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NITI Aayog

NITI Frontier Tech Hub

Reimagining Manufacturing: India's Roadmap to Global Leadership in Advanced Manufacturing

October 2025

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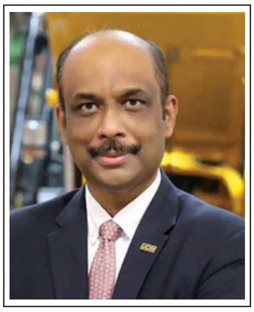

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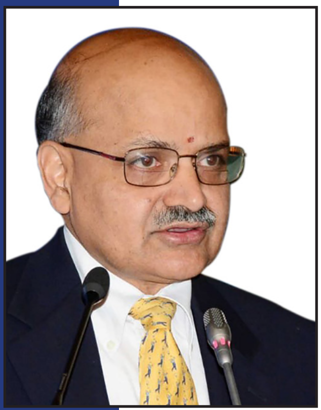
Foreword



The trajectory of our nation's economic ascent is inextricably linked to the strength and sophistication of our manufacturing sector. It is the bedrock upon which sustained growth, large-scale job creation, and global geopolitical influence will be built.

While India has demonstrated incredible resilience and growth in recent years, incremental change will not suffice to meet our destiny.

NITI Frontier Tech Hub's *Roadmap for Global Leadership in Advanced Manufacturing* lays out a decisive, time-bound pathway for India to emerge as a true Advanced Manufacturing Powerhouse by 2035. It identifies high-impact sectors and outlines the strategic enablers required to integrate frontier technologies—Artificial Intelligence, Digital Twins, Robotics, Advanced Materials, and beyond—into the very fabric of Indian industry.

Our vision extends beyond expanding production capacity. It is about building **precision, resilience, and sustainability** into our manufacturing DNA—creating globally competitive "Made in India" brands, high-quality jobs, and a deeply inclusive growth model that draws strength from every Indian state.

As global competition accelerates, we must act with the highest sense of urgency and purpose. Advanced Manufacturing Leadership must become a **national priority under the India National Manufacturing Mission**, ensuring that technology adoption moves from fragmented experimentation to coordinated transformation—across sectors, clusters, and enterprises. This will demand seamless collaboration between government, industry, and the states, underpinned by long-term commitment and shared ambition.

The decade ahead offers an unprecedented window to reimagine India's role in the global manufacturing order. The journey to 2035 is not merely about transforming our factories—it is about transforming lives, building resilience, and positioning India as an undisputed leader in advanced, high-value manufacturing on the world stage.

BVR Subrahmanyam
CEO, NITI Aayog

While discussions on frontier technologies often spotlight AI, robotics, and other innovations in isolation, there has been far less attention on modernizing India's manufacturing backbone — the foundation of our economic strength, job creation, and global competitiveness. Accounting for 15–17 percent of GDP today, manufacturing remains the fulcrum of India's journey to Viksit Bharat 2047. Achieving this vision will require not incremental progress, but transformation — a decisive re-engineering of factories, supply chains, and innovation ecosystems across the nation.

Despite steady gains, the sector continues to face deep structural challenges — productivity shortfalls, fragmented infrastructure, limited digital integration, and outdated processes. Overcoming these calls for more than efficiency gains; it demands a **complete reimagination of India's manufacturing ecosystem**, powered by the strategic deployment of frontier technologies.

NITI Aayog's Frontier Tech Hub's Roadmap to Global Leadership in Advanced Manufacturing charts a clear course for this transformation. It explores how frontier technologies can anchor India's transition to advanced manufacturing in an era defined by reconfigured and resilient global supply chains. Specifically, the roadmap aims to:

1. Define the role of frontier technologies in shaping the future of advanced manufacturing.
2. Identify opportunities for enhancing sectoral performance and increasing manufacturing's contribution to GDP — positioning India as a pivotal node in global value chains.
3. Outline the strategic imperatives, risks, and mitigation pathways required to enable this transformation.

If executed with urgency and ambition, this transformation can, by 2035, elevate manufacturing's share of GDP to 25 percent, generate millions of high-quality jobs, and establish India as a trusted and indispensable player in next-generation global manufacturing networks.

But the window to act is narrow. The choices we make today will determine whether India leapfrogs into a tech-driven industrial future or risks falling behind. This roadmap lays the foundation for sector-specific strategies, governance reforms, and investment priorities that can embed frontier technologies into the very DNA of Indian manufacturing. In doing so, we can unlock a new era of **productivity, resilience, and sustainability** — ensuring that by 2047, India's factories are not just engines of growth, but **symbols of innovation, quality, and national strength**.

I am deeply grateful to the **Expert Council** for their invaluable insights and guidance in shaping this roadmap, and to our **knowledge partners — Deloitte and CII —** for their strong collaboration and commitment throughout this journey.

Ms Debjani Ghosh,
Distinguished Fellow, NITI Aayog

Executive Summary

India stands at a decisive inflection point as rapid advances in technology adoption could unlock a step-change in the country's manufacturing productivity and exports, provided the deployment is systematic, inclusive, and cluster-focused. With the right interventions, manufacturing could contribute over 25% to the nation's GDP, generate 100+ million jobs, and establish India as one of the top three global hubs for advanced manufacturing.

The point of arrival for advanced manufacturing in 2035 that would create the platform for Viksit Bharat @ 2047 therefore needs to focus on the following with tangible outcomes:

1. Long term competitiveness – Total Factor Productivity
2. Supply chain resilience – Share of global exports.
3. Make in India – Global champion brands.
4. Skilled job creation – Jobs added.
5. Inclusive development – States with high manufacturing GSDP
6. Value innovation – Low cost, high quality, and hyper personalized products

The current reality highlights the urgency for action. Today, India's manufacturing sector is constrained by gaps when compared with those in peer nations including inadequate infrastructure in industrial corridors, shortage of highly skilled talent, low investment in research and development, and fragmented supply chains that limit scale and efficiency.

These challenges not only decelerate growth but also prevent firms in India from moving up the global value chain. To address this, **thirteen high impact sectors** have been shortlisted from a long list of sectors in manufacturing through a detailed evaluation framework and grouped into **five core clusters** to enable a focused approach to advanced manufacturing through deployment of frontier technologies. Across the five core clusters (thirteen sectors), addressing key considerations encompassing R&D and innovation, integrated and smart value chains, workforce capability, sustainable and circular manufacturing and MSME enablement would accelerate manufacturing contribution to India's GDP from the current 15%-17% to 25%.

To address the key considerations, strategic enablers including adoption of frontier technologies, R&D ecosystems, industrial infrastructure, and future-ready workforce development should work in tandem. Specifically, adoption of frontier technologies at scale in high-potential sectors is critical for sustained growth and competitiveness of India's manufacturing sector. Building on this, a set of 16 frontier technologies have been identified through detailed research that included a study on the focus areas of leading countries in manufacturing and technology (China, Japan, Germany and the USA) and on global institutions that work in the forefront of manufacturing sector. Subsequently, a **Multi-Criteria Decision Framework (MCDF)** was deployed to shortlist four frontier technologies that are disruptive, actionable, scalable, and aligned to India's long-term manufacturing vision. These include **Artificial Intelligence and Machine Learning, Advanced Materials, Digital Twins, and Robotics**. Focus on a prioritized set of frontier technologies enables the sectors and organizations to adopt them at scale, drive real progress internally and in their ecosystem, cross pollinate learnings and create competencies that are sustainable.

India will not only risk a historic window of opportunity if the country fails to adopt frontier technologies in the high impact sectors but also encounter a **potential loss in additional manufacturing GDP to an extent of US $270 billion by 2035 and US $1 trillion by 2047**. Beyond the economic impact, India would also forfeit a strong position in global manufacturing markets and deepen its dependence on imports for critical technologies and components. Such vulnerability would expose the economy to external supply shocks, weaken the ability to leverage India's demographic dividend, and result in India trailing behind peer economies that are rapidly scaling investments in frontier technologies.

To seize the opportunity, a 10 year (FY 2026- FY 2035) strategic roadmap with a comprehensive set of interventions has been developed to create a future-ready, frontier technology-enabled manufacturing ecosystem that would drive India's transformation into a global leader in manufacturing by 2035. The roadmap has been structured in three phases

Phase 1 (FY2026 - FY2028): Ecosystem Build and Adoption

1. Positioning Advanced Manufacturing as a strategic priority under the National Manufacturing Mission (NMM)
2. Establishing the Global Frontier Technology Institute (GFTI) in India as a Center of Excellence (CoE)
3. Developing a future-ready skilling ecosystem through large-scale, modular, and cluster-aligned programs focused on frontier tech capabilities
4. Creating technology access platforms that are inclusive to reduce entry barriers and ensure advanced manufacturing capabilities are widely available across the value chain
5. Fostering technology adoption at the enterprise level, driven by champion organizations in advanced manufacturing
6. Designing frontier technology-enabled supply chain models across manufacturing clusters and sectors to enable seamless value chain integration and democratized technology access
7. Deploying digital and industrial infrastructure to enable the frontier technology ecosystem through the creation of twenty "Plug & Play Frontier Technology-enabled Industrial Parks" across India on a combination of states and sectors

Phase 2 (FY2029 - FY2031): Acceleration

8. Driving 'Servicification of Manufacturing' to transform India's manufacturing landscape from being a product manufacturer to being a solution provider

Phase 3 (FY2032 - FY2035): Sustenance

9. Continuous monitoring of the maturity level of frontier technologies in India and planning for targeted interventions in the future

This roadmap is the first version of this perspective. The insights and recommendations in this roadmap will be periodically reviewed to reflect the evolution of technology as well as the global context. This will keep India's strategy for Advanced Manufacturing relevant, resilient and future ready.

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1. VISION FOR INDIA'S MANUFACTURING @ 2047

1.1 Role of manufacturing in India's economic transformation

Historically, manufacturing has contributed 15%–17% to India's GDP, a figure significantly lower than that of East Asian economies like China and South Korea, where manufacturing accounted for over 25%–30% during their peak development phases. For India to achieve the vision of Viksit Bharat by 2047, elevating the share of manufacturing to 25% of GDP is crucial not only for sustaining high economic growth but also for creating quality employment at scale.

A robust, globally competitive, and technologically advanced manufacturing sector is required to achieve the vision of a 25% contribution from manufacturing to the GDP and evolve into a high-value-added, innovation-led industrial powerhouse, integrated deeply into global value chains. However, if India were to sustain the current levels of growth in manufacturing, **there would be a significant gap of US $5.1 trillion by 2047** against the targeted point of arrival.

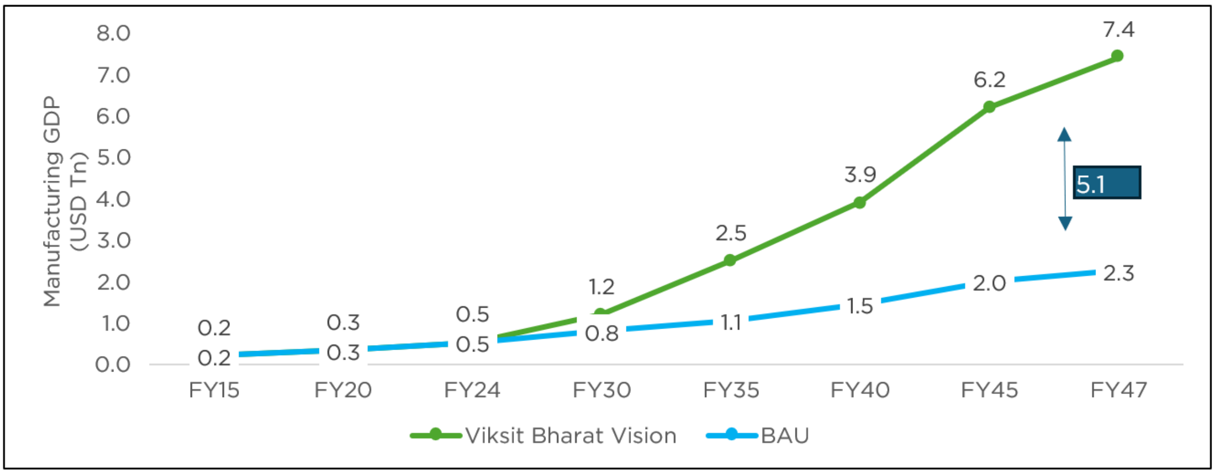


Exhibit 1 - Manufacturing GDP forecast (USD Tn)

Global manufacturing is today undergoing a tectonic shift driven by *friend-shoring, near-shoring,* and the race for *technology sovereignty*. Nations are no longer competing only on costs but on *resilience, sustainability,* and *innovation capability and capacity*. This shift and the associated realignment of value chains offers India a once-in-a-generation opportunity to redefine its role in the global value chain: from a cost-efficient alternative to a *frontier technology leader* anchored in self-reliance and innovation.

Accelerating the transition to an advanced manufacturing economy, powered by frontier technologies, would be pivotal to this transformation. Developing and deploying a clear roadmap with a near-term 2035 vision is critical to ensure that India not only meets but leads in the realization of its 2047 ambitions.

Many of India's peer nations have embarked on this journey with their strategic priorities reflecting the focus areas for the respective nations and their manufacturing ecosystems. Specifically in the region, China, South Korea, and Vietnam are examples where the contribution of manufacturing to the GDP is in line with India's aspirations.

Country	GDP ($ Tn)	Manufacturing GDP ($ Tn)	Manufacturing Share of GDP	Frontier Tech Integration	Strategic Priorities Articulated
China	18.75	4.66	25%	High	• Made in China 2025 (MIC 2025) • China Mfg. Innovation Centers • New Generation Artificial Intelligence Development Plan 2030 • AI Plus
South Korea	1.88	0.52	27%	Very High	• Manufacturing Renaissance Vision 2030 • Strategy to Foster the National High-tech Industry • Strategy for Global R&D Leadership in Emerging Technologies
Vietnam	0.48	0.12	24%	Growing	• List of Strategic Technologies and Strategic Technology Products • Digital Infrastructure Master Plan 2030 • Breakthrough in Science, Technology, Innovation and National Digital Transformation

Exhibit 2 - Strategic priorities of peer nations for the manufacturing sector

1.2 Point of arrival for India's manufacturing sector: 2035 and 2047

Over the next decade, the vision for India's manufacturing is to evolve into integrated ecosystems at the sectoral level, anchored by advanced technologies, high-quality products, services, solutions, and sustainable supply chains. The evolution would be enabled by targeted fiscal and non-fiscal support, talent availability and innovation ecosystems. Together with public-private collaboration, the manufacturing sector would be characterized by productivity gains, shifts into higher value-added segments, increased margins, and enhanced export competitiveness.

S. No.	Focus Dimension	Metric	Point of arrival	
			2035	2047
1	Long-term competitiveness	Improvement in TFP (CAGR%)	3.5%	5.0%
2	Supply chain resilience	Share of the global merchandize exports (%)	6.5%	10.0%
3	Make in India – Brands	Global champion brands made in India (nos)	60	100

4	Skilled job creation	Highly skilled jobs to support accelerated manufacturing growth (million jobs)		100
5	Inclusive development	States with over US $250 billion in GSDP	6	
		States with over US $500 billion in GSDP		10
6	Value innovation	Building global competitiveness	Low cost, high quality and hyper personalized products	

Exhibit 3 – Point of arrival for India's manufacturing sector

2. REACHING THE POINT OF ARRIVAL

Reaching the points of arrival in 2035 and 2047 will require an immediate focus on strategically significant and high-impact sectors. This would enable creation and deployment of the blueprint to accelerate the journey, optimize resource allocation, establish tailored policy frameworks, and implement targeted initiatives to deliver quantifiable outcomes. This concentrated approach would foster deeper public–private–academic collaboration to pilot advanced technologies, strengthen supply-chain ecosystems, and validate scalable leading practices. By showcasing early successes in the identified sectors, the model can be replicated across other domains, thereby expediting the sector's transformation and maximizing economic, social, and technological returns on investment.

2.1 Evolution of high-impact sectors and clusters

A structured and data-driven framework has been deployed to shortlist sectors. The framework is based on two equally weighted dimensions—Economic Impact and Strategic Alignment— defined by four pillars, namely:

1. Industry Potential
2. Economic Relevance
3. Sectoral Importance
4. Technology Orientation

Across the four pillars, fourteen sub-parameters ensure that the shortlisted sectors are both commercially robust and aligned to national priorities. The list of twenty sectors considered for evaluation is detailed in Annexure B.

Dimension 1: Economic Impact – 100%

Parameters	Weight
Pillar 1 - Industry potential	**50%**
• Domestic industry size (INR Cr)	30%
• Domestic industry growth (CAGR of last 5 years)	20%
• Value added exports in FY2024 (INR Cr)	30%
• Value added exports growth (CAGR of last 5 years)	20%
Pillar 2 - Economic relevance	**50%**
• Contribution to GVA (%)	50%
• Trade balance (Exports minus Imports) (INR Cr)	30%
• Employment (% of manufacturing industry employment)	20%

Dimension 2: Strategic Alignment– 100%

Parameters	Weight
Pillar 3 - Sectoral importance	**50%**
• Strategic criticality of the sector	30%
• SC resilience – GVC coverage and value addition requirements	30%
• Sector growth projections – India	20%
• Sector growth projections – Global	20%
Pillar 4 - Technology orientation	**50%**
• Requirement for innovation and R&D – IP ownership	40%
• Competitiveness driven by technology	30%
• Enabling factors – e.g., utility, sustainability, specialized skill development	30%

Exhibit 4 – Framework for sector evaluation and shortlisting

Basis the evaluation, the sectors emerging as "Drivers" (sectors that are high on both economic and strategic importance) and "Pioneers" (sectors with a strong alignment India's priorities but with relatively lower economic output currently) together with specific ones (Leather and Footwear - considering the ecosystem similarity with Textiles and Apparel, Food Processing - considering the sector size, and Renewable Energy Equipment - considering growing importance) have been shortlisted as sectors for immediate focus, making at total of thirteen.

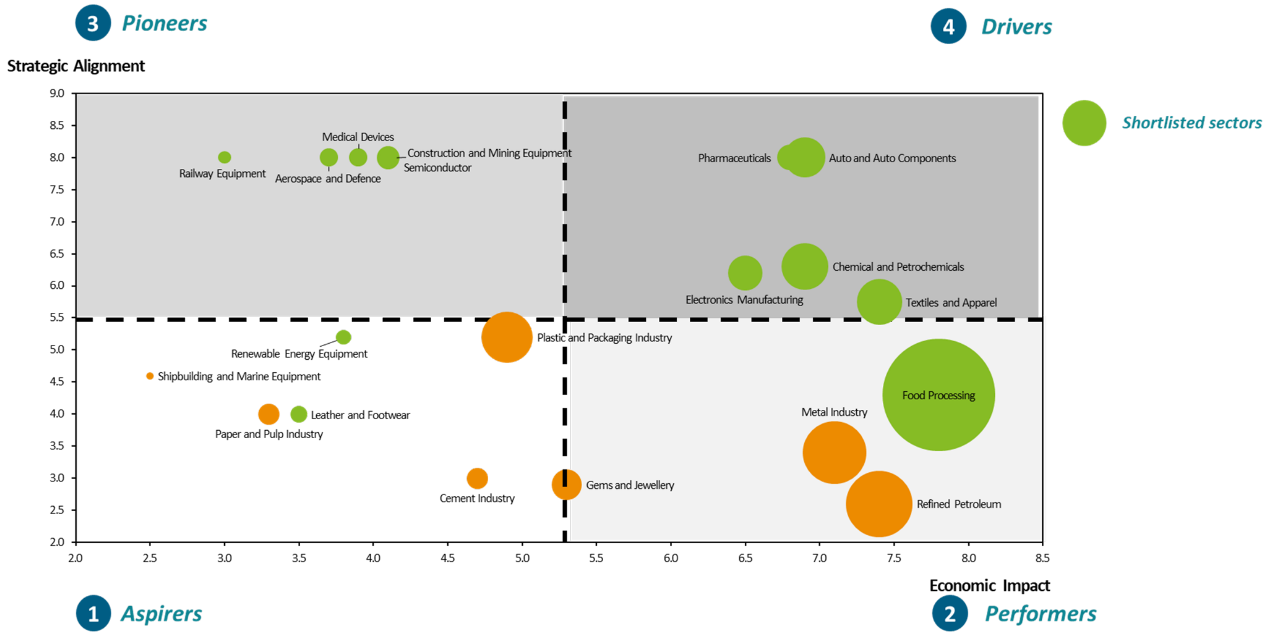


Exhibit 5 – Sector prioritization matrix

The thirteen manufacturing sectors that have been shortlisted have been grouped into five core clusters to enable a focused approach towards adoption of frontier technologies. Clustering was guided by three key criteria:

1. Similarity in value chains and operating models
2. Commonality in customer segments
3. Synergy in ecosystem requirements

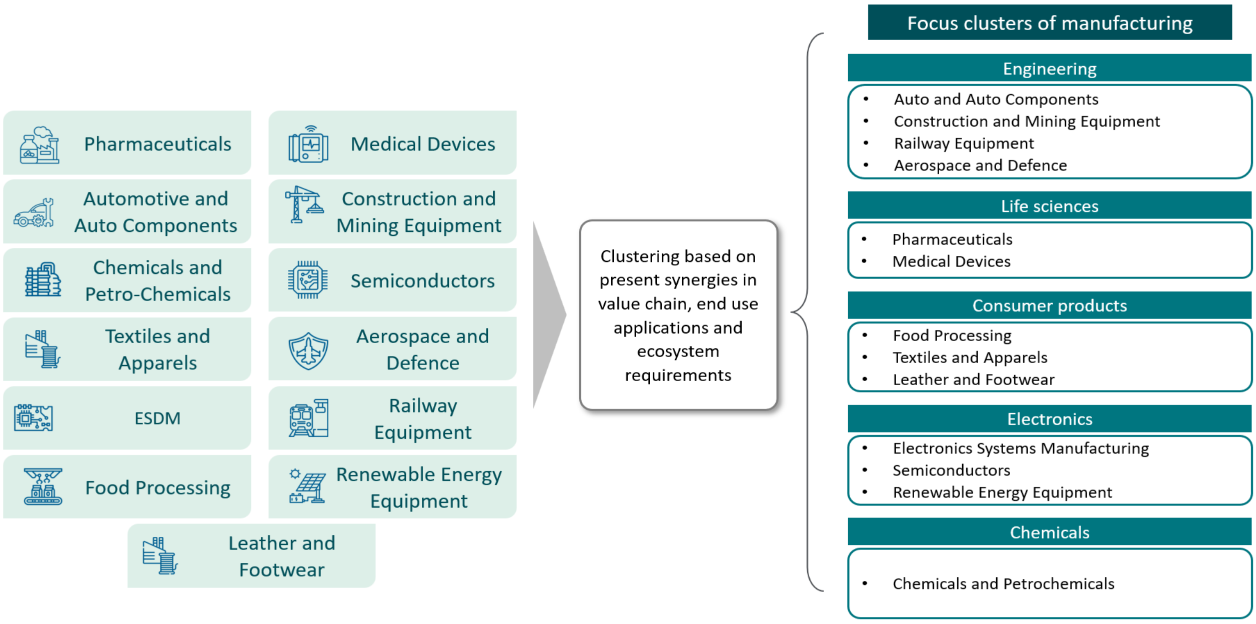


Exhibit 6 - Clustering of the shortlisted sectors

2.2 Future state of manufacturing clusters

Across the five clusters (thirteen sectors), six common themes characterize the evolution of the sectors leading to 2035 and beyond. These six themes would be of significance to India's manufacturing vision and would also provide significant opportunities for the sectors and organizations in the sectors to achieve economies of scale and scope.

1. **Strategic self-reliance** through localized manufacturing and enhancing supply chain resilience
2. **Focus on advanced materials** that drive tailored properties and create differentiated market offerings
3. **Design-led and tech-enabled** manufacturing ecosystem with sustainable practices
4. **Globally compliant portfolio** of products, services and solutions homologated to specific markets
5. **End-to-end traceability** leveraging digital technologies that ensure quality, performance and compliance
6. **Servicification of manufacturing** with significant integration of services and solutions into core product portfolio

Current State - 2025	Future State - 2035
Engineering goods	**Smart engineering and equipment systems**
• OEM-centric, capex-driven models • Operates as a Tier 2/3 component suppliers • Inconsistence in compliance with global standards	• Servicification of manufacturing – service and solution integrated into core products • Design and technology led manufacturing operations with sustainable practices • Advanced materials in product design to meet market specific requirements • Export compliant portfolio of products, services and solutions
Consumer products	**Smart and sustainable consumer products**
• Commodity-led production with limited design capabilities • Sustainability efforts limited to meeting compliance. Low use of eco-materials • Packaging is functional and opaque and lacks data integration	• Innovation-led ecosystems with globally recognized brands and design IP • Full-scale circular manufacturing driven by tech enabled manufacturing ecosystem • Traceability across the value chain leveraging digital technologies that ensure standardized experience on quality, performance and compliance
Life sciences	**Smart and connected health technology**
• Predominantly generic drugs and devices manufacturing with high dependance on imports • Limited digital integration across manufacturing, R&D, and supply chains • Weak linkage between product performance and clinical data. Limited post-market feedback	• Healthcare ecosystem driven by self-reliance through localization of manufacturing and innovation • End-to-end digitalized operations enhancing time-to-market and global competitiveness • Integrated digital feedback loops enabling continuous product refinement
Electronics	**Full stack electronics and systems**
• Focus on assembly and low-value manufacturing. Absence of P and design ownership • Environmental sustainability largely compliance-driven • Market potential constrained by absence of value chain ecosystem and import dependency	• Full-stack global design and manufacturing hub with platform-level innovation • Core integration of carbon neutrality, water recycling, and hazardous waste management with real-time sustainability tracking • Globally competitive exports driven by high-quality, integrated, and resilient value chains
Chemicals	**Advanced chemical solutions**
• High dependence on imported intermediates and feedstocks, especially from China • ESG data is fragmented or unavailable. Limited tracking of sustainability performance • Value chains are fragmented with weak domestic backward linkages	• Strategic self-reliance through localized manufacturing and enhancing supply chain resilience • National digital registry with ESG ratings and product-level benchmarks • Strengthened domestic value chains integrated with global supply networks

Exhibit 7 – Evolution of the manufacturing clusters

2.3 Structural challenges to be addressed

As the clusters and the sectors evolve, India needs to address key challenges that are specific to the sectors and those that are common across sectors. Addressing them would be crucial in accelerating the manufacturing contribution to GDP from the current 15%-17% to 25%.

Consumer Products | Engineering goods | Chemicals | Electronics | Life Sciences

Challenges common across clusters

Limited investments in R&D and innovation	▪ Life sciences: Indian manufacturers spend only 6% of revenue on R&D while leading global companies spend 20% of revenue that inhibit their entry into high value segments ▪ Electronics: Most Indian ESM companies invest less than 1% of their turnover in R&D, far below the global majors (5%–8%) leading to limited focus on design, prototyping, or product innovation
Fragmented value chain with scalability and integration challenges	▪ Textiles & Apparel: Fragmented manufacturing base with presence of informal sector limits consistency, productivity, and quality—resulting in scalability and integration challenges ▪ Engineered goods: Significant part of value chain with MSMEs that lack scale and quality accreditations —limiting localization and pushing OEMs for imports of precision parts
Shortage of skilled workforce	▪ Chemicals: Growing talent shortage, particularly in areas requiring specialized skills such as green chemistry, process automation, and regulatory compliance ▪ Electronics: Lack of expertise in advanced and emerging technologies like high-end automation, robotics, and IoT hardware integration, which are crucial for manufacturing competitiveness
Limited awareness on circular economy principles	▪ Chemicals: Investments in technologies such as solvent recovery, chemicals reuse and waste valorization are negligible impacting unit economics leading to lower competitiveness ▪ Consumer products: MSMEs constrained by limited access to advanced packaging solutions like vacuum sealing, modified atmosphere packaging , and cost-effective preservation technologies
Regulatory complexity and policy uncertainty	▪ Textiles & Apparel : Fragmented manufacturing base with presence of informal sector limits consistency, productivity, and quality—resulting in scalability and integration challenges ▪ Engineered goods : Significant part of value chain with MSMEs that lack scale and quality accreditations —limiting localization and pushing OEMs for imports of precision parts
Limited automation and technology adoption	▪ Chemicals : Technologies like APC, SCADA, and DCS remain largely confined to large plants while majority of MSMEs still operate with minimal automation ▪ Textiles & Apparel : Current structure leads to low levels of automation and digital adoption that hinder productivity, traceability and visibility
Barriers to Unlocking Servicification of Manufacturing	▪ Engineering goods: Service based models rare because of low digital maturity, fragmented customer bases and limited-service delivery infrastructure. ▪ Life Sciences: Hindered by regulatory complexity, liability concerns, and limited digital readiness to support performance monitoring and outcome-based contracts

Exhibit 8 - Challenges across manufacturing clusters

These challenges are across five major impact areas

1. R&D and innovation focusing on servicification of manufacturing
2. Integrated and smart value chains driving efficiency and visibility
3. Workforce capability enhancement through skilling ecosystem
4. Sustainable and circular manufacturing to achieve ESG objectives
5. MSME enablement through technology to drive scale and scope

Bridging challenges with enablers to achieve the vision

To overcome the identified challenges, strategic enablers including adoption of frontier technologies, R&D ecosystems, industrial infrastructure and future-ready workforce development should work in tandem. These enablers together with supportive policies would help India's manufacturing clusters achieve the vision.

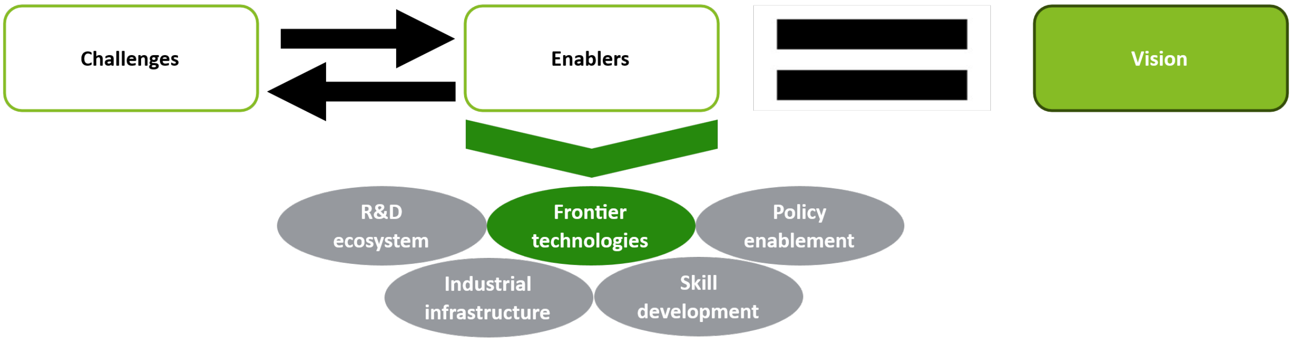
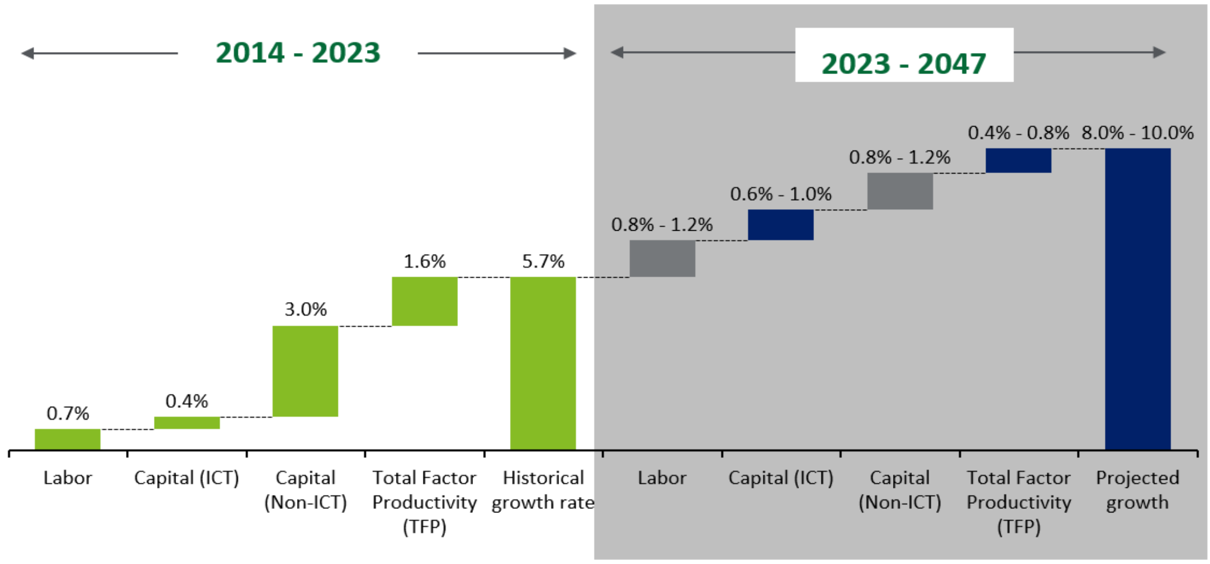


Exhibit 9 - Enablers to achieve the vision

2.4 The case for frontier technologies in manufacturing

Peer nations had witnessed a **real GDP growth of ~2%,** driven by technology and associated elements such as growth in Information and Capital Technology assets (ICT) and an increase in Total Factor Productivity (TFP). Adoption of frontier technologies in high-impact sectors at scale would therefore be critical for sustainable growth of the Indian manufacturing sector.



Labor : Measured by size of labor force and quality including skills and qualifications

TFP : Measured by changes in productivity based on technology, innovations, market reforms, etc.

Non - ICT : Assets incl. such as buildings, transport equipment, and machines

ICT : Information & Capital Technology assets

Exhibit 10 - Real GDP growth contribution by factors (%)

3. TRANSFORMATION OF INDIA'S MANUFACTURING

Focus on select set of frontier technologies would enable the sectors and organizations to adopt them at scale, drive real progress, cross pollinate learnings and create sustainable competencies. At the national and state levels, it helps in establishing clear funding priorities, shaping appropriate regulatory frameworks, and building specialized training pathways. This targeted strategy lays the groundwork for pilot projects, generates early wins, and sets a replicable template for driving breakthroughs across sectors

3.1 The choice of frontier technologies for the transformation

To shortlist Frontier Technologies (FTs) for adoption and deployment across sectors, a Multi-Criteria Decision Framework (MCDF) was deployed with the objective of identifying frontier technologies that are that are disruptive, actionable, scalable, and aligned to India's long-term manufacturing vision. The MCDF focused on parameters around feasibility, readiness, impact, and strategic value from the deployment.

Parameters	Weight
Feasibility and readiness	**100%**
Technical feasibility	30%
Economic viability	25%
Skills availability and development	15%
Infrastructure readiness	15%
Policy and regulatory support	15%

Parameters	Weight
Impact and strategic value	**100%**
Productivity/Quality/Cost impact	50%
Environmental sustainability	20%
Strategic importance	30%

Exhibit 11 – Multi-Criteria Decision Framework to prioritize frontier technologies

Sixteen frontier technologies were identified through detailed research that included a study on the areas of focus of leading countries in manufacturing and technology (China, Japan, Germany, and the USA) and on global institutions that work in the forefront of manufacturing sector. The identified technologies were validated with industry stakeholders for relevance from India perspective and evaluated on the MCDF. Four of them have been shortlisted as India specific priorities that have the potential for high impact across the sectors of manufacturing:

1. Artificial Intelligence and Machine Learning
2. Advanced Material Sciences
3. Digital Twins
4. Robotics

A prioritized set of frontier technologies enables the sectors and organizations to adopt them at scale, drive real progress internally and in their ecosystem, cross pollinate learnings and create competencies that are sustainable. The way forward should be on orchestrating their deployment across real-world production environments. By targeting industrial clusters—with their shared infrastructure, interconnected supply chains, and collective skill base—India can drive a coordinated adoption to reshape the manufacturing landscape in the near to medium term.

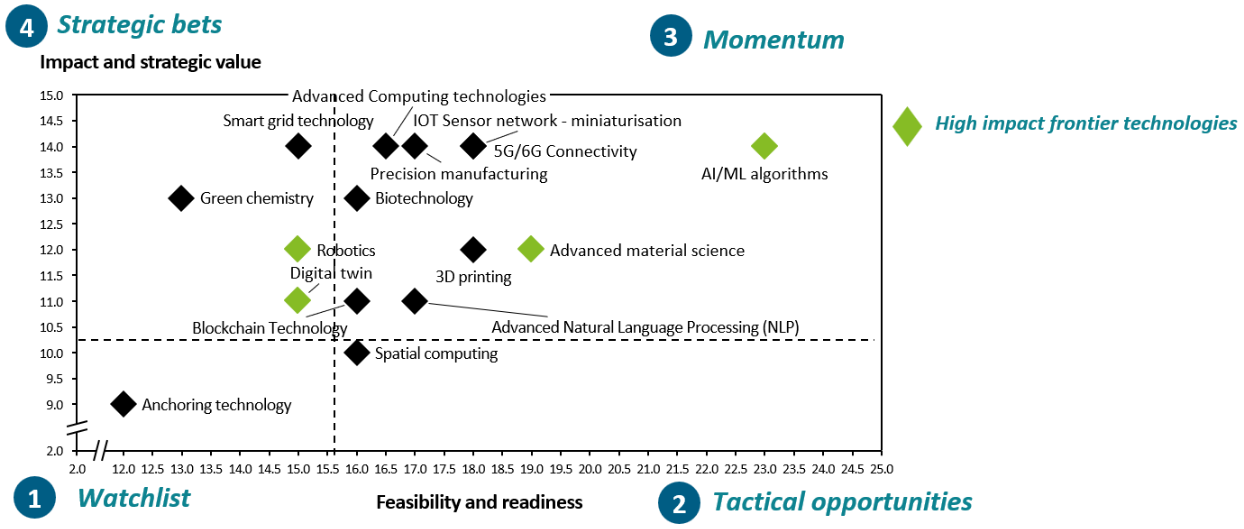


Exhibit 12- Prioritization of frontier technologies

3.2 Creating the frontier technology pathways

Deployment of the four frontier technologies would provide significant opportunities for sectors to address the challenges across the five impact areas from R&D to MSME enablement which is key to India's manufacturing growth.

Impact Area	AI/ML	Advanced Material Science	Digital Twins	Robotics
R&D and innovation	Drives rapid R&D via predictive design and automated optimization	Unlocks next-gen materials (lightweight, high-strength)	Enables virtual prototyping—cutting development time and cost	Automates routine tasks, freeing experts to focus on breakthrough work
Integrated and smart value chains	Cross-border demand forecasting, dynamic supplier scoring and risk-heat mapping	Develops materials that meet diverse international standards	Models multi-tier networks end-to-end—synchronizing virtual replicas of global suppliers, plants, and logistics	Deploys adaptive automation in international hubs (port, warehouse and last mile)
Workforce capabilities enhancement	Augments worker expertise with real-time decision support and prescriptive guidance for complex troubleshooting	Upskills teams in handling and applying next-gen materials via hands-on R&D	Builds workforce proficiency through immersive simulations that mirror live operations and track performance metrics	Transitions labor to advanced roles—programming, supervision, maintenance—by offloading routine and dangerous task
Sustainable and circular manufacturing	Optimizes resource use and minimizes waste through algorithmic control	Develops recyclable, bio-based and low-emission materials	Simulates full product lifecycle to design out waste and energy hotspots	Enables precision disassembly and remanufacturing for true circularity
MSME enablement	Democratizes advanced analytics via cloud-based ML services	Grants access to high-performance materials at scale	Offers affordable "digital pilots" so MSMEs can validate processes virtually	Modular, plug-and-play robots that boost MSME productivity with low Capex

Exhibit 12a – Addressing the impact areas through frontier technologies

"Frontier pathways"—distinct avenues for applying AI/ML, advanced materials, digital twins, and robotics—hold the potential to transform each sector and the way it would function in the future. These pathways provide systematic approaches for organizations to leverage frontier technologies across the enterprise to maximize value from adoption and deployment.

3.2.1 Artificial Intelligence and Machine Learning (AI/ML)

AI/ML can function as the orchestration layer of Indian manufacturing—embedded across production lines, logistics networks, design systems, and product interfaces. The shift would be from isolated automation to intelligent, agentic ecosystems capable of perceiving, predicting, and acting autonomously across the value chain. Clusters would transition from siloed deployments to interconnected AI networks that replicate cognitive value chains in real time.

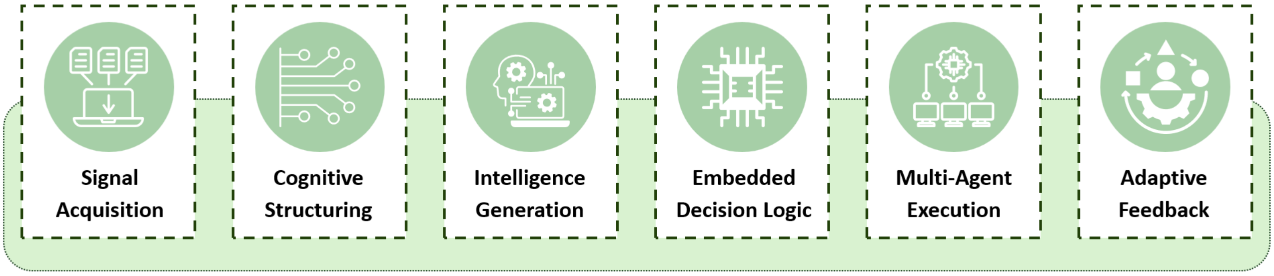


Exhibit 13 - AI/ML orchestration layer

There are five potential frontier pathways for leveraging AI/ML in manufacturing:

(i) Hyperlocal demand intelligence for decentralized manufacturing: Consumer clusters—especially in textiles, processed food, and leather—would witness the adoption of AI platforms that ingest vernacular content, social commerce trends, and regional consumption patterns to create real-time hyperlocal demand maps. These platforms would become AI-powered command centres for micro-factory networks, creating an India-specific model for demand-responsive manufacturing at scale that would be a differentiator in the global market

- A textile hub in Punjab or a leather cluster in Uttar Pradesh could automatically adjust production priorities based on wedding season spikes in any part of India or export trends to the USA.

(ii) Foundation model-powered design copilots for MSME tooling and component innovation: In design and engineering-intensive clusters like auto components, MSMEs are challenged with building in-house design capabilities. AI/ML-powered design copilots—trained on India's industrial design libraries, CAD archives, and material catalogues—would assist tier-2 and tier-3 suppliers in rapidly co-designing parts, jigs, or dies. These copilots, fine-tuned for sector-specific tolerances and supply constraints, would help local units simulate, iterate, and optimize component designs in days, not months—integrating traditional craftsmanship with next-gen intelligence

(iii) Autonomous Agentic AI ecosystems in complex assembly manufacturing: In high-mix manufacturing environments—such as aerospace, automotive, and railway rolling stock—companies would deploy a mesh of intelligent AI agents, each overseeing a critical decision domain: predictive maintenance, inventory ordering, human-robot coordination, defect triaging, etc. These agents would operate semi-autonomously and report to a central cognitive control layer, allowing the system to behave as a fully autonomous, adaptive factory.

(iv) **Autonomous batch release in regulated sectors:** In pharmaceuticals and chemicals, the batch release process is heavily regulated and error-prone due to the reliance on static SOPs and human supervision. Regulatory-aware AI agents would be embedded across the shop floor and QC labs to track real-time compliance, flag anomalies, cross-verify with digital batch records, and recommend conditional release. Over time, these agents would gain trust with regulators via blockchain-backed traceability and explainable AI tools—reducing time-to-market while enhancing global regulatory trust in Indian manufacturing.

(v) **Reinforcement learning for cluster-level energy optimisation:** AI/ML would extend beyond the plant, especially in energy-intensive areas like Chemicals and Engineering. Here, AI agents—trained via reinforcement learning—dynamically coordinate energy consumption across multiple units based on load forecasts, green energy availability, and cost signals. Over time, cluster-wide "energy orchestration layers" will emerge, hosted on public-private digital platforms. These will not only reduce emissions but also create new markets for real-time carbon accounting, energy arbitrage, and sustainable industrial services.

With AI-powered design copilots, demand intelligence systems, and autonomous agents, India's manufacturing clusters will evolve into self-learning and responsive ecosystems—cutting lead times, boosting precision and unlocking MSME-led innovation at scale

3.2.2 Advanced Material Science

Advanced materials would serve as the backbone of India's global competitiveness in manufacturing, enabling a transformative leap in what can be manufactured, how sustainably it can be done, and how rapidly innovation can scale. Material breakthroughs such as bioengineered packaging, smart textiles, nanostructured composites, and self-healing polymers would enhance both performance and environmental resilience across India's manufacturing clusters.

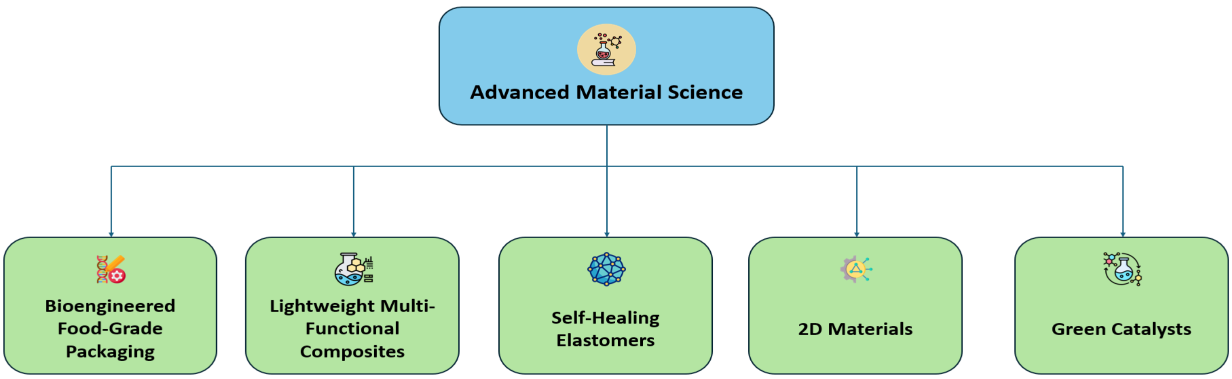


Exhibit 14 - Constituents of Advanced Material Science

There are five potential frontier pathways for leveraging Advanced Material Science in manufacturing:

(i) Bioengineered food-grade packaging in decentralized food processing: Consumer goods manufacturers in India's food processing clusters would deploy next-generation biodegradable films engineered from marine biomass or agricultural waste. These materials would match the barrier performance of plastics while enabling full composability in rural environments

- A Gujarat-based mid-scale dairy may switch to enzyme-activated edible pouches, reducing its packaging waste to near-zero while complying with future-ready EU food contact norms—unlocking premium markets through material innovation.

(ii) Lightweight multi-functional composites in railways and defence Engineering: Manufacturers of railway equipment and defence aerospace would shift from conventional aluminium alloys to thermoplastic composites reinforced with graphene or carbon nanotubes. These materials would combine structural integrity with embedded functionalities such as electromagnetic shielding, vibration damping, and shape memory

- A defence PSU in Telangana may integrate such composites into modular UAV airframes, allowing rapid reconfiguration in the field without redesign or structural compromise.

(iii) Self-healing elastomers in footwear and mobility: In the leather & footwear and auto clusters, firms in India would commercialize self-healing elastomeric materials that extend product life without compromising aesthetics. These materials, activated by heat or sunlight, would autonomously repair micro-tears or scratches

- A footwear manufacturer in Tamil Nadu could offer durable, repair-on-wear soles for industrial safety shoes, while a mobility OEM in Haryana integrates these materials into door seals and seat trims—lowering lifecycle maintenance costs.

(iv) 2D Materials in high-density electronic systems: In the electronics manufacturing clusters, organizations would begin integrating 2D materials like molybdenum disulfide and borophene into chip packaging, battery components, and RF modules. These materials would enable miniaturized thermal management, faster electron mobility, and flexible form factors, crucial for edge devices and wearables

- A semiconductor design organization in Karnataka can pioneer multi-layered interconnects using atomically thin conductors, reducing energy loss and improving signal clarity in telecom-grade applications.

(v) Green catalysts for low-emission chemical synthesis: Chemical manufacturing would adopt nano-engineered green catalysts for low-temperature, low-pressure synthesis of critical intermediates—especially in pharmaceutical APIs, agrochemicals, and industrial solvents.

- A speciality chemical firm in Maharashtra can deploy bio-inspired zeolite catalysts that eliminate reliance on imported precursors for a key fluorochemical, drastically improving India's strategic supply chain resilience while complying with global ESG benchmarks.

With bioengineered packaging, multifunctional composites, and self-healing materials, Indian manufacturers will leap into a new era of sustainable, high-performance production—reducing import dependence, opening global markets, and extending product life cycles across sectors.

3.2.3 Digital Twins

Digital twins are virtual, data-driven replicas of physical systems and expected to become the digital backbone of Indian manufacturing. Their role would expand far beyond equipment diagnostics to encompass the full product lifecycle, regulatory compliance, multi-tier supply networks, and even entire industrial clusters. As India navigates constraints around resources, emissions, and infrastructure, digital twins would enable real-time monitoring, predictive simulation, root-cause diagnostics, and scenario testing at scale, fuelling precision-led, capital-efficient industrial growth.

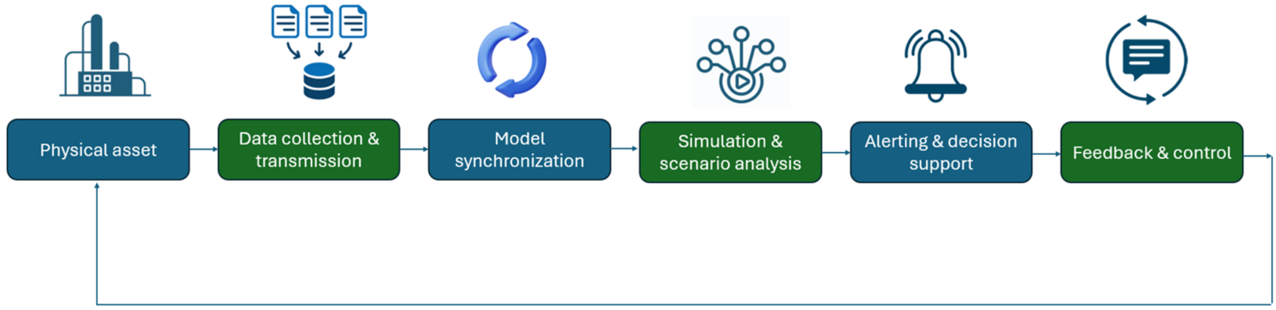


Exhibit 15 - Digital twin architecture

There are four potential frontier pathways for leveraging Digital Twins in manufacturing:

(i) **Accelerating innovation in the aerospace & defence sector:** Digital twins can revolutionize aerospace R&D by enabling engineers to virtually design, simulate, and validate aircraft components under real-world conditions—long before physical prototypes are built. These dynamic models help analyze aerodynamics, thermal loads, material fatigue, and structural stress, leading to safer and more efficient designs. By unifying cross-functional teams through a shared, real-time model—and integrating AI for intelligent design suggestions—digital twins significantly reduce development time, physical testing costs, and enhance regulatory compliance.

(ii) **Transforming clinical trials in the pharmaceutical sector:** Digital twins can accelerate pharmaceutical R&D by enabling in-silico clinical trials—virtual simulations using patient-specific data like genetics, physiology, and medical history. These digital cohorts allow researchers to predict drug responses, optimize dosing, and identify safety risks across diverse populations without exposing real patients to harm. By supporting adaptive trial design, digital twins enable faster, more targeted studies and reduce development costs. With growing support from regulators, they are paving the way for precision medicine and a more efficient, data-driven future of drug development.

(iii) **Data-driven optimization in chemical manufacturing:** In chemical plants, each processing unit, including reactors, columns, exchangers, etc., can be mirrored as a digital twin, enabling real-time simulation and control. These dynamic models would help engineers monitor key parameters like temperature, pressure, and flow, and fine-tune them to maximize yield and efficiency. For example, a reactor twin can optimize residence time, while a distillation twin can reduce energy consumption without compromising purity. Teams can also run virtual "what-if" tests on raw materials or process changes, reducing downtime and scale-up risks. Together, these unit-specific twins drive higher productivity, lower costs, and safer, more agile operations.

(iv) Predictive maintenance in the construction and mining equipment industry in construction and mining equipment manufacturing, digital twins can create real-time replicas of machines like excavators and loaders, using sensor data to monitor wear, stress, and performance. These models detect early signs of failure such as pressure build-up or vibration, allowing precise, just-in-time maintenance that reduces downtime and extends asset life. Manufacturers also use field data from these twins to improve design, optimize warranties, and deliver predictive service offerings. As a result, digital twins shift maintenance from reactive to proactive, maximizing uptime and lowering operating costs in rugged, high-value environments.

Digital twins can transform industries by enabling virtual modeling, real-time monitoring, and predictive decision-making—driving innovation, efficiency, and smarter lifecycle management across R&D, operations, and service. and extending product life cycles across sectors.

3.2.4 Robotics

Robotics can fundamentally redefine how India manufactures - transitioning from fixed automation to intelligent, modular and collaborative systems seamlessly integrated across shop floors. These next-generation robots would be context-aware, safety-certified, and AI-enabled, capable of operating fluidly in unstructured environments alongside human workers. Rather than displacing India's vast industrial workforce, robotics will augment human capabilities, supporting a scalable "human + machine" synergy tailored to India's heterogeneity in factory sizes, workflows, and capital intensity.

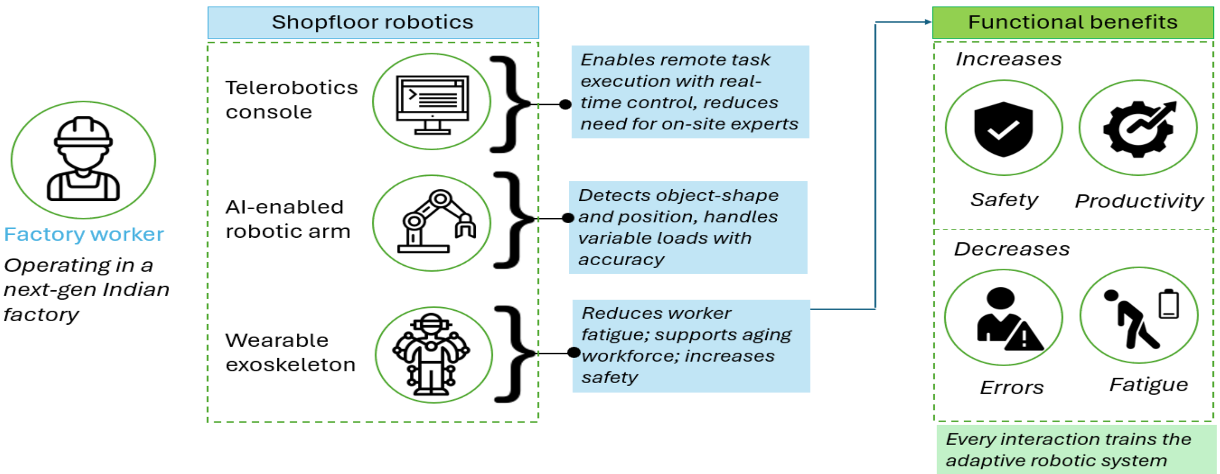


Exhibit 16 - Shopfloor Robotics

There are five potential frontier pathways leveraging Robotics in manufacturing:

(i) **Expanding manufacturing boundaries with telerobotics**: Telerobotics would enable operators to control robots remotely, allowing manufacturing tasks to be performed from distant or hazardous locations. This is especially valuable in high-risk environments such as chemical plants, nuclear facilities, or offshore rigs. With advancements in 5G, haptic feedback, and real-time data transmission, telerobotics will allow for precision control and reduced human exposure to danger. It also supports business continuity by enabling expert intervention without the need for physical presence. As connectivity improves, telerobotics is poised to redefine remote operations in manufacturing.

(ii) **Precision manufacturing in the electronics sector:** In electronics manufacturing, robotics ensures the precision, speed, and consistency required for assembling miniaturized components. Robotic arms handle SMT placement, micro-soldering, and PCB assembly—tasks often too delicate for manual labour. Robots also automate repetitive tasks like fastening, labelling, and packaging, reducing errors and downtime. In cleanrooms such as semiconductor fabs, robotics ensures contamination-free handling. Overall, robotics drives higher throughput, lower defects, and greater operational efficiency—making it critical to modern electronics production.

(iii) **Boosting safety and efficiency on the factory floor with Exoskeletons**: Exoskeletons are wearable devices that augment human movement, significantly reducing physical strain in manufacturing environments. By providing support to the back, shoulders, and arms, they help workers perform repetitive or strenuous tasks with greater ease and reduced risk of injury. With proper training and task alignment, exoskeletons offer a promising future for ergonomic and efficient manufacturing operations.

(iv) **Driving precision & efficiency with humanoids in the auto industry**: These robots can perform activities such as parts assembly, inspection, and machine tending by mimicking human motion—allowing them to operate tools, press buttons, or work alongside humans without requiring major layout changes. Their ability to adapt to different tasks and handle variability makes them ideal for model changeovers and high-mix production lines. By supporting flexible automation, reducing ergonomic strain on workers, and maintaining consistent output quality, humanoids would enhance efficiency and agility in next-generation automotive plants.

(v) **Smarter Unloading with AI-Powered Robotics**: AI and robotics together would revolutionize unloading by enabling systems to manage complex, variable loads with speed, precision, and adaptability. AI provides real-time object recognition, environmental sensing, and decision-making, allowing robots to identify items, assess orientations, and plan optimal pick paths—even in unstructured or dynamic settings. Robotic arms, grippers, and mobile platforms then conduct precise unloading, efficiently managing varied shapes, weights, and stacking patterns. This intelligent automation not only reduces errors and enhances worker safety but also supports continuous, scalable operations—resulting in faster, more flexible, and cost-effective logistics workflows.

From telerobotics and exoskeletons to AI-powered automation and humanoid robots, advanced robotics technologies are reshaping manufacturing by enabling safer, smarter, and more flexible operations—enhancing precision, adaptability, and efficiency across diverse use cases and environments.

4. THE POTENTIAL COST OF INACTION

In a business-as-usual scenario aligned to past trends, India's manufacturing GDP would grow at a CAGR of 6.5% to reach US $1.05 trillion (FY 35) from the current US $527 billion (FY 24). Of this, the five clusters (thirteen sectors) of manufacturing accounted for ~75% of manufacturing GDP (FY 24) and projected to contribute ~85% (FY 35).

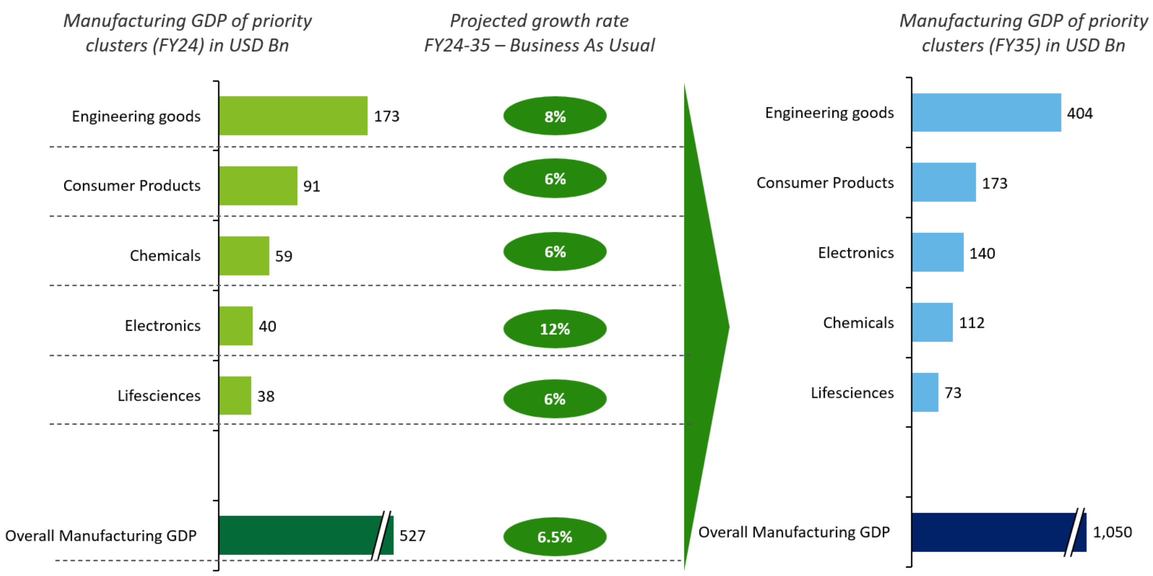
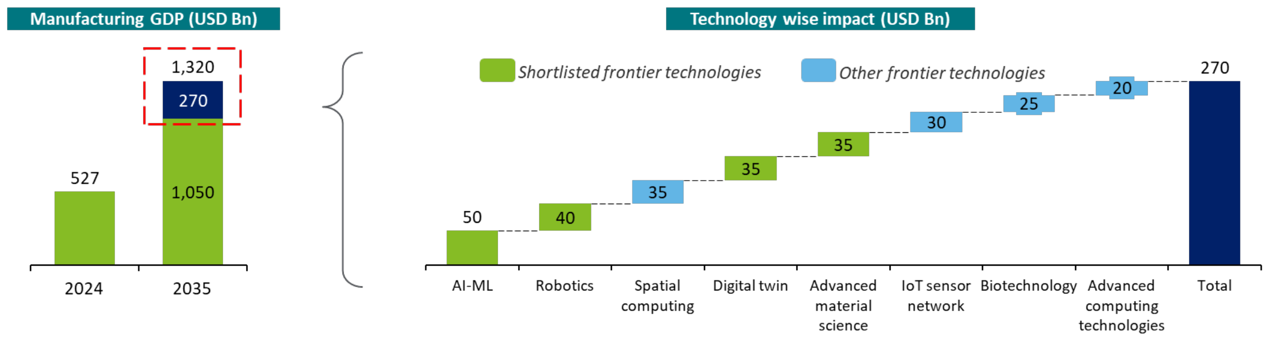


Exhibit 17 – GDP contribution of manufacturing clusters

Frontier technologies—AI/ML, digital twins, robotics, and advanced materials—can significantly boost efficiency, quality, and competitiveness in India's manufacturing sector. Delaying the adoption and deployment has major economic and marketplace impacts that include

1. **Economy:** *F*ailing to adopt these key technologies in the focus sectors could result in India losing **US $270 billion** by 2035 and **US $1.1 trillion** by 2047 **in additional manufacturing GDP**. The magnitude of the potential loss signifies that the time to act is now
2. **Quality:** Manual-heavy processes may not be able match the precision of frontier technology enabled products from peers, leading to high costs and low competitiveness. India's contribution to global merchandise trade could remain be stagnant at ~2%
3. **Time to market:** Rolling out new product lines or expanding capacity without advanced simulation and design tools can take months longer—and burn through more capital.
4. **Competition:** Organizations in India could lose market share to faster, leaner competitors peer nations —raising import bills and weakening India's standing in global markets.

Economic assessment of frontier technologies 2035



Economic assessment of frontier technologies 2047

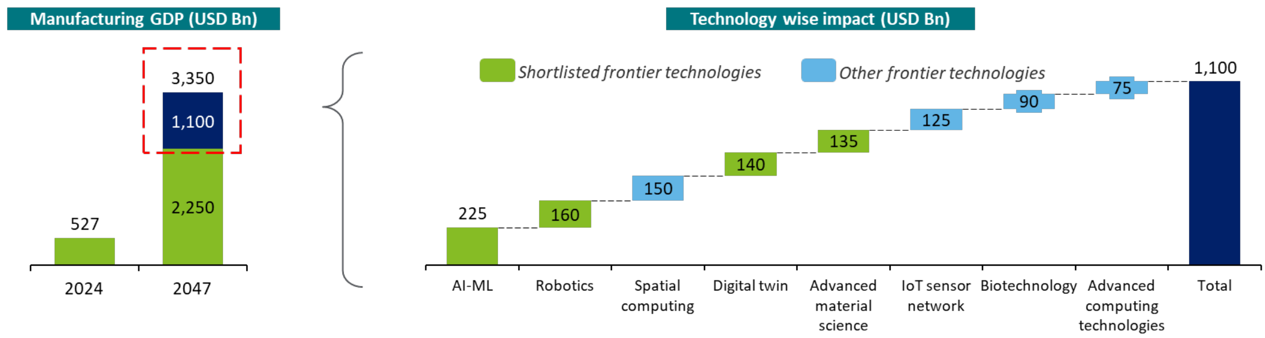


Exhibit 18 - Economic impact of frontier technologies

5. STRATEGIC ROADMAP AND RECOMMENDATIONS

As highlighted, accelerated implementation of frontier technologies would unlock an additional USD 1 trillion in manufacturing GDP by 2047. This would create over 100 million skilled jobs and expand India's export share to 6.5%, firmly positioning the country as a global manufacturing leader. These gains would be driven by enhanced productivity, process innovation, and integration into high-value global value chains across sectors.

However, the implications of delayed or inadequate adoption of these technologies would be substantial, resulting in reduction in manufacturing contribution to GDP primarily driven by erosion of competitiveness. India's share of global manufacturing could decline from the current **3.5% to 2.5% by 2035** if transformative measures for adoption of frontier technologies are not undertaken. Such an outcome would decelerate value addition in India, increase import dependence, reduce exports, and weaken India's position in emerging technology-led industries.

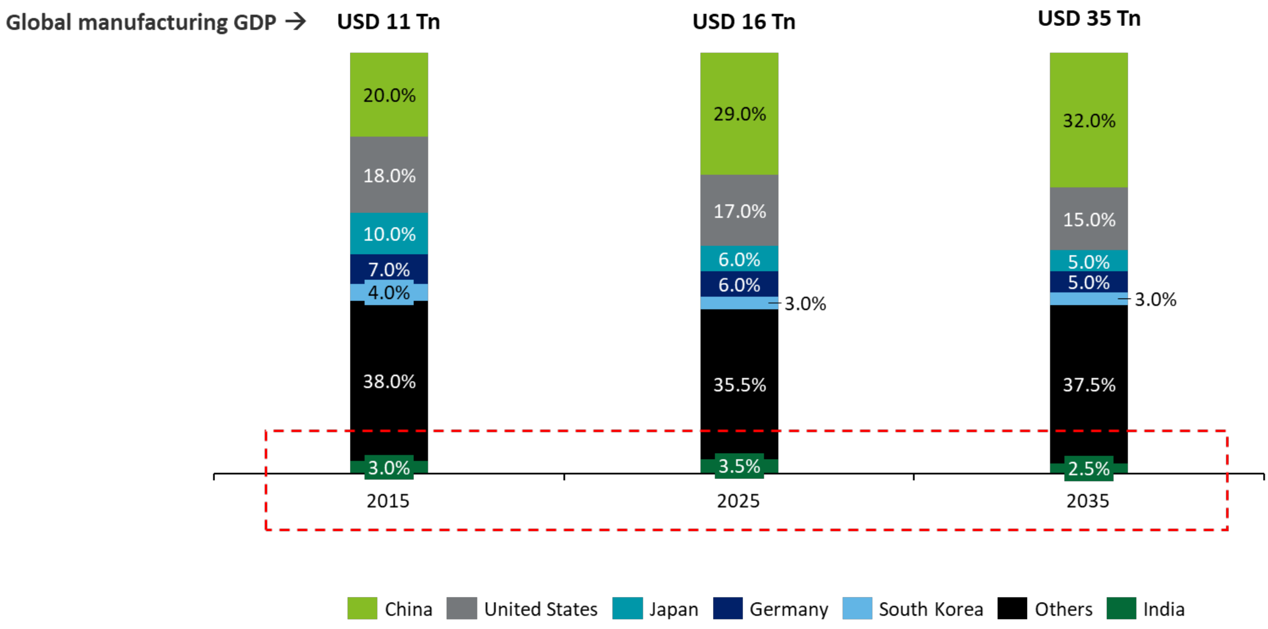


Exhibit 19 - Contribution of nations to global manufacturing GDP

Foundational enablers for frontier tech-led manufacturing transformation

India would need to activate foundational enablers that form the base to realise the full potential of frontier technologies in manufacturing. These enablers drive the shift from pilot scale to widespread adoption and in their absence, efforts to scale frontier technologies may remain fragmented or ineffective. They include

5.1 **Business environment:** While India has made significant strides in simplifying business processes, advanced manufacturing presents new regulatory demands. The sectors emerging in the new advanced manufacturing era will require:

(i) Streamlined approval mechanisms for modern technology applications (e.g., Robotics, AI etc.)

(ii) Clear IP regimes, especially for cross-border collaborations in high-tech joint ventures or R&D-led investments

(iii) Cost-effective access to energy especially green and reliable energy

(iv) Industrial infrastructure with ready access to high-speed data, utilities, and modern logistics hubs

5.2 **Ecosystem:** India's technology enabled manufacturing transformation would significantly depend on how rapidly organizations – including MSMEs – can adapt, absorb, and deploy frontier technologies into shop floors. This will require:

(i) Sustained funding by the government and industry for technology innovation to support pilot-to-scale transitions in technologies such as robotics, and advanced materials

(ii) Shared R&D and testing infrastructure to reduce individual capex burdens and promote collaborative innovation

(iii) Public-private technology accelerators embedded in industrial corridors to scale deep-tech startups by providing capital, mentorship, and market access

(iv) Accelerated investments in industrial parks, renewable energy clusters, reliable power, and multimodal logistics hubs as the backbone for scaling frontier technologies and reducing structural cost disadvantages

(v) High-speed networks with 5G/6G speed connectivity would enable real-time operations, digital twins, and predictive analytics on shop floors, while expanding affordable access for MSMEs to advanced digital tools

5.3 **Talent and workforce readiness**: As production systems become more digital, automated, and data-driven, the demand for new skill sets would rapidly outpace supply. Addressing this gap requires a focused push on the following areas:

(i) Industry-aligned curricula and certification in frontier technology domains across the technical education value chain – ITIs, Polytechnics and Engineering Institutes

(ii) Technology apprenticeships and modular skilling programs, delivered in partnership with the industry

(iii) Centers of Excellence (CoE) in Tier 2/3 cities, focused on frontier technologies to enable skilling access across all regions

5.4 **Technology infrastructure and governance:** The successful deployment and scaling of frontier technologies in manufacturing depends on a robust foundation of digital infrastructure, trusted data ecosystems, and agile governance frameworks. The following interventions are critical to strengthen this foundation:

(i) National digital backbone for manufacturing, including secure cloud infrastructure, standardized machine data protocols and APIs for real-time industrial IoT integration

(ii) Sector-specific regulatory sandboxes to enable safe experimentation under controlled conditions

(iii) Open, interoperable technical standards that ensure compatibility across OEMs, vendors, and digital platforms within industrial supply chains

(iv) National testbed networks and demonstration sites, including both greenfield and retrofitted brownfield facilities, to validate and de-risk modern technologies before wider rollout.

Roadmap to maximize strengths and bridge gaps

With the foundational enablers for frontier technology adoption defined, the next step is to translate these into a structured path for action. The next decade offers India's manufacturing sectors an unprecedented opportunity to leverage technology as a growth accelerator.

To seize this opportunity, **Leadership in Advanced Manufacturing must be positioned as a core national priority under the India National Manufacturing Mission (NMM)**—anchoring India's journey from scale-driven production to innovation-led, high-value manufacturing. This strategic focus would ensure that frontier technologies are not adopted in isolation, but embedded systemically across sectors, clusters, and enterprises through coordinated action between government, industry, and states.

The following 10-year roadmap, structured in four stages and three phases, outlines a set of comprehensive interventions to create a future-ready, frontier technology-enabled manufacturing ecosystem that can drive India's transformation into a global leader by 2035.

Exhibit 20 - Strategic roadmap for frontier technology-led manufacturing transformation

Building a robust, technology-driven manufacturing landscape requires more than individual initiatives—it demands a cohesive national framework that aligns policy, funding, skills development, and infrastructure to support every link in the value chain. The following recommendations outline critical actions to reinforce this ecosystem, laying the groundwork for a resilient, future-ready manufacturing sector.

Phase 1 (FY2026 - FY2028): Ecosystem Building and Adoption

1 **Positioning Advanced Manufacturing as a strategic priority** under the National Manufacturing Mission (NMM) to rapidly start frontier technologies in the Indian manufacturing sector and drive adoption. The focus areas for advanced manufacturing as part of NMM should be:

(i) Enabling access to frontier technologies to the manufacturing sector to create structured access pathways for industry players across clusters through Government-to-Government (G2G), Government-to-Business (G2B), and Business-to-Business (B2B) channels. These could include bilateral cooperation, public tech repositories, and shared demonstration platforms to ensure smaller firms are not excluded

(ii) Facilitating collaboration and partnerships that forge strong networks between academia, industry, startups, and global technology leaders to accelerate co-creation and commercialization of frontier solutions. This includes joint R&D programs, innovation consortia, and open innovation challenges focused on critical technologies

(iii) Developing policies and schemes to tailor forward-looking incentive schemes and IP-friendly environments that encourage rapid prototyping, piloting, and scaling of advanced manufacturing solutions

(iv) Defining infrastructure requirements to develop the physical and digital infrastructure required to support technology-intensive manufacturing. This includes smart industrial parks, 5G-enabled production zones, cyber-physical infrastructure, and shared R&D and testing facilities

(v) Executing the policies, schemes, and initiatives at each cluster of manufacturing sectors in coordination with the state governments and industry, and planning for specific interventions to accelerate the adoption of frontier technologies

The Advanced Manufacturing Pillar under NMM should work on three core tenets

- **Cluster-focused approach**: Frontier technologies and associated initiatives/interventions should be specific to each cluster of the respective manufacturing sectors
- **Standardization of outcomes**: Outcomes on the adoption of frontier technologies should be clearly defined at the sector level and at the enterprise level while respecting existing differences in the current maturity levels
- **Collaborative delivery**: All stakeholders – State Governments and individual organizations – should work together within the framework of the advanced manufacturing pillar to ensure targeted outcomes

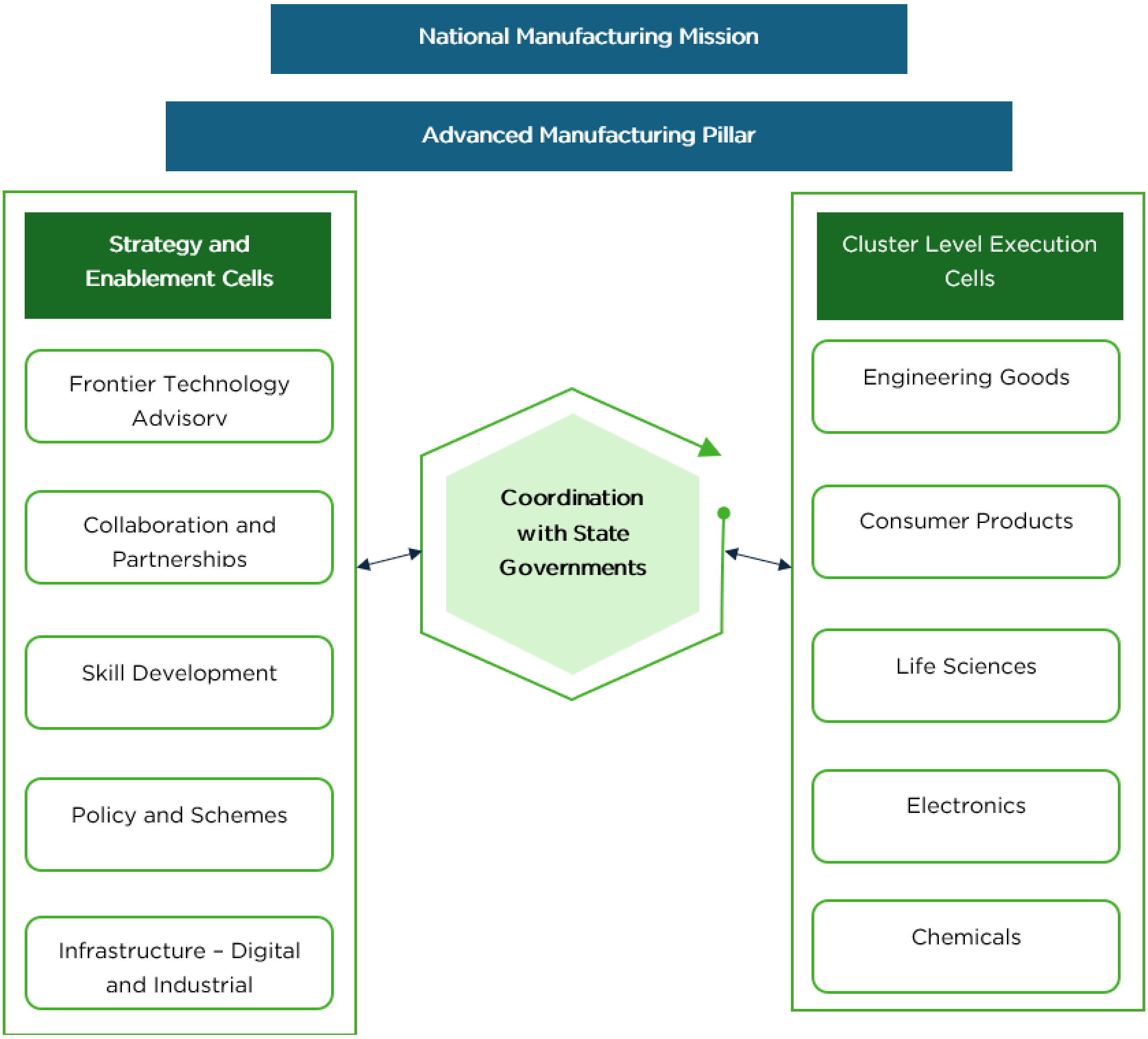


Exhibit 21 - Advanced Manufacturing Pillar under the National Manufacturing Mission (NMM)

2 **Establishment of Global Frontier Technology Institute (GFTI)** in India as a Center of Excellence (CoE). The GFTI should focus on:

(i) Core research and development in frontier technologies with the objective of keeping India ahead of competing countries while ensuring sustained access to the latest technologies to Indian enterprises

(ii) Development of frameworks for technology development and governance to ensure meaningful deployment of frontier technologies in industrial applications

(iii) Assessment and certification of organizations on their capability and maturity in leveraging frontier technologies

(iv) Forging strategic partnerships with leading organizations focusing on frontier technologies and skill development

(v) Fostering collaboration and cooperation with major manufacturing countries on policies and actions on development and deployment of frontier technologies

3 **Development of a future-ready skilling ecosystem** through large-scale, modular, and cluster-aligned programs focused on frontier tech capabilities. The initiative should adopt a **'Focused State – Focused Sector/Geography – Focused Technology'** approach to tailor curricula and apprenticeships. An industry-integrated skilling institution that blends experiential, modular, and technology-driven pedagogy with deep partnerships with leading organizations, creating factory-ready professionals in frontier technologies would bridge the gap between education and industry readiness. India's skilling ecosystem needs to therefore

(i) Design modular, stackable programs aligned to industry needs, including short-term and long-term certification in the domains of frontier technologies, taking into consideration foundational educational qualifications, and adapted to specific sector context

(ii) Establish cluster-based apprenticeship and onsite learning for enabling hands-on, immersive training aligned to actual shopfloor technologies. This would help bridge the last-mile gap between training and employment, particularly in the MSME segment

(iii) Launch focused skilling missions at the state level, tailored to local manufacturing strengths and workforce aspirations. For example, a Precision Engineering & Robotics Mission in Tamil Nadu or a Green Mobility & Battery Tech Mission in Maharashtra—each designed with private sector and academic partnerships

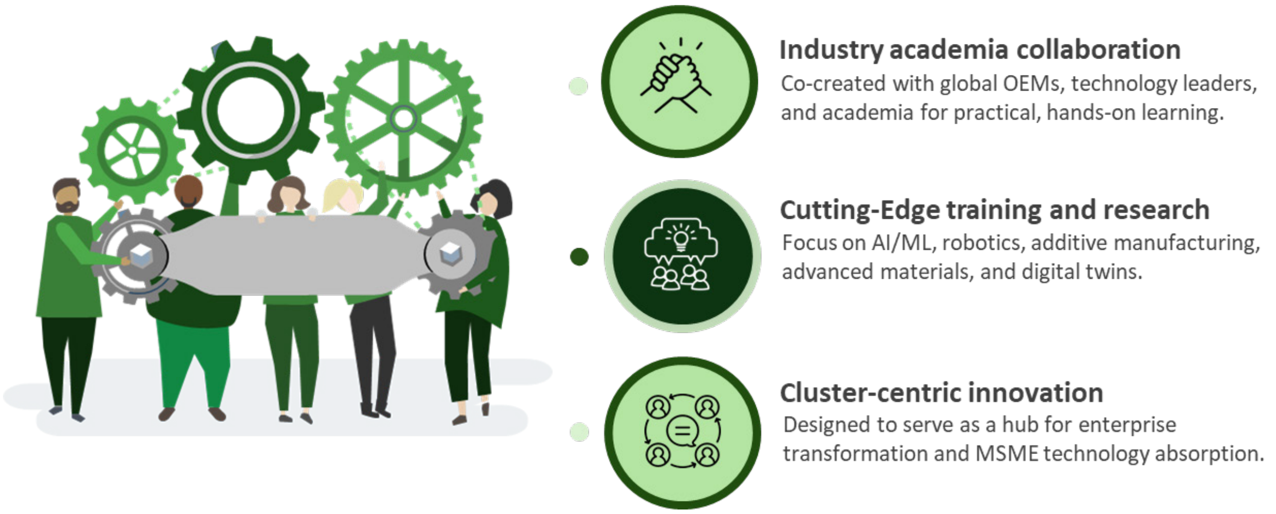


Exhibit 22 - Dimensions of a future ready skilling ecosystem

4 **Creation of technology access platforms that are inclusive** to reduce entry barriers

and ensure that advanced manufacturing capabilities are not concentrated within a few large enterprises but are widely available across the value chain and specifically to MSMEs. The following are the proposed initiatives:

(i) Establishing regionally distributed, cloud-based digital infrastructure hubs where manufacturers—especially MSMEs—can access high-performance computing, simulation tools, data lakes, and digital twin platforms without upfront capital investment. The hubs would be operated on a subscription or pay-per-use basis

(ii) Curating and disseminating open-source libraries, codebases, and implementation playbooks for frontier technologies such as AI/ML-based predictive maintenance, machine vision systems, or cobotics integration. The materials should be developed in collaboration with leading research institutes and translated into sector and language specific variants

(iii) Providing targeted subsidies or pooled procurement support for manufacturers to access commercially licensed digital platforms (e.g., PLM, MES, CAD/CAM), frontier tech APIs, and essential middleware—especially where economies of scale can lower unit costs. This could include negotiating national-level licenses or providing shared access within industrial clusters

5 **Champion organization enabled adoption of frontier technologies in clusters:** Champion organizations —those at the forefront of advanced manufacturing— would be critical to accelerating technology adoption across India's manufacturing landscape. With their strong R&D capabilities, innovation-driven operations, and global competitiveness, these firms can function as role model institutions driving transformation across clusters.

Key interventions to leverage the strengthen this role include:

(i) **Cluster-based demonstration programs:** Cluster-based programs create shared value for all participants. For champion organizations, they provide a platform to showcase frontier technologies, validate outcomes, and accelerate the readiness of their supply chains, ensuring partners are capable of operating within a technology-enabled ecosystem. For smaller firms and MSMEs, these programs offer hands-on exposure, peer learning, and reduced adoption risk, enabling them to quickly catch up with technological standards

(ii) **Enterprise-to-enterprise adoption models:** Champion organizations can accelerate peer adoption by providing structured handholding to smaller firms in their networks. This includes shared resources, process templates, and onboarding toolkits that lower adoption barriers. Such models ensure that suppliers and partners evolve in step with champions, strengthening ecosystem reliability while reducing risks for smaller firms. For champions, this creates more resilient supply chains; for smaller firms, it lowers the cost and risk of technology adoption

(iii) **Collaboration with ecosystem:** Champion organizations can create co-development platforms with startups, academia, and MSMEs by offering capital, market access, and testbeds. In return, they gain early access to disruptive innovations, faster R&D cycles, and solutions tailored to their operational needs. For startups and academia, these collaborations provide real-world validation and commercialization pathways, while champions secure a pipeline of localized, cost-effective technologies that strengthen their competitiveness. This shared innovation approach ensures India's manufacturing ecosystem advances in a way that is both globally competitive and locally relevant.

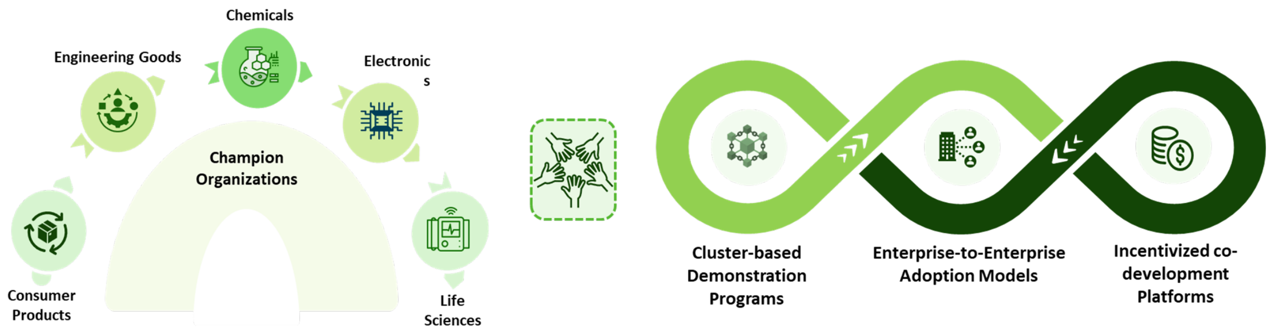


Exhibit 23 - Technology adoption model driven by champion organizations

6 **Design of frontier technology-enabled supply chain models** across manufacturing clusters and sectors to enable seamless value chain integration and democratized technology access. This intervention aims to build digitally connected, intelligence-led, and resilient supply chain operating frameworks that cater to the distinct characteristics of each manufacturing cluster and sector. These next-generation models should incorporate key components such as:

(i) End-to-end digital visibility platforms that leverage IoT, AI, and blockchain to enable real-time tracking, predictive analytics, and data sharing across suppliers, manufacturers, and distributors.

(ii) Standardized digital interfaces and open APIs that facilitate seamless integration between tier-1, tier-2, and MSME suppliers, reducing information asymmetry and enabling just-in-time responsiveness.

(iii) Sector-specific templates for advanced planning systems, logistics orchestration, and inventory optimization—customized for high-impact industries such as Automotive, Electronics, Aerospace, and Pharmaceuticals.

(iv) Incentivized onboarding of smaller players through shared technology access, digital upskilling, and co-investment models to ensure equitable participation across the value chain

7 **Deployment of digital and industrial infrastructure to enable the frontier technology ecosystem** through creation of twenty "Plug & Play Frontier Technology enabled Industrial Parks" across India starting with five most impactful sectors including Aerospace & Defense, Semiconductors, Electronics, Automotive and Pharmaceuticals.

Each industrial park would function as a **technology sandbox**, enabling firms—especially MSMEs—to access and experiment with cutting-edge technologies such as **AI/ML, robotics, additive manufacturing, advanced materials, and**

industrial IoT, without incurring prohibitive capital costs. Core features to include:

(i) Shared infrastructure like high-end simulation labs, 5G-enabled industrial networks, and testing/certification facilities

(ii) Integrated logistics and utilities to reduce operational friction and turnaround times

(iii) Embedded Centers of Excellence (CoEs) to offer continuous R&D, training, and innovation support

(iv) Co-location of academia, startups, and anchor firms to drive collaboration, knowledge spillovers, and localized innovation

Phase 2 (FY2029 - FY2031): Acceleration

8 **Driving 'Servicification of Manufacturing':** With the enablers in place and phase-1 of a transformed manufacturing ecosystem in action, India's next competitive leap revolves around the **servicification of manufacturing**, which has a potential to transform the landscape of manufacturing in India.

"Servicification of Manufacturing" would require the transformation of Indian manufacturers from pure product manufacturers to **solution providers** in which physical goods are increasingly bundled with services such as R&D, design, engineering, installation, aftermarket support, remote monitoring and performance guarantees and monetized through recurring revenue models like pay-per-use, subscription, or outcome-based contracts. This shift is critical for India as it would enhance its global value chain (GVC) participation and enable alignment with evolving customer focused business models. This trend is catalyzed by frontier technologies such as:

- **IoT** and **digital twins** for real-time asset tracking
- **AI/ML** for predictive analytics and diagnostics
- **Cloud and edge computing** for scalable service delivery

The convergence of these technologies would allow Indian manufacturers to embed intelligence, feedback loops, and customization into their offerings—transforming their relationship with customers and creating new value streams.

The transition to servicification of manufacturing would be enabled by:

- Driving investments in R&D and innovation in five core clusters of manufacturing and frontier technologies with significant participation by Indian entities to ensure localization of capabilities and capacities
- Deploying executions models to integrate Global Capabilities Centers (GCC) focusing on frontier technologies to ensure continued access to global developments

Phase 3 (FY2032-FY2035): Sustenance

9 **Continuous monitoring of frontier technologies evolution** and their alignment with economic development objectives in comparison with competing countries and planning for targeted interventions to enable and ensure continuity of India as a leading technology provider to the world.

Self-reliance, enhanced capabilities and holistic adaption on frontier technologies vis-à-vis competing countries would be critical for India to leap and sustain leadership in advanced manufacturing. Thus, the Global Frontier Technology Institute (GFTI) along with the Advanced Manufacturing Pillar under NMM would play the lead role in enabling availability latest technologies and continued adaption for Indian organizations.

6. ANNEXURE

A. Manufacturing sectors considered for evaluation

To develop a forward-looking strategy for the future of manufacturing in India, it was essential to begin with a robust and comprehensive identification of sectors that warrant deeper analysis and policy attention. The selection process for these sectors was guided by a multi-dimensional framework that factored in current economic performance, export strength, and strategic national priorities.

Champion sectors for manufacturing

- Aerospace and Defense
- Automotive and Auto Components
- Pharmaceuticals
- Medical Devices
- Biotechnology
- Capital Goods
- Textiles and Apparels
- Chemicals and Petro-Chemicals
- Electronics System Design and Manufacturing (ESDM)
- Leather and Footwear
- Food Processing
- Gems and Jewellery
- Marine and Shipping
- Railways
- Construction
- New and Renewable Energy

Top sectors by Gross Value Addition (GVA)

- Metal Industry (Ferrous and Non-Ferrous)
- Chemicals and Petro-Chemicals
- Petroleum
- Food Products
- Automotive and Auto Components
- Pharmaceuticals
- Textiles and Apparel
- Cement
- Plastic and Packaging
- Paper and Pulp Industry

Top sectors for export performance

- Electronics
- Automobile and Auto Components
- Pharmaceuticals
- Medical Devices
- Textiles and Apparels
- Chemicals and Petro-Chemicals

Strategically critical sectors

- Metal Industry (Ferrous and Non-Ferrous)
- Engine and Turbine
- Power Transmission Equipment
- Electrical Equipment
- Construction and Mining Equipment
- Aerospace and Defense
- Railway Equipment
- Semiconductors

A total of twenty sectors were shortlisted for evaluation, drawn from an intersection of four primary lenses:

1. **Champion Sectors for Manufacturing:** Identified under initiatives like Make in India and the PLI scheme, are recognized by the Government of India for their high potential to drive growth, innovation, employment, and global competitiveness.

2. **Top Sectors by Gross Value Added (GVA):** GVA measures a sector's contribution to the national economy, highlighting those that dominate industrial output and value creation.

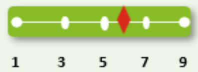
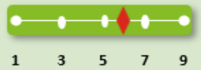
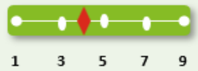
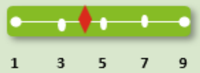
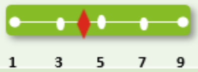
3. **Top Sectors by Export Performance:** Export-driven sectors are central to India's manufacturing goals, reflecting global competitiveness, quality, and innovation.

4. **Strategically Critical Sectors:** Sectors, though not current economic leaders, are vital for national interests like self-reliance, security, infrastructure, and tech sovereignty. They address strategic goals—reducing import dependence, enhancing defense readiness, and future-proofing key technologies—and warrant focused investment for long-term national gains.

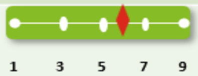
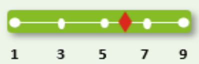
B. Application areas and/or potential use cases for Frontier Technologies

Cluster – Engineering goods

Sector – Auto & Auto Components

Functional use case	Definition	Primary Frontier Technology	Supporting Frontier Technology	TRL
Auto and Auto components				
Solid State Batteries	Transition from conventional lithium-ion to solid-state batteries using solid electrolytes (and lithium/silicon-based anodes	Advanced materials science	Smart grid and energy storage	
Software Defined Vehicles	Integrate software-driven systems for over-the-air updates, AI optimizations, and cloud-based remote diagnostics and predictive maintenance via telematics and vehicle-to-grid communication	Quantum computing	AI/ML algorithms	
Vehicle to Everything Connectivity Integration	Leverage V2X technology to enable real-time communication between vehicles, smart infrastructure and pedestrians to facilitate dynamic traffic control	5G/6G connectivity	IOT sensor network – mass application	
Autonomous Vehicles	Advance ADAS to higher levels (level 3-5) for real-time traffic optimization and adaptive vehicle operations	5G/6G connectivity	Quantum computing	
Net-Zero Vehicles & Battery Systems	Develop vehicles powered by hydrogen produced via water electrolysis, ensuring emissions of only water vapor	Smart grid and energy storage	Blockchain technology	
Zero Intervention Manufacturing	Deploy AI-driven robotics for fully autonomous, end-to-end manufacturing processes	IOT sensor network – mass application	Cobots	

Sector – Construction and Mining Equipment

Functional use case	Definition	Primary Frontier Technology	Supporting Frontier Technology	TRL
Construction and Mining equipment				
Task-Specific Machinery Development	Integrate adaptive robotic systems to enable task-specific machinery that optimizes performance for niche applications	IOT sensor network – mass application	AI/ML algorithms	
IoT-Enabled Predictive Maintenance	Deploy IoT-enabled sensors on machinery components that analyze real-time equipment data to predict both failures and unsafe operating conditions before they occur	IOT sensor network – mass application	Quantum computing	
3D Printing for On-Site Spare Parts Manufacturing	Develop mobile additive manufacturing units to produce custom spare parts on-site, reducing lead times	3D printing	Advanced material science	
Alternative Fuel-Powered Heavy Machinery	Develop and deploy construction and mining equipment running on hydrogen, biofuels, EV powertrains, and hybrid energy solutions to replace diesel-powered machinery	Smart grid and energy storage		
Autonomous Construction Vehicles	Develop AI-driven, fully autonomous bulldozers, loaders, and haulers for large-scale projects	5G/6G connectivity	Quantum computing	
Carbon Capture-Integrated Equipment	Equip large-scale machinery with onboard carbon capture technology to reduce emissions at source	Advanced materials science	Smart grid and energy storage	

Sector – Railway Equipment

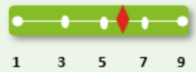
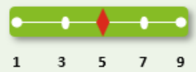
Functional use case	Definition	Primary Frontier Technology	Supporting Frontier Technology	TRL
Railway equipment				
Energy-efficient HVAC systems	Develop advanced HVAC systems that optimize energy consumption based on passenger load and ambient conditions	IOT sensor network – mass application	AI/ML algorithms	 1 3 5 7 9
AI-Driven Predictive Safety Systems	Develop an AI-driven system that analyses real-time train operation, wear, track conditions, and sensor data to predict critical failures before they occur	IOT sensor network – mass application	AI/ML algorithms	 1 3 5 7 9
Graphene-Based Lightweight Materials	Integrate graphene-infused composites and lightweight materials in coach and wagon manufacturing for improving fuel efficiency and durability	Advanced materials science		 1 3 5 7 9
Adaptive Suspension Systems	Develop suspension systems that automatically adapt to varying track conditions and loads, improving ride quality and reducing wear	Sensor network - Mass application	Quantum computing	 1 3 5 7 9
Interchangeable Power Modules	Design railway locomotives with interchangeable power modules (hydrogen, battery, electric, hybrid) swappable based on operational needs	Smart grid & energy storage	Battery as a Service (BaaS)	 1 3 5 7 9
Superconducting Maglev Components	Develop superconducting magnet systems for maglev-based propulsion to reduce reliance on track-based friction	Advanced materials science		 1 3 5 7 9

Sector – Aerospace and Defense

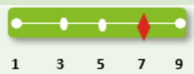
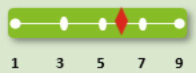
Functional use case	Definition	Primary Frontier Technology	Supporting Frontier Technology	TRL
Aerospace and Defense				
Quantum Radar system	Develop quantum radar systems that use quantum entanglement to detect stealth aircraft and other low-observable targets	Quantum computing	Sensor network - Mass application	 1 3 5 7 9
Virtual reality(VR) training programs	Implement VR-based training programs providing immersive simulations for complex scenarios and equipment handling	Sensor network – mass application		 1 3 5 7 9
Hypersonic propulsion systems	Develop hypersonic propulsion systems for missiles and aircraft, enabling speeds greater than Mach 5	3D printing	Advanced materials science	 1 3 5 7 9
ZeroUI for autonomous systems	Integrate Zero User Interface technology into autonomous systems, allowing for intuitive control through voice commands and gestures	AI/ML algorithms		 1 3 5 7 9
Generative AI for strategic planning	Utilize generative AI to simulate and optimize strategic defence scenarios, including resource allocation and mission planning	Digital twin	AI/ML algorithms	 1 3 5 7 9
Space-based solar power stations	Develop space-based solar power stations that collect solar energy and transmit it to Earth using microwave or laser technology	Smart grid & energy storage	Advanced materials science	 1 3 5 7 9

Cluster – Consumer products

Sector – Textiles

Use case	Potential value/benefits	Primary Frontier Technology	Supporting Frontier Technology	TRL
Textiles				
Manufacturing automation and robotics	Sewing robots, laser cutting and automated garment finishing streamlines fabric cutting, sewing and quality control	Cobots	IoT sensor network - Mass application	
Automating design processes	AI-driven design automation helps analyze past designs and customer preferences to generate innovative, personalized fashion, streamlining the traditional design process	AI/ML algorithms		
Closed-loop molecular textile recycling	Use of green chemistry to break down blended fabrics (like cotton-polyester) at the molecular level, separating them into reusable raw materials for new textiles	Advanced material science	Green chemistry	
Anti-microbial and self-cleaning textiles	Prevent odor and bacteria buildup and repel dirt using nano-coatings or bio-based agents, ideal for healthcare, sportswear, and travel	Advanced material science	AI/ML algorithms	
Smart textiles	Integration of sensors, conductive fibers and advanced materials helps enable functionalities like temperature regulation, moisture control, and biometric tracking	Advanced material science	IOT sensor network – Mass application	
Ai-designed self-evolving textiles	Textiles designed by AI that adapt their properties over time such as changing fit, ventilation, insulation based on user behavior, environmental conditions, or repeated use	AI/ML algorithms	Advanced material science	

Sector – Leather & Footwear

Use case	Potential value/benefits	Primary Frontier Technology	Supporting Frontier Technology	TRL
Leather & Footwear				
AI-powered defect detection system	Use of AI and computer vision to automatically identify defects or inconsistencies in hides during inspection or processing	AI/ML algorithms	Quantum computing	
Automated leather cutting with robotics	Deployment of robotic arms and vision-guided systems to automate the cutting of leather for footwear and accessories with high precision	Cobots	IoT sensor networks – mass application	
3D foot scanning with ai-based mass customization	Utilizing 3D scanning technology to create bespoke shoe lasts, ensuring personalized fir and comfort	AI/ML algorithms		
Smart footwear with embedded sensors	Footwear integrated with biosensors that monitor bodily functions providing useful diagnostic intelligence that are useful for athletes and elderly users	IOT sensor network – Mass application	5G/6G networks	
Chrome-free & bio-based tanning technologies	Replacement of traditional chrome-based tanning methods with bio-based or enzymatic alternatives to reduce environmental and health impact	Advanced material science	Green chemistry	
Biofabricated (lab-grown or cell based) leather	Development of lab-grown leather using microbial or cellular agriculture (like mycelium, collagen producing yeast) with significant lower environmental impact	Advanced material science	Tissue engineering	

Sector – Food Processing

Use case	Potential value/benefits	Primary Frontier Technology	Supporting Frontier Technology	TRL
Food Processing				
Smart packaging with embedded sensors	Integrates sensors into food packaging to monitor freshness, temperature, and contamination in real-time	Advanced material science	IoT sensor networks – Mass application	1 3 5 7 9
Smart cold chain logistics	Deploy IoT-enabled cold chain logistics with real-time tracking and predictive analytics to manage the temperature of perishable goods in transit	IoT Sensor network - Mass application	AI/ML algorithms	1 3 5 7 9
Edible coatings for fresh produce	Develop edible coatings made from non-harmful innovative biopolymers to extend the shelf life of fruits and vegetables	Advanced material science	Green chemistry	1 3 5 7 9
Drone-based direct-to-customer food delivery	Enables fast, hygienic delivery of fresh and processed foods via autonomous drones with cold chain support and minimal human contact	Robotics	AI/ML algorithms	1 3 5 7 9
Biodegradable packaging materials	Deploy advanced biodegradable materials for food packaging to reduce environmental impact	Green chemistry	Enzyme Engineering	1 3 5 7 9
Smart farming	Establishes vertical farms using CEA to grow crops in urban areas with minimal water and land use, focusing on widely used crops	IoT Sensor network - Mass application	AI/ML algorithms	1 3 5 7 9

Cluster – Life sciences

Sector – Pharmaceuticals

Use case	Potential value/benefits	Primary Frontier Technology	Supporting Frontier Technology	TRL
Pharmaceuticals				
Virtual product design	Leverages digital simulations to test and validate drug molecules, and manufacturing processes without physical prototypes	Quantum computing	AI/ML algorithms	1 3 5 7 9
High-throughput formulation optimization	Leverage high-throughput screening combined with machine learning to rapidly optimize drug formulations	High-throughput screening	Quantum computing	1 3 5 7 9
Connected sensor networks & IOT platforms	Integrates intelligent sensors and IOT platforms across the value chain to enable real-time data exchange and supplier-buyer coordination	IOT sensor network – Mass application	Blockchain technology	1 3 5 7 9
Process optimization in API production	Integrate AI algorithms to fine-tune reaction conditions and optimize scale-up processes in API production	AI/ML algorithms	IOT sensor network – Mass application (Industrial IOT)	1 3 5 7 9
Cloud enabled predictive maintenance	Utilizes cloud-based analytics for real-time monitoring and predictive maintenance of production infrastructure	Cloud computing	IOT sensor network – Mass application (Industrial IOT)	1 3 5 7 9
Alternative chemical synthesis pathway	Develop innovative synthesis routes using sustainable, alternative feedstocks for API manufacturing	Green chemistry	Biocatalysis	1 3 5 7 9

Sector – Medical devices

Use case	Potential value/benefits	Primary Frontier Technology	Supporting Frontier Technology	TRL
Medical Devices				
3D printed implants	Enables patient-specific implants, prosthetics, and anatomical models for precise surgical planning	3D Printing	Advanced material science	1 3 5 7 9
AI-assisted diagnostic imaging	Utilizing AI for analyzing medical images and lab results to detect diseases early and personalizing treatments using patient data with the help of ML	AI/ML algorithms	IOT sensor network – Mass application	1 3 5 7 9
Robotics in surgery	Robotic-assisted surgical systems integrate real-time imaging, haptic feedback, and AI-driven precision tools to enhance dexterity and control	Cobots (collaborative robots)	AI/ML algorithms	1 3 5 7 9
Targeted neuromodulation using bioelectric devices	Implantable and wearable bioelectronic devices use neuromodulation to regulate nerve signals, offering targeted treatment for inflammatory diseases and chronic conditions	Advanced material science	IOT sensor network – Mass application	1 3 5 7 9
Organ on chip disease modelling	Microfluidic chips replicate the properties of human organs, enabling real-time simulation of biological responses for drug testing, disease modeling and precision medicine	Advanced material science	Quantum computing	1 3 5 7 9
Quantum-enhanced medical diagnostics	Leverages quantum entanglement and superposition to improve sensitivity and resolution of diagnostic tools such as MRI and PET scans	Quantum computing	IOT sensor network – Mass application	1 3 5 7 9

Cluster – Electronics

Sector – Electronic system manufacturing

Use case	Potential value/benefits	Primary Frontier Technology	Supporting Frontier Technology	TRL
Electronics Systems Manufacturing				
Self-powered electronics	Devices that generate their own power using energy harvesting (solar, thermal, kinetic, RF), reducing reliance on batteries	Smart power grid	Advanced materials science	1 3 5 7 9
flexible and transparent displays	Displays that are bendable/stretchable/transparent, enabling foldable phones, wearables, and heads-up interfaces	Advanced material sciences	Human-machine interaction	1 3 5 7 9
Biodegradable electronic components	Components made from biodegradable materials that decompose safely minimizing e-waste	Advanced materials science	Circular manufacturing	1 3 5 7 9
Haptic and Sensory Feedback Systems	Interfaces that simulate touch/feedback through vibration, pressure, texture or temperature to enhance user experience	Human-machine interaction	AI/ML algorithms	1 3 5 7 9
Voice-activated and touchless interfaces	Devices that use voice recognition and gesture sensors to control electronic functions, reducing need for physical buttons or screen	Human-machine interaction	IoT sensors –Mass application	1 3 5 7 9
Electromagnetic pollution shielding devices	Consumer gadgets designed to block or reduce exposure to EMF radiation from phones, routers, or home electronics, promoting digital wellness	Smart power grid	Advanced materials science	1 3 5 7 9

Sector – Semiconductors

Use case	Potential value/benefits	Primary Frontier Technology	Supporting Frontier Technology	TRL
Semiconductors				
Advanced lithography techniques	The adoption of Extreme Ultraviolet (EUV) lithography enables finer transistor patterning, facilitating the continuation of Moore's Law by allowing more transistors per chip	Precision manufacturing	Advanced materials science	
Self-healing semiconductor materials:	Use advanced polymers or perovskites that autonomously repair micro-cracks or defects, boosting durability in space systems, automotive ECUs, and implanted devices	Advanced materials science	Iot sensors –mass application	
Terahertz (thz) semiconductor devices	Utilize InP or graphene to operate at ultra-high frequencies (0.1–10 THz), powering 6G wireless, non-invasive medical imaging, and security screening systems	High-frequency electronics	Advanced materials science	
Novel semiconductor materials	Emerging materials like SiC, GaN, and 2D materials could overcome silicon's limitations, enabling ultra-efficient power electronics, miniaturized transistors, and next-gen photovoltaics	Advanced materials science	Smart power grid	
Silicon photonics	Integrating optical components with electronic circuits on silicon substrates to facilitate faster data transmission using light signals	Advanced materials science	Precision manufacturing	
Nano-reconfigurable logic devices	Reconfigurable nanoscale hardware enabling AI, secure comms, and adaptive processing for edge, defence, and IoT applications	Quantum materials	AI/ML algorithms	

Sector – Renewable energy equipment

Use case	Potential value/benefits	Primary Frontier Technology	Supporting Frontier Technology	TRL
Renewable Energy Equipment				
Perovskite solar cells	Lightweight, flexible, and low-cost solar tech with high efficiency, enabling widespread and versatile solar adoption that can significantly lower energy costs	Advanced materials science	Smart power grid	
Floating offshore wind turbines	Deep-water wind turbines on floating platforms unlocking vast, untapped offshore wind resources	Advanced materials science	Anchoring technology	
Wave Energy Converters with AI Control	AI-optimized devices that harness ocean wave power , ideal for coastal grids, island energy systems, and offshore platforms	IoT sensors –Mass application	AI/ML algorithms	
Next-gen bifacial solar panels	Solar panels that capture sunlight on both front and rear sides, increasing total energy output when installed over reflective surfaces	Advanced materials science		
Hydrogen electrolyzers for grid-scale storage	Systems that convert excess renewable electricity into green hydrogen via water electrolysis, enabling long-term and seasonal energy storage	Green chemistry	Smart power grid	
Self-healing coatings for solar panels and blades	Nano-engineered coatings that can autonomously repair micro-cracks or surface wear on solar panels and wind turbine blades, improving longevity	Advanced materials science		

Cluster – Chemicals

Sector – Chemicals and petrochemicals

Use case	Potential value/benefits	Primary Frontier Technology	Supporting Frontier Technology	TRL
Chemicals & Petrochemicals				
Carbon-to-chemicals conversion platforms	Converts CO_2 emissions into valuable chemicals using catalytic, electrochemical, or biological methods, reducing emissions and reliance on fossil resources while promoting a circular carbon economy	Advanced materials science	Smart grid and energy storage	1 3 5 7 9
Hydrogen fuel cell & advanced cell chemistry	Investments in emerging hydrogen fuel cell technology and advanced cell chemistry enable energy-efficient production processes	Smart grid and energy storage	IOT sensor network - mass application	1 3 5 7 9
Molecular-level simulation for material design	Enables virtual testing of atomic-scale interactions, accelerating the discovery and optimization of materials like polymers and catalysts without physical experiments	Quantum computing	AI/ML algorithms	1 3 5 7 9
Plasma-assisted synthesis	Leverages highly reactive plasma environments(ionized gases) to drive chemical reactions at low temperatures, enabling solvent-free, energy-efficient production of nanomaterials, catalysts, and clean fuels	Advanced materials science		1 3 5 7 9
Quantum-accelerated catalyst design	Uses quantum simulations to model atomic interactions precisely, enabling the discovery of highly efficient catalysts for chemical reactions	Quantum computing	AI/ML algorithms	1 3 5 7 9
Smart self-assembling polymers	AI-driven development creates adaptive, self-repairing, biodiversity-safe materials	Advanced materials science	AI/ML algorithms	1 3 5 7 9

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D. Glossary of terms

Term	Definition
Advanced Biosimilars	Highly similar, clinically equivalent versions of biologic drugs that incorporate next-generation improvements in efficacy, delivery, or stability
Agentic AI	Artificial intelligence systems capable of autonomous goal setting, decision-making, and action with minimal human oversight
Autonomous Haulage System	A driverless, AI-enabled transport solution—commonly used in mining or construction—for moving heavy loads safely and efficiently with minimal human intervention
Circular Economy	An economic model focused on resource efficiency through reuse, recycling, and reduction of waste
Copilots	AI-powered assistants embedded in software tools or workflows that support human users with context-aware suggestions, insights, or task automation
Cyber Physical Systems	Integrated systems where physical processes are tightly coupled with digital control, often involving sensors, networks, and software for real-time interaction
Exoskeletons	Wearable robotic systems that augment human movement and strength, often used in manufacturing to reduce strain, and prevent injuries
Green chemistry	The design of chemical processes and products that reduce or eliminate hazardous substances, minimizing environmental and health risks
Humanoid	The remote operation of robots via wireless communication, enabling tasks in hazardous, distant, or inaccessible environments
Industrial Internet of Things (IIoT)	A network of interconnected industrial devices and sensors that collect, share, and analyze data to optimize manufacturing operations
Information and Communication Technology (ICT) Assets	Hardware and software systems used for computing, connectivity, and automation in industry
In-silico clinical trials	Computer-simulated clinical studies that use virtual patient models to test drugs or treatments without involving real human subjects

Term	Definition
Organ-on-a-chip	A micro-engineered device that simulates the structure and function of human organs, enabling realistic drug testing and disease modelling in laboratory settings
Reinforcement learning	A type of machine learning where agents learn optimal behavior through trial-and-error interactions with their environment to maximize rewards.
Self-healing elastomers	Smart polymer materials capable of autonomously repairing damage or cracks, extending product life and reducing maintenance needs
Smart textiles	Smart textiles are fabrics integrated with sensors, actuators, or conductive materials that can sense and respond to environmental stimuli such as temperature, pressure, or movement
Telerobotics	The remote operation of robots via wireless communication, enabling tasks in hazardous, distant, or inaccessible environments
Technology sandbox	A safe, controlled environment used to test, experiment with, or develop modern technologies, software, or policies without affecting real-world systems or data
Total Factor Productivity (TFP)	A measure of output growth not explained by increases in labor or capital, attributed to efficiency and technology gains

Notes

NITI Frontier Tech Hub

THE ONLY WAY TO PREDICT
THE FUTURE IS TO CREATE IT...

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