Bharat Cleantech Manufacturing Platform: Transmission Indigenisation Pathways

Accelerating an Aatmanirbhar, Green and Viksit Bharat

bharat CLIMATE FORUM

Council for International Economic Understanding

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]

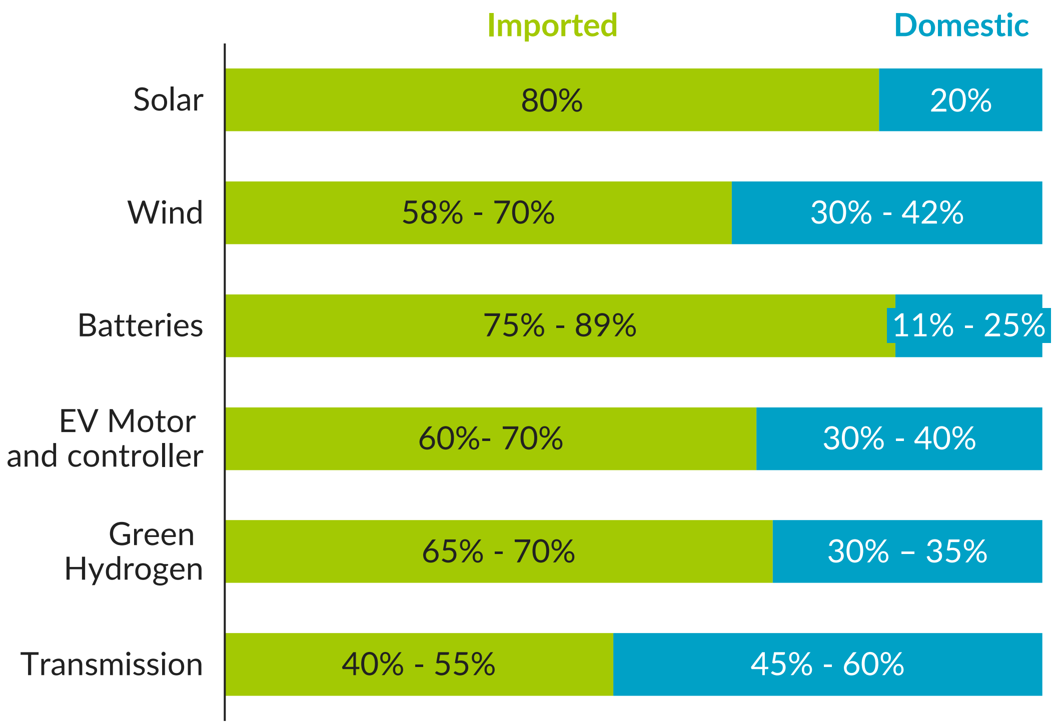
30% EV *sales penetration*[2]

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*

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SECTION ONE

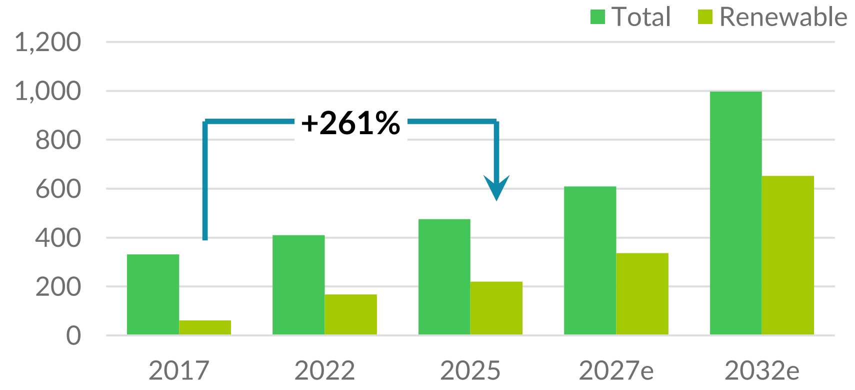
TRANSMISSION LANDSCAPE IN INDIA

Meeting India's 500 GW renewable energy target by 2030 will require significant expansion and strengthening of transmission grid capacity

India has built large transmission infrastructure in the past 5 years…

- **Set up a unified national grid of ~485 GW with ~4.92 lakh ckm**[1] of High Voltage (HV) transmission[2] lines as of 2025
- **Launched Green Energy Corridor (GEC) to evacuate renewable energy from resource-rich regions to major load centers**
  - Expanded network and contributed to **2.5 x RE growth** from 62 GW in 2017 to **220** GW in 2025
  - Reduced transmission congestion from 16% to 0.06% of power constrained between 2015-2021

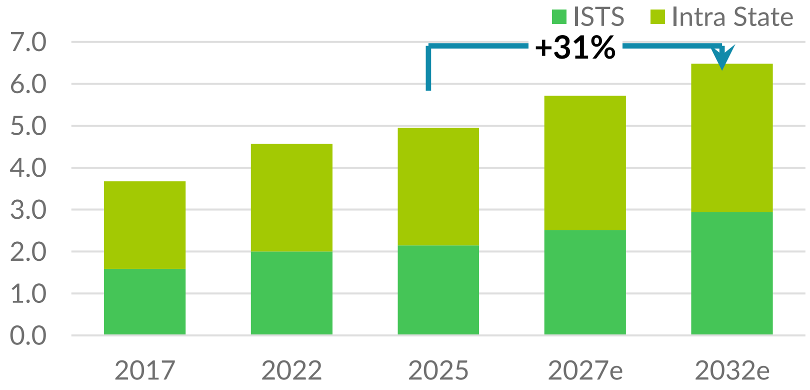
Installed Electricity Generation Capacity 2017-32 *(GW)*



…but needs to invest further to meet the growing electricity expansion ambitions

- **Electricity demand expected to grow at 5-6% annually**, with peak power demand to rise to 270GW in 2025 from 250GW in 2024
- By 2032, will add 259 GW of renewable energy **requiring efficient power evacuation corridors** and **expansion of Inter state transmission** systems (ISTS)
- **Transmission delays are currently affecting 30-40%** of solar and wind energy capacity in India

Transmission Line Length 2017-32 (lakh ckm)

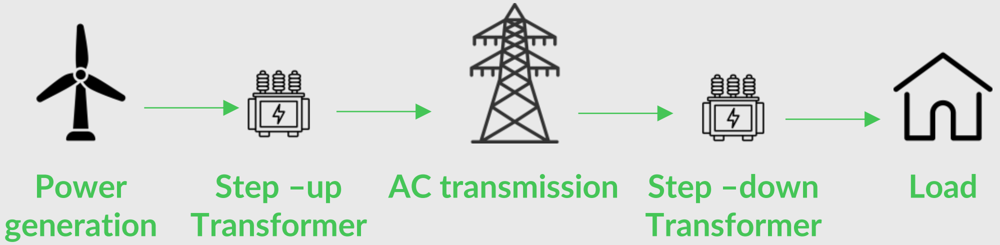


(1) circuit-kilometer (2) High Voltage Transmission: ≥220 kV Source: CEA National Electricity Report Vol I & Vol II; PIB press releases; Ministry of Power

For long-distance, high-capacity power transfer, High Voltage Direct Current (HVDC) is more efficient and cost-effective than High Voltage Alternating Current (HVAC) transmission

There are two types of HV transmission systems:

A. High Voltage Alternating Current (HVAC) Transmission



Power generation → Step –up Transformer → AC transmission → Step –down Transformer → Load

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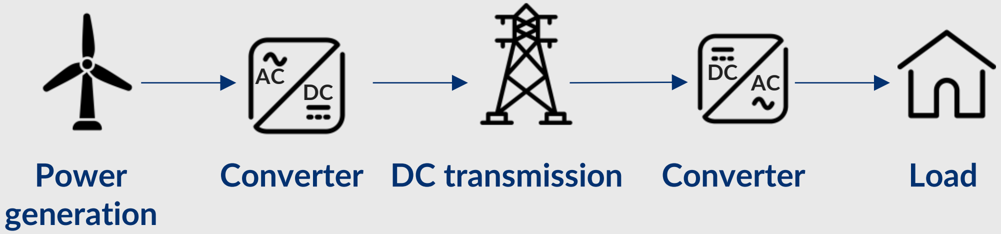
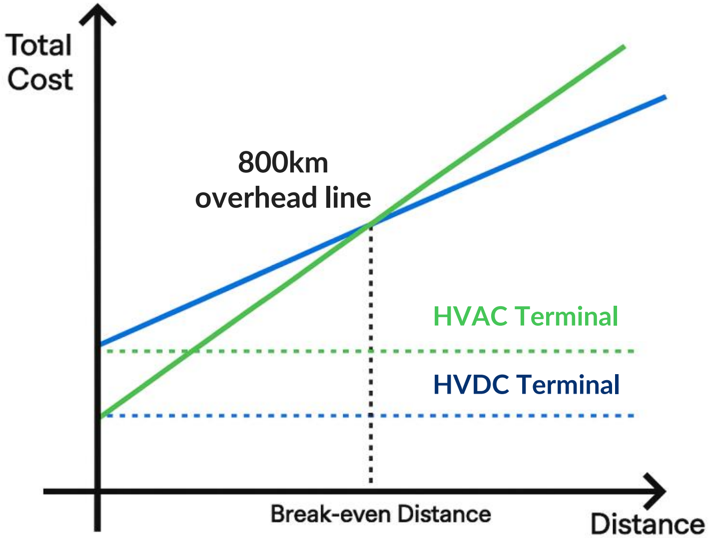
B. High Voltage Direct Current (HVDC) Transmission



Power generation → Converter → DC transmission → Converter → Load

Cost comparison of HVAC and HVDC



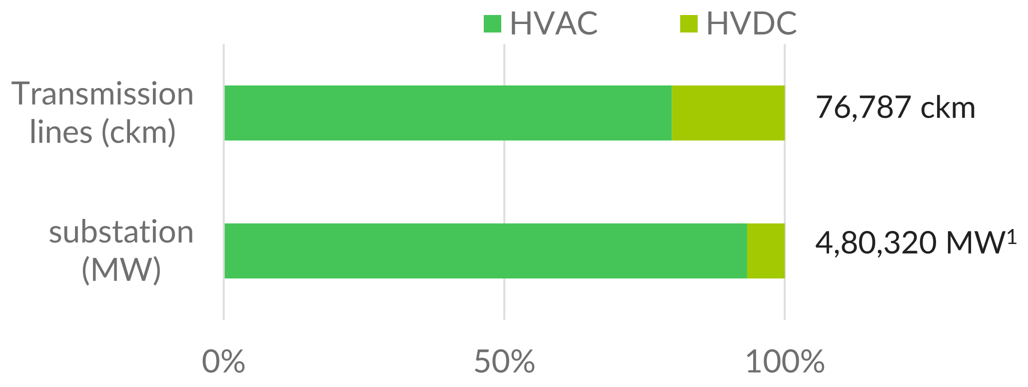
- While HVDC incur **30-40% higher upfront costs**. with reduced losses and fewer parallel lines needed, their **overall Levelized Cost of Energy per MWh is lower than HVAC** by 5-10% beyond 800km distances
- Solar and wind hubs in Rajasthan, Gujarat etc. are far away from major load centers, increasing **long distance transmission requirement**

Source: CEA -National Electriticity Planning Report (2024)

Council for International Economic Understanding Dalberg

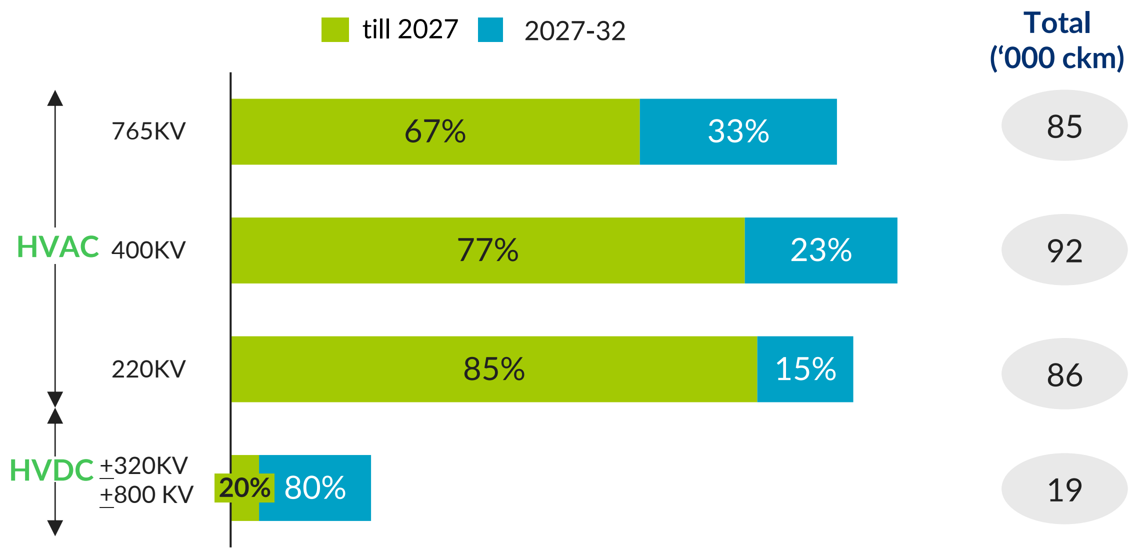
As renewable energy capacity expands and long-distance bulk power transfers increase, India is prioritizing development of higher-voltage transmission infrastructure (>220 kV), with a particular emphasis on HVDC

Planned additions of lines & substations, 2027 -2032



- To enable long-distance bulk power transfers, **India plans to double its HVDC capacity** by 2032 to 66GW of installed capacity
- Key HVDC projects include the 5 GW Leh–Kaithal corridor, **offshore wind connectors**, and **long renewable corridors** from Rajasthan and Ladakh
- HVDC expansion also **supports cross-border trade**, island grid links, and green hydrogen hubs requiring long-distance high-capacity transmission

Planned capacity additions by voltage level, 2027 -2032



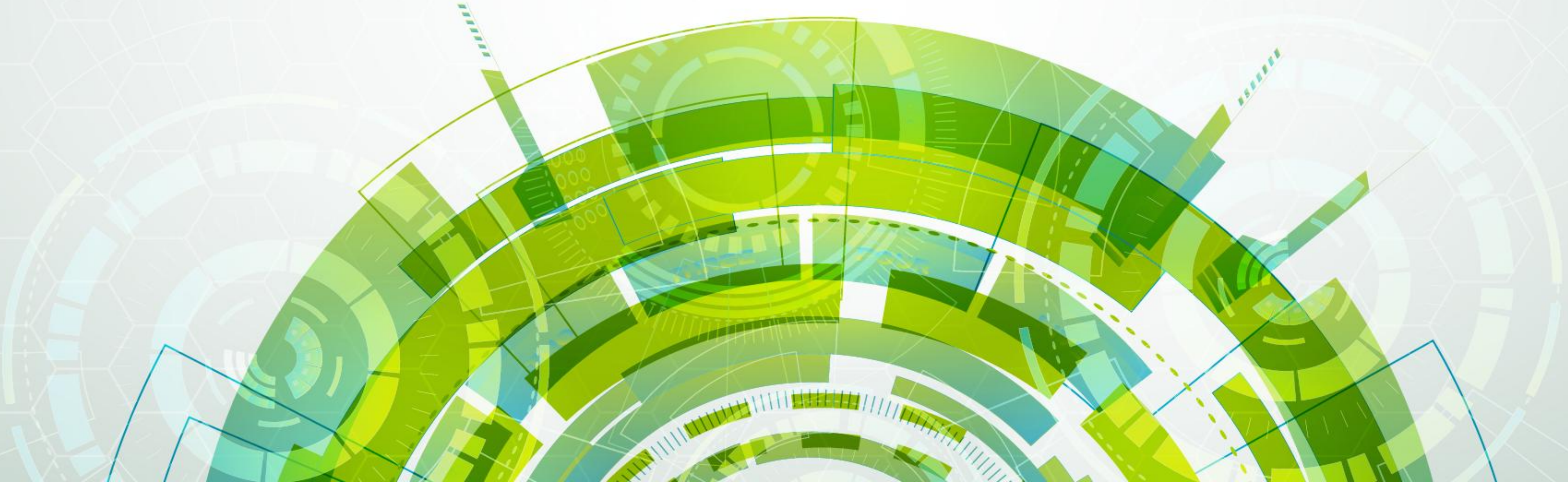
320 kV HVDC typically uses **Voltage Source Converter (VSC)** technology, suited for **shorter distances,** and **offshore integration**; 800 kV HVDC systems use **Line-Commutated Converter (LCC)** technology for **long-distance, bulk power transfer** - split between LCC and VSC not clearly defined in the transmission planning report

India plans to invest ~$59 bn in transmission expansion between 2027-2032, of which $18bn is for building HVDC systems

(1) AC substation MVA converted to MW equivalent using 0.9 power factor assumption for indicative comparison only; actual AC transfer capacities differ due to redundancy, utilization, and network topology. Source: CEA -National Electriticity Planning Report (2024)

SECTION TWO

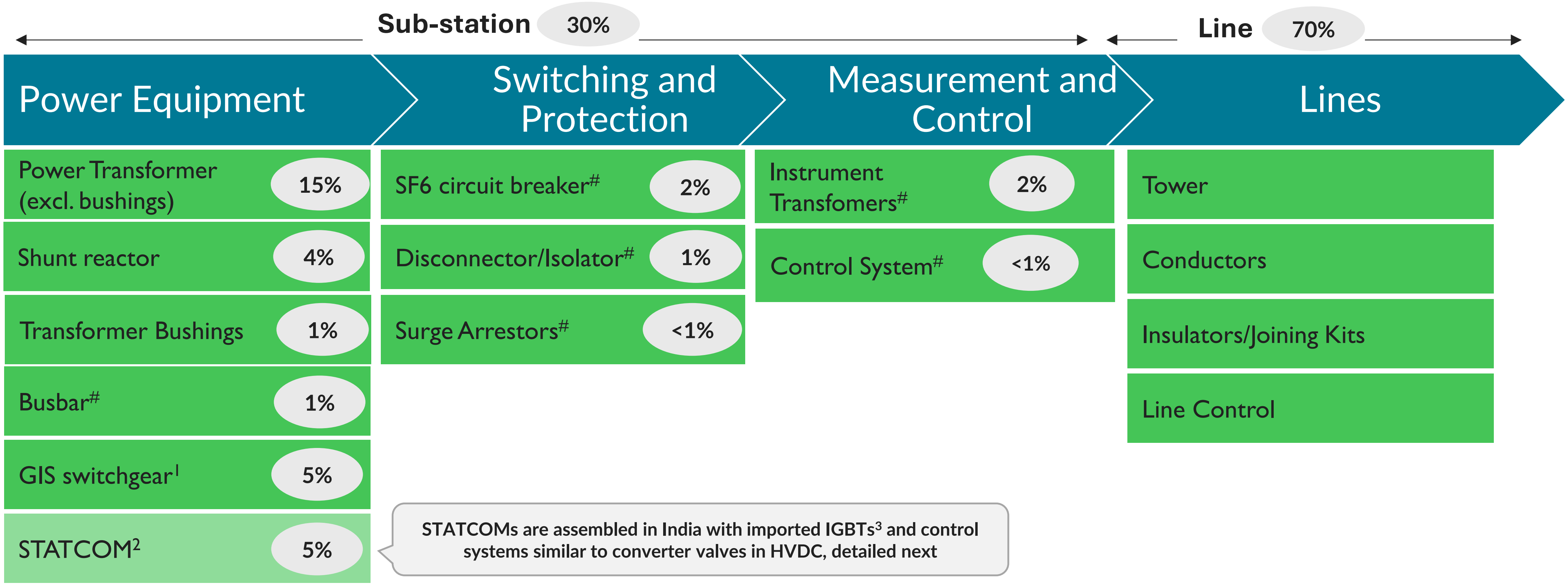
TRANSMISSION INDIGENISATION PATHWAYS FOR INDIA



Most of the HVAC equipment required is currently being manufactured in India, except for STATCOMs

HVAC Equipment Value Chain in India

🟩 Manufactured locally · ▩ Assembled locally, sub parts imported · ▢ Imported · (xx%) Cost contribution to the value chain



Sub-station 30%

Line 70%

Power Equipment	Switching and Protection	Measurement and Control	Lines
🟩 Power Transformer (excl. bushings) 15%	🟩 SF6 circuit breaker# 2%	🟩 Instrument Transfomers# 2%	🟩 Tower
🟩 Shunt reactor 4%	🟩 Disconnector/Isolator# 1%	🟩 Control System# <1%	🟩 Conductors
🟩 Transformer Bushings 1%	🟩 Surge Arrestors# <1%		🟩 Insulators/Joining Kits
🟩 Busbar# 1%			🟩 Line Control
🟩 GIS switchgear[1] 5%			
▩ STATCOM[2] 5%			

STATCOMs are assembled in India with imported IGBTs[3] and control systems similar to converter valves in HVDC, detailed next

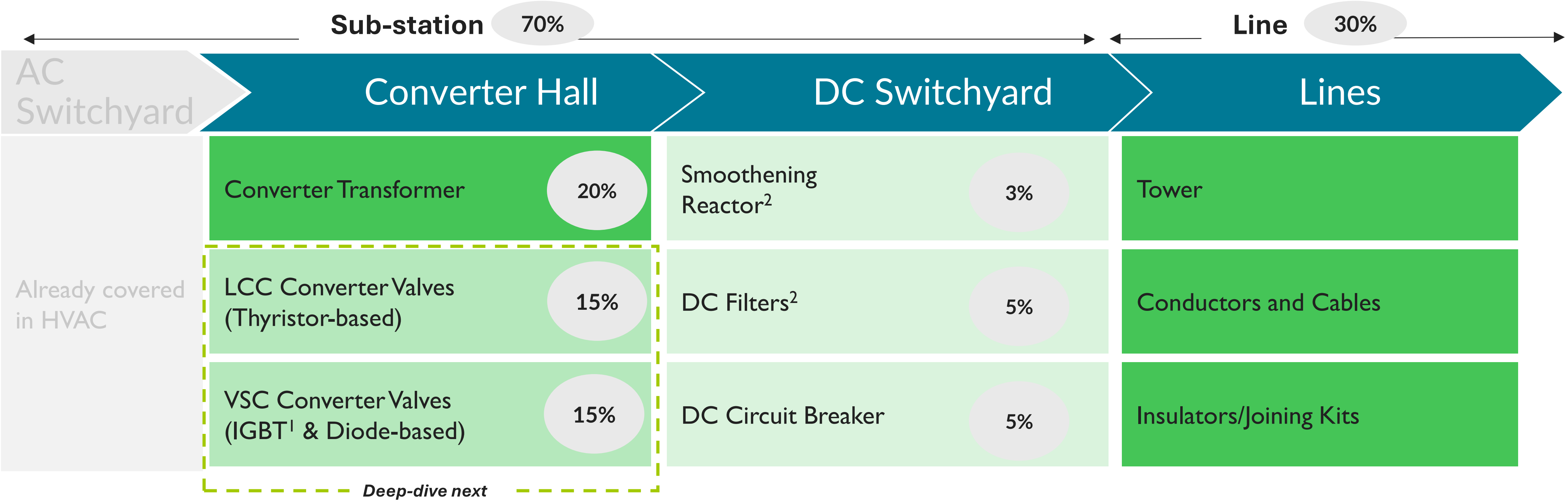
~ 5% of the HVAC equipment by cost is currently being imported into India, mainly STATCOM

(1) GIS complements used as replacement of AIS; all "#" components are enclosed within gas-insulated modules instead of stand-alone air-insulated units (2) STATCOM is used in selected projects with weak grids (3) Insulated-gate bipolar transistor: Source: Industry Expert Inputs;Dalberg Analysis

However, manufacturing capacity for HVDC systems is limited to transformers and lines, with majority substation equipment currently being imported

HVDC Equipment Value Chain in India

Manufactured locally | Assembled locally, sub parts imported | Imported | xx% Cost contribution to the total value chain (approx.)



Sub-station 70%

Line 30%

AC Switchyard	Converter Hall	DC Switchyard	Lines
Already covered in HVAC	Converter Transformer 20%	Smoothening Reactor[2] 3%	Tower
	LCC Converter Valves (Thyristor-based) 15%	DC Filters[2] 5%	Conductors and Cables
	VSC Converter Valves (IGBT[1] & Diode-based) 15%	DC Circuit Breaker 5%	Insulators/Joining Kits

Deep-dive next

~50% of the HVDC substation equipment by cost is currently being imported into India[3]; **25-30%** of that is from converter valve imports

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(1) Insulated Gate Bipolar Transistor used in valves (2) Manufacturing capacity exists only up to 500KV, hence imported for 800KV requirements (3) Calculated after excluding 30% of installation and civil work expenses under substation costs

Source: Industry Expert Inputs; Dalberg Analysis

Converter Valves: India assembles valves locally with most of the cost intensive sub-components currently being imported

Converter Valves (Thyristor/IGBT) are manufactured and installed in four steps

	Die/Chip fabrication	**Module Packaging**[2]	**Valve module & internal assembly**	**Valve Hall assembly and installation**
% of total "valve system" cost[1]	**15-20%**	**16-22%**	**35-40%**	**25-33%**
Major value drivers	Silicon Wafers doped to create specialized HV power devices (Thyristors/IGBTs)	Packaging dies into valve devices with heat sinks, localised cooling and insulation	Assembling multiple valve devices with specialized driver electronics (fiber optics) and other HV passive components (reactors, capacitors etc.)	Installing valves on the site with large cooling systems and commissioning services
Import Dependence	**100%**	**100%**	**40-60%**[3]	**<10%**[5]
Unlocks required for localisation	• Semiconductor fabrication infrastructure • IP-protected technology to dope the wafers	• High precision packaging tools • Pure quality raw material for insulation, heat sink plates etc.	• HV power electronics • HV DC capacitors and reactors [4]	N/A .

Focus for localisation

Given the high capex requirement and IP protection challenges for Chip fabrication, India could instead focus on module packaging and valve module assembly processes to increase domestic value addition in valve manufacturing by 5-10%

(1) Cost estimate covers both IGBTs and Thyristors; IGBT die fabrication and packaging are more expensive than Thyristors (2) In HVDC, module packaging and die fabrication occur in a single step, unlike others where the process is split. (3) Cost variation exists as IGBTs use more imported and critical components (4) Low-voltage DC capacitors are domestically produced. (5) Valve hall setup is largely indigenised with minimal imports

Source: Industry Experts, Dalberg Analysis

Scaling domestic HVDC manufacturing capacity requires focused R&D and investment to bridge the technology and capacity gaps across different components

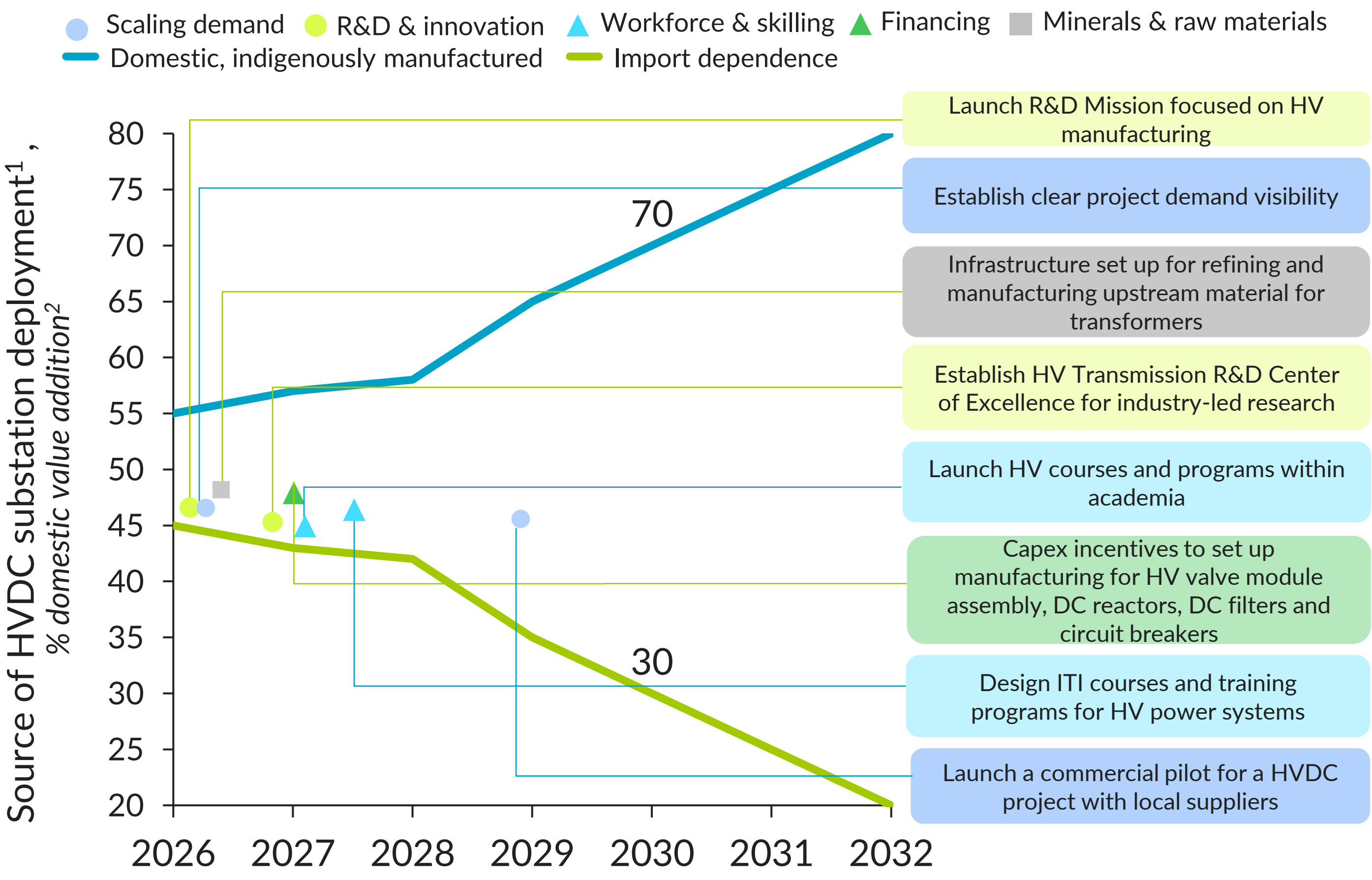
	HVDC Components		Manufacturing Pathway
Technology Constraints – ***lack of domestic IP and equipment design know-how***	Valve Optical Triggering Systems	Converter Valve dies/chips (Thyristor, IGBT)	→ **Need large Capex and IP concentrated within few companies –** continue importing
	DC capacitors DC Circuit Breakers	Gate Driver Electronics Smoothening Reactors DC Filters	→ **Adapt current technology to High-Voltage Transmission –** R&D and investment
Volume Constraints- ***importing due to supply shortage***	Converter Transformers		→ **Streamline demand and supply -** long term demand planning and investment

Source: Industry Announcements; Dalberg Analysis

Providing long-term demand visibility and targeted investment in core technologies can increase Domestic Value Addition (DVA) in the HVDC value chain up to 80%

Provide clear long term demand signal for HVDC deployment and invest early in R&D and manufacturing infrastructure by 2027-28

Transmission Indigenisation Pathway to increase DVA and reduce import dependence



Launch R&D Mission focused on HV manufacturing

Establish clear project demand visibility

Infrastructure set up for refining and manufacturing upstream material for transformers

Establish HV Transmission R&D Center of Excellence for industry-led research

Launch HV courses and programs within academia

Capex incentives to set up manufacturing for HV valve module assembly, DC reactors, DC filters and circuit breakers

Design ITI courses and training programs for HV power systems

Launch a commercial pilot for a HVDC project with local suppliers

To achieve 80% DVA, targeted policy interventions for localisation are required

- Create **a 10-15 year roadmap for inter and intra state HVDC projects**, clearly outlining technologies and systems needed so manufacturers can plan investments confidently
- **Invest ₹500-780 cr in R&D via ANRF** to build HVDC research capabilities and support research commercialization between government, industry, and universities aimed at tech commercialization
- Provide **capital subsidy on plant and machinery, PLI incentives per ton** and other fiscal incentives to make recycled copper critical for manufacturing HVDC equipment
- Prioritize bids with **DVA milestones for HVDC components** in the future transmission projects
- Build **training programs** with global HVDC centers in **France, UK and Japan** to develop skilled and ultra skilled workforce in High Voltage technologies

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1. Only substation costs are considered for the analysis of DVA and includes 30% installation and civil costs that are already indigenised. 2. DVA calculated based on cost contribution to the value chain and not the margins; Numbers are based on preliminary analysis and are subject to changes based on industry expert inputs

Source: CEA National Electricity Plan Volume 2, Company Announcements, BHEL Product Profile, Industry experts, Dalberg Analysis

There are several opportunities that could be captured through HVDC value chain indigenisation by 2032

Up to INR 25,800 Cr

Investment for HVDC valve and switchgear sub-components manufacturing

Up to INR 700 Cr

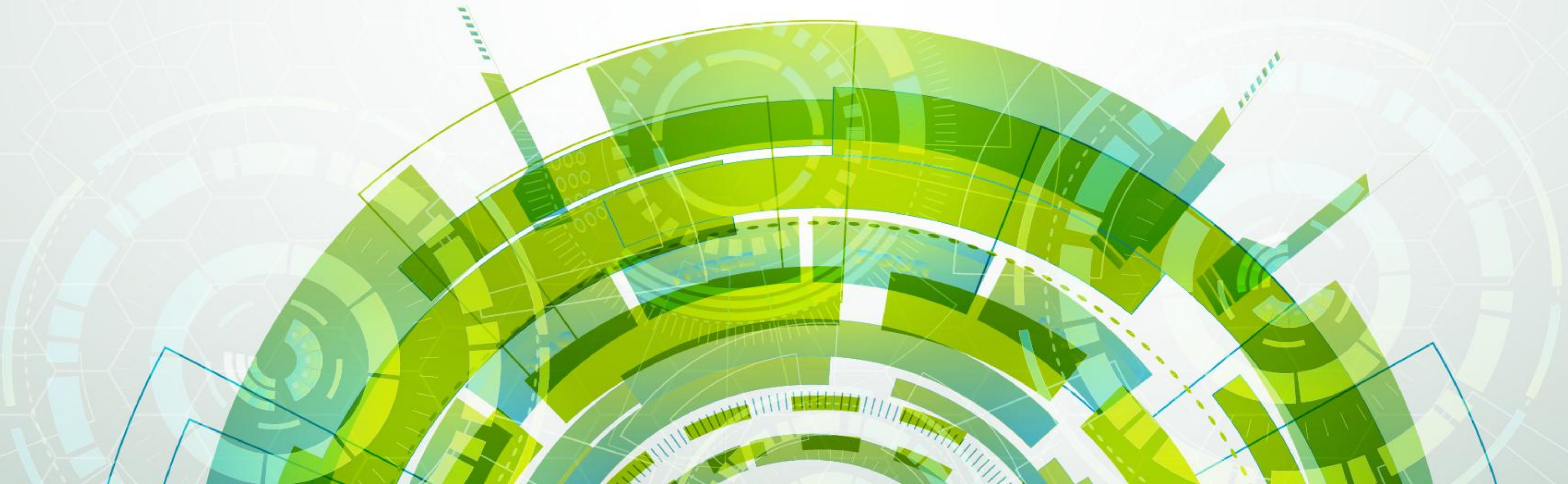
Investment for raw material recycling infrastructure

~8000 jobs

Across high voltage transmission manufacturing value chain

SECTION TWO

TRANSMISSION INDIGENISATION PATHWAYS FOR INDIA: DETAILED BY CROSS-CUTTING THEMES



1

Demand | Given the high import dependency, localising manufacturing of HVDC equipment could have commercial and strategic benefits for India

Why indigenisation is beneficial for India

Reductions in manufacturing cost

- Low voltage switch gear indigenisation (400KV) reduced costs by 30-40% between 2015-2024[1] – can expect similar cost reduction for HVDC components if indigenised
- Licensing fee for tech transfer could cost 4-5%[2] of revenue, making effective project costs to reduce by 20-25% at least

Fewer project delays and reduced costs

- Material import constraints led to delivery timelines for converter transformers increase by 2-3x in the past 10 years
- Global prices for switchgear imported has risen by nearly 50% since 2020, along with increasing lead times

Increased domestic value addition

- India currently imports 50% of HVDC substation components by cost
- Indigenisation of the value chain (switchyards and converter valves) could increase DVA by 20-25%

Detailed next

How China achieved economies of scale[3]

Timeline:

- Reduced import dependence for HVDC components from 80% to 10-15% between 2010-2020

Cost Reductions:

- 20-30% manufacturing cost reductions with 40% reduction in project delivery timelines

Levers implemented:

- Forced tech transfer from global OEMs early on[3]
- Created large domestic demand (10s of HVAC/HVDC projects identified)
- Government incentives for local manufacturing

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1. Based on cost comparison of a 400KV switch bay in 2015 (Hitachi estimates) of 7-8 cr to recent 5-6 crore tender in 2024 (PGCIL)., and accounting for inflation in that period
2 .ABB India reporting in 2018 3.China required foreign OEMs(Hitachi, GE, Siemens) to form JVs with local firm, share designs, and meet local content rules, making tech transfer a condition for participation in national HVDC projects ; Sources: GEP.com, Market Publishers HVDC Report , Paulson Institute Report, Expert Inputs

1 Demand | While long-term HVDC transmission demand is robust, reforms are essential to make it predictable at component level for domestic manufacturers

Large scale, policy-driven demand exists:

- Transmission sector demand including HVDC is largely **government driven**
- Setting up **transmission planning rules** helped create a **long-term view** on the transmission capacity plan for India between 2022-2032
- CEA National Electricity Plan (NEP) announced **~1.91 lakh ckm** and **>1200 GVA transformation capacity** addition by **2032**
- Demand for transmission infrastructure is cyclical, with **project delivery taking ~5 years** & **planned asset life of 35 years** in India

However, OEMs lack component-level demand visibility to plan long-term investments

A **System & equipment design variations** across projects result in differing component needs with no aggregate demand visibility for OEMs

➡ **Standardize design templates** (HVDC topology, voltage levels, number of circuits etc.) & publish a 10-year component-level demand outlook parallel to the NEP

B Process issues like **delays in component eligibility screening** for projects & **RoW**[1] **reroutes** disrupt OEM order pipelines

➡ **Review & streamline approval processes** by standardizing component quality requirements and creating a unified RoW–environment clearance mechanism to reduce procurement uncertainties

Project developers also lack incentive to procure critical components locally

C **60% Minimum Local Content** (MLC) requirement for turnkey HVDC projects is **largely met through AC-side components**

➡ Launch **component-specific PLI** aligned with **MLC targets for DC-side equipment** such as valves and switch gear

D MLC thresholds for three recent HVDC projects **were relaxed to 25%** due to limited domestic manufacturing capacity

➡ Implement **phased, gradually increasing MLC requirements for valves** to build domestic manufacturing capability over time

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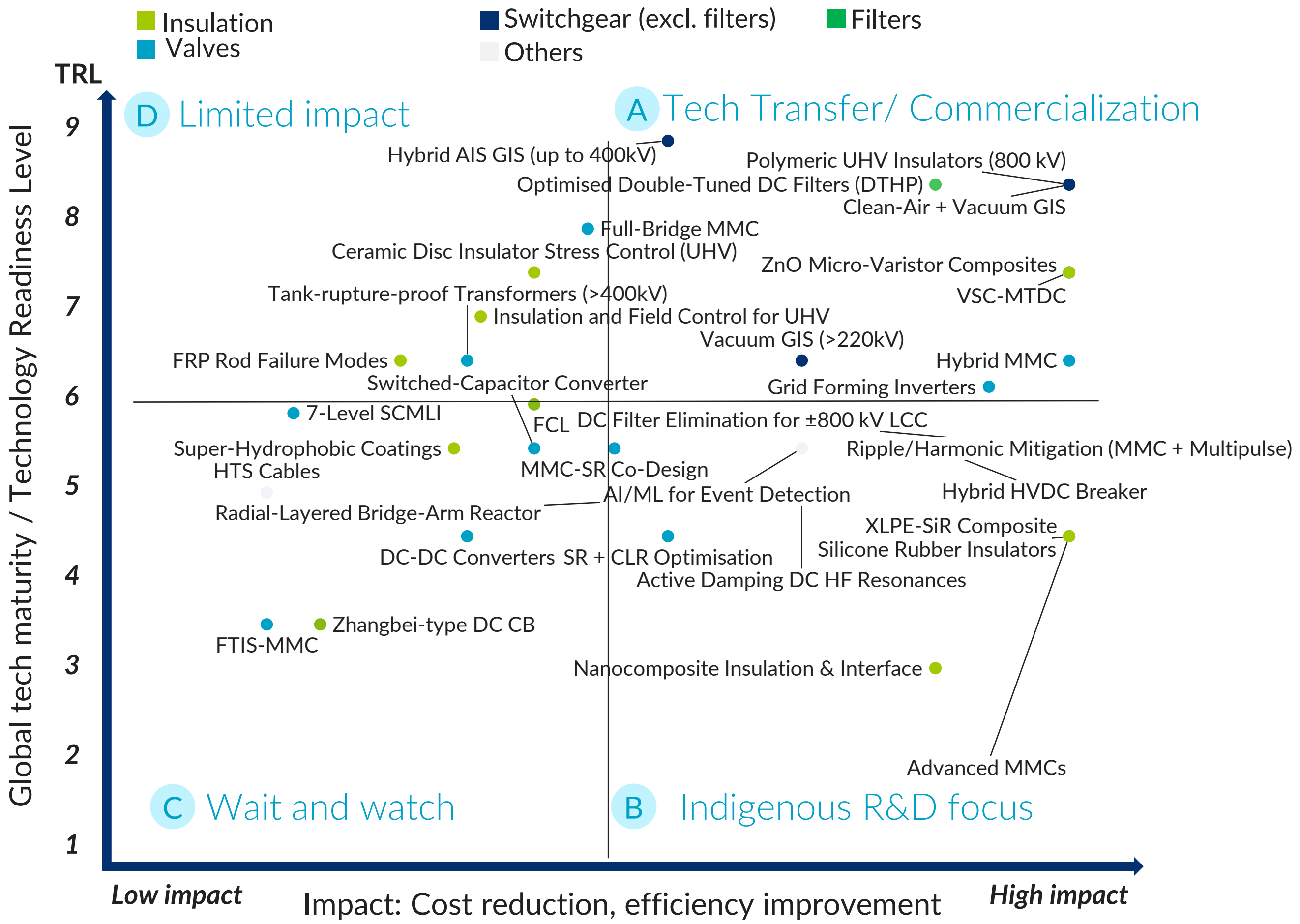
1. Right of Way 2.

R&D | Global advancements in technologies for HVDC components highlight the importance of strengthening domestic R&D capacity as a strategic national priority

Potential technologies for commercialisation in India



Key Insights

Tech transfer/ commercialization:

- Clean-Air + Vacuum GIS Replaces SF_6 with dry or clean-air mixtures for insulation and uses vacuum interrupters for switching. Offers electrical performance comparable to SF_6 GIS with a **smaller footprint** than AIS and **lower lifecycle emissions**. While initial purchase cost is slightly higher, **OPEX is 10–15% lower** due to simplified gas handling and reduced leak maintenance.
- Hybrid MMC is a voltage-source converter combining full-bridge and half-bridge submodules to withstand or block DC faults with **lower losses** than all full-bridge designs. Uses **30–60% fewer full-bridge cells**, enabling a **CAPEX reduction** for equivalent fault performance.
- VSC-MTDC is a multi-terminal HVDC networks Enables flexible power transfer across **three or more nodes/terminal**, improving grid reliability and renewable integration. Delivers **lower curtailment** in renewable corridors and **millisecond-level contingency response**. India can pilot with a **3-terminal hybrid- system** (e.g., Khavda to major load centers).
- Polymeric UHV Insulators (800 kV) is a Silicone rubber–housed, FRP-cored long-rod insulators for UHV AC/DC applications. **Lighter, cleaner, and more pollution-resistant** than porcelain or ceramic alternatives, offering **weight savings** and **faster erection times**.
- ZnO Micro-Varistor Composites Epoxy/silicone composites embedded with micro-scale ZnO varistors for field grading in bushings, terminations, and insulators. Achieve **lower local field peaks**, enabling **hardware cost savings** by reducing the need for metallic grading components.

Source: *Dalberg Analysis*

2

R&D | India's HV transmission R&D lacks an industry-led framework focused on deployment, slowing the transition from prototype to large-scale adoption

Challenges	Current Status
Fragmented R&D ecosystem & weak coordination	• **No national research agenda** for HV transmission; IITs/IISc focus on low-TRL technologies disconnected from current domestic manufacturing base (e.g. hybrid converter valve topologies, DC circuit breaker) • **National programs are dormant** or not power systems specific. For example, NAMPeT[1] is stalled and ISM[2] lacks HV transmission focus in power electronics • **No incentives to develop** and adopt domestically designed transmission equipment
No demand certainty for domestic manufacturers	• BHEL JVs & national projects have **not translated into scaled local manufacturing** • **Turnkey awards to global OEMs** restrict knowledge transfer • Project **developers lack confidence** in quality of domestically manufactured equipment and have low risk appetite to give them the first chance
Insufficient infrastructure & skills	• **Limited testing capacity** for ≥ 400 kV systems; equipment design research in academia currently relies largely on simulations • **Limited HV-focused talent** with hands-on equipment design and R&D skills within the industry and academia

(1) National Mission on Power Electronics Technologies (2) India Semiconductor Mission *Source: Dalberg Analysis, Insights from Industry Experts, Academia*

2

R&D | Building a robust R&D ecosystem, driven by industry can scale indigenous HV transmission technologies

Recommendation	Key Initiatives	Global Examples
Align national R&D around industry needs	• Launch a national **HVDC specific R&D program** with milestone-grants from concept to deployment for selected technologies • Introduce **design-backed PLI** for domestic R&D to **reward IP** held by Indian entities • Revive NAMPeT with a **focused mandate** on power electronics and HV semiconductor design	🇺🇸 Low-cost domestic manufacturing mission 🇮🇳 Design-backed PLI for telecom sector
Co-develop technologies through pilots & partnerships	• Run a **commercial pilot** with domestic sourcing to build confidence in technology & navigate multi-vendor tendering • Fund **2–3 focused workstreams** spanning from R&D → installation on an upcoming project with local research entities & OEMs • Run **joint research and pilots with other countries (e.g., UAE and Saudi Arabia)** to strengthen India's capability to manufacture for future cross-border power links	🇪🇺 Multi-vendor HVDC interoperability pilots 🇮🇳 UHVAC pilot at Bina, 2016 🇯🇵 OEM-academic-utility consortia R&D
Strengthen test infrastructure & embedded talent	• Establish an **integrated R&D & certification network** with simulation, prototyping, and test labs across IITs, BHEL & CPRI • Launch **resident engineer & faculty-in-industry programs** for 6–12-month secondments to drive **knowledge transfer** • Define **common standards** after a gap analysis of existing standardization	🇩🇪 Industry-embedded doctorate programs in HV systems 🇪🇺 Turned HV pilot projects into harmonized standards

Source: Dalberg Analysis, Insights from Industry Experts, Academia

2 **R&D infrastructure** | India could invest INR 1,000-1,300 Cr to upgrade & consolidate core HV transmission R&D facilities, expand testing capabilities, and create a coordinated national framework for innovation

Number of labs

2-3 System Studies Labs	₹ 100-110 Cr
1-2 Equipment Design & Small Test Bays	₹ 160-300 Cr
1 Central Large Hardware Test Facility with Accreditation Center	₹ 730-840 Cr

Total cost of labs

₹ 1,000-1,300 Cr

Represents **0.7-0.9%** of estimated national HVDC expenditure from 2022-2032

Prospective existing labs for upgrade

IISc/IITs Power Electronics

PGCIL System Simulation

BHEL Small & Large Test Bays

CPRI Accreditation Facility

Machinery needs

- Real-time software grid simulators
- Small HV test bench
- Rigs for power electronics & cooling systems
- Large HV halls for full-scale testing
- High-current & short-circuit stations
- Dedicated synthetic test circuits
- Heat, humidity, corrosion, vibration chambers
- Benches for protection & communication relays

Manpower and support needs

- Offices to manage technology transfer
- Templates for licensing, MoUs & IP protection
- Focused programs to attract & train young engineers to address the current talent gap in universities and labs

Source: Academia and industry experts

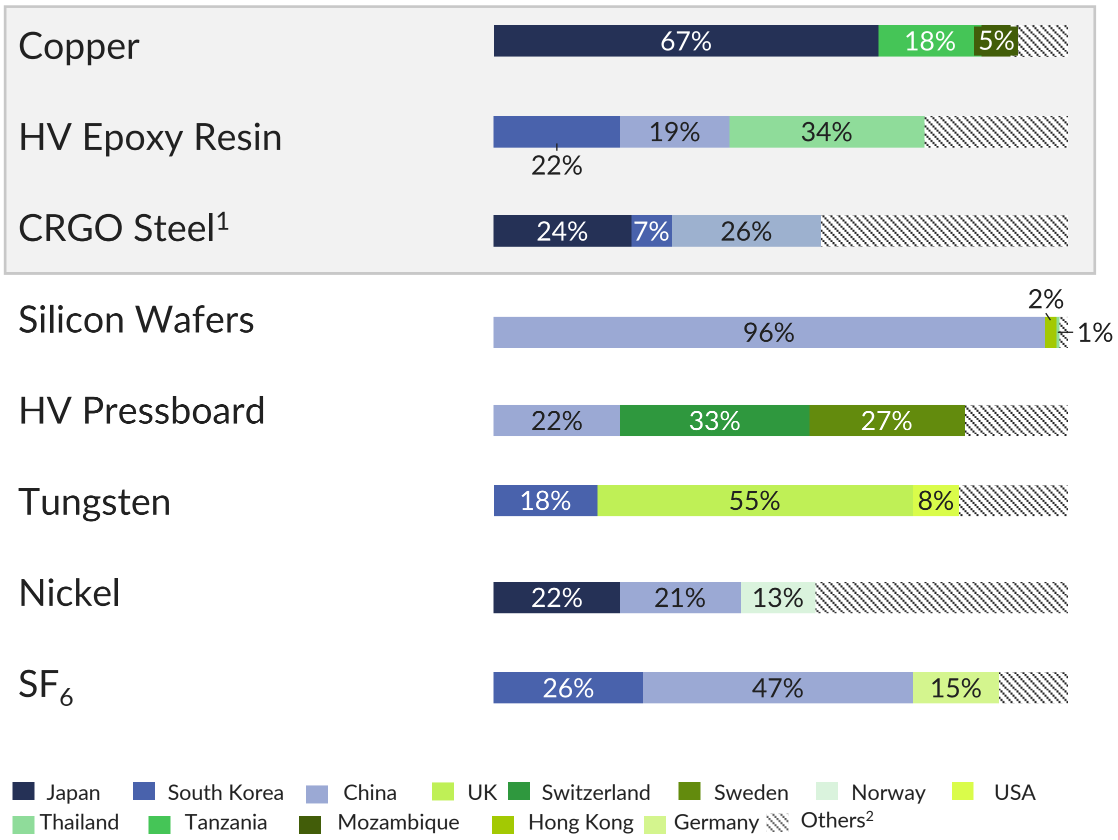
3

Raw Materials | Targeted incentives and investments can help reduce India’s import dependence on Copper and HV graded epoxy resins that are critical for HV transmission equipment

India has significant import dependency on raw material required to manufacture HV transmission equipment

▨ Prioritized based on cost & volume contributions

Critical Raw Material | **Countries importing to India (% of Volume)**



With focused investments and incentives, capacity for Copper and HV Epoxy Resin material can be increased

Current Status	Recommendation
Copper	
• **More than 50%** of India’s copper needs are currently met through imports • HV transmission **requires high purity (99.99%) copper** which has even lower recycling rates	• **Provide capex subsidies** for recycling copper to meet **40-50% of the transmission demand locally**[3] • **Formalize and upgrade scattered and unorganized sector** engaged with collection and recycling.
HV Epoxy Resin	
• **Limited domestic manufacturing know-how** and dependent on import for raw material ie. BPA and ECH and high purity curing agents	• Build capacity for high-voltage epoxy resin with export potential • Accelerate domestic manufacturing of BPA and ECH
CRGO	
• > 90% of CRGO is currently imported • **Capacity expanding** (JSW-JFE JV) **to cover domestic demand** by 2028	• De-risk cost inflation short term through **time bound strategic buffer stocks** for projects needed in the next 3-4 years until domestic capacity ramps up

(1) Cold Rolled Grain Oriented Steel – assumed import mix is the same for both cold rolled and hot rolled grain oriented electrical steel; Import data from 2024-25 where Chinese manufacturers with existing contracts could still export to India (2) Others’ category may include countries already shown in the legend; (3) Assuming current import dependence is at least 50%

Source: Ministry of Commerce and Industry: Trade Stats , Ministry of Mines: Press Release; Copper India Report ;PIB Dalberg Analysis

3

Raw Materials | Current import dependency among transformers and transmission lines could be addressed through targeted scaling of recycling and process capacities of critical materials (1/2)

Execution Potential: 🟩 High 🟨 Medium 🟥 Low

		Indigenisation pathways		
Raw Material	**Current bottlenecks**	**Production expansion**	**Recycling**	**Import diversification**
CRGO steel	• Complex technology and limited patents • Domestic producers shifted their production to CRNO which is used in EV • No long-term demand assurance to manufacturing firm by govt.	🟥 Manufacturing capacity under development that can cover domestic demand by 2028 (JSW-JFE partnership)	🟥 Recycling not suitable for high-voltage converter transformers as scrap CRGO has higher core losses.	🟥 High-grade CRGO steel produced only by a few global suppliers due to tech constraints
Copper	• Domestic smelting/refining capacity is less than demand; higher reliance on imported cathode/rod. • For recycling there's a fragmented collection units and underdeveloped recycling infrastructure • 67% percent of copper comes from Japan	🟥 Listed as a critical mineral under Critical Minerals Mission. Demand may still outgrow supply	🟩 Copper can be fully recycled and reused - needs capex to build out plants	🟩 Potential to diversify to other countries such as Chile and Congo
Silicon Wafers	• Getting specialized tools (power-wafer process IP) and process for fabrication is challenging • Long lead times to set up fabrication units	🟩 Leverage existing domestic capability to localise press-pack assembly while **continuing to import dies;** potential for localisation through tech transfer	🟥 Recycled silicon wafers are unsuitable for HVDC systems; only limited value from recovering silver/nickel (Ag/Ni) from wafer metallization.	🟨 Potential to diversify our imports from Japan, Taiwan, South Korea and EU Stock pile for at least 6 month for any supply shock

Source: Dalberg analysis; PIB India; U.S. Department of Energy (DOE) :Electric Grid Supply Chain Review(2022); Economic Times; CEA: imported Equipment list

3

Raw Materials | Current import dependency among transformers and transmission lines could be addressed through targeted scaling of recycling and process capacities of critical materials (2/2)

Execution Potential: 🟩 High 🟨 Medium 🟥 Low

		Indigenisation pathways		
Raw Material	**Current bottlenecks**	**Production expansion**	**Recycling**	**Import diversification**
Insulation Material (pressboard Insulation)	• Kraft pulp required for pressboard still needs to be imported from cold weather countries • Very few mills have the technology to produce IS-compliant electrical pressboard used in HV	🟨 Upgrade select board mills to HVDC electrical grades—India has capacity for Lower Voltage applications	🟥 Not recyclable for HVDC-grade insulation	🟥 Limited countries to provide pulp required
Insulation Material (Epoxy Resin in bushings)	• Limited domestic know-how for electrical-grade high voltage epoxy formulations and curating agents • Raw material precursors for resins Bisphenol-A (BPA), Epichlorohydrin (ECH), specialty hardeners etc. also must be imported	🟩 Accelerate domestic manufacturing of epoxy resins and hardeners using LV epoxy manufacturing capabilities	🟥 HV complex resins can't be recycled	🟥 Limited countries manufacturing HV grade epoxy resins
SF6	• No local manufacturing capacity exists • Global pressure to not use SF6 in future hence no demand visibility to invest	🟥 Limited demand as industry moves to SF6-free alternatives	🟨 Need to import tech required to recycle SF6	🟩 Import concentrated in China and Norway; potential to diversify across Russia, USA, Europe
Nickle	• No existing Ni mining in India for extraction	🟥 Not applicable	🟩 Nickel is 60-70% recyclable and can be used in HVDC systems	🟥 Nickel imports are diversified—key suppliers include Norway, Russia, Cannada & Japan.
Tungsten	• India's tungsten reserves are very limited • India imports ~43% of its tungsten from China	🟥 Domestic mining/refining at scale takes time and and high-capex	🟨 Tungsten can be recycled and used in HVDC	🟩 Potential to diversify toward South Korea, the USA, Austria, and Germany

bharat CLIMATE FORUM

Source: Dalberg analysis; PIB India; U.S. Department of Energy (DOE) :Electric Grid Supply Chain Review(2022); Economic Times; CEA: imported Equipment list

Council for International Economic Understanding

Dalberg

Capital equipment & infrastructure | Despite India's growing HV transmission market, limited machinery demand and technology concentration among few global companies constrain local manufacturing potential

High import reliance for capital equipment exists across the most cost intensive HV transmission components

Component	Import Reliance[1]	Key Machines
Transformers (Power & Converter)	**70-80%**	⚪ CNC press brake, CNC HV/LV wire-winding machine, vacuum drying oven, CNC plasma cutting table, column & boom welding manipulator, pressboard cutting 🟢 Foil winding machine, Mobile VPD service plant, Step-lap core cutting line, offline/automatic core-stacking robot & software, automatic insulation taping machine
GIS	**70-80%**	⚪ Heat-treat ovens, floor-type horizontal boring & milling, large-envelope VTL, clean/dry room, Ag/Ni plating line 🟢 Low-pressure die-casting cell, 5-axis gantry machining centre, filtration & storage skids, APG press, vacuum epoxy casting system, gas evacuation & recovery cart
Converter Valves	**40-50%**	⚪ Lightning impulse generator, HV AC/DC sources, clean assembly hall, vacuum brazing furnace, DI/UPW system 🟢 Fiber harnessing benches, SMT line, IEC 60700-1 valve test bay, burn-in racks, precision hydraulic clamping rigs, PD measurement system

Two major challenges exist in localising capital equipment manufacture

Machinery already manufactured in India

- **20-30%** of transformer & GIS machinery is **manufactured domestically**. Machinery **demand base is small** as only **5-6 projects** are required by 2032, but **cross-industry** use keeps domestic suppliers viable
- Converter valves are not yet manufactured in India, **but 50-60%** of required machinery is **domestically available**
- Existing domestic fabrication OEMs could **scale production** quickly with **limited investment** as build rate increases

Import dependent machinery

- **15-20%** machinery across the three components **can be manufactured domestically**, supported by **existing supply chains** for raw material/subcomponents. However, **low domestic & export demand volume** and **concentrated suppliers** create high barriers of entry for Indian manufacturers
- **45%** machinery has critical subcomponents based on **patented mechanisms** & **trade-secret softwares** which are not available without partnerships and would incur costs – potentially not viable for low volumes of demand

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(1) Calculated by cost and volume required to fulfil component demand for 2032

Source: Company Announcements, Dalberg Analysis

4

Capital equipment & infrastructure | India to continue importing HV transmission machinery due to limited supplier depth, small demand base and high precision thresholds for manufacturing locally

Key challenges in developing domestic capital equipment manufacturing

Niche, low-volume market	**Low volume market** of **less than few hundred units/ year** for very **specialized machinery** which is **dominated by Germany** owing to **decades of development** & proprietary methods. Other countries like Italy, Switzerland, Japan play focused roles
Insufficient demand anchor	India's HV transmission demand ($59B, 2027-32) potentially **not enough for machinery manufacturing to be viable**. China, despite larger demand ($89 B in 2025 alone), imports key machines from Europe
HV-grade precision barrier	Machinery requires ultra-tight tolerances, certified clean assembly, vacuum/gas handling, & long qualification, well **beyond existing indigenous LV machinery.** India would need **JVs/tech-transfer,** adding capex premium that would **drive up landed component cost**
Limited precision ecosystem	Domestic base of ultra-precision machinery from **adjacent industries is shallow**. Absence of local suppliers lead to **slow learning cycles & high integration costs**, resulting in longer lead time for HV manufacturing machinery development

Germany's dominance in HV-transmission capital equipment

Context: HV transmission component production depends on ultra-precision capital equipment, global supply led by Germany.

How Germany built lead

- Decades of cumulative know-how (since 1950) compounded in domestic **automotive, electrical machinery, & wire/cable industries**
- **Large machine-tool base** with dense suppliers in motion control, metrology, spindles, & vacuum systems enabled small-batch innovation

Supplier landscape: Mid-sized, 40+ years-old family-owned[1] firms manufacture machinery in the **dozens to low hundreds** per year, with **up to 90% export** share.

*Considering the priorities for HV transmission manufacturing in India, **indigenous machinery manufacturing, particularly for highly specialised equipment could be deprioritised***

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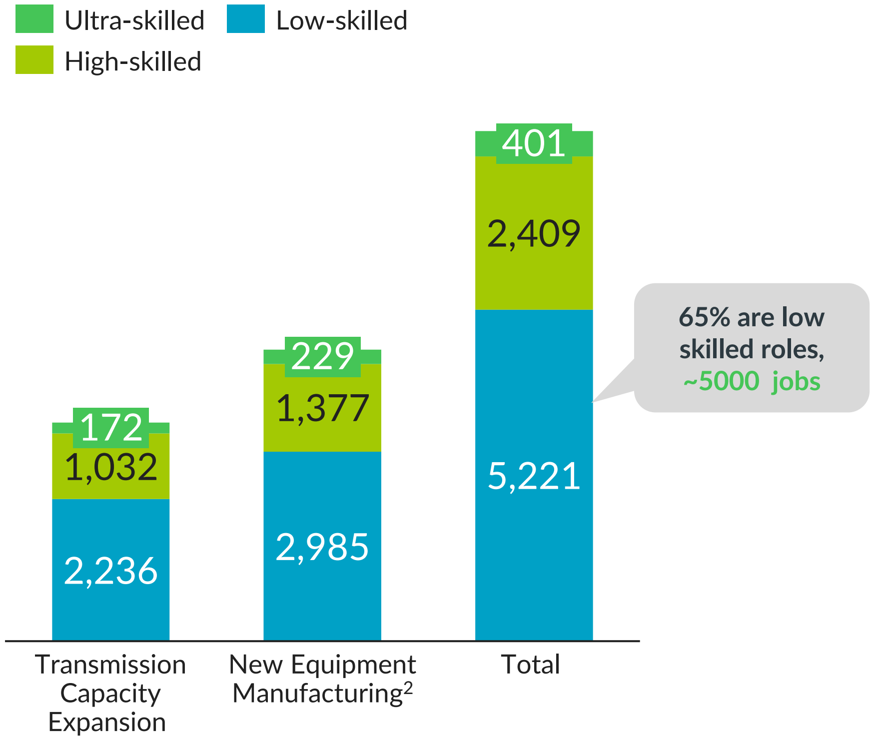
(1) Georg (family-owned, €72M FY21 revenue); DILO (~$10–25M revenue, 100–250; Hedrich (~€60M 2024 revenue); Niehoff (family-owned, ~€288m FY23 revenue); Sources: Company Announcements, Dalberg Analysis

5 Workforce and Skilling | India would require an additional ~8000 skilled workers across Transmission manufacturing by 2032, who could be trained with a ₹250-280 crore budget

Focus training workforce on substation components like converter transformers, AC/DC switchyards and control/protection systems since transmission lines are already highly indigenised

Current & projected (2032) workforce requirement for Transmission manufacturing, ‘000



65% are low skilled roles, ~5000 jobs

Skill level and sources of talent for Transmission manufacturing

Ultra-skilled	**R&D and system design Innovation experts** Research labs, PhD/Postgrad, programs, Tier-1 engineering and technical institutes
High-skilled	**Engineers & component specialists** Tier-1 and Tier-2 engineering colleges, lateral hires from industrial automation sector
Low-skilled	**Production line workers** ITIs, vocational training programs

Skilling Investment Required

Personnel training cost

₹ 175 - 200 Cr

+

Training centers investment[3]

₹ 75 - 80 Cr

=

Total budget

₹ 250 - 280 Cr

Note- (1) Additional workforce requirements aligned with the 15th National Electricity Plan (target year 2032); (2). Prioritized the indigenisation of DC switchyard manufacturing to import dependency (2) Includes 100% indigenisation of AC and DC switch gear for HVDC systems (3) Does not include lab equipment needed for ultra –high skilled workforce as it is included in R&D set up cost already

Source:; World Energy Employment Report; NITI:ITI Report (2024); Dalberg Analysis

5 Workforce and Skilling | To successfully build this workforce, concerted action is needed across education, industry and policy certification stakeholders

Skill Level 🟩 Ultra-high 🟨 High 🟦 Low

Current Challenges			Recommendations
Uneven and limited training capacity	**Lack of targeted skilling program** for transmission sector, particularly HV focused, for low skilled workers	🟨🟦	**Expand NPTI's current Diploma and short courses** into HV transmission systems, co-developed with PGCIL[1] and BHEL
	Absence of a national workforce planning exercise to align human capital needs with transmission expansion goals	🟨🟦	National Skill Development Council **(NSDC)** and the Power Sector Skill Council **(PSSC),** in partnership with utilities, OEMs and EPCs, to **conduct a national skill gap assessment** aligned with transmission planning and manufacturing goals
Curriculum–technology mismatch	**Curricula in Tier I/II institutions lag** sector needs; minimal coverage of HVDC/VSC, smart grid infrastructure etc.	🟩🟨	**Upgrade university-level transmission curriculum** in partnership with PGCIL, BHEL, and international institutes (e.g., KTH[2], SuperGrid Institute)
	ITIs have basic infrastructure, but advanced labs/equipment and syllabi for modern transmission technologies do not exist	🟩🟨🟦 🟦	**Establish a Center of Excellence** under Ministry of Skill Development & Entrepreneurship (MSDE) for transmission system, developing training curriculum and cascading training capacity at a national level **Modernize ITI infrastructure** under National and State Skilling Missions, in partnership with utilities, EPCs and OEMs
Limited Industry–academia links and certification standards	Large OEMs (e.g., L&T, Tata Power) run in-house programs, while **SMEs (accounting for ~90% of production) lack access** to any training programs	🟦	Establish **transmission focused shared training centers** for SMEs under the MSME[3] Cluster Development Programme
	Credentials are fragmented (PSSC, NPTI, state licenses, OEM programs) with no unified registry, limiting employer visibility and comparability.	🟩🟨🟦	PSSC to **establish a unified national certification framework** aligned with global transmission skilling standards

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(1) Power Grid Corporation of India Limited (2) KTH Royal Institute of Technology (Sweden) (3) Micro, Small and Medium Enterprises

Source: IEEMA: Electrical equipment mission plan ; IEA : World Energy Employment Report; NITI : ITI Report; Dalberg Analysis

6 Financing | An estimated INR 22,200-26,500 crore will be needed to build domestic HVDC manufacturing, along with INR 3,000–4,000 crore of targeted viability funding for remote HVDC corridors

Government funding will be required across R&D, workforce development, and capital subsidies to establish India as a leading manufacturer of advanced HVDC systems by 2032

Theme	Total Funding Required (INR Cr) - approx	Government Funding Required (INR Cr) - approx	Key Activities	Potential Outcomes
Demand& Market Architecture	3,400-4,500	3000-4000	Set up HV transmission projects of ~6 lakh ckm by 2032. Government to provide viability gap funding to remote HVDC projects[1]	Sufficient transmission capacity to evacuate more than 250GW of renewable energy planned by 2032 across India and cross-borders
R&D & product Innovation	1,000-1,300	500-780	Set up 2–3 System Studies Labs in universities, 1–2 Equipment Design & Small Test Bays and 1 Central Large Hardware Test Facility	Indigenous development of HVDC technologies;
Upstream Raw Materials & Critical Inputs	450-700	80-120	Provide input subsidies up to 20% on domestic copper recycling and HV epoxy resin manufacturing plants[2]	Reduce import dependency on Copper cathodes used in transmission systems by 30-40 % of total demand
Capital Equipment & Infrastructure	22,200-26,500	2,200-2,600	Expanding HVDC manufacturing ecosystem will require INR 19.2-23K Cr investment. Provide 5 - 10 % Production Linked Incentives on HVDC component manufacturing (reactors, filters, DC capacitors, etc.[3])	Reduce import dependence from 100% to complete localisation of critical HVDC switchgear and converter valve components
Talent & Workforce	250-280	75-80	Setting up Center of Excellence for training the workforce in HVDC systems; Train ~8000 skilled workers through new courses & apprenticeships	Ensuring a stable supply of skilled workers in HVDC systems; build capabilities to carry our globally competitive R&D in HVDC
TOTAL	27,200-33,200	5,900-7,600		

(1) Assumed funding support needed for Leh-Kaithal, project costing approximately 50% of the Ladakh – Kaithal project that received INR 8000 Cr funding from Green Energy Corridors; (2) Assumed a plant of 1ktpa of HV epoxy resin could be set up as a brownfield plant within a domestic epoxy resin factory with 1.5-2x times the capex required for HV grade manufacturing. 1ktpa is higher than domestic need and hence expected to be built for export opportunities as well (3) Includes large HV testing infrastructure which is assumed to be non existent in India and accounts for a significant share of the Capex for manufacturers. Some of the components such as DC capacitors need to be set up at scale targeting exports as well to be commercially viable; Source: Dalberg Analysis

Financing | India could adopt a range a financing mechanisms tailored to the needs of domestic HVDC manufacturers

Remote HVDC Corridor Viability Funding

- **Secure dedicated Viability Gap Funding (VGF) under Green Energy Corridor** in the coming phases for future HVDC projects in remote corridors (e.g., Leh-Kaithal being proposed)
- Explore potential for **additional VGF funding for higher HVDC domestic content**

HVDC Manufacturing Capex Finance Facility

- Set up a **concessional capex financing facility** via institutions such as NaBFIDI[1] with **partial credit guarantees** for domestic HVDC manufacturing investments
- Make **funding accessible** to both large OEMs and **Tier 2/3 suppliers** with smaller production volumes

Long-Visibility HVDC PLI Scheme

- Launch a bespoke **HVDC transmission PLI** with upfront capex incentive (5-10%) for HVDC components i.e., valves and switchgears
- Provide a **7-10 year long incentive** to align with the long production and project deployment cycles

(1) National Bank for Financing Infrastructure and Development; Source: Industry experts input, Dalberg Analysis

ANNEX

Converter Valves: Leveraging existing manufacturing capabilities and cross-industry synergies, India can manufacture valve sub-components and package valve modules locally

	Die/Chip Fabrication	Module Packaging	Valve Internal Assembly
Localisation requirements	**Tech:** Specialized doping technology concentrated with few OEMs globally - took them 15-20 years to develop **Capex**: Need ‘0000s(RS 91000 cr) of crores to set up a silicon wafer fabrication unit Takes up to 10 years to set up a whole semiconductor value chain	**Tech:** HV specific insulation, thermal management, and precision assembly processes that differ significantly from LV/MV power electronics **Capex**: Need ‘000s of crores to set up a module packaging unit Mix of green and brownfield investments required to adapt to a HV packaging facility	**Tech**: specialized HV integration technology, precision electrical layout, and high-reliability auxiliary component assembly **Capex**: Need ‘00s of crores to manufacture the components but lesser than packaging Takes 1-2 years to set up factories with tech transfer /JVs
Existing manuf. Capabilities	• **Doping technology** and process tools (lithography, epitaxy) **don’t exist in India** • Tech transfers/JVs are required, and **critical raw material** (Si/SiC wafers, specialty gases) **need to be imported**	• Existing power module packaging facilities for **LV in adjacent industries** (defense, automotive etc.) can be upgraded • **HV testing beds, heat sinks and insulation material** can be transferred or developed indigenously • **Optical triggering systems** are highly specialized and **continue to be imported**	• Have manufacturing capabilities for **LV DC capacitors and gate driver electronics in adjacent industries** that can be upgraded with R&D investment • Focus on **tech transfers/JVs** short term and invest in **indigenous R&D capacity** for long term
Localisation potential	**Low**	**Low –Medium**	**Medium-High**

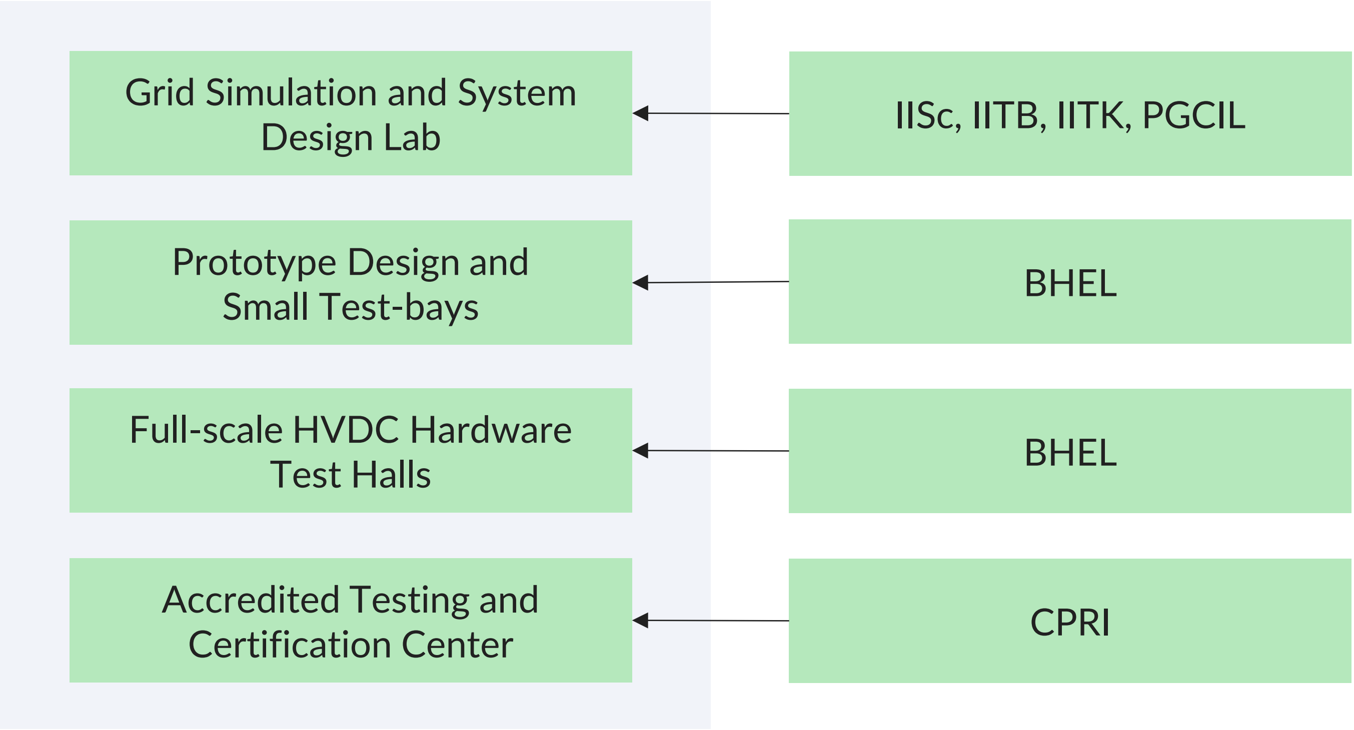
Source: Industry Expert Input, Dalberg Analysis

TRANSMISSION EQUIPMENT R&D & PRODUCT INNOVATION

2

R&D | Strengthening India's HV transmission R&D ecosystem will require coordinated investments in simulation labs, prototyping facilities, and large-scale test infrastructure across key institutions

Core facilities required for HV transmission R&D



Grid Simulation and System Design Lab ← IISc, IITB, IITK, PGCIL

Prototype Design and Small Test-bays ← BHEL

Full-scale HVDC Hardware Test Halls ← BHEL

Accredited Testing and Certification Center ← CPRI

Key insights on domestic R&D infrastructure

- **IISc & IITs** currently host advanced power-system and converter-control labs that can transform into a **real-time simulation & modeling cluster**, providing HV transmission design backbone.
- **PGCIL system-planning and operational modeling tools** can be **linked with academic simulation hubs** to validate control & protection logics pre-deployment.
- **BHEL Bhopal** operates a ±1200 kV UHV test bay & transformer design lab, which can be expanded to include **converter-valve and power-electronics prototyping** facilities.
- **CPRI** has ±1200 kV DC dielectric and pollution test capability which can be upgraded with accredited certification processes to form the **national hub for HVDC equipment certification**.

Case Study: SuperGrid Institute France was established in 2014 as a PPP-model HVDC R&D center with €220 million funding over 10 years, of which one-third was invested as capital for R&D infrastructure. It operates ±600 kV test halls, converter & cable platforms, DC-breaker labs, and real-time simulation facilities, showing how a centralized center of excellence can pool government & industry resources for large-scale transmission innovation.

Source: Academia and industry experts

R&D | India should focus on tech-transfer in 6-8 mature technologies and indigenous R&D in other 9-10 technologies to reduce import of critical components in HVDC (1/4)

Key Insights

(continued tech transfer/ commercialization):

- Grid Forming Inverters enable **voltage and frequency control ("synthetic inertia")** instead of passive grid-following, enhancing **stability and black-start capability** in high-renewable systems. They lead to **fewer under-/over-frequency (UF/UV) events**, **faster frequency recovery**, and **notable curtailment reduction** in weak or isolated grids.
- Optimized Double Tune DC Filters employ **dual harmonic tuning within a single filter bank**, delivering compliance with **fewer branches** compared to single-tuned filters. The design enhances **damping bandwidth** while maintaining harmonic performance and reliability
- Hybrid AIS GIS (Upto 400KV) integrates **factory-assembled GIS breaker/isolator modules** with traditional AIS yards, combining **compactness, faster construction, and higher reliability**. This configuration enables **reduced substation footprint** and improved project economics where full GIS deployment is not justified

Indigenous R&D focus:

- Advanced MMCs (e.g., alternate-arm, clamp-double, mixed energy buffers) are still in RnD phase aim to deliver **fault-blocking with lower losses and fewer components** than today's converters. They widen operating range on weak grids and enable compact stations. Target **0.2–0.4 percentage-point loss reduction** vs conventional FB-dominant MMCs; **smaller reactor/capacitor bank sizing** through smarter energy circulation and control; faster DC fault recovery. Potential **5–10% converter CAPEX** saving from reduced silicon, reactors and auxiliaries; lower lifetime losses reduce OPEX
- Hybrid HVDC Breaker combines a low-loss mechanical path with a solid-state path to **interrupt DC faults in ~2–5 ms**, enabling selective protection in MTDC grids and rapid restoration. **Millisecond isolation** limits energy let-through and equipment damage; enables **meshed VSC–MTDC.** Near-term unit cost high, but system-level benefit
- DC Filter Elimination for ±800 kV LCC engineering the **removal or drastic minimization** of DC harmonic filters on UHVDC links where telecom interference risk is low and smoothing reactors/line design suffice—**shrinking station footprint** and complexity
- AI/ML for Event Detection uses PMU/SCADA/DAS data with ML to **detect incipient faults, oscillations, and equipment anomalies** early; accelerates root-cause analysis and restoration.**faster disturbance detection**, **reduction in SAIDI/SAIFI** on instrumented corridors; fewer nuisance trips. Software-led; **low capex, high OPEX savings** (fewer truck rolls, targeted maintenance); avoids major outage penalties
- DC Filter Elimination for ±800 KV involves the **removal or drastic minimization of DC harmonic filters** in UHVDC systems where **telecom interference is negligible** and smoothing reactors suffice. This approach **simplifies converter stations**, achieving **terminal CAPEX savings**, **smaller DC yards**, and **O&M reductions** by avoiding capacitor and resistor banks

Source: Academia Input, *Dalberg Analysis*

R&D | India should focus on tech-transfer in 8-10 mature technologies and indigenous R&D in other 9-10 technologies to reduce import of critical components in HVDC (2/4)

Key Insights

(continued Indigenous R&D focus):

- Ripple/Harmonic Mitigation (MMC + Multipulse) is hybrid architecture where a **diode bridge handles bulk power** and an MMC injects controlled waveform to **cancel harmonics**, cutting passive filter needs and losses for one-way/high-capacity links. **1–2% converter loss reduction** vs pure MMC at scale; **significant harmonic suppression** without large DC filters. **converter CAPEX** saving from fewer submodules/reactors and smaller filters; reduced footprint.
- Active Damping DC HF Resonances is control algorithms in converters to **sense and damp high-frequency resonances** between AC networks and DC converters—**avoiding instability without extra hardware**. **reduces oscillatory trips**, **widens stable operating range**; improves RE hosting capacity on weak grids.
- Radial-Layered Bridge-Arm Reactor is a novel MMC arm-reactor geometry that **optimizes AC/DC impedance and cooling**, reducing hot-spots and material use while maintaining fault-limiting behavior. **5–10% lower reactor losses**, improved thermal margins; potential **10–20% volume/weight reduction**
- XLPE-SiR Composite is a hybrid **cross-linked polyethylene (XLPE) + silicone rubber (SiR)** insulation for joints/bushings, combining **high bulk strength** and **hydrophobic surfaces—reducing partial discharges and space-charge issues** in HVDC accessories. **higher PD inception margins**, **longer service life** in pollution/humidity; fewer forced outages.
- Nanocomposite Insulation & Interface Treatments are Polymer dielectrics with nano-fillers (e.g., Al_2O_3, SiO_2, MgO) and engineered interfaces to **raise breakdown strength, reduce losses and charge build-up**, improving cables, bushings and insulators. Lab evidence of **lower dielectric loss**, **better DC ageing**; enables **thinner insulation/compact designs**. Near-term material premium, but **lifecycle cost down** via longer life and compact accessories; opportunity for **local material substitution**.

Wait and Watch:

- Floating Tree Inter Submodule MMC is an **experimental converter architecture** that **shares energy and storage paths across arms** to cut component count. Theoretical models suggest **fewer capacitors/reactors** and **converter CAPEX savings**, but it remains **unproven at HVDC scale**. **Integration, fault isolation, and control risks** are untested, and **redesign and testing costs** currently offset potential near-term gains.

Source: Academia Input, *Dalberg Analysis*

R&D | India should focus on tech-transfer in 8-10 mature technologies and indigenous R&D in other 9-10 technologies to reduce import of critical components in HVDC (3/4)

Key Insights

(continued Wait and Watch):

- Floating Tree Inter Submodule MMC is an **experimental converter architecture** that **shares energy and storage paths across arms** to cut component count. Theoretical models suggest **fewer capacitors/reactors** and **converter CAPEX savings**, but it remains **unproven at HVDC scale. Integration, fault isolation, and control risks** are untested, and **redesign and testing costs** currently offset potential near-term gains.
- Zhangbei-type DC Circuit Breaker uses a **hybrid mechanical–power-electronic design** to **clear DC faults within milliseconds**, enabling **meshed VSC-MTDC grid operation**. However, **high unit costs, auxiliary complexity, and limited field adoption** make it **uneconomical for point-to-point HVDC links**, increasing project CAPEX without immediate benefit.
- HTS Cables employ **liquid-nitrogen cooling** to achieve **near-zero resistance** and **extremely high-power density** in constrained corridors. They provide **very low electrical losses** and **superior ampacity per trench** but currently face **2–4× higher CAPEX than XLPE**, plus **ongoing OPEX for cryogenic systems** and specialized maintenance. **Long-distance reliability** is still under demonstration
- Switched-Capacitor Converter replace traditional magnetics with **switched-capacitor networks** to achieve **higher power density**, showing promise in **laboratory and medium-voltage applications**, though **HVDC suitability remains unproven**. Early lab tests demonstrate **converter efficiency** and strong compactness benefits; however, **device stress, balancing, and surge control challenges** persist at HVDC ratings. While **theoretical material savings** are possible, **real-world costs may rise** due to additional protection and control requirements.
- FRP Rod Failure Modes programs involve **analytical and testing initiatives** to study **brittle fracture and aging in glass-fiber reinforced polymer (FRP) rods** used in composite insulators. These programs **enhance forensic understanding, design standards, and procurement specifications**, but deliver **no step-change in corridor capacity or system reliability** beyond robust QA practices. Potential value lies in **minor OPEX savings** through fewer premature replacements
- Super-Hydrophobic Coatings use **nano-structured or fluoropolymer surface treatments** to improve **water repellency and reduce pollution-flashover frequency**. Field pilots report **higher pollution withstand capability** and lower washing needs, though **UV exposure and abrasion degrade performance over time**, and **reapplication cycles remain uncertain under Indian climatic conditions**.
- DC–DC Converters for stations deploy **solid-state or resonant converter designs** to **interconnect DC grids operating at different voltage levels**, a critical enabler of **true multi-terminal DC (MTDC) flexibility**. They target **device efficiency**, offering high system value **only when multi-node DC networks exist**; current Indian HVDC programs remain **predominantly point-to-point**, limiting near-term applicability

Source: Academia Input, *Dalberg Analysis*

R&D | India should focus on tech-transfer in 8-10 mature technologies and indigenous R&D in other 9-10 technologies to reduce import of critical components in HVDC (4/4)

Key Insights

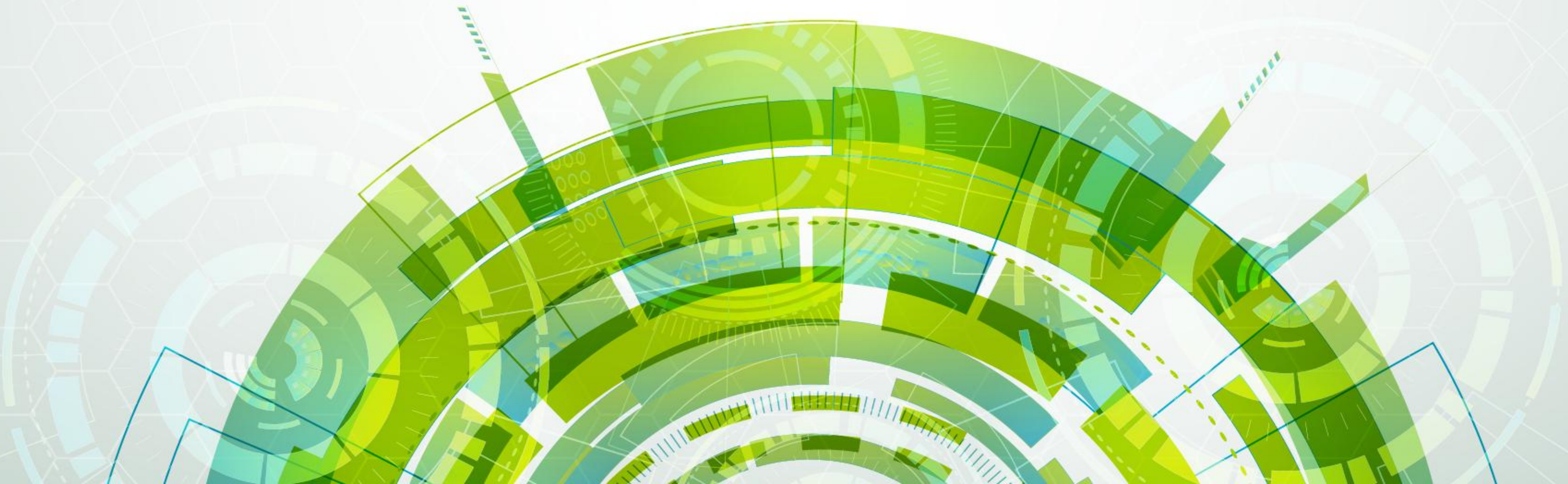
Limited Impact

- Ceramic Disc Insulator Stress Control (UHV) uses coronas rings/semiconductive glazes and optimized hardware to smooth electric-field stress along long porcelain strings on UHV AC/DC lines. Outcome: incremental reliability improvement on legacy ceramic strings. maintains rated withstand; typical **reduction in local field peaks** and marginal flashover risk reduction versus un-optimized strings. No impact on power transfer or corridor footprint.

- FRP Rods Failure Modes program is a test and analytics initiative aimed at understanding brittle fracture and ageing in fiberglass rods within composite insulators. The program drives tighter procurement QA, improved sealing practices, and better vendor qualification, resulting in reduced premature insulator failures from poor production lots. While it delivers incremental efficiency and reliability gains, it does not alter corridor capacity or station performance. Financial impact is limited **to minor OPEX savings** from fewer early replacements, with negligible CAPEX implications at the project level.
- 7-Level SCMLI uses switched-capacitor cells to synthesize multilevel waveforms with fewer DC sources/magnetics. Lab-scale results show **>95% converter efficiency** and lower part count; at HV/HVDC, balancing and surge protection reduce net benefit. Potential **materials saving** offset by added protection/control; **uncertain CAPEX/OPEX gains** for HVDC terminals.
- Fault Current Limiter devices that insert impedance within milliseconds to limit fault current on AC grids. Outcome: equipment protection and avoided switchgear upgrades in select nodes; **limited relevance to point-to-point HVDC**. Effective limiting in trials. **High unit CAPEX**; payback only on constrained substations where breaker upgrades are prohibitive.
- Full Bridge MMC Converter built entirely with full-bridge submodules to **block DC faults** and widen control range. Outcome: robust operation—but with **higher losses and silicon count** than half-bridge/hybrid MMCs. **Higher CAPEX** (more semiconductors) and modestly higher OPEX (losses) vs hybrid MMC delivering similar fault performance; limited footprint benefit.
- Insulation and field Control (UHV) ensure that **electric fields are evenly distributed** across equipment, avoiding local overstress and partial discharge failures. These solutions combine **optimized geometry, grading rings, field-shaping electrodes, and advanced composite materials** in bushings, terminations, and valve hall. improves **insulation reliability by 20–30%**, extends component life, and enables **more compact layouts** in converter halls and yards. Insulation optimization adds marginal equipment but avoids expensive failure events and outages.

Source: Academia Input, *Dalberg Analysis*

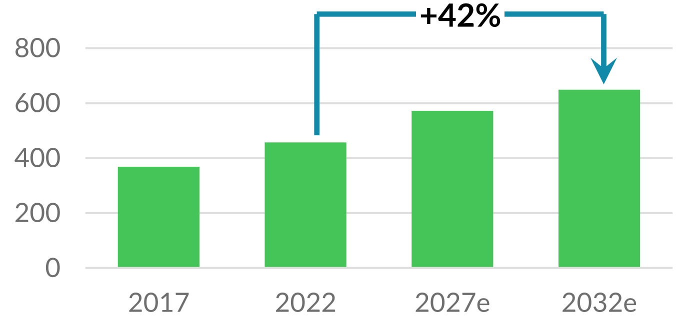
Summary Slides



Demand | India's transmission planning signals long-term demand for the sector but manufacturers lack component-level demand visibility and incentives to invest

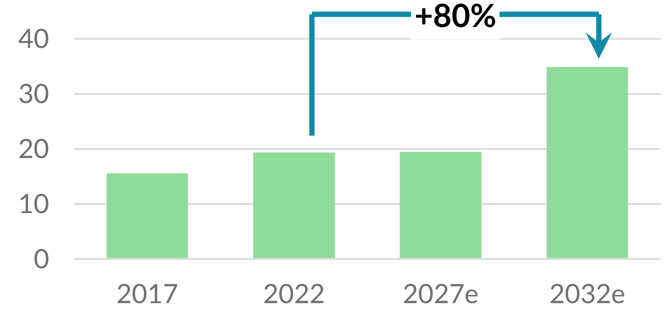
India is expanding High Voltage (HV) transmission significantly by 2032

HV transmission capacity growth, '000 ckm



HVDC[1] transmission network is expected to outpace overall grid expansion

HVDC transmission capacity growth, '000 ckm



Demand is largely government driven through transmission planning reports developed until 2032

However, demand visibility at component-level remains fragmented with no targeted incentives for HVDC component manufacturers

Current Challenges	Key Recommendations
System & equipment design variations across projects result in differing component needs, **reducing clarity on aggregate component demand** for OEMs[2]	**Standardize design templates** (HVDC topology, voltage levels etc.) & publish a **5–10-year component level demand outlook** aligned with the transmission planning
Process issues like **delays in component eligibility screening** for projects & **RoW[3] reroutes** (ex. GIB corridors) disrupt OEM order pipelines	Streamline approval processes by **standardizing component quality requirements** & creating a **unified RoW–environment clearance** mechanism
The **60% Minimum Local Content** (MLC) thresholds for three recent HVDC projects **were relaxed to 25%** due to limited domestic manufacturing capacity	Implement **phased ramp up of MLC** requirements supported by **component-specific PLI[4]** such as for converter valves

Attracting HVDC manufacturers in India requires policy alignment on design standards, component-level roadmaps, localisation incentives, and streamline approvals

(1) High Voltage Direct Current (2) Original Equipment Manufacturer (3) Right of Way (4) Production linked incentives

Source: Insights from Industry Experts, Dalberg Analysis

R&D | A collaborative R&D ecosystem driven by industry and enabled by government is essential to scale HV transmission innovations from research to deployment

India lacks a coordinated national R&D framework for HV transmission

Fragmented R&D Ecosystem

- There is currently no national research agenda for HV transmission. Academic efforts in IITs/IISc remain theoretical and disconnected from domestic manufacturing needs
- Existing national missions are either dormant or lack power systems focus. Example: NAMPeT[1] is paused and ISM[2] does not address HV transmission

Insufficient Research Infrastructure & Skills

- There is limited testing capacity for HV systems. Equipment design research in academia is largely simulation-based
- Premier universities have limited faculty specializing in HV power systems
- Turnkey project awards to MNCs with high import dependence restrict domestic industry-led research and limit knowledge transfer

Scaling HV research into manufacturing and deployment requires coordinated, industry-led programs backed by sustained government partnerships and targeted funding

Key Recommendations

- Launch HV equipment-specific R&D programs with milestone grants from concept → prototype → deployment. Revive NAMPeT[1] with a focused mandate on power electronics and HV semiconductor design
- Short-term: Fund manufacturing of 2-3 indigenised component specific pilots spanning from R&D to installation on an upcoming project with local research entities & OEMs
- Long term: Run an end-to-end commercial pilot with domestic sourcing for all components to build confidence in indigenous technology & navigate multi-vendor tendering
- Launch resident engineer & faculty-in-industry programs for 6–12-month secondments to drive knowledge transfer

Research Facilities & Investment Required

2-3 System Design & Simulation Study Labs	1-2 Equipment Design & Small Test Bays	1 Central Large Hardware Test & Accreditation Center
₹ 100-110 Cr	₹ 160-300 Cr	₹ 730-840 Cr

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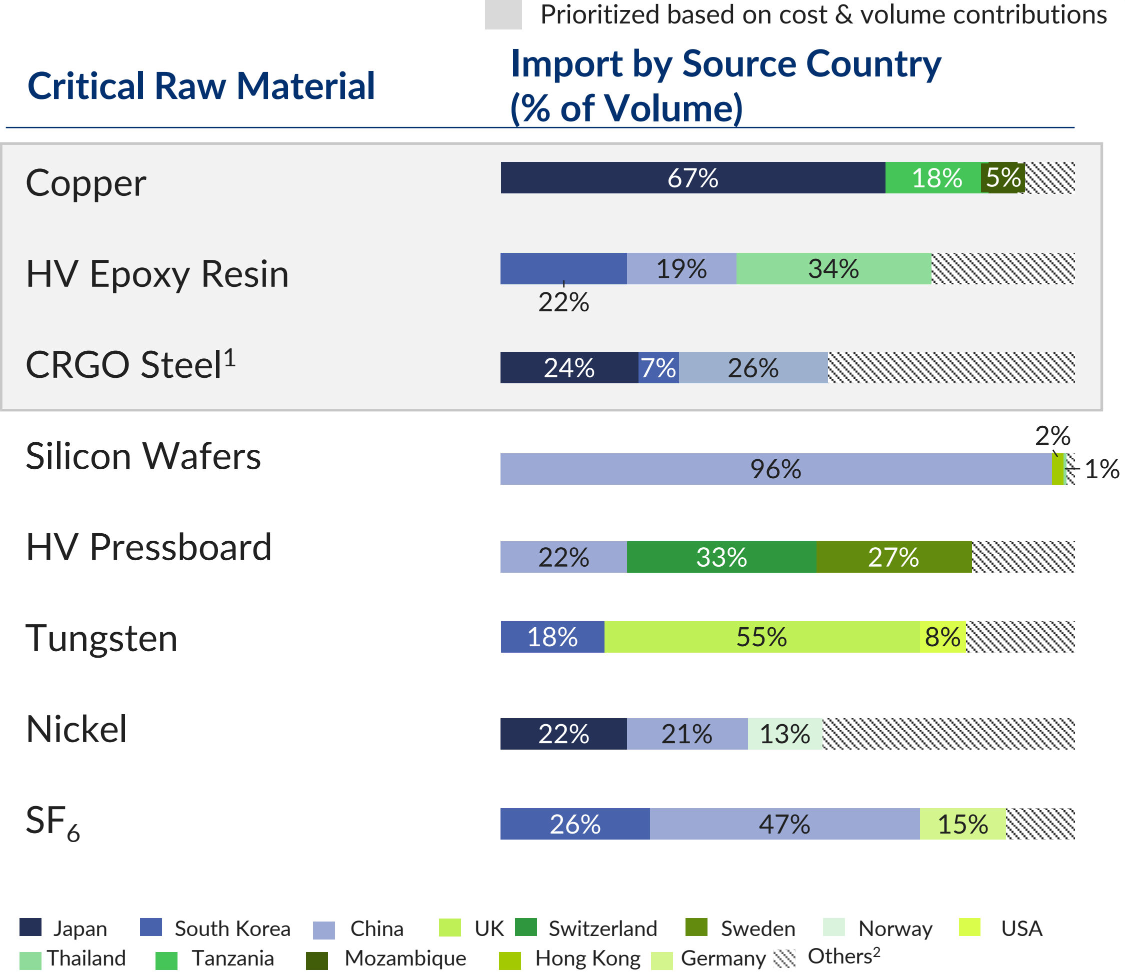
(1) National Mission on Power Electronics Technologies (2) India Semiconductor Mission

Source: Dalberg Analysis, Insights from Industry Experts, Academia

Upstream Raw Material | Targeted incentives and investments can help reduce India's import dependence on Copper and HV graded epoxy resins that are critical for HV transmission equipment

India has significant import dependency on raw material required to manufacture HV transmission equipment



With focused investments and incentives, capacity for Copper and HV Epoxy Resin material can be increased

Current Status	Recommendation
Copper	
• More than 50% of India's copper needs are currently met through imports • HV transmission requires high purity (99.99%) copper which has even lower recycling rates	• Provide capex subsidies for recycling copper to meet 40-50% of the transmission demand locally[3] • Formalize and upgrade scattered and unorganized sector engaged with collection and recycling.
HV Epoxy Resin	
• Limited domestic manufacturing know-how and dependent on import for raw material ie. BPA and ECH and high purity curing agents	• Build capacity for high-voltage epoxy resin with export potential • Accelerate domestic manufacturing of BPA and ECH
CRGO	
• > 90% of CRGO is currently imported • Capacity expanding (JSW-JFE JV) to cover domestic demand by 2028	• De-risk cost inflation short term through time bound strategic buffer stocks for projects needed in the next 3-4 years until domestic capacity ramps up

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(1) Ministry of Commerce track CRGO under HSN code 72251100 which includes both cold rolled and hot rolled grain oriented electrical steel; b) India is still importing CRGO from China because of the existing contracts. (2) Others' category may include countries already shown in the legend; (3) Assuming current import dependence is at least 50%

Source: Ministry of Commerce and Industry: Trade Stats , Ministry of Mines: Press Release; Copper India Report ;PIB Dalberg Analysis

Capital Equipment and Infrastructure | Despite India's growing HV transmission market, limited machinery demand volumes and technology concentration globally constrain local manufacturing potential

High import reliance for capital equipment exists across most cost intensive HV transmission components

Component	Import Reliance[1]	Key Machines
Transformers (Power & Converter)	70-80%	● CNC[1] press brake, CNC HV/LV wire-winding machine, vacuum drying oven, CNC plasma cutting table, column & boom welding manipulator, pressboard cutting ● Foil winding machine, Mobile VPD[3] service plant, Step-lap core cutting line, offline/automatic core-stacking robot & software, automatic insulation taping machine
GIS	70-80%	● Heat-treat ovens, floor-type horizontal boring & milling, large-envelope VTL[4], clean/dry room, Ag/Ni plating line ● Low-pressure die-casting cell, 5-axis gantry machining centre, filtration & storage skids, APG[5] press, vacuum epoxy casting system, gas evacuation & recovery cart
Converter Valves	40-50%	● Lightning impulse generator, HV AC/DC sources, clean assembly hall, vacuum brazing furnace, DI/UPW system ● Fiber harnessing benches, SMT[6] line, IEC 60700-1 valve test bay, burn-in racks, precision hydraulic clamping rigs, PD measurement system

Two major challenges exist to localise manufacturing of capital equipment

Machinery manufactured in India

- **20-30%** of transformer & GIS machinery is **manufactured domestically**. Machinery **demand base is small** as only **5-6 projects** are required by 2032, but **cross-industry** use keeps domestic suppliers viable
- Converter valves are not yet manufactured in India, **but 50-60%** of required machinery is **domestically available**
- Existing domestic fabrication OEMs could **scale production** quickly with **limited investment** as build rate increases

Import dependent machinery

- **15-20%** machinery across the three components **can be manufactured domestically**, supported by **existing supply chains** for raw material/subcomponents. However, **low domestic & export demand volume** and **concentrated suppliers** create high barriers of entry for Indian manufacturers
- **45%** machinery has critical subcomponents based on **patented mechanisms** & **trade-secret softwares** which are not available without partnerships and would incur costs – potentially not viable for low volumes of demand

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(1) Calculated by cost and volume required to fulfil component demand for 2032 (2) Computer Numerical Control (3) Vapour Phase Drying (4)Vertical Turning Lathe (5) Automatic Pressure Gelation (6) Surface Mount Technology

Source: Company Announcements, Dalberg Analysis

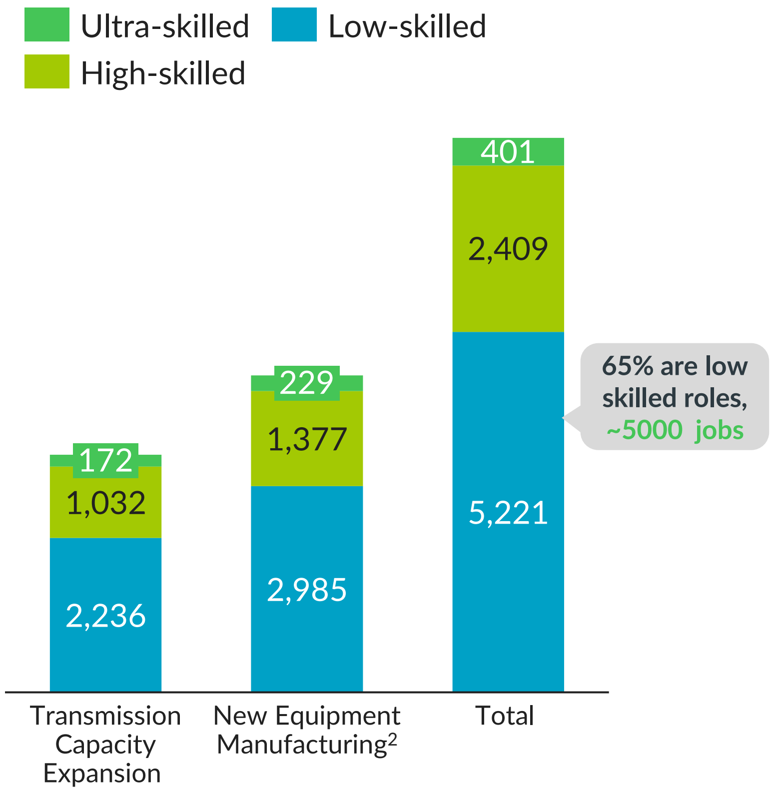
bharat CLIMATE FORUM

Council for International Economic Understanding

Dalberg

Workforce & Skilling | India would require an additional ~8000 skilled workers across HV transmission manufacturing by 2032, who could be trained with a ₹250-280 crore budget

Current & projected (2032) workforce requirement[1]



65% are low skilled roles, ~5000 jobs

Concentrated action across education, industry and policy needed to train the required workforce

1. **Undertake a national skill gap assessment in transmission sector** aligned to sector goals - in partnership with National Skill Development Council **(NSDC),** Power Sector Skill Council **(PSSC),** utilities, OEMs and EPCs
2. **Establish a HV transmission Center of Excellence** under Ministry of Skill Development & Entrepreneurship (MSDE), developing training curriculum and cascading training capacity at a national level
3. Establish HV transmission focused **shared training centers for SMEs** under the MSME Cluster Development Programme
4. **Upgrade university-level transmission curriculum** in partnership with PGCIL[3], BHEL, and international institutes (e.g., KTH[4], SuperGrid Institute)

Skilling Investment Required

Personnel training cost

₹ 175-200 Cr

+

Training centers investment[5]

₹ 75 - 80 Cr

=

Total budget

₹ 250 - 280 Cr

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(1) Additional workforce requirements aligned with the 15th National Electricity Plan (target year 2032); (2) Prioritized the indigenisation of DC switchyard manufacturing to import dependency (3) Power Grid Corporation of India Limited (4) KTH Royal Institute of Technology (Sweden) (5) Does not include lab equipment needed for ultra –high skilled workforce as it is included in R&D set up cost already;

Source:; World Energy Employment Report; NITI:ITI Report (2024); IEEMA: Electrical equipment mission plan ; IEA : World Energy Employment Report; NITI : ITI Report; Dalberg Analysis

Financing | An estimated INR 22,200-26,500 crore will be needed to build domestic HVDC manufacturing, along with INR 3,000–4,000 crore of targeted viability funding for remote HVDC corridors

Government funding will be required across R&D, workforce development, and capital subsidies to establish India as a leading manufacturer of advanced HVDC systems by 2032

Theme	Total Funding Required (INR Cr) - approx	Government Funding Required (INR Cr) - approx	Key Activities	Potential Outcomes
Demand& Market Architecture	3,400-4,500	3000-4000	Set up HV transmission projects of ~6 lakh ckm by 2032. Government to provide viability gap funding to remote HVDC projects[1]	Sufficient transmission capacity to evacuate more than 250GW of renewable energy planned by 2032 across India and cross-borders
R&D & product Innovation	1,000-1,300	500-780	Set up 2–3 System Studies Labs in universities, 1–2 Equipment Design & Small Test Bays and 1 Central Large Hardware Test Facility	Indigenous development of HVDC technologies;
Upstream Raw Materials & Critical Inputs	450-700	80-120	Provide input subsidies up to 20% on domestic copper recycling and HV epoxy resin manufacturing plants[2]	Reduce import dependency on Copper cathodes used in transmission systems by 30-40 % of total demand
Capital Equipment & Infrastructure	22,200-26,500	2,200-2,600	Expanding HVDC manufacturing ecosystem will require INR 19.2-23K Cr investment. Provide 5 -10 % Production Linked Incentives on HVDC component manufacturing (reactors, filters, DC capacitors, etc.[3])	Reduce import dependence from 100% to complete localisation of critical HVDC switchgear and converter valve components
Talent & Workforce	250-280	75-80	Setting up Center of Excellence for training the workforce in HVDC systems; Train ~8000 skilled workers through new courses & apprenticeships	Ensuring a stable supply of skilled workers in HVDC systems; build capabilities to carry our globally competitive R&D in HVDC
TOTAL	27,200-33,200	5,900-7,600		

(1) Assumed funding support needed for Leh-Kaithal, project costing approximately 50% of the Ladakh – Kaithal project that received INR 8000 Cr funding from Green Energy Corridors; (2) Assumed a plant of 1ktpa of HV epoxy resin could be set up as a brownfield plant within a domestic epoxy resin factory with 1.5-2x times the capex required for HV grade manufacturing. 1ktpa is higher than domestic need and hence expected to be built for export opportunities as well (3) Includes large HV testing infrastructure which is assumed to be non existent in India and accounts for a significant share of the Capex for manufacturers. Some of the components such as DC capacitors need to be set up at scale targeting exports as well to be commercially viable; Source: Dalberg Analysis