% utilisation of current electrolyser factories with 2.1 GW/year capacity, between 2026-2030. An additional 25.9 GW/year manufacturing capacity is planned or announced, but may all not come live by 2030 due to meek demand and slow investments
Source: 1. How can Hydrogen Electrolysers be made in India, CEEW, 2024; 2. CEEW and Dalberg analysis; 3. NGHM website, accessed 2025; 4. SECI, 2024

India can achieve 59% domestic value addition (DVA) in electrolyser manufacturing by 2030 through a focused push on indigenisation and scale-up of local manufacturing

To accelerate domestic electrolyser capacity growth and boost DVA, key policy interventions would be required

Green Hydrogen Indigenisation Pathway to reduce import dependence



Together, these interventions will enhance the DVA from 36% to 59%[4] by 2030

- The **current DVA** across alkaline and PEM electrolysers stands at **36%**[3]
  - For **Alkaline electrolysers**, the current DVA is 50% for the balance of plant (BOP) and 25% for the stack
  - For **PEM electrolysers**, the current DVA is 50% for the balance of plant (BOP) and 25% for the stack
- **DVA can be enhanced from 36% to 59% by 2030** through the indigenisation of key stack components and domestic manufacturing of a large part of the BOP
- Achieving this target will require **coordinated action across critical areas** viz demand acceleration, R&D, upstream raw materials, workforce and skilling, and financing
  - The milestones required across these focus areas from 2025 to 2030 are depicted in the graph on the left and elaborated upon in the subsequent slides

Notes: 1. Blending mandates will be phased from 2026-30. 2. Fiscal incentives will be phased from 2026-30; Numbers are based on preliminary analysis and are subject to changes based on industry expert inputs; Source: How can Hydrogen Electrolysers be made in India, CEEW, 2024; Dalberg analysis; NGHM website, accessed 2025; SECI, 2024 3. Of the total electrolyser capacity by 2030, it is estimated that 80% will comprise of Alkaline systems and 15% of PEM systems 4. This assumes that domestic electrolyser manufacturing projects will be constructed and commissioned in time to be part of green hydrogen plants by 2030. If this construction gets delayed, then green hydrogen plants would have to rely on imported electrolysers, thus pushing the achievement of 59% DVA beyond the 2030 timeframe

Domestic Value Addition (DVA) | Alkaline Electrolysers: While BoP components can achieve 75% DVA by 2030, stack DVA can increase to 57%, with the major potential coming from bipolar plates and PTL

Bipolar Plate (BPP)

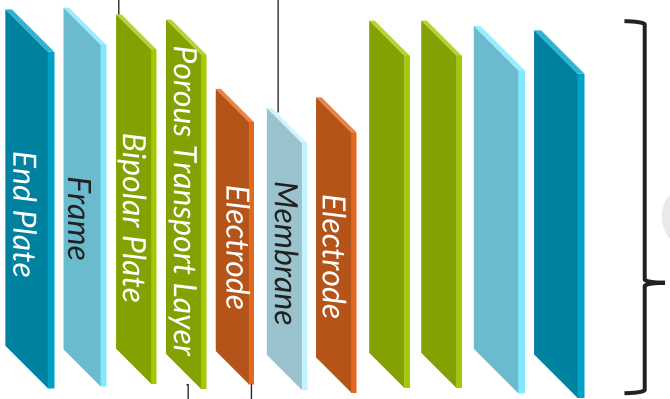
Current DVA : *0%* ➡ **Potential DVA : *99%***

The **complete manufacturing** of the BPP (Ni-coated stainless steel) can be done in-house, offering **significant scope for DVA**, with nickel being the only imported component

Membrane

Current DVA : *0%* ➡ **Potential DVA : *35%***

If India develops the technical capability to integrate domestically available polymer and zirconium dioxide into functional membranes, the DVA potential would be significant (with zirconium dioxide as the only imported material)[4]



1\. Single Repeating Unit (SRU)

Porous Transport Layer (PTL)

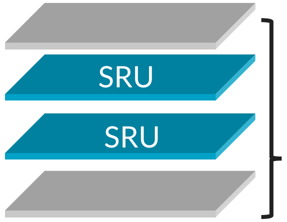
Current DVA : *0%* ➡ **Potential DVA : *50%***

There's scope for DVA in terms **of manufacturing the PTL (Nickel foam)** through electrodeposition and sintering, however the core component i.e., Nickel would need to be imported

Electrodes

Current DVA : *0%* ➡ **Potential DVA : *15%***

DVA is possible through **in-house electrode manufacturing**, but since the electrode materials (which account for the bulk of the cost) will still be imported, the overall value addition remains limited



Current collect plate and two end plates per stack

2\. **Stack**

Current DVA : ***25%*** ➡ Potential DVA : ***55%***

Current **stack DVA is 26%** due **to indigenisation of components** such as end plate, frame, balance of stack and sealants & gaskets

3\. **Balance of Plant (BoP)**

Current DVA : ***50%***[4] ➡ Potential DVA : ***75%***

Many balance-of-system components such as **power electronics** and **process control systems** (sensors) are not yet indigenised but **could be localised to a great extent** by leveraging strong capabilities from adjacent industries[4]

4\. Electrolyser

Together, the stack and BoP form the electrolyser

Notes: 1. DVA is calculated as the share of component costs that can be indigenised, i.e., the portion of costs from processes or parts that can be made locally. 2. Potential DVA is equivalent to the DVA that can be achieved by 2030. 3. DVA calculations have been done basis internal Dalberg analysis and using the following sources: CEEW, IRENA, The Oxford Institute for Energy Studies 4. Insights collected from interviews with experts

Domestic Value Addition (DVA) | PEM Electrolysers: While BoP components can achieve 75% DVA by 2030, stack components' DVA can increase from 24% to 40%, with major potential coming from PTL

Bipolar Plate (BPP)

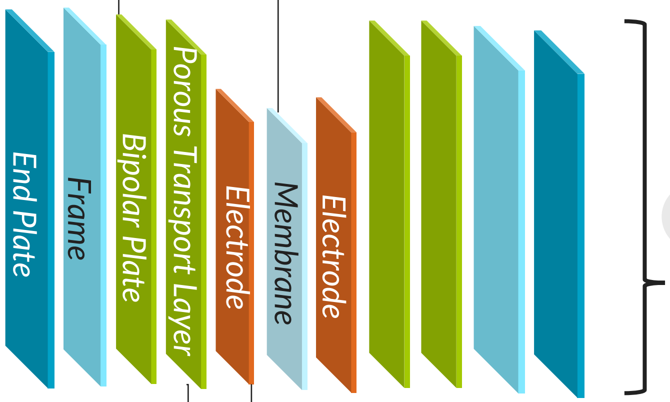
Current DVA : *100%* ➡ Potential DVA : *100%*

The complete manufacturing of the BPP (including blanking, stamping, and gold coating of the stainless-steel roll) is carried out **entirely in-house**, making it a fully domestically value-added process.

Membrane

Current DVA : *0%* ➡ Potential DVA : *0%*

DVA for Nafion membranes is likely to remain absent by 2030. However, **significant R&D, tech partnerships,** and expiry of Nafion patent could lead to development of substitutes for imported Nafion in the long run



1. Single Repeating Unit (SRU)

2. **Stack**

Current DVA : *25%* ➡ Potential DVA : *40%*

Current **stack DVA is 24%** due **to indigenisation of components** such as BPP, end plate, frame, balance of stack and stack assembly

3. **Balance of Plant (BoP)**

Current DVA : *50%*[4] ➡ Potential DVA : *75%*

Many balance-of-system components such as **power electronics** and **process control systems** (sensors) are not yet indigenised but **could be localised to a great extent** by leveraging strong capabilities from adjacent industries[4]

Porous Transport Layer (PTL)

Current DVA : *0%* ➡ Potential DVA : *60%*

There is **significant potential** for DVA by **processing Ti powder** (for the anode PTL) **and resin polyacrylonitrile (PAN)** (for the cathode PTL) in-house, with only raw materials (such as Ti powder) needing to be imported

Electrodes

Current DVA : *0%* ➡ Potential DVA : *1%*

DVA is possible through **in-house electrode ink preparation and coating**, but since the electrode materials (Pt, Ir etc.) account for the bulk of the costs and will be imported, the overall value addition remains miniscule

4. Electrolyser

Together, the stack and BoP form the electrolyser

Notes: 1. DVA is calculated as the share of component costs that can be indigenised, i.e., the portion of costs from processes or parts that can be made locally. 2. Potential DVA is equivalent to the DVA that can be achieved by 2030. 3. DVA calculations have been done basis internal Dalberg analysis and using the following sources: CEEW, NREL (2024), NREL (2019) 4. Insights collected from interviews with experts

A coordinated strategy across demand creation, R&D, and upstream raw materials can unlock India's green hydrogen ecosystem and drive domestic value creation

Demand & Market Architecture

- Introduce **end-use obligations in refinery & CGD sectors,** and enable **import substitution in fertilisers** supported by guaranteed offtake agreements
- **Provide subsidy** for 3 major sectors, **fertiliser, CGD, and steel**, to minimize price impact on the consumers which can be eventually tapered down
- Develop a **weighted DVA score** for electrolysers favoring in-house component manufacturing and **embed DVA in green hydrogen production incentives**

Overall **Government** fiscal incentives required:
INR 5,836 Cr

R&D & Product Innovation

- Enable greater **collaboration among industry and academia** through joint initiatives
- **Establish national hydrogen R&D hubs and open-access testbeds** to pool infrastructure, talent, and reduce setup costs for startups, academia, and MSMEs
- Upgrade and expand **1–2 development labs and 4–5 testing labs** under a coordinated national mission to accelerate prototype-to-commercial transitions

Overall **Government** investment :
INR 125 Cr

Upstream Raw Materials & Critical Inputs

- Set up **in-house facilities to process and manufacture electrolyser components** thereby accruing import bill savings upwards of ~**INR 9,000 Cr**
- Promote **circularity pathways** for platinum group metals (PGMs) and other critical minerals and **substitution R&D** through targeted incentives to reduce import dependence and exposure to supply shocks

Overall **Government** investment required:
-

Detailed in Annex: *Demand Acceleration*; *R&D Ecosystem*; *Upstream Raw Materials*

Source: Guaranteed offtake agreements key to unlock India's green H2 potential, Clarifications-01 SIGHT-EM T-II; Academia and industry experts

Complementing ecosystem enablers, targeted investments in manufacturing infrastructure, skilling, and financing will anchor India's transition toward self-reliant green hydrogen production

Capital Equipment & Infrastructure

- **Leverage existing industrial capabilities** to the extent possible for coating & sintering processes to reduce new capital needs
- **Invest in new machinery for membranes and bipolar plates**, where domestic capacity or retrofitting potential is low
- **Partner with global equipment suppliers** to localise high-precision casting and stamping machinery

Incremental capex investment required:
INR 12,120 Cr

Talent & Workforce

- Develop **specialised hydrogen curricula** and **'Train the Trainer' programs** across engineering colleges and it is
- Build applied **learning infrastructure and demo facilities** to strengthen hands-on training for O&M, manufacturing, and safety skills
- Create **industry-linked apprenticeships and R&D skilling pathways** to connect academia, startups, and enterprises in the green hydrogen value chain

Overall **Government** investment:
INR 200 Cr

Financing & Taxation

- **Drive additional investment** for domestic capacity setup and expansion of **membrane manufacturing, bipolar plate manufacturing, and PTL and bipolar plate coating processes**
- Provide **interest subvention** of ~INR 236 Cr on capex financing for component manufacturing machinery
- **Provide INR 1,980 Cr** to cover price premium of domestically manufactured electrolysers

Overall **Government** fiscal incentives required:
INR 2,220 Cr

*Achieving **55% indigenisation** in electrolyser manufacturing requires ~**INR 8,400 Cr** total government investment by 2030 and could result in upwards of **INR 9,000 Cr of** total import bill savings.*

Detailed in Annex: *Capex and Infra*; *Workforce*; *Financing*

There are several opportunities that could be captured through value chain indigenisation – the green hydrogen indigenisation pathway could help capture these opportunities till 2030

Up to ~INR 99,000 Cr
Annual electrolyser domestic market potential by 2030[1]

Upwards of ~INR 9,000 Cr
Cumulative import bill savings from 2025-30

Up to ~92,000 direct jobs
Across electrolyser manufacturing and green hydrogen production by 2030

Up to ~INR 20,000 Cr
Annual electrolyser export potential by 2030[2]

~INR 12,100 Cr
Capex financing gap closure for electrolyser and component manufacturing by 2030[3]

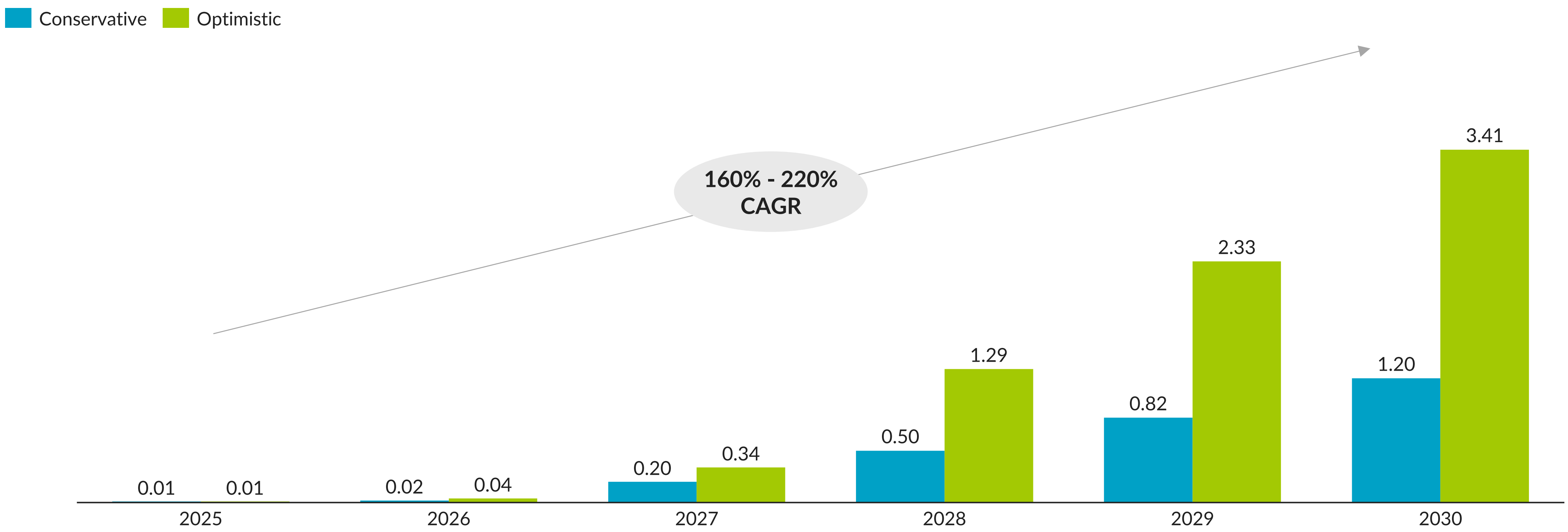
Notes: 1. Assumes 22 GW of domestic alkaline electrolyser capacity and 4GW of domestic PEM capacity by 2030; assumes cost of USD 400/kW for alkaline electrolysers and USD 540/kW for PEM electrolysers; 2. Assumes 5.8GW of alkaline electrolyser export potential optimistically by capturing 10% of the international market not already captured by green hydrogen exports; 3. Includes investment required for electrolyser gigafactories and machinery for domestic component production
Source: Dalberg analysis

SECTION TWO

GREEN HYDROGEN INDIGENISATION PATHWAYS FOR INDIA: DETAILED BY CROSS-CUTTING THEMES

1 Demand | Total green hydrogen demand from domestic and export markets could grow to reach ~1.2 – 3.4 MTPA by 2030

Green hydrogen total projected demand including domestic and exports – Conservative and optimistic scenarios
MTPA, 2025-2030

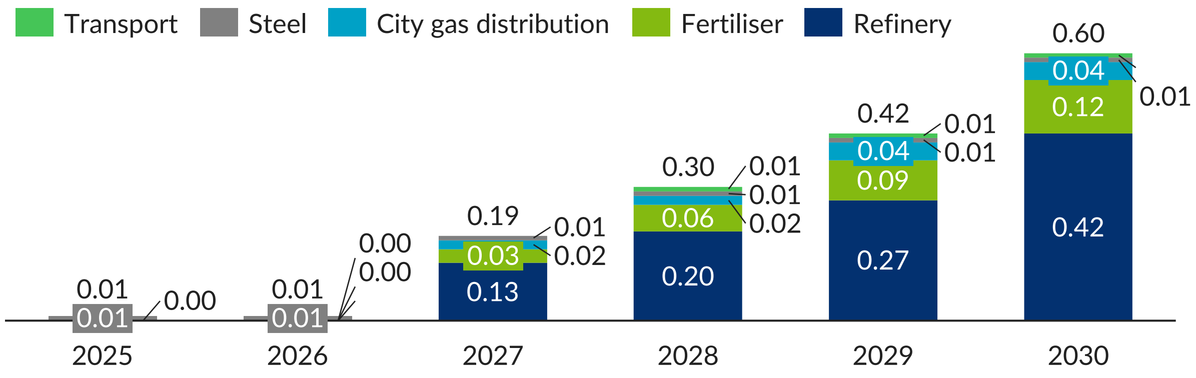


Source: CEEW and Dalberg analysis

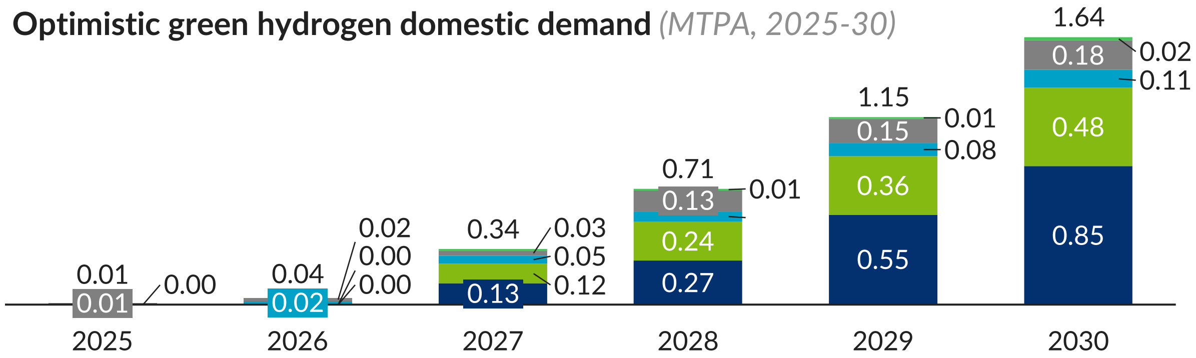
Demand | As opposed to the government's 5 MTPA target, domestic demand is projected to reach only ~0.6 MTPA conservatively, and ~1.6 MTPA optimistically by 2030

Domestic demand could grow to 0.6 MTPA conservatively, and 1.6 MTPA optimistically by 2030, with refinery forming a major sector

Conservative green hydrogen domestic demand *(MTPA, 2025-30)*



Optimistic green hydrogen domestic demand *(MTPA, 2025-30)*



Primary reason for domestic demand lagging the expectations is the prohibitive costs

- **The projected domestic demand for green hydrogen by 2030 would still fall short of the intended 5 MTPA target**
- **This can be mainly attributed to the currently prohibitive costs…**
  - Current production costs—**$3.5–$5 per kg** of green hydrogen vs. $2.3 - $2.5 per kg of grey hydrogen typically are not yet competitive
  - Driven by RE electricity that forms 50-70% of the green hydrogen production costs
- **…and insufficient demand surety in high-potential sectors like oil refining**
  - Only a small capacity of ~42 ktpa tendered by refineries as of August 2025

Notes: 1. Conservative scenario for fertilisers corresponds to tendered green ammonia capacity; optimistic scenario assumes 100% import substitution of ammonia starting 2027. 2. Refinery sector was assumed to reach 309 Mtpa of capacity by 2030 from 256 in 2024; conservative scenario corresponds to a gradual green H2 blending from 5% in 2027 to 15% by 2030 for refiners with >50KTPA H2 consumption; optimistic scenario corresponds to a gradual blending from 5% in 2027 to 30% by 2030 for refiners with >50KTPA H2 consumption. 3. Additional 6,800 TPA authorised to JSW Energy under the SIGHT scheme has been factored in 2025 demand over and above the built 3,800 TPA

Source: Harnessing Green Hydrogen, NITI Aayog, RMI, 2022; Financing Green Hydrogen in India, BNEF, CEEW, 2024;Financing Green Hydrogen in India, BNEF, CEEW, 2024; How can Hydrogen Electrolysers be made in India, CEEW, 2024; SECI, 2024; From Promise to Purchase: Unlocking India's Green Hydrogen Demand, Bain, 2025; Dalberg analysis

1 Demand | Even to reach the ~0.6–1.6 MTPA by 2030 in domestic demand, a phased approach to mandating green hydrogen usage in refineries and city gas networks would be crucial

Key recommendations

Refinery:

- Introduce gradual mandates, starting with **5% of total H2 usage to be green in 2027 to 15% in 2030 in the conservative scenario**; gradual mandate starting with **5% of total H2 usage to be green in 2027 to 30% in 2030 in the optimistic scenario**
- Mandate to be introduced for refiners with total >50KTPA H2 consumption; refiners would have the flexibility to pick the refineries where economies of scale can be achieved, as long as total portfolio blending %s are achieved
- Even a 30% green hydrogen blend (at USD 4.5/kg), would only lead to a <2% average increase in the price of petroleum products, making this the most suitable sector for demand acceleration

Fertiliser:

- Tenders for green ammonia in non-urea fertiliser plants will lead to a **25% import substitution (conservative)**; additional tranches can lead to a **100% import substitution (optimistic)** of ammonia
- Lesser potential to increase blending as sector is already heavily subsidized due to its link with farming
- However, the record-low green ammonia prices discovered in the 2025 SECI tenders rely on subsidies worth **INR 1500 Cr** from the SIGHT scheme covering 724 KTPA of green ammonia; an additional ~**INR 5000 Cr** would be required for the optimistic scenario

City gas distribution:

- Mandate **2% of green H2 blending by 2030 conservatively**, and **5% optimistically**, based on proven use cases of blending piped natural gas in city gas distribution with hydrogen. Blending to be done for PNG (commercial & industrial) and CNG.
- For blending, target the **top 10 states**[1] basis the **pipeline/CNG station density** and **CGD sales volume** to strategically locate green hydrogen plants that can supply multiple high-volume CGD networks
- A 2% blend (by volume) would lead to a ~1% increase in the price of natural gas ; a 5% blend would cause a ~4% increase

Source: Dalberg and CEEW analysis; Harnessing Green Hydrogen, NITI Aayog, RMI, 2022; Financing Green Hydrogen in India, BNEF, CEEW, 2024; Charting the future: Green hydrogen expansion and PNGRB's pivotal role, ICF, The World Bank, PNGRB, 2024; Charting the Future: Green Hydrogen Expansion and PNGRB's Pivotal Role, ICF, 2024; SIGHT Scheme 2A Guidelines, MNRE, 2024; SIGHT 2A Amendments, MNRE, 2024 Notes: 1. Basis internal Dalberg analysis the top 10 states for CGD blending in decreasing order of priority are: Gujarat, Delhi, Haryana, Uttar Pradesh, Maharashtra, Karnataka, Punjab, Rajasthan, Tamil Nadu and Telangana

Demand | Additionally, import substitution of grey ammonia with green ammonia in the fertiliser sector along with some adoption in the steel sector can be expected

Key recommendations

Steel:

- Hard to abate sector and hence green hydrogen adoption will have to be led by the government
  - The NGHM has already sanctioned pilot projects for the use of green hydrogen in steelmaking
  - The National Mission on Sustainable Steel envisions incentives worth INR 5000 crore till 2030 for emission intensity reduction
  - The Carbon Credits Trading Scheme also deploys market-based mechanisms to cap emission intensity and incentivize reductions year-on-year
  - These schemes, depending on their implementation, will lead to accelerated hydrogen use but likely beyond 2030

Transport:

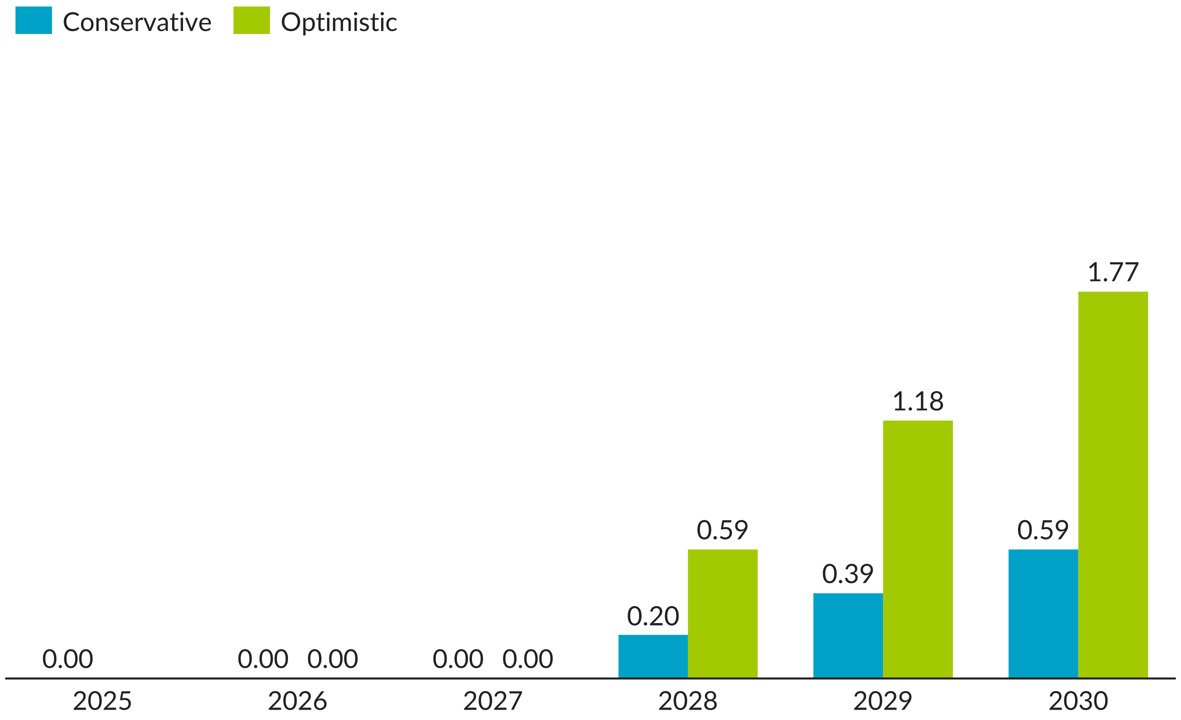
- H_2-powered vehicles are being trialled by various manufacturers and operators, with 37 testbeds sanctioned under the NGHM alone
- Several state-level green hydrogen policies provide financial support for around 1000 trucks/buses and 50 H_2 refuelling stations by 2030 amounting to over INR 500 crore
- The central government additionally targets the deployment of 1000 hydrogen-fuelled vehicles by 2030
- Beyond these initiatives, scope for market-driven growth may be limited by cost-competitiveness until well beyond 2030

Source: Harnessing Green Hydrogen, NITI Aayog, RMI, 2022; Financing Green Hydrogen in India, BNEF, CEEW, 2024; Dalberg and CEEW analysis

1 Demand | Exports could form another ~0.6 to 1.8 MTPA by 2030, based on green hydrogen commitments of global countries, especially from Europe

Export markets are expected to play a crucial role for making India a green hydrogen hub, complementing domestic demand

Green hydrogen export demand – Conservative and optimistic scenarios
MTPA, 2025-30



Trade agreements with major European importers of green hydrogen required to tap into this demand

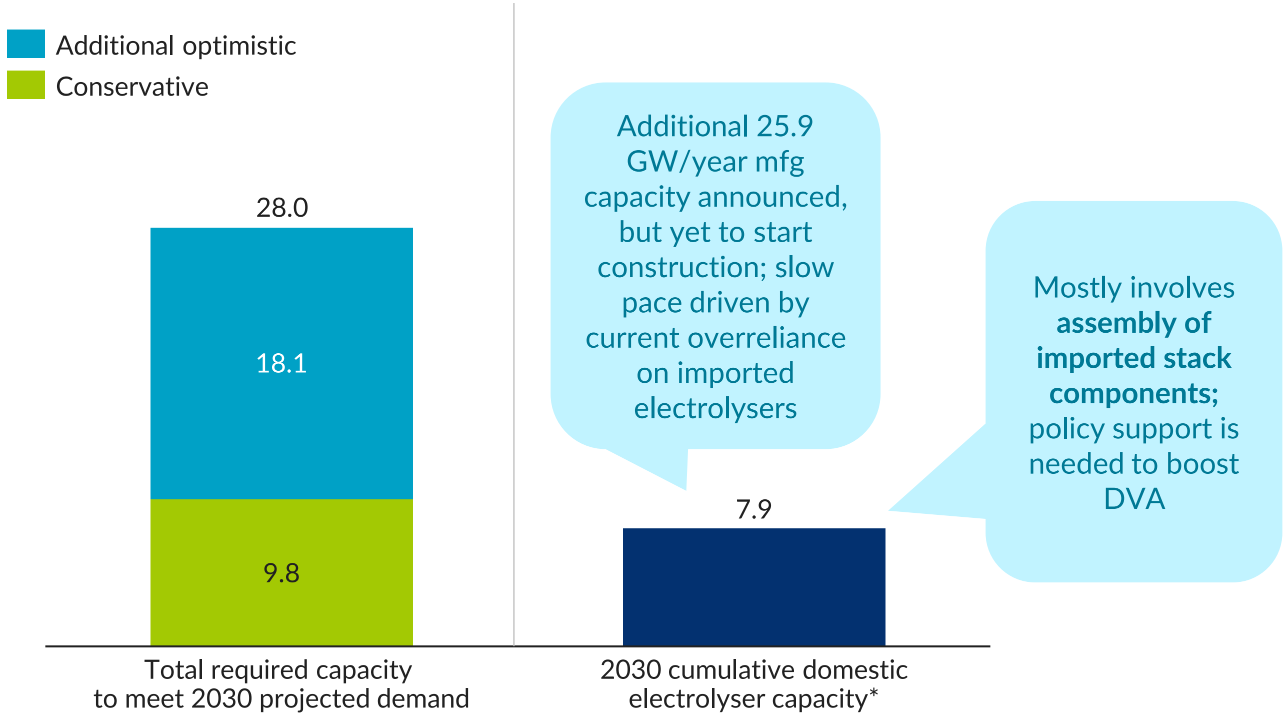
- **Establish trade agreements with major European importers of hydrogen**
  - International green hydrogen imports are expected to form **~6 MTPA** by 2030[1]; Europe, Japan, Singapore, South Korea and the UK could be major importers[2]
  - Our conservative scenario assumes we capture 10% of this market, while the optimistic scenario assumes a 30% of the market, giving us **0.6 MTPA – 1.8 MTPA**
  - Trade agreements with these countries would be important while setting up dedicated green hydrogen corridors to connect India's production clusters to European markets
- **Explore potential for long-term pathway on export of cell and stack components that can be produced in India**
  - Consider export of indigenously produced membranes, PTLs, electrodes, bipolar plates to above countries
  - However, this pathway may not materialize by 2030 owing to nascent supply chains and manufacturing

Note: Export potential calculated based on a meta-analysis of 2030 green hydrogen production and consumption targets for various countries. Those countries that project a higher consumption than domestic production were considered import-dependent.
Source: 1. Financing Green Hydrogen in India, IEA, 2024; 2. World Bank, WITS, accessed 2025; 3. Dalberg and CEEW analysis

Demand | Cumulative domestic electrolyser capacity at 7.9 GW with more announced projects; however, mostly involves imported stack components that are assembled in India

While domestic capacity to reach 7.9 GW with many more projects announced, policy shifts are needed to ensure true domestic value creation

Required electrolyser capacity vs. Cumulative domestic electrolyser capacity*
Gigawatts, 2030



Challenges in boosting domestic capacity

- While DVA requirements are specified for electrolyser incentives, **they are the same for manufacturers who make components in-house, as well as those who only assemble them**
- Moreover, **overall green hydrogen production incentives do not specify domestic electrolyser procurement requirements**
  - This means that projects could gain access to incentives **even without having a locally manufactured electrolyser**

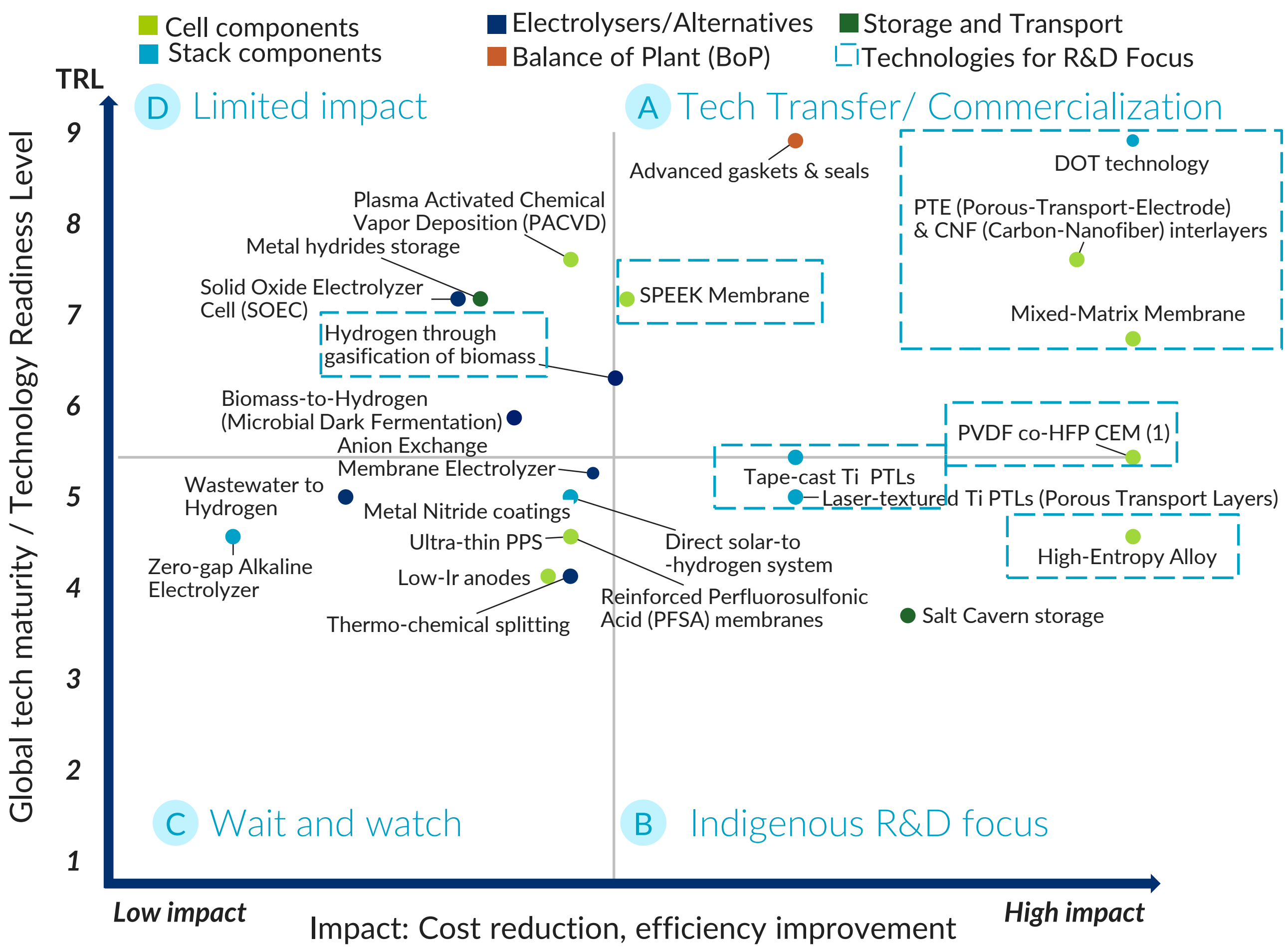
Key recommendations

- Develop a **weighted DVA score for electrolysers** such that a higher weight is assigned to making components in house, thus discouraging only assembly
- Embed the **DVA metric into SIGHT Component-II** rules (which provide a per kg incentive to produce green hydrogen). The rules should require bidders to meet **a minimum DVA score** to qualify and offer additional incentive top-ups for higher localisation of strategic components
  - However, this could mean a tradeoff for the overall pace of growth of the green hydrogen projects

Notes: *2030 cumulative domestic electrolyser capacity considers 75% utilisation of current electrolyser factories with 2.1 GW/year capacity, between 2026-2030. An additional 25.9 GW/year manufacturing capacity is planned or announced, but may all not come live by 2030 due to meek demand and slow investments.
Sources: CEEW and Dalberg analysis; NGHM website, accessed 2025

2 R&D | India can accelerate indigenisation by focusing on cost-saving tech transfer, scaling up proven membrane/stack innovations, and building R&D depth in indigenous alternative catalysts and electrolysers

Potential technologies for commercialization in India[1]



Key insights on R&D ecosystem development

- **Innovative membrane** and **bipolar plate coating technologies** [Quadrant A: Tech transfer / commercialization]
  - Most technologies have been **tested and piloted outside India** with strong potential for **cost reduction and efficiency improvements** in electrolyser performance
  - **Large-scale manufacturing infrastructure** is still under development
  - India can leverage **existing research labs** and partnerships with global companies (i.e. Fraunhofer, Ionbond) to commercialize for local contexts
- Other avenues such as **alternative alloy catalysts** and **porous transport layers** to reduce imports [Quadrant B: Indigenous R&D Focus]
  - Components usually have **high import dependence** on critical minerals for PGM catalysts and coatings
  - Innovations are **nascent**, but hold potential for commercialization given **their efficiency and reduced critical mineral use**
- Beyond electrolyser cell and stack manufacturing, there are ongoing R&D efforts in **alternative ways to produce and store hydrogen**
  - **Biomass to hydrogen** is proven as an alternative to electrolysis, but the reliable supply of biomass at scale is still a challenge
  - SOEC and AEM electrolysers are not as relevant efficiency-wise – India is **focusing on PEM and Alkaline electrolysers**

Note: 1. PVDF-co-HFP copolymer based polymeric cation exchange membranes;
Source: Dalberg Analysis

2 R&D | Focus of R&D efforts are on developing and commercializing alternative membranes, improving efficiency of electrodes, PTLs and bipolar plates, while reducing the loading of critical minerals

Components of an Electrolyser Stack

Definition

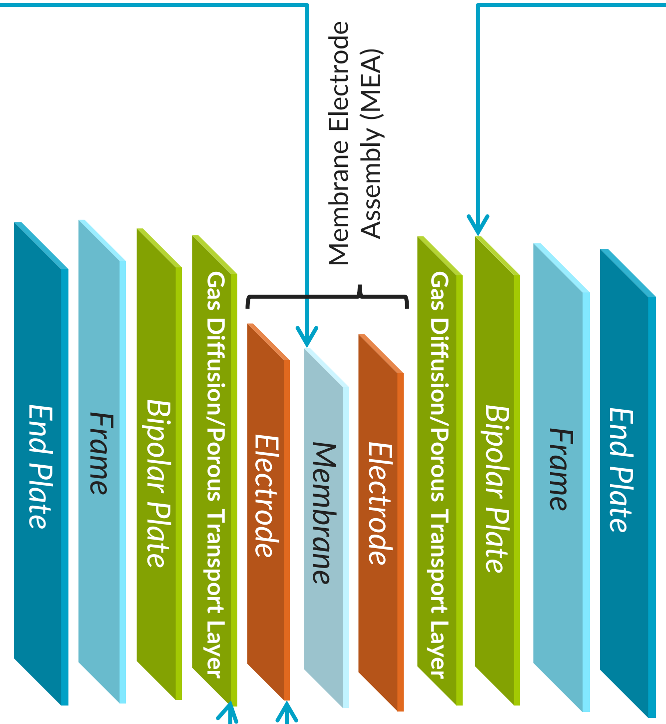
R&D Focus

Membrane: Separates the anode and cathode – allowing the selective transport of ions. Currently imported – Nafion (PEM) and Zirfon (Alkaline)

- R&D focus is on **developing indigenous alternative membranes** to significantly **reduce cost and import dependence**
- Membranes are **still being tested in industrial contexts**
- Commercialization could occur in 5-10 years with scale-up manufacturing, academia-industry collaboration, and required investments

Gas Diffusion/ Porous Transport Layer: Usually nickel, gold or platinum, coated on steel, Ti or polyurethane foam to transport gases and prevent gas crossovers

- R&D focus on **efficiency gains** via laser-texturing and cost reduction via tape-casting
- Both technologies are at lab/pilot stage
- With **investment in capital equipment and global partnership**, could be commercialized within 5 years



Bipolar Plate (BPP): Graphite or stainless steel plates coated with Ti, Gold or nickel to conduct current and evenly distribute water over the MEA (Membrane Electrode Assembly)

- R&D focus is on **reducing critical mineral use** and **improving the efficiency** of bipolar plate coating
- Most technologies are pre-commercial or have been commercialized outside of India
- With **technology transfer**, thermal spray coating can be commercialized in India in the next 5 years

Electrode: Conducting metals coated with catalysts or tape-cast on both sides of the membrane. Nickel electrodes (Alkaline) and Catalyst-Coated Membranes with Platinum and Iridium (PEM)

- R&D focus is on **reducing the use of critical minerals** such as Iridium (Ir) and Platinum (Pt) to **tackle import dependence**
- **Alloys** can reduce rare mineral usage for PEM electrolysers and improve catalytic efficiency
- At lab stages, still needs to be tested at a pilot/commercial level

Source: Dalberg Analysis, CEEW - How can Hydrogen Electrolysers be Made in India?

2

R&D | A collaborative R&D ecosystem with industry-academia-government collaboration is needed to support prototyping to commercialization for indigenous green hydrogen innovations

Key insights on R&D ecosystem development

- Partnerships
  - **Fragmented collaboration**—most R&D partnerships are limited to government grants, and few involve deep co-development with industry. Partnership models rarely **incentivize risk sharing** or **IP commercialization**
  - Launch industry-academia innovation clusters with **clear commercialization targets**, and rigorous reporting on trial results
  - Require each funded project to include **an industry partner** (preferably a co-investor or a "customer" for pilot results)
- Capital Access
  - Most labs and projects need critical capital access to move beyond TRL 4; **However, commercial banks/industry remain hesitant to finance "unproven" green hydrogen technologies at TRL 4-5**
  - "Mission-mode" R&D grants targeting public–private consortia are needed **to support technologies at TRL 4-5**
  - **Blended finance** programs (Govt., DFI, VC/private equity) for large test facilities

Invest in 5-7 R&D labs to set up new or upgrade existing labs

	DEVELOPMENT LABS	TESTING LABS
Number of labs	**1-2 development labs** *Additional national mission-mode labs*	**4-5 testing labs** *Standardized integrated testing across components*
Cost per lab, INR Cr	**INR 10 Cr** *Upgrading development facility*	**INR 50 Cr** *MW-scale testing facility*
Existing labs for upgrade	*IIT Bombay*; *IISc*; International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) – *DST*	Central testing facility – *NISE lab*
Machinery needs	• Material synthesis and deposition machines • Coating machines • Casting machines	• Material testing equipment • Efficacy testing machines (including lab, field, and commercial testing)
Manpower and support needs	• **Advanced training** for new equipment/ materials; leveraging researchers' pre-existing tech know-how	• **Professional external lab management team** • **Efficiency benchmarks for industry and standardized testing criteria**

Source: Dalberg Analysis; Insights form industry experts, academia and start-ups (MNRE Green Hydrogen R&D Conference)

3 Upstream: Raw Materials | Some raw material indigenisation is feasible for PEM electrolyser minerals through circularity, while Alkaline electrolyser minerals remain largely import dependent

Potential for indigenisation pathway: Low / Medium / High / Long term potential beyond 2030 may exist

Electrolyser Type	Mineral Requirements	Import Dependency	Pathway to Indigenisation: Extraction	Pathway to Indigenisation: Refining	Pathway to Indigenisation: Circularity
Alkaline *~75% of the electrolyser capacity[1]*	**Nickel**	Indonesia, Russia, Canada	Laterite reserves exist but no commercial output; ~45,000 t/yr[2] **demand met by imports**	Only small-scale operations (Vedanta)-**bulk refining absent.** Potential to make nickel foam/sheet/coatings exists	Most recycled nickel goes into new alloys and stainless steel, **not the specialised form** needed for electrolysers
	Zirconia	Australia, South Africa	Imported due to **limited reserves** in India	Refined for nuclear/industrial use with high grade refined zirconia produced by **global specialist producers**	Recycling of Zr from electrolysers is an area of pilot R&D and **not commercially developed**
	Molybdenum	China, Thailand, Chile	No domestic mines with all mineral concentrate **being imported**	Low grade molybdenum processed, however, **absence of dedicated refining operations**	Molybdenum loadings in electrodes are thin catalytic layers, making **mineral recovery challenging** with current recycling methods
	Zirfon (Specialty Chemical)	Proprietary material imported from companies like Agfa	*Not Applicable*		
PEM *~25% of the electrolyser capacity[1]*	**Platinum**	South Africa, UAE, UK	Platinum group deposits exist in Odisha but **no operating mine** ; 100% import dependent	Lack of large-scale platinum refining. All primary platinum is **imported**	**Established recovery methods** from auto catalysts and fuel-cell stacks exist[5]
	Iridium	South Africa, USA, UAE	No Indian production today and **no known commercial deposits**	Refined by **specialist firms** which are concentrated abroad	**Recoverable** from end-of-life CCM
	Titanium	China, Netherlands, South Korea	India has 11%[3] of world's ilmenite reserves but **mining is limited** due to regulations	India has only 1 Ti sponge plant with **low capacity. Potential** to compact & sinter Ti exists	**Established recovery methods** from scrap and biplor plates
	Gold	Switzerland, UAE	Domestic gold mining is negligible	**Organized refinery sector** for gold has rapidly grown in India	~11% of India's supply comes from **"old gold" scrap[4]** with collection networks expanding
	Nafion (Specialty Chemical)	Proprietary material imported from companies like Du Pont	*Not Applicable*		

Notes: 1. Computed based on the global electrolyser capacity by 2030 (Global Hydrogen Review 2023) and the awarded electrolyser capacity under the SIGHT electrolyser manufacturing scheme. 2. Indian Minerals Yearbook 2017, 3. Fortune India, 4 World Gold Council, 5. Heraeus

Upstream: Raw Materials | India refines some REEs to oxides but lacks high-purity grades for SOE electrolyser use while circularity for most of the minerals remains research-stage and not commercialized

Potential for indigenisation pathway: Low | Medium | High | Long term potential beyond 2030 may exist

			Pathway to Indigenisation		
Electrolyser Type	**Mineral Requirements**	**Import Dependency**	**Extraction**	**Refining**	**Circularity**
SOE *Still in the nascent stages and hence would not contribute to the 2030 electrolyser capacity*	**Nickel**	Indonesia, Russia, Canada	Laterite reserves exist but no commercial output; ~45,000[2] t/yr **demand met by imports**	Only small-scale operations (Vedanta) with **bulk refining absent**	Most recycled nickel goes into new alloys and stainless steel, **not the specialised form** needed for electrolysers
	Zirconia	Australia, South Africa	Imported due to **limited reserves** in India	Refined for nuclear/industrial use with high grade refined zirconia produced by **global specialist producers**	Recycling of Zr from electrolysers is an area of pilot R&D and **not commercially developed**
	Lanthanum[1]	China	Lanthanum is available domestically, but **advanced grades** required for electrolysers are imported.	Basic refining capacity exists in facilities such as IREL[3], but **advanced processing remains nascent**	**Emerging research efforts** to extract La from end-of-life SOE stacks exist but no commercial recycling stream exists
	Cerium[1]	China	Cerium reserves present in monazite sands, however most cerium for **specialised applications is imported**	Advanced downstream processing and alloying for SOE components is **generally limited**	Studies exist to extract cerium for end-of-life electrodes, but **no such recycling is in the commercial phase**
	Gadolinium[1]	China	Vast majority of gadolinium required for SOE and other **advanced technological applications is imported**	High-purity, application-specific forms are still largely **processed overseas** with India have refining capabilities for basic industrial uses	Research to produce Gd from materials such as hospital effluents exist but **recycling is nonexistent**
	Scandium[1]	China	Scandium reserves exist however **scandium production has remained minimal** at 45 tonnes in 2022[4]	Advanced processing is **predominantly conducted abroad**	**No commercial application** indicating the production of scandium through circular recycling method
	Strontium	Mexico, Germany	All SOE-grade strontium is **produced internationally** due to purity constraints	Most **specialist processing is performed in exporting countries** before import into India	Research has shown recycling of Sr from industrial wastes but **no evidence** of commercial scale recycling

Notes: 1. These minerals are rare-earth elements (REEs) , 2 Indian Minerals Yearbook 2017, 3 Compendium on Rare Earths and Heavy Minerals 4. imarcgroup

3 Upstream: Raw Materials | While raw material import dependency will continue, processing and manufacturing of most Alkaline and PEM components can be done in-house in the near term

Currently most components of the electrolyser stack are directly imported. However, India can produce these in-house, while importing only the minerals required

Component	Alkaline	PEM	SOE
Membrane	Membranes can be **developed locally** using imported zirconium, but domestic capacity and know-how must be built; efforts to produce substitutes would rely on **sustained R&D**	Can develop indigenous cheaper substitutes of Nafion, but requires **significant R&D** and licensing/tech partnerships to reach electrolyser grade quality	Raw Material (SSZ[1] powder) would need to be imported. India can develop **tape-casting and ball mining capabilities** to mix SSZ with organic solvents to make the electrolyte membrane
Cathode	Ni and Mo would be imported , Ni sheet processing (catalyst coating) can be made in-house through the **plasma coating process**[4]	Cathode material (Pt, Ir, ionomer, Ru) would be imported with the potential of doing cathode **ink preparation & coating** in house[3]	Imported nickel oxide and gadolinia-doped ceria (GDC) can be used to **prepare and screen print** cathode slurry in-house
Anode	Ni (powder & porous sheet) would be imported with potential to make catalyst coated Ni sheet in-house through the **plasma coating process**[4]	Anode material (Pt) would be imported with potential to do the anode **ink preparation and coating** on the membrane in house[3]	Imported lanthanum strontium cobalt ferrite (LSCF) powder can be used to **prepare and screen print** anode slurry in-house
PTL[2]	Imported Ni can be used to do the **processing of polyurethane foam** (electrodeposition of nickel and sintering) in house	**Compacting, sintering and gold coating** of imported Ti powder can be done in house, **Carbon cloth** can also be produced in house	GDC powder would need to be imported while the further processing (**screen printing and sintering**) can be done in house to prepare the GDL[2]
Bipolar Plates[2]	**Nickel coating of stainless steel** can be done domestically by importing nickel	The production of gold coated stainless steel bipolar plates is **already indigenised**	**Manufacturing of interconnect** can happen in house with essential raw material for coating (manganese cobalt oxide) and ferritic steel being imported
End Plate	The production of end-plate using stainless steel is **already indigenised**	The production of end-plate using stainless steel is **already indigenised**	There is **potential to indigenise** production of end-plate using stainless/cast steel

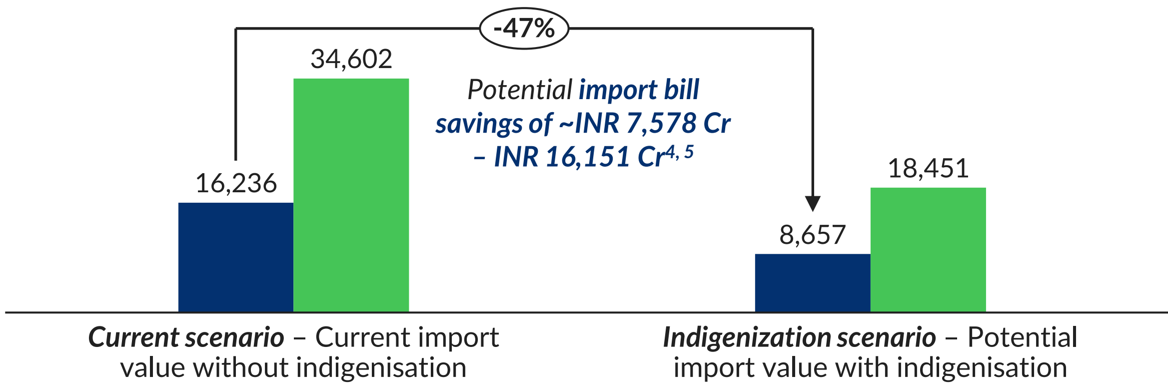
Legend: Component's production already indigenised; Short term potential to make component in house while importing raw materials; Long term potential beyond 2030 to make component in house while importing raw materials

Source: CEEW Report Notes: 1 SSZ - Scandia-stabilised zirconia powder 2. In SOE electrolysers ,the functional equivalent of a PTL is the gas diffusion layer (GDL) and that of a bipolar plate is the interconnect. 3. Active R&D efforts are underway to reduce Pt/Ir loadings through atom efficient catalyst designs. 4. Active R&D efforts are underway to replace pure Nickel loadings with nickel & cobalt/iron alloys (i.e. high entropy alloys) to reduce dependence on imported Nickel

Upstream: Raw Materials | In-house component processing & manufacturing will lead to import bill savings worth ~INR 9,000 Cr - INR 27,000 Cr to meet domestic electrolyser manufacturing capacity by 2030

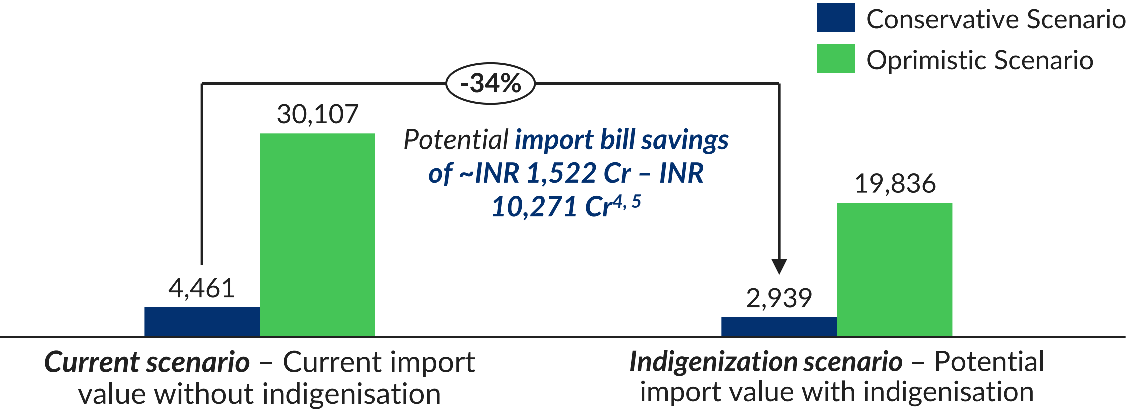
A component level analysis of the potential import bill savings accrued by indigenising electrolyser component manufacturing *(in INR Cr)*

Alkaline Electrolysers[1]



- Indigenisation scenario considers **in-house manufacturing of Zirfon membrane, electrodes, PTL, bipolar plates, and BoP components** *(power electronics, sensors)* while still importing the upstream raw materials
- Graph above considers total estimated domestic alkaline electrolyser capacity of ~**8 – 17 GW,** with
  - Import cost of finished components without indigenisation at **INR 20,202/kW**
  - Import cost with indigenisation at **INR 10,772/kW** (The analysis assumes that imports will be restricted to raw materials, with most of the finished components manufactured domestically)
- Thus, **import bill savings of ~INR 7,578 Cr – INR 16,151 Cr** are accrued due to indigenising component manufacturing (Indigenising component manufacturing allows these savings to circulate within the domestic economy)

PEM Electrolysers[2]



- Indigenisation scenario considers **in-house manufacturing of Catalyst Coated Membranes (CCMs), PTL, and BoP components** *(power electronics, sensors)* while still importing the upstream raw materials
  - Bipolar plates (stainless steel with gold coating) are already indigenised and hence do not feature in above scenario
- Graph above considers total estimated domestic PEM electrolyser capacity of **1 – 10 GW,** with
  - Import cost of finished components without indigenisation at **31,095/kW**
  - Import cost with indigenisation at **INR 20,487/kW** (The analysis assumes that imports will be restricted to raw materials, with most of the finished components manufactured domestically)
- Thus, **savings of ~INR 1,522 Cr – INR 10,271 Cr** are accrued due to indigenising component manufacturing (Indigenising component manufacturing allows these savings to circulate within the domestic economy)

Sources: 1. Alkaline electrolyser analysis based on: CEEW's Study, 2 PEM electrolyser analysis based on: NREL's Study 4. Internal Dalberg and CEEW analysis estimates total import and indigenisation costs based on 2030 electrolyser targets, assuming **80% Alkaline** and **15% PEM** capacity (see annex for details) 5.The lower limit of the range corresponds to the conservative scenario and the upper limit to the optimistic scenario

3 Upstream: Raw Materials | Moreover, raw material import dependency can be reduced through refining and circularity pathways for Alkaline and PEM electrolysers in the near-term

Electrolyser Type	Pathway to Indigenisation
Alkaline	**Near-term pathway –** ***a) Refining***: Scope to scale domestic refining capacity for electrolyser-grade nickel (foam/sheet) **Long-term pathway -** *a)* ***Circularity***: Emerging recycling routes for Ni and Zr can reduce net import dependence, however the potential is long term and requires substantive R&D *b)* ***Extraction***: India has laterite reserves for Nickel but no active mines, potential exists to commercialize extraction in long term
PEM	**Near-term pathway –** *a)* ***Refining***: Specialised refining is concentrated abroad; Scope exists to indigenise Ti refining; Gold refining is already well developed *b)* ***Circularity***: Established recovery routes for all metals (from end-of-life electrolyser components, automobile parts etc.) exist. **~20% -50%[1] of platinum, iridium and titanium** required for electrolyser production can be recovered through commercial circularity by 2030 **Long-term pathway –** ***a) Extraction***: Long-term potential exists for Pt (Odisha PGM deposit) and Ti (large ilmenite reserves)
SOE	**Long term pathway –** *a)* ***Extraction***: Some potential to commercialize Nickel extraction in the long term, however all other critical inputs (REEs Zr, Sc) are highly import-dependent *b)* ***Refining***: Some early-stage capabilities exist with potential to build advanced facilities (advanced downstream refining is still nascent) *c)* ***Circularity:*** Recycling R&D is emerging for REEs and Sr, but no commercial-scale recovery streams are in place yet

Sources: State of the Sector, Critical Energy Transition Minerals For India; Enabling fuel cell circularity with platinum; Recycling of Critical Raw Materials for a Circular Hydrogen Economy; Compendium on Rare Earths and Heavy Minerals Book Notes: 1. Internal Dalberg estimates

Upstream: Raw Materials | For the raw materials that would continue to be imported, there is a need for de-risking supply through long-term contracts, diversification of partners, and recycling

3

	Alkaline Electrolysers	PEM Electrolysers	SOE Electrolysers
Key Dependency Risks	• **Nickel and zirconium are strategic chokepoints**, with India lacking both upstream reserves and refining scale, leaving supply exposed to a few countries • **Molybdenum and Zirfon are niche imports**, where even small market shifts can inflate costs due to thin global supply chain	• Mineral supply is **tightly** concentrated (for instance South Africa is a dominant Pt and Ir supplier) creating **exposure to price shocks** • PFSA Membranes (Nafion) are dominated by **proprietary suppliers** limiting supplier diversification and creating a **supply choke point**	• Rare earth elements (REEs) are almost **entirely processed in China**, making India highly dependent • High-purity zirconia and dopants (scandia, ceria) are **niche products with thin supply chains**, where small disruptions can cause major cost spikes
Recommendations	• Pre-emptively secure medium to long-term **offtake contracts** via a central aggregator, sourcing from **multiple suppliers/geographies** to diversify origin risk[3] • Pursue **equity investments** (with sovereign partners and experienced local firms) to **acquire mining and processing stakes** overseas[3] *(for instance KABIL seeking a 20% stake in SQM's Lithium projects in Australia[4])* • De-risk processing/refining concentration by evaluating domestic processing capacity and **pursuing diversified processing access[3]** (through joint ventures or partnerships with processors across multiple geographies)	• Use **incentive schemes[2]** provided under the **National Critical Mineral Mission (NCMM)** to prioritize **PGM recycling in India** (from spent catalysts and electronics), which has proven recovery rates of 90–95%[1] globally, to reduce fresh imports • Secure **dual supply lines for membranes** by signing long-term contracts with membrane suppliers, while evaluating a joint venture for small-scale domestic PFSA production	• Pursue **strategic partnerships & joint ventures[6]** to diversify REE supply, ensuring technology transfer and mutual value creation by **expanding partnerships with countries such as Australia[5]** reducing over-reliance on Chinese supply • Leverage NCMM's recycling fund of INR 1500 cr[2] to **pilot REE recovery from e-waste and industrial residues** to build a partial local loop • **Form joint R&D–supply partnerships with established SOE material suppliers** to co-develop alternative materials for electrolytes to reduce dependence on imported REEs

Source: 1 Science Direct, 2 PIB, 3 CEEW (Building Resilient Mineral Supply Chains for Energy Security), 4 Money Control, 5 Discovery Alert 6 ODI Europe

4 Capital equipment & infrastructure | Achieving the projected green hydrogen demand by 2030 will require ~INR 11,000 – 29,000 Crore in capital investments to set up electrolyser gigafactories

Capital investment required for setting up electrolyser gigafactories by 2030

	Electrolyser gigafactories		
	Forecasted additional domestic electrolyser capacity *(GW)*[1]	Required capital investment for setting up electrolyser gigafactories *(INR Cr per GW)*[2]	**Total capital investment required *(INR Cr)***
Conservative Scenario	6.4	1,760	**11,200**
Optimistic Scenario	21.8	1,320	**28,740**

*In addition to the above capital investment for electrolyser gigafactories, there is **investment needed in heavy machinery** to indigenise production of various electrolyser components. This analysis is elaborated further in the subsequent slides*

Source: 1. CEEW and Dalberg analysis 2. How can India indigenize and boost domestic hydrogen electrolyser manufacturing , CEEW

4 Capital equipment & infrastructure: Alkaline electrolyser | While there are some adjacencies, India needs to build heavy equipment for domestically manufacturing alkaline membranes, bipolar plates, and coatings

Potential pathway for catalyzing India's capital equipment manufacturing for alkaline electrolysers

	1 Domestic manufacturing *of electrolysers with indigenous balance of plant (BoP)*	+ 2 Domestic manufacturing *of membranes, electrodes, PTLs, and bipolar plates*	+ 3 Import *of raw materials for all components*
Potential for using existing infra	• Most of BoP already done in-house, barring **power-electronics and sensors that are currently imported** • However, ongoing efforts under **India Semiconductor Mission** and **Electronics Component Manufacturing Scheme** could help boost in-house manufacturing of power electronics and sensors by 2030	• Equipment to **melt or solution cast polymer and zirconia into membranes** is **not present** • Metal forming capabilities exist, but **large-scale bipolar plate stamping machinery absent** • Coating & electrodeposition of nickel **happens in adjacent industries**; However, **additional capacity to be built**	• N/A; raw materials such as Zirconium and nickel will continue to be imported
Contribution to cost per kW	**70%**	**15%**	**15%**
Capital equipment to be newly built	**No**	**Yes**	**No**

Source: Expert interviews, Dalberg analysis

Capital equipment & infrastructure : PEM electrolyser | Capital equipment exist in adjacent industries but additional capacity to be built for green hydrogen; membranes will continue to be imported in near term

Potential pathway for catalyzing India's capital equipment manufacturing for PEM electrolysers

	1 **Domestic manufacturing** *of electrolysers with indigenous balance of plant (BoP)*	+ 2 **Domestic manufacturing** *of electrodes, PTLs and bipolar plates*	+ 3 **Import** *of membrane and raw materials for all components*
Potential for using existing infra	• Most of BoP already done in-house, barring **power-electronics and sensors that are currently imported** • However, ongoing efforts under **India Semiconductor Mission** and **Electronics Component Manufacturing Scheme** could help boost in-house manufacturing of power electronics and sensors by 2030	• Metal forming capabilities exist, but **large-scale bipolar plate stamping machinery absent** • Ink preparation, coating, compacting, sintering processes have **synergies in adjacent industries;** however, **additional capacity to be built**	• N/A; raw materials such as Platinum, Iridium, and the **Nafion membrane will continue to be imported**
Contribution to cost per kW	**70%**	**10%**	**20%**
Capital equipment to be newly built	**No**	**Yes** *but to lesser extent compared to alkaline electrolyser by 2030, as indigenous PEM membrane would still not be market-ready*	**No**

Source: Expert interviews, Dalberg analysis

Capital equipment & infrastructure | Capital equipment for large scale membrane and bipolar plate manufacturing cannot be leveraged from adjacent industries and will need investment

Potential synergies with other industries: High / Medium / Low

Production Process	Existing Machinery in India	Source Industry	Potential synergies	Can be leveraged for Green Hydrogen?	Total Required Investment
Slot die roll-to-roll production and die cutting systems for membranes	Vacuum/pressure die casting, solution casting, roll-to-roll casting, sintering, Phase inversion (wet/dry)	• Water filtration industry • Battery separator film industry	Low	**Mostly no** *The know-how for membrane production exists (Water filtration membrane) but machinery-specific to alkaline membrane are non-existent*	INR 200 Cr
Ni, Ti, gold coating & sintering systems for bipolar plates and PTLs	PVD/CVD coating machines, spluttering machines	• Medical • Automotive • Aerospace • Electronics, Tooling • Jewellery (Gold coating	Medium	**Somewhat yes** *It is directly compatible with some of the **automotive/aerospace/medical industry equipment used for coating**, but may need additional capacity*	INR 380 Cr
Large-scale stamping machines for bipolar plates	CNC shops, hydraulic/forming presses, roll forming, heavy-duty press lines	• Automotive, • Heavy Engg • Energy • Defence	Low	**Mostly no** *There is retrofitting of metal forming from automotive, defence, etc. But there are no bipolar specific stamping machines at commercial scale*	INR 110 Cr
Power electronics & sensors	Module/inverter lines, sensor manufacturing, industrial electronics assembly	• Automation • Smart Grid, • Automotive • Rail Process	High	**Yes** *Sector-agnostic efforts are already ongoing to boost domestic manufacturing under the India Semiconductor Mission and Electronics Component Manufacturing Scheme*	-

Sources: BARC; MarketsandMarkets; Science Direct; Happy Forgings India; Feintool; Bharat Forge; Harison Machines; Economic Times; Industry Experts; CEEW & Dalberg Analysis

4

Capital equipment & infrastructure | Large-scale membrane and bipolar plate manufacturing, and additional capacity for coatings can be imported from other countries

Solution/Melt Casting (Membranes)

- Some **basic phase inversion machinery can be leveraged** from water filtration industry
- However, casting machines **unique to ZiO2 coating/sintering** and **electrochemical quality control** need to be **imported**

Proposed source of capital equipment

Japan and USA have proven capacity in solution and melt casting heavy equipment

For example, Toray Engineering Co. Japan (Casting Machines), New Era Converting Machinery USA

Ni, Ti, Gold Coating & Sintering (Bipolar Plates & PTL coating)

- Retrofitting from automotive/aerospace is possible, however **some customization for BPP fixtures & rotation is required**
- Additional machinery to **produce required volumes for green hydrogen** would need to be **imported**

Proposed source of capital equipment

Japan, Germany and Netherlands have large-scale coating and sintering machinery

For example, IHI Ionbond Japan (Thermal Spray), von Ardenne Germany, Hauzer Techno Coating Netherlands

Large-Scale Machining/Forming (Bipolar Plate Manufacturing)

- Retrofitting from aerospace/defense is possible only for **metal forming and rolling**
- However, bipolar specific stamping machines to ensure commercial scale **quality control and no hydrogen leakage** need to be **imported**

Proposed source of capital equipment

Germany and Switzerland have proven commercial level bipolar plate manufacturing

For example, Feintool Switzerland (Bipolar and Additive Manufacturing), Schuler Group Germany

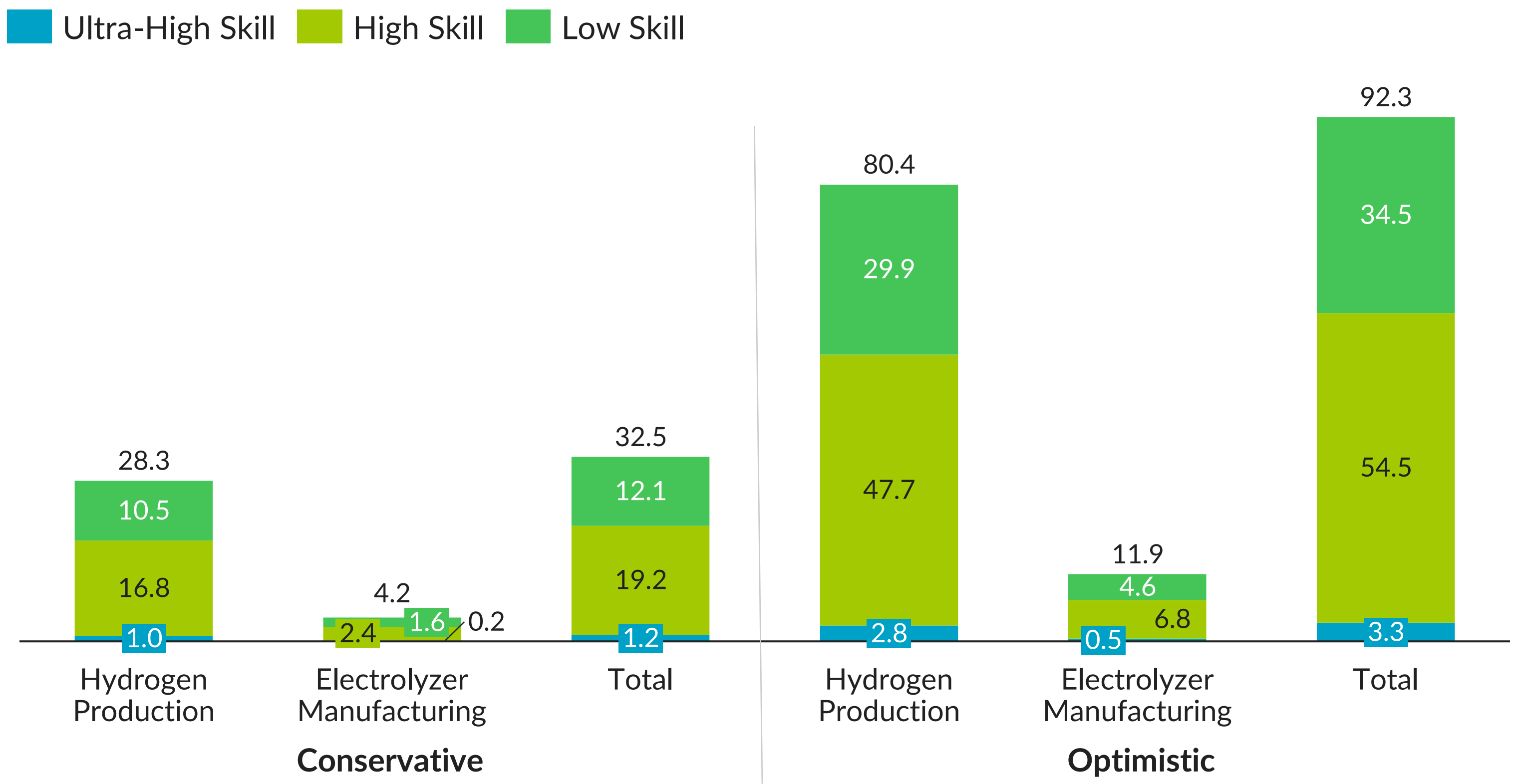
Potential for retrofitting: High; Medium; Low

Source: Toray; NewEra; von Ardenne ; Ionbond; Hauzer; Feintool; Schuler Group; ; Happy Forgings India; Bharat Forge; Harison Machines;

Workforce | ~33,000 - ~92,000 workforce by 2030 for green hydrogen can be achieved through industry linkages, INR 219 – 545 Cr investment in infrastructure and specialised courses in engineering colleges and ITIs

Targeted interventions would be required across four levers including trainers & curriculum, industry participation, infrastructure, R&D along with global partnerships

Projected (2030) direct workforce for green hydrogen production & manufacturing electrolyser value chain, '000



Total training cost
INR 212 - 537 Cr

\+

Total demo facility investment
INR 7.8 Cr

=

Total budget
INR 219 - 545 Cr

Includes INR 160 – 455 Cr for Low-skilled workers (<1% of ITI upgradation budget)

Detailed in Annex

Source: SSCGJ - Green Hydrogen Skills Gap Report; Hindustan Times; Skill Outlook; Industry experts; Dalberg analysis

5 Workforce | To successfully build this workforce, action would be required across four critical levers: trainers & curriculum, industry participation, infrastructure and R&D

LEVERS	CURRENT STATUS	RECOMMENDATIONS
Trainers & Curriculum	• Lack of trained professors and professionals to teach green hydrogen specific courses • Curriculum is fragmented and lacks real-world feasibility for R&D innovations	• Launch "**Train the Trainer**" at Tier-1 & Tier-2 engineering institutions and ITIs, jointly enabled by **National CoEs** (GERMI, IITs) and **international partners** from Germany and the Netherlands (Hydrogen Valley Fellowship Programme) • Leverage **AICTE Faculty Development Intiatives, and PMKVY 4.0** to develop faculty and standardized green hydrogen curriculum for industry ready skills • Introduce **micro-credentials** for key hydrogen topics (safety, regulatory, etc.) in 60 ITIs designed around recognized **global standards like ISO and OSHA**
Industry Participation	• Lack of public industry knowledge to push youth participation in green hydrogen • Few structured apprenticeship or upskilling models	• **Co-develop training curricula** through the **Hydrocarbon Sector Skill Council (HSSC) SCGJ**, **OEMs and end-use industry partners** (i.e. BPCL, IOCL, TPSDI) • Create **government-incentivized apprenticeships** for students with industry partners similar to the AICTE Industry Fellowship Programme for faculty
Infrastructure	• Lack of infrastructure for training modules focused on practical training • Workforce lacks the experience of tinkering required to fill in gaps for O&M	• Focus on applied learning modules at ITIs for **repair and maintenance skills** • **Invest INR 7.8 Cr amount in building demo facilities (5-10 kW) for classroom and applied learning** across 60 Hub ITIs (approx. 2 electrolyser facilities/state) and 20 top non – IIT engineering colleges
R&D	• Un-coordinated R&D skilling and efforts for advanced green hydrogen locally • Lack of connectivity between innovations in academia and entering the start-up pipeline	• Fund R&D through national centers of excellence in green hydrogen **leveraging CSIR – Capacity Building and Human Resource Development fund** • Establish **centralized processes for R&D** within academia to ensure innovations move from B.tech → M.tech → PhD students and enter the start-up pipeline • Create centralized **mapping of technologies** to influence effective labor sorting

Source: CEEW - Green Jobs Report; Insights from MNRE's 1st Green Hydrogen R&D Conference (2025); AICTE

6 Financing | Key investments would be required from the government to kickstart and maintain demand and ensure cost-competitiveness, some of which is already budgeted

Government funding of ~INR 8,400 Cr would be required across demand acceleration, R&D, workforce skilling and subsidies on capex and interest by 2030 to achieve these goals

Theme	Total Funding Required (INR Cr)	Government Funding Required (INR Cr)	Key Activities	Potential outcomes
Demand & Market Architecture	5,836	5,836	Leverage existing NGHM budget of INR 19,000 Crore to allocate additional INR 5,800 Cr to reduce price impact on consumers in fertilisers, steel, and CGD sectors	Additional subsidies for fertilisers, steel, and CGD will help absorb price impacts on the consumers
R&D & Product Innovation	250	125	Leverage existing R&D and testing infra budgets totaling to ~590 Cr to fund at least 50% of the additional required mission-mode dev and testing labs	Mission-mode labs for development and industry grade integrated testing labs will help accelerate lab to commercialization and ensure uniform testing standards
Upstream Raw Materials & Critical Inputs	-	-	Raw material dependency to continue in the near term; explore long-term pathway of circularity that could require investments, but beyond 2030	Long-term circularity for PGMs and other low-reserve minerals could help reduce import dependency
Capital Equipment & Infrastructure	12,120	236	Provide interest subvention for setting up heavy equipment for roll-to-roll production and die cutting for membranes, coatings, and stamping for bipolar plates	Upfront investments in capital infrastructure will help localise manufacturing of electrolysers and critical stack components, thus enabling higher DVA
Talent & Workforce	200	200	Leverage existing INR 35 crore NGHM skilling budget, 1% of ITI budget, and 1-3% of CSIR budget for targeted interventions across trainers, curriculum, industry participation, and infrastructure	Early investments in skilling will ensure a job-ready workforce for upcoming electrolyser manufacturing and green hydrogen production plants
Cost Competitive-ness	1,980	1,980	Introduce additional INR 1,980 Crores for absorbing the cost differential of domestically manufactured electrolysers vs. those that are imported as prices are not going down enough through existing PLIs	Support would ensure that the proposed introduction of DVA requirements and domestic electrolyser usage in overall green hydrogen production is economically feasible for developers
TOTAL	20,386	8,376		

Financing | Policy interventions are needed in the near-term to ensure green hydrogen production costs are comparable to grey hydrogen

Subsidies to ensure stability across fertiliser, steel, and CGD sectors could reduce production cost of green hydrogen by 38% vs. current costs, ensuring cost competitiveness with grey hydrogen

Subsidies have proven to be effective in maintaining price stability in the fertiliser sector, and could be expanded

- **Green Ammonia tenders have seen rates as low as INR 2.6/kg owing to subsidies of ~INR 1,500 Cr & offtake agreements led by government**
- However, this forms only 1/5th of 2030 projected fertiliser demand

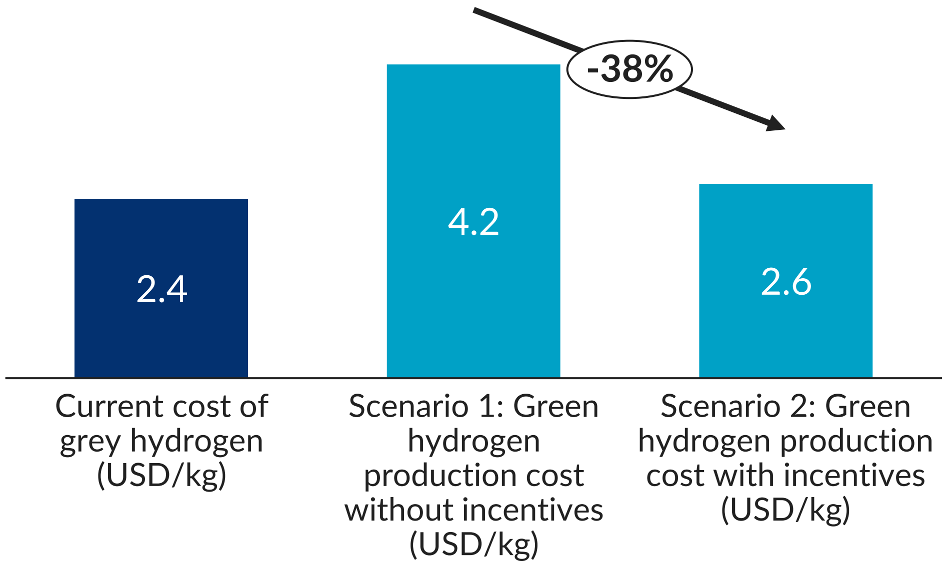
Sectors such as steel and city-gas distribution (CGD) may not be able to absorb the increased cost themselves

- **Steel and CGD with green hydrogen use in large public-sector projects and for exports, would need interventions to stabilize production costs**
- Refinery is expected to absorb the marginal cost increase of 0.5-1% while transport sector already receives **INR 500 Cr** from state governments

Proposed interventions:

- **Expand subsidy for green ammonia to entire 2030 projected fertilize r demand,** involving an additional **~INR 5,000 Cr** investment
- **Support steel and CGD sectors with a subsidy** of **~INR 836 Cr** to ensure competitive costs for public sector projects, and for export competitiveness of green steel

Comparison of grey hydrogen and green hydrogen production costs



Targeted subsidies to absorb cost increases
~INR 7,800 Cr till 2030

Notes. 1. Assumes that green ammonia tender prices can be extended to remaining fertiliser demand for 2030; 2. Assumes that marginal cost increase in refinery sector will be absorbed by the sector
Source: CII report, 2025; CEEW & Dalberg analysis

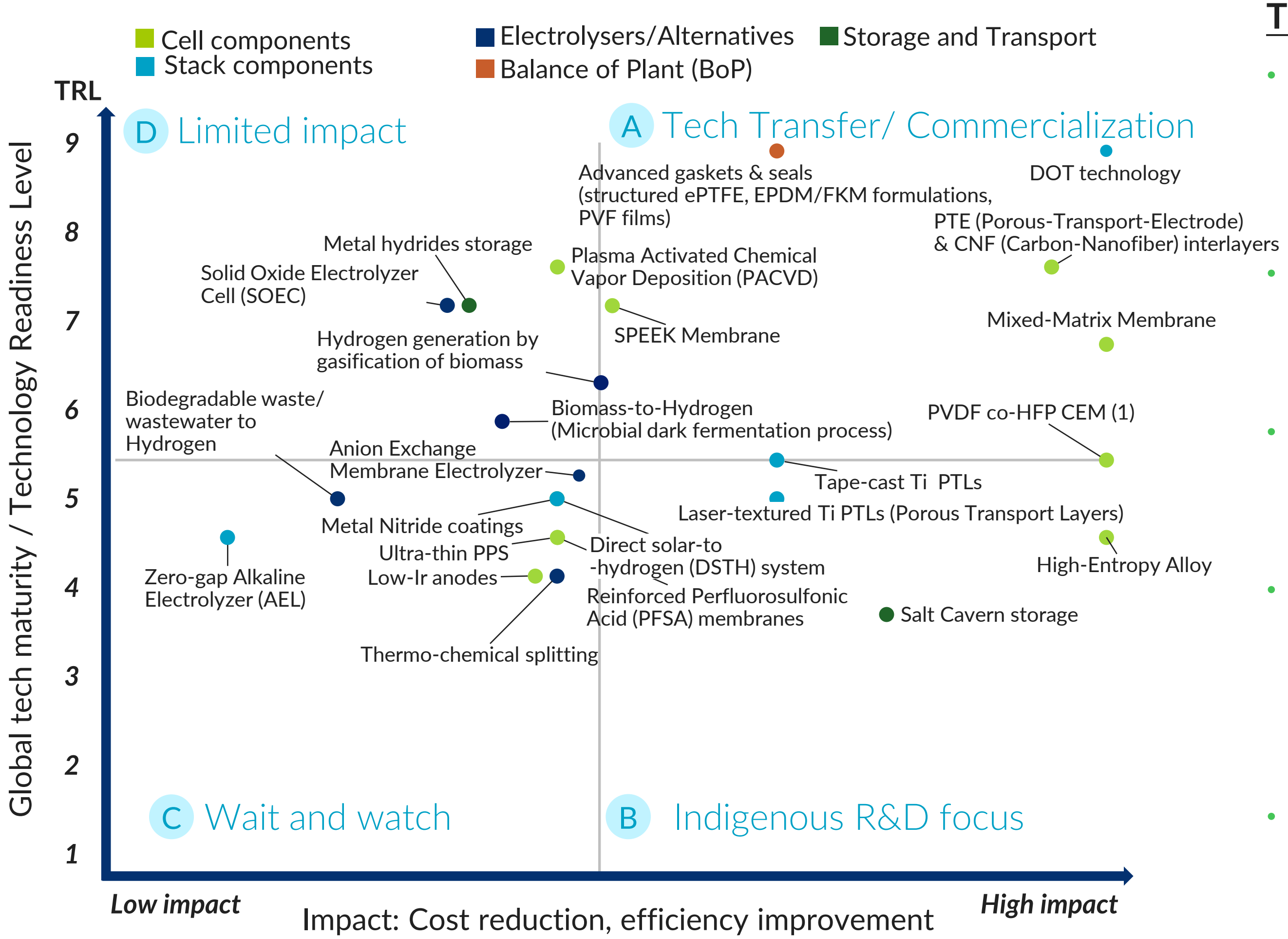
Detailed in Annex

SECTION THREE

ANNEX

R&D | India should invest in 10-15 indigenous R&D technologies to reduce import of critical minerals and improve efficiency through alternatives for membranes, catalysts, stack components and electrolysers (1/4)

Potential technologies for commercialization in India[1]



Key Insights

Tech transfer/ commercialization:

- **Mixed Matrix Membrane** has been indigenously developed through the BARC-BHEL partnership for use in Alkaline electrolysers. It is equivalent to Zirfon's efficiency and cell voltage with >99% pure hydrogen and 5000 A/m2 current density. It is 4 times cheaper (~$50) than Zirfon (~$200) and BHEL is set to manufacture the membrane with electrolysers.
- **DOT™ Technology (Double-layer Titanium-Carbon coating)** is a thermal coating spray for bipolar plates commercialized globally (e.g. Ionbond) with presence in India. 2-6% thermal spray coverage provides comparable results to solid gold 100% coating, reducing cost and use of noble metals.
- **PTE (Porous-Transport-Electrode) & CNF (Carbon-Nanofiber) interlayers** has been tested in electrolyser contexts in Sweden (e.g. Smoltek) with no R&D in India yet. It increases the catalytic surface area by 30x and reduces iridium by up to 95% to just 0.1 mg/cm^2(instead of >1-2 mg/cm^2), thus highly reducing cost.
- **SPEEK (Sulphonated Poly-Ether-Ether-Ketone) Membrane** was developed globally (e.g. China, South Korea) as a Nafion alternative membrane for PEM electrolysers with high proton conductivity similar to Nafion but shows excessive swelling at a high degree of sulfonation. It costs $40 - 120/$m^2$compared to imported Nafion at $500-$1500/m^2. The base material PEEK can be sourced from Indian suppliers.
- **Advanced gaskets & seal** material such as structured expanded polytetrafluoroethylene (ePTFE), Ethylene propylene diene monomer (EPDM) /Fluoroelastomer (FKM) synthetic rubber formulations, PVF (Polyvinyl Fluoride) films are commercially available globally

Note: 1. PVDF-co-HFP copolymer based polymeric cation exchange membranes;
Source: *Dalberg Analysis*

R&D | India should invest in 10-15 indigenous R&D technologies to reduce import of critical minerals and improve efficiency through alternatives for membranes, catalysts, stack components and electrolysers (2/4)

Key Insights

(continued tech transfer/ commercialization):

- **Hydrogen generation by gasification of biomass** is an alternative to electrolysers using biomass/feedstock. It has advanced to real-world pilot deployments but is not yet fully commercialized globally (UK, Germany, Croatia). India has piloted gasification plants (e.g. Indian Oil & IISc, Bangalore, KPIT & Ankur Scientific) and possessed the capabilities for technologically advanced sub-processes. Plants running on biowaste have the potential to produce hydrogen at a cost as low as $3/. Energy efficiency ranges from 40-70% and yields fuel-cell-grade hydrogen via steam or oxy-steam gasification. Planned efforts to develop pipelines for steady supply of biomass

Indigenous R&D focus:

- **High-Entropy Alloy Catalyst** being indigenously developed (Centre for Nano and Soft Matter Sciences (CeNS) in Bengaluru) and globally researched (USA, New Zealand) as an alternative for platinum in the catalyst coated membrane (CCM) for PEM electrolysers. It has better catalytic efficiency than pure platinum and requires 7x less platinum, significantly reducing the cost of the overall CCM.
- **PVDF (Polyvinylidene Fluoride) co-HFP (Hexafluoropropylene) Cation Exchange Membrane** was indigenously developed and lab tested as a Nafion alternative in India (e.g. CSMCRI). It costs Rs.3,000 ($35) $/m^2$compared to imported Nafion at Rs. 50,000 ($588)$/m^2$. It showed good stabilities (oxidative and acid) and other physicochemical properties essential for high performance PEM electrolysis.
- **Salt Cavern storage** is still being explored and tested globally (France, USA, and UK) and in India (Bikaner) as a feasible option for Hydrogen storage. The potential hydrogen storage in India is predicted to be up to 22 610 terawatt-hours (TWh) in deep saline aquifers. It is among the cheapest methods for large hydrogen storage with low capital costs andit offers flexibility regarding its injection and withdrawal cycles to respond to the needs of the hydrogen market.
- **Laser textured PTLs (Porous Transport Layers**) increases surface wettability and creates microstructures that improve water and gas transport in PTLs. They are shown to reduce mass-transport losses and local overpotentials compared to plain titanium, leading to higher current densities and better cell efficiency. There is emerging research and pilot stage laser texturing for hydrogen production and PTL components globally (Fraunhofer Hydrogen Network) and in India (BARC, CAT or CLPM) but it has yet to be fully commercialized. Laser texturing technology (5-axis machines) already exists in India and can be extended to PTLs.
- **Tape Cast PTLs (Porous Transport Layers)** have been tested in lab environments for PEM electrolysers but not yet piloted in an integrated electrolyser system. The tape casted PTL with a ratio of 60:40 Ti:PMMA (polymethyl methacrylate beads) with 60 µm PMMA size outperforms standard Ti PTL by 62 mV at 4 A/cm^2 (notable cell gain). It is more efficient than typical titanium powder-based PTL due to a balanced tradeoff between gas removal and sufficient interfacial contact – lowering overpotentials. Most labs are testing the most cost-effective tape-casting techniques.

Source: *Dalberg Analysis*

R&D | India should invest in 10-15 indigenous R&D technologies to reduce import of critical minerals and improve efficiency through alternatives for membranes, catalysts, stack components and electrolysers (3/4)

Key Insights

Wait and Watch:

- **AEM (Anion Exchange Membrane) electrolyser** is currently similar in efficiency to Alkaline/PEM electrolysers but has shorter lifetimes. It enables the use of non-precious metal catalysts (like nickel), which are cost-effective compared to platinum and iridium required for PEMs, making stack costs cheaper. However, the costs of Balance of Plant (BoP) required for AEM electrolysers are higher, thereby offsetting the stack cost savings today.
- **Ultra thin PPS (Polyphenylene Sulfide)** is an improvement on the Zirfon membrane that has been tested in the laboratory (China) with no estimation on costs for production. It adds a ceramic-polymer composite such as such as CeO^2 and TiO^2 to the PPS mesh. It is more efficient than Zirfon due to lower area resistance on the membrane resulting in higher efficiency hydrogen production and lower energy consumption of the entire hydrogen production system.
- **Low-iridium anodes via engineered catalyst layers (ionomer/porosity tuning)** consists of a thin catalyst mixed with ionomer for proton conduction tested in labs globally (USA) with no R&D in India. This thin catalyst layer reduces iridium use (down to 0.1–0.5 mg/cm^2 or even lower) compared to conventional designs that require 1–3 mg/cm^2. It reduces the cost due to low Iridium use but still has reduced efficiency over time compared to conventional iridium anodes.
- **Reinforced PFSA (Perfluorosulfonic Acid) Membranes (short-side-chain Aquivion®)** are composite materials that enhance the mechanical stability and dimensional stability of PFSA membranes (Nafion) for proton exchange membrane (PEM) applications. It is in the lab testing stages (Italy) with no estimation on costs for production. Electrochemical tests for efficiency showed better water splitting performance for the reinforced Aquivion® based membrane-electrode assembly as compared to the benchmark based MEA (membrane-electrode assembly) but it has not reached a pilot stage in an electrolyser yet.
- **Zero-gap AEL (Alkaline Electrolyser**) is in the lab ideation and testing phases (Netherlands) which consists of a flow & spacing redesign (Zirfon diaphragm combined with a zero gap configuration) to cut ohmic/bubble losses and increase efficiency at industrial current densities. However, Zero gap AEL have area resistances that are significantly higher, ranging from 0.23 to 0.76 Ω cm^2 compared to the current AEL with AR 0.1–0.15 Ω cm^2 in 30% KOH (Potassium Hydroxide – electrolyte) at 80 °C
- **SPEEK/PES (Sulphonated Poly-Ether-Ether-Ketone / poly(ether sulfone)) blend membrane** is an improvement on the SPEEK membrane to reduce swelling while keeping proton conductivity. It is still in the lab testing stages (China) but the PES/SPEEK blend membrane has been shown to be superior to SPEEK membrane under equivalent sulfonate concentration. Currently, there is no clear estimation on costs of production, but it is a promising alternative to Nafion membranes.

Source: *Dalberg Analysis*

R&D | India should invest in 10-15 indigenous R&D technologies to reduce import of critical minerals and improve efficiency through alternatives for membranes, catalysts, stack components and electrolysers (4/4)

Key Insights

(continued wait and watch):

- **Thermo-chemical splitting (Iodine–Sulphur, HyS, Cu–Cl cycles)** is an alternative to electrolysers driven by high-temperature heat and has potential for cost-competitive hydrogen (below $2–3/kg) if integrated with advanced nuclear or solar thermal systems. I-S and HyS has been piloted globally (Japan (JAEA), France (CEA), and the U.S. (DOE labs). India has I-S pilots (i.e. BARC) integrated with high-temperature nuclear reactors while research on Cu–Cl cycle has been supported through partnerships. Electricity demand is lower however challenges remain around corrosive intermediates (HI, H_2SO_4, HCl) and high operating temperatures (often >500–850°C) for BoP.
- **DSTH (Direct Solar-To-Hydrogen) system** is an alternative to electrolysers that has been lab developed (Australia) but still needs to be tested for commercial viability. Current systems till date either required expensive materials or presented low solar-to-hydrogen (STH) conversion at 20%. STH efficiencies of 25% can be achieved with realistic improvements in the perovskite cell and an LCOH (Levelized Cost of Hydrogen) below ≈$3/kg is feasible.
- **Wastewater to Hydrogen** is under development and being piloted globally (UK, Australia) and in India (e.g. CSIR - Indian Institute of Chemical Technology (IICT)). It currently shows differing efficiencies in lab studies but are generally low compared to PEM. It may rival cost of PEM or could be higher depending on site, water purification process and availability of viable wastewater sources (e.g. dairy wastewater, municipal, agricultural, industrial)

Limited Impact:

- **SOECs (Solid Oxide Electrolyser Cell**) is on the cusp of commercialization with some companies manufacturing SOECs globally (US, UK, Estonia) while others are still focused on integration and cost-reduction. It is in development and adoption stages in India – only with early commissioned pilots (e.g. HPCL). SOECs still have high capex due to high temperature BoP (Balance of Plant) and stack costs along with long start-up/ramp-up times which is inefficient for intermittent renewable energy sources. They have high efficiency at high temperatures but still have scope for improvement on current density, degradation rate and lifetime (hours).
- **Biomass-to-Hydrogen (Microbial dark fermentation process)** is pre-commercial globally, with scattered pilots and no large-scale deployment yet. It has been piloted in India (e.g. IIT Kharagpur, TERI) with efforts to improve efficiency. However, it has comparatively low hydrogen yields, high capital and operating costs, and the need for reactor integration or process hybridization (such as with methanation or photofermentation) to improve energy recovery and economic viability. Thus, it currently has limited impact on the R&D landscape in its current state.
- **Metal Hydride hydrogen storage** offers safe, high-density hydrogen storage at low pressures, with efficiencies up to 93% however material costs around $20/kg due to critical minerals required for metal hydrides. Globally, systems are commercialized (e.g., GRZ, GKN), while in India research is at prototype/pilot stage (IITs, BHU). Key barriers remain slow kinetics for hydrogen absorption and thermal management (60-90°C for hydrogen release), requiring scale-up and cost reduction for broader adoption ($10/kg MH costs would make it competitive with 350-bar compressed gas storage)

Source: *Dalberg Analysis*

R&D | Indigenous R&D efforts for commercialization should be focused on membranes, critical minerals reduction and moving processing of stack components in-house through investment and scale-up testing

Components of an Alkaline Electrolyser Stack

Definition

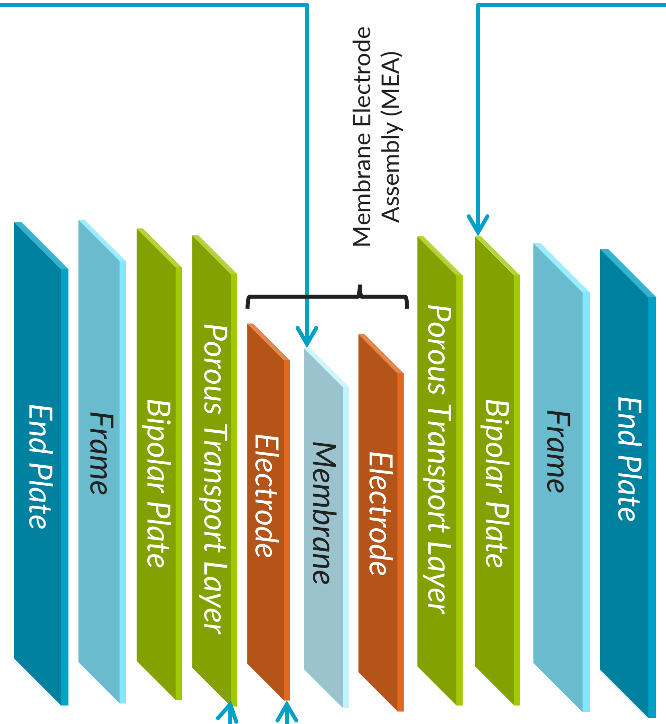
Membrane: Separates electrodes– allowing the transport of ions. Currently imported Zirfon membrane (85% zirconium dioxide and 15% polymer)

R&D Focus

- R&D focus is on **developing indigenous alternative membranes** to **reduce cost, thickness, and import dependence**
- **Mixed Matrix & other alternatives**
- Membrane innovations **currently at pilot scale** and **still being tested in highly commercialized contexts**
- Commercialization could occur in 5-10 years with scale-up manufacturing and required investments

Porous Transport Layer Nickel is electrodeposited on the polyurethane foam to fabricate the nickel foam sheet that draws out the gases

- R&D focus on **efficiency gains** via thinner PTLs and reducing interface resistances from the catalyst layer to PTLs



Bipolar Plate (BPP): Stainless steel plates are spray-coated with Nickel and then stamped to inscribe the flow fields to transport water to the electrodes

- R&D focus is on **improving the efficiency** of bipolar plate coating and metallic flow fields Nickel coating is mostly done abroad with only some small-scale domestic manufacturers; has potential to be indigenised in India

Electrode: They are 50 per cent porous nickel sheet leached with NaOH and then coated with a Nickel-Aluminium (Ni-Al) alloy known as raney nickel through a plasma coating process

- R&D focus is on improving the **efficiency gains** through **increasing the catalyst surface area** and developing **thinner electrodes**
- Nickel coating process has **indigenisation potential** in India

Source: Dalberg Analysis, CEEW - How can Hydrogen Electrolysers be Made in India?

R&D | Indigenous R&D efforts for commercialization should be focused on membranes, critical minerals reduction and moving processing of stack components in-house through investment and scale-up testing

Components of a Proton Exchange Membrane PEM Electrolyser Stack

Definition

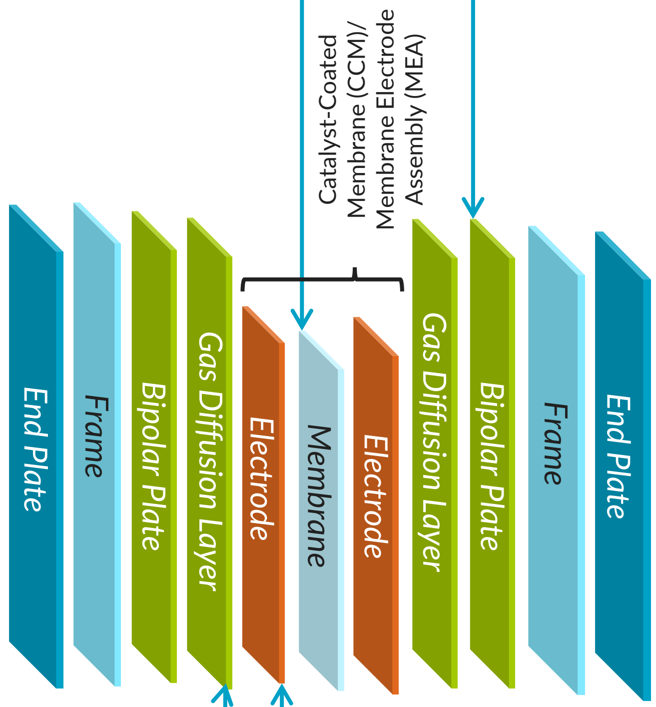
R&D Focus

Membrane: Separates electrodes–allowing the transport of ions. Currently imported Nafion membrane (sulfonated tetrafluoroethylene–based fluoropolymer)

- R&D focus is on **developing indigenous alternative membranes** to significantly **reduce cost and import dependence**
- **SPEEK membrane & PVDF co-HFP Cation Exchange Membrane**
- **Alternatives have been tested in labs** but have not been proven to be highly efficient in pilot or commercial use yet

Gas Diffusion Layer: Anode-side PTL is made of titanium felt coated in gold and the cathode side is a carbon cloth (polyacrylate nitrile resin woven in fabric)

- R&D focus on **efficiency gains** via thinner PTLs and laser-texturing and cost reduction via tape-casting
- Both R&D tech are at lab/pilot stage
- With capital investment and global partnerships (i.e. Fraunhofer), could be commercialized within 5 years



Bipolar Plate (BPP): Usually gold or platinum coated on a titanium felt/graphite plates/stainless steel – that covers the CCM and transports gases away from the electrode and acts as a current collector.

- R&D focus is on **reducing critical mineral use** and **improving the efficiency** of bipolar plate coating
- Most technologies have been **commercialized outside of India**
- With **technology transfer** and **sufficient demand creation**, thermal spray coating such as can DOT™ Technology (Double-layer Titanium-Carbon coating) be commercialized in India in the next 5 years

Electrode: They are platinum-group materials – platinum on the anode and Pt-Ir/Ir oxide and ruthenium on the cathode – as catalysts on both sides of the Catalyst-Coated Membrane or MEA

- R&D focus is on **reducing the use of critical minerals** such as Iridium (Ir) and Platinum (Pt) to **tackle import dependence**
- **Alloys** can reduce Pt use (7x) and improve catalytic efficiency
- At lab stage, it still needs to be tested at a commercial stage

Source: Dalberg Analysis, [CEEW - How can Hydrogen Electrolysers be Made in India?]

R&D | Establishing open-access R&D infrastructure and facilitating industry-academia collaboration can help maximize resource efficiency and drive prototyping to commercialization

LEVERS	CURRENT STATUS	RECOMMENDATIONS
Create R&D, open-access infrastructure	• Major bottleneck is high-cost, large-scale test beds and lack of collaborative facilities • Costs of lab equipment are high, with 30–50% of GH2 project capex spent on electrical systems	• **Improve access to R&D national testbeds** and **sandboxes for startups, academia, and MSMEs,** tackling the gap in scale-up facilities beyond 1 kW • **Enable shared use of complex test systems** across academia and industry, reducing duplication and cost barriers
Academia - Industry Participation	• Majority of academic projects lack industrial partners, slowing commercialization • Vast majority of R&D remains grant-funded by government ministries; industry involvement still weak	• **Mapping to industry trends and needs** could ensure **academia GH2 innovations are relevant** and can move beyond TRL 4 to commercialization with **industry capital**, tackling the issues of prototypes failing without market pull • Communicate **cost efficiency industry benchmarks** to facilitate targeted R&D in academia
R&D Coordination	• R&D efforts are fragmented across government agencies (MNRE, DST) and sectors (transport, steel, fertilisers) • Lack of focused skilling and mission efforts in one hub	• Establish **hubs that pool infra and talent**, tackling fragmentation across scattered R&D efforts • Drive **mission-mode hydrogen R&D** under government leadership, ensuring coordinated national goals like defense/space

Global & Sectoral Linkages	• Bilateral and multilateral R&D tie-ups are only at beginning stages
	• Use of digital twin/AI infrastructure in hydrogen R&D is not yet industry standard/ widely spread
		• Forge **bilateral R&D alliances**, tackling India's slower IP development
		  ◦ Japan: Tech development (fuel cell, electrolysis, ammonia conversion)
		  ◦ Middle East: Large-scale hydrogen export corridor development
		  ◦ Denmark for electrolysers and catalysts, Sweden for steel decarbonization, Netherlands for capacity-building
		• Establish digital twin/AI infra as industry standard to improve efficiencies

Source: CEEW; IFRI ; GH2 India; Xynteo

R&D | India could invest INR 250 - 300 Cr to upgrade current green hydrogen R&D labs, establish new facilities, and ensure needed human resource for efficient lab operations

	DEVELOPMENT LABS	TESTING LABS
Number of labs	**1-2 development labs** *Additional national mission-mode labs*	**4-5 testing labs** *Standardized integrated testing across components*
Cost per lab	**INR 10 Cr** *Upgrading development facility*	**INR 50 Cr** *MW-scale testing facility*
Prospective existing labs for upgrade	*IIT Bombay lab* *IISc* International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) AN AUTONOMOUS R&D CENTRE OF DEPARTMENT OF SCIENCE & TECHNOLOGY, GOVERNMENT OF INDIA *DST lab*	**Central testing facility** *NISE lab*
Machinery needs	• Material synthesis and deposition machines • Coating machines • Casting machines	• Material testing equipment • Efficacy testing machines (including lab, field, and commercial testing)
Manpower and support needs	• **Advanced training** for new equipment/ materials; leveraging researchers' pre-existing tech know-how	• **Professional external lab management team** for max. capacity utilisation and access for all stakeholders • **Efficiency benchmarks for industry and standardized testing criteria** to inform relevant research

Source: Academia and industry experts

Upstream raw materials | The cost analysis highlights significant savings potential through indigenising component manufacturing for Alkaline and PEM electrolysers

Component indigenisation could save worth ~**INR 9,000 Cr – INR 27,000 Cr,** from the current import bill

A component level analysis across different electrolyser types to estimate the cost savings due to component indigenisation

		Current Scenario		Indigenisation Scenario		
Electrolyser type	**Components which can be indigenised**	**Import Costs – without indigenisation** *(per kW)*	**Total import costs[1]**	**Import Costs – with indigenisation** *(per kW)*	**Total import costs[1]**	**Import bill savings due to indigenisation**
Alkaline[2]	Membrane, Electrode, Bipolar Plates, PTLs, BoP components not presently indigenised (power electronics and sensors)	INR 20,202[4]	INR 16,236 Cr – INR 34,602 Cr[5]	INR 10,772[4]	INR 8,657 Cr – INR 18,451 Cr[5]	47% (~ INR 7,578 Cr – INR 16,151 Cr[5])
PEM[3]	Catalyst Coated Membrane (CCM), PTL, BoP components not presently indigenised (power electronics and sensors)	INR 31,095[4]	INR 4,461 Cr – INR 30,107 Cr[5]	INR 20,487[4]	INR 2939 Cr – INR 19,836 Cr[5]	34% (INR 1,522 Cr – INR 10,271 Cr[5])
Total **Import Bill Savings** due to component **indigenisation**	***~INR 9,100 Cr – INR 26,422 Cr***					

Notes: 1. Total import costs are computed based on electrolyser target (in GW by 2030) for the specific electrolyser type 2. Base data points for the analysis are taken from CEEW's study 3. Base data points for the analysis have been taken from NREL's study 4. Estimates basis Dalberg's and CEEW's analysis. 5. The lower limit of the range corresponds to the conservative scenario, and the upper limit corresponds to the optimistic scenario

Upstream raw materials | To meet India's green hydrogen targets, competitive and sustainable production will require indigenisation through extraction, refining, and circularity

Developing domestic capacities for manufacturing of electrolyser components could accrue import bill savings worth **~INR 8,000 Cr – INR 32,000 Cr[1]**, ensuring long-term input security for green hydrogen

Pathways for reducing India's import dependance in the green hydrogen value chain

Sources of minerals and metals

Domestic extraction capacities

- India has reserves of minerals such as nickel laterite, ilmenite (titanium) & zirconium but **commercial-scale extraction is nascent /absent**
- India holds the world's 5th largest REE reserves, but the **ores have a low rare earth content** & are associated with high **radioactivity**, making extraction a complex and costly process[2]
- Early policy push can align mining investments with India's green hydrogen roadmap for **long-term input security**

Domestic refining capacities

- **High-purity refining** for electrolyser applications (e.g., titanium sponge, high-grade zirconia, REE oxides) **remains limited** in India
- Developing refining capacity could **reduce costs** by upto **~50%[1]**, by processing imported raw materials directly instead of importing finished components

Scaling circularity

- Recycling pathways for **platinum, iridium and titanium** could meet up to **20-50%[2]** of the mineral demand for PEM electrolyser production
- Circularity improves **resource security** while **reducing lifecycle emissions** from electrolysers
- India's metals **recycling ecosystem can be extended** to cover spent catalysts, coatings, and electrolyser stacks

Notes: 1. Detailed analysis present on the previous page , 2. Internal Dalberg estimates

Capital equipment & infrastructure: Case Study | Belgium built capital infrastructure for large-scale Zirfon manufacturing by leveraging print film roll production expertise and unlocking government funding

Belgium's roadmap for building large-scale Zirfon production capacity

2007

- ***AGFA, Belgium*** *had historical expertise in roll-to-roll solution coating for* ***photographic and printing film businesses***
- *AGFA and* ***VITO*** *collaborated to develop the Zirfon membrane in 2007 with demonstrations at industry scale*

2009

AGFA and VITO signed license agreement to ***commercialize*** *Zirfon membrane*

2021

Zirfon powered ***~3GW*** *of electrolysers world-wide*

2023

- *AGFA received* ***€11 million grant from EU Innovation Fund*** *for building a high-capacity Zirfon facility in Mortsel, Belgium*
- *Site previously housed* ***film coating equipment*** *that would be* ***repurposed*** *for Zirfon production*

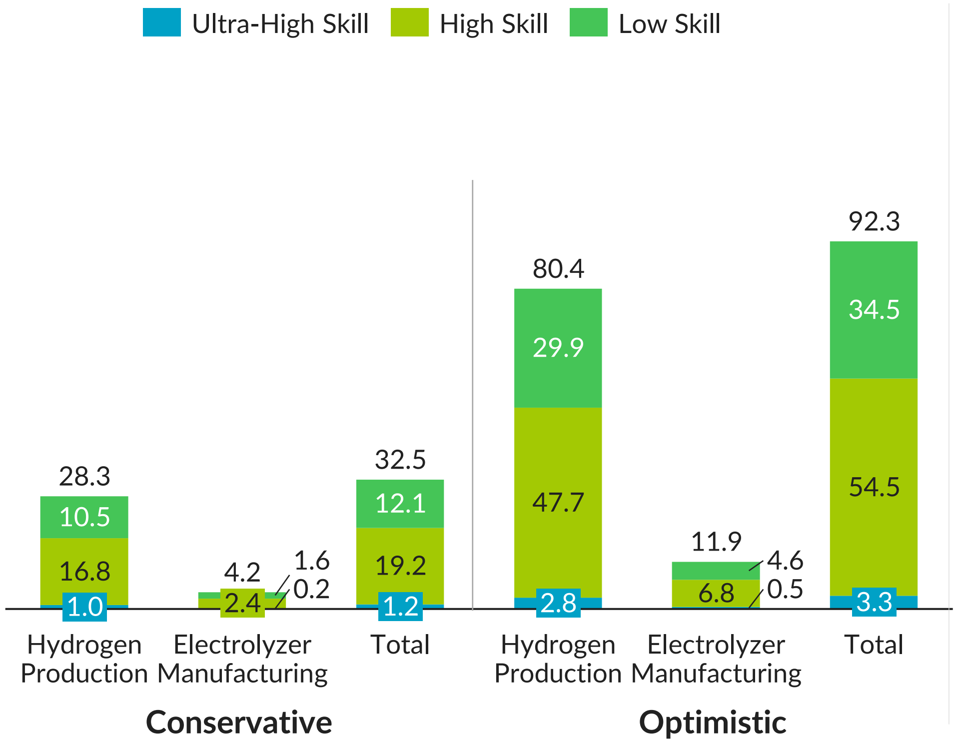
2025

- *The new facility is designed with modular scalability to adjust for varying global demand*
- *Facility can produce* ***1 million sq. meter*** *of membrane annually, equivalent to* ***20GW of alkaline electrolyser*** *capacity*

Source: EARTO, Zirfon success story; Hydrogen Insight, Article, 2025; Brussels Morning, Article, 2025; AGFA, Publication, 2025

Workforce & skilling | India would require a direct workforce of ~33,000 - 92,000 by 2030 who would need to be trained by through specialised green hydrogen courses and interventions

Projected (2030) direct workforce for green hydrogen production & manufacturing electrolyser value chain, '000



Skill levels and sources of talent for GH2 manufacturing

Ultra-skilled	**Leadership & R&D Experts** *PhD/Post-graduate programs, Tier-1 engineering institutes & labs, experienced professionals*
High-skilled	**Engineers & Technical Specialists** *Tier-1 and Tier-2 engineering colleges*
Low-Skilled	**Technicians, O&M** *ITIs, vocational training programs*

Industry insights

- Hiring potential from **adjacent industries**
  - Thermal Power sector (O&M)
  - Chemicals / Fertilisers
  - Oil & Gas - refineries, gas transport (Safety, Process, etc.)
  - Heavy Engineering/Manufacturing
  - **Reskilling/upskilling** will be required for ~80-100% of the workforce needed (L3 – L8)
- **Indirect jobs** projections for green hydrogen production and electrolyser manufacturing range from 1.05 lakhs – 3.01 lakhs[3] (~3.3x indirect job multiplier)

Total training cost[1]
212 - 537 Cr

+

Total demo facility investment[2]
INR 7.8 Cr

=

Total budget
INR 219 - 545 Cr

Includes INR 160 – 455 Cr for Low-skilled workers (<1% of ITI upgradation budget)

Note: 1. Training cost includes NGHM skilling budget, skilling low-skill workers at ITIs and 6% of ultra-high skill workers through CSIR fellowships (Assumed a 6% acceptance rate for CSIR fellowships) TimesofIndia, 2. 5-10 kW demonstration facilities for skilling across 60 Hub ITIs (2 electrolyser facilities/state) + 20 top non – IIT engineering colleges, 3. Assuming 85% of the total capacity will be achieved through domestic electrolysers; 3.49x Multiplier (Hydrogen Production), 1.75x Multiplier (Electrolyser Manufacturing) Source: SSCGJ - Green Hydrogen Skills Gap Report; Hindustan Times; Skill Outlook; Industry experts; Dalberg analysis

Workforce & skilling | Efforts across skill levels could focus on strengthening industry linkages and global partnerships, along with offering specialised courses in engineering colleges and ITIs

Levers: ● Trainer & Curriculum ● Industry Participation ● Infrastructure ● R&D

Skill level	Recommendations	Responsible Ministry/Agency
Ultra-skilled	**Develop 'Train the Trainer'[1] program** to train trainers and professors from Tier-1 & 2 engineering institutes through local and global (Germany, Denmark, Netherlands) partnerships with academia and industry	Ministry of Education (MoE), Ministry of Skill Development and Entrepreneurship (MSDE), Directorate General of Training (DGT)
	Establish research fellowships and advanced labs (CoEs) in Tier-1 institutes with industry-led hydrogen projects and global institutes, enabling leadership in technology innovation	Council of Scientific and Industrial Research (CSIR), MoE
	Establish centralized, university-led or **national platforms to map hydrogen technology** Develop and create pipelines for transitioning **research into start-ups** for ultra-skilled	MSDE, CSIR
High-skilled	Deploy **5-10 kW electrolyser demonstration facilities co-developed with industry** in top engineering institutions for classrooms and applied learning	MSDE, Tier 1 & 2 Engineering Colleges, Industry Partners, MoE
	Create government-incentivized apprenticeships and in-factory training programs with industry partners	MSDE, DGT, Industry Associations
	Introduce cleantech manufacturing curriculum and standardized green hydrogen curriculum with **modules to ensure industry-readiness for innovations and skills**	Ministry of Education, MSDE
Low-skilled	**Introduce short certification programs and micro-credentials** covering core hydrogen topics such as safety procedures, regulatory compliance, and emergency response	National Council for Vocational Education and Training, Skill Council for Green Jobs
	Deploy **5-10 kW electrolyser demonstration facilities** for applied learning, focusing on modules for repair and maintenance skill development for diploma and ITI graduates	MSDE, ITIs, Industrial Skill Centers (e.g. Tata Power Skill Development Institute (TPSDI))
	Launch a Digital Cleantech Training Platform – an online learning hub with courses, certification programs, and job-matching services	MSDE, ITIs

Note: 1. The "Train and Trainer" program is applicable to the high-skilled workforce as well
Source: CEEW - Green Jobs Reports; SSCGJ - Green Hydrogen Skills Gap Report

Financing | Capital investment of ~INR 688 – 1,456 Cr would be needed to set up the heavy machinery required for in-house component manufacturing

Electrolyser	Equipment	CAPEX per system[1]	Throughput	Effective electrolyser capacity per system[2]	Required CAPEX (Conservative)	Required CAPEX (Optimistic)
Alkaline	CCM - Plasma coating	INR 39.4 Cr	179 m^2/hr	2.2 GW	**157.6 Cr**	**INR 315.2 Cr**
	CCM - Die cutting	INR 1.3 Cr	7000 parts/hr	14.3 GW	**INR 1.3 Cr**	**INR 2.6 Cr**
	BPP - Stamping	INR 15.7 Cr	660 parts/hr	1.3 GW	**INR 94.1 Cr**	**INR 203.9 Cr**
	BPP - Physical vapor deposition	INR 4.0 Cr	12 m^2/hr	0.1 GW	**INR 235.3 Cr**	**INR 502.5 Cr**
	PTL (Anode + Cathode) - Electrodeposition	INR 1.1 Cr	12 m^2/hr	0.1 GW	**INR 107.3 Cr**	**INR 227.7 Cr**
PEM	CCM - Slot die coating	INR 39.4 Cr	179 m^2/hr	23.0 GW	**INR 39.4 Cr**	**INR 39.4 Cr**
	CCM - Die cutting	INR 1.3 Cr	7000 parts/hr	142.8 GW	**INR 1.3 Cr**	**INR 1.3 Cr**
	BPP - Stamping	INR 15.7 Cr	660 parts/hr	13.4 GW	**INR 15.7 Cr**	**INR 15.7 Cr**
	BPP - Physical vapor deposition	INR 4.0 Cr	12 m^2/hr	1.0 GW	**INR 8.0 Cr**	**INR 39.9 Cr**
	Anode PTL - Sintering	INR 19.6 Cr	120 parts/hr	2.4 GW	**INR 19.6 Cr**	**INR 78.2 Cr**
	Anode PTL - Physical vapor deposition	INR 4.0 Cr	12 m^2/hr	1.4 GW	**INR 8.0 Cr**	**INR 27.9 Cr**
	Cathode PTL - Die cutting	INR 1.3 Cr	7000 parts/hr	142.8 GW	**INR 1.3 Cr**	**INR 1.3 Cr**
Total					**INR 688 Cr**	**INR 1,456 Cr**

1. CAPEX required for a system of the given throughput, includes installation and building costs; 2. Total electrolyser capacity that can be supported annually by one manufacturing system, calculated using system throughput and stack specifications of 1 MW system; 3. Throughput for plasma coating system assumed to be the same as slot die coating system. Sources: CEEW, NREL (2024), CEMAC – NREL (2017)

Financing costs could also be lowered via concessional capital from DFIs, MDBs, bilateral funding, and lowering domestic borrowing costs through credit guarantees, concessional lines of credit, among others

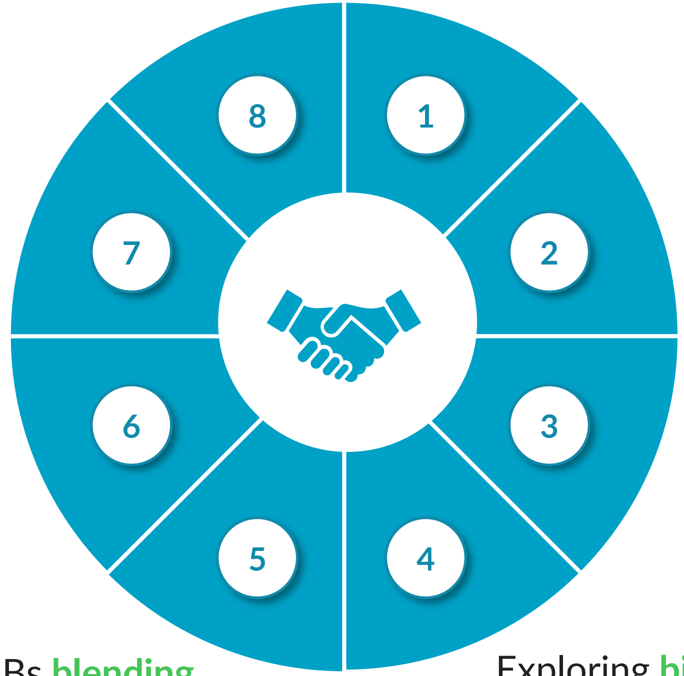
ILLUSTRATIVE | NON-EXHAUSTIVE

Government must create an enabling environment to facilitate tapping of domestic and international capital sources at concessional rates – targeted policies for green hydrogen and other cleantech manufacturers required

Structured guarantee instruments and **grants to reduce guarantee fees** to promote green bond issuances among first time issuers

Leveraging DFIs and Multilateral concessional capital potentially backed by EU, bilateral guarantees E.g. EU Global Gateway strategy, India-ETFA TEPA

Extending Priority Sector Lending and **concessional line of credit** to banks for electrolyser and component manufacturing (similar to China's CERF program)



Utilizing GIFT-IFSC's regulatory flexibility and lower transaction costs for green/transition bond listings and attracting foreign equity

Establishment of proposed **National Green Finance Institution** with dedicated corpus and relevant enablers to provide low-cost financing for green hydrogen production & deployment

Easing access to equity capital by **relaxing exchange listing requirements** on profitability for manufacturers to reflect their longer path to profitability

Developing **structured bonds** with DFIs and MDBs **blending INR and foreign currency** denominated tranches to fund projects requiring significant imports of capital machinery

Exploring **bilateral concessional funding with Middle Eastern nations** for setting up overseas manufacturing and deepening trade partnerships bharat CLIMATE FORUM

Thank you!

Council for International Economic Understanding

Dalberg CEEW