Trade, Techno-Nationalism and Export Controls: Harnessing Science and Innovation for India's Strategic Autonomy

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Knowledge as a public good, peer review of science, prominence attached to open publications, and a premium placed on professional recognition and scientific autonomy in governance have remained the hallmark of science for the last three centuries. Robert K Merton, the leading sociologist of science, wrote a classic thesis that led to what has come to be known as the most important 'paradigm' of autonomous and open academic science, encapsulated in his 'ethos of science' or normative structure of science.[1] This social contract between open science and society, which governed much of our global science system in the post-Second World War era, has undergone a major transformation since the 1990s.[2] As we transitioned to the 21st century, the emergence of globalisation has challenged the existing science–society social contract, which has prioritised the market and corporatisation of science and innovation.

The wave of globalisation reshaped this landscape in profound ways. The liberalisation of trade, the spread of multinational enterprises, and the free movement of knowledge, technologies, and talent enabled countries such as India, China, and several East Asian economies to develop strong scientific and technological capacities in various ways, transforming their industrial and innovation systems.[3] This phase of liberal, democratic and globalised science was characterised by unprecedented international collaboration, cross-border R&D partnerships, and the diffusion of advanced technologies through trade, foreign direct investment and global value chains.[4]

Yet, globalisation also had its problematic dimensions. The asymmetry in technological ownership between advanced and developing nations deepened, intellectual property regimes became increasingly restrictive, and dependence on a few technologically dominant countries persisted. Despite these challenges, the global system still allowed room for international technology transfer and capacity building, enabling emerging economies, particularly in Asia, to integrate into global innovation networks and enhance their domestic technological base.[5] This delicate balance of cooperation and competition marked the high point of global interdependence in science and technology before the recent turn toward techno-nationalism in the Trump era.[6]

Today, a new phase of techno-geopolitics is unfolding. Trump's trade policies, the resurgence of techno-nationalism and the tightening of export controls—particularly in strategic materials like rare-earth magnets—represent the three defining pillars of the emerging global technology order.[6] These measures, aimed at reshaping global supply chains and curbing the transfer of advanced technologies, are intensifying competition among major powers such as the United States and China.[7] For countries like India, the implications are profound. As global trade and technology flows become increasingly

securitised and restricted, India faces the urgent task of reducing its technological dependence in critical sectors such as semiconductors, advanced batteries, electric vehicles (EVs), and defence manufacturing. Building indigenous capacities through targeted national public and private R&D, strategic industrial policy and partnerships with trustworthy countries will be crucial.

Science and Innovation Missions

Over the past decade, India has launched nearly a dozen major science, technology, and innovation missions aimed at strengthening self-reliance in strategic sectors. In crucial areas such as Quantum Technologies, EVs, Energy, Semiconductors and Active Pharmaceutical Ingredients (APIs), the country continues to exhibit varying degrees of technological dependence on foreign sources. As already pointed out, India's technological autonomy has become indispensable in these fields in the current situation. These national missions are designed to build domestic capacities through public–private partnerships, targeted incentives and focused R&D investments. Their immediate objectives include fostering indigenous research ecosystems, promoting local manufacturing and nurturing human capital in frontier critical technologies. However, the scale of investment and implementation efficiency will determine how far India can reduce its external technological dependence in the coming decade. Given the limitations of space and time, this discussion will focus on a select few critical sectors and issues.

Semiconductors

Having missed earlier opportunities in the 1980s and 2000s, India has now recognised the urgency of developing its indigenous semiconductor capabilities. The Semiconductor Mission, launched in 2021 with an outlay of ₹76,000 crore, aims to address the country's near-total dependence on imported chips. Under this mission, private firms receive 50% co-funding support. Currently, six semiconductor units—including one fabrication plant (fab) and five ATMP/OSAT units, along with the modernisation of the Mohali laboratory—are under construction or nearing completion. Global and domestic players are joining the effort: Kaynes Semicon and Micron (USA) have established units in Sanand, Gujarat, while the two fab units at Dholera, Gujarat—India's first commercial fabrication venture—are being set up by the Tata Group in collaboration with Powerchip Semiconductor Manufacturing Corporation (PSMC), Taiwan. These fabs from Tata are expected to produce 50,000 wafers per month across 28 nm, 40 nm, 55 nm, and 90 nm nodes by early 2026, supplying chips for automotive, AI, wireless communication, and other advanced applications.[8,9]

In contrast, China operates 44 fabs with 22 more under construction, while South Korea has 21 operational units. As Ajai Chaudhury, co-founder, HCL and current head of Quantum Mission, observed 'out of 190 million mobile phones produced annually, 60% are Chinese, 20% Samsung, and 20% Apple—India still lacks an indigenous brand. We need to establish about a dozen more fabs in the coming years to drastically reduce technological dependence.[10]

The Adani Group is planning a collaboration with Israel, while the L&T Group has shown interest in a fabless chip company. Similarly, Dixon Technologies is exploring a technology partner for a display fabrication unit, with a focus on LED and OLED panels. In addition, reports indicate that around 15 semiconductor start-ups are emerging across various regions of the country, which are expected to further strengthen the sector's ecosystem.[11,12] With 97% of the initial Semiconductor Mission 1.0 (₹76,000 crore) fund already committed, the government must expedite the launch of Semiconductor Mission 2.0—with an expected budget of ₹1.76 lakh crore—to establish additional fabs. It is estimated that nearly 20% of the world's chip-design engineers are based in India, and leading global firms—including Qualcomm, Intel, NVIDIA, Broadcom and MediaTek—operate major R&D centres in the country. India must strategically leverage this strong talent pool to strengthen domestic semiconductor firms and accelerate the growth of a robust, competitive chip-design ecosystem of its own.[13] We could strengthen and expand the semiconductor design platform to higher levels with the Design Linked Incentive (DLI) scheme.

APIs in Pharma

India has the third-largest pharmaceutical industry in the world, yet it remains heavily reliant on China for critical raw materials, including key starting materials and APIs. In 2014, Ajit Doval, India's National Security Adviser, highlighted serious security concerns, noting that India's dependence on China for APIs was as high as 85%. By 2023, the country's overall import dependence remains above 70%, and for 45 critical APIs, it continues to be entirely reliant on foreign sources.[14] The country's reliance on imports is expected to persist through 2024–25.

Given India's strong scientific base and proven technological capabilities in the pharmaceutical sector, it is striking that the country remains heavily dependent on imports of critical APIs. To address this, India must accelerate indigenous API production through sustained R&D investment, process innovation, and achieving economies of scale. Under the Make in India initiative, the Department of Pharmaceuticals, in collaboration with CSIR, has identified 56 priority APIs. Three schemes, including the Production-Linked Incentive (PLI) Program for pharmaceuticals and bulk drug production, have been allocated ₹25,000 crore over a ten-year period. To effectively overcome this strategic vulnerability, the government should reassess these schemes and consider a greater infusion of funds.

Quantum Technologies

India has established four quantum hubs, focusing on computing, communication, sensing and metrology, as well as materials and devices, involving leading institutions such as the IITs, IISc, C-DOT, and private firms like HCL.[15] However, the current status reveals that India lags significantly behind global leaders. While India has made some progress in quantum publications, it remains far behind leading countries in patents and quantum processing units (QPUs).[16] Between 2019 and 2023, India accounted for just 5% of global quantum computing publications, compared to China's 23% and the USA's 22%. Between 2014 and 2025, China leads in patenting with 7,308 patents, followed by the USA (2,301), Japan (863), South Korea (623), and India (424). QPUs are a key indicator of technological maturity, with the USA leading at 58 units, followed by China with 16, France with 15, the Netherlands and Australia with 9 units each, the UK and Germany with 8 units each, and India with 2 units.

In hardware, IBM recently unveiled Condor, a 1,121-Qubit processor[17] and plans to develop a 100,000-qubit computer by 2033. Google, Amazon, Microsoft and Intel are also advancing with comparable platforms. China unveiled its 504-qubit "Tianyan" chip[18] and ez-Q Engine 2.0, reportedly capable of supporting over 1,000 qubits.[19] Fifty leading Chinese universities and companies have joined a project to explore quantum applications. Among the world's top 10 universities in quantum physics, as ranked in the Nature Index for 2024, four are Chinese, with USTC, Hefei, ranking first.[20] India's effort remains nascent: TIFR has developed a 7-qubit system, while a Bengaluru-based start-up announced 25 and 64-qubit processors, aiming to scale up to 300 qubits in the near future. In the medium term, the plan is to develop quantum computers with 50 to 1,000 Qubits within 8 years (2025-2033).

China's public investment in 2022 is 15.3 US$ billion in Quantum compared to the USA (3.7 billion) and India (1.0 billion). India entered the global quantum technology race relatively late, with the National Quantum Mission and a modest budget (INR 6,003 crore), which limits its immediate ability to compete with countries like the USA, China, and Europe, which have invested heavily in research, infrastructure, and talent development over the past decade. As a result, India faces significant gaps in technological maturity, patenting, and deployment of quantum hardware, making accelerated investment and strategic planning critical to catch up. Technological sovereignty is becoming indispensable as several countries, such as the USA, have imposed high restrictions on the export of quantum computing with more than 34 Qubits and related technologies.

Coal and Nuclear Energy

India remains heavily reliant on coal, which accounts for 48% of the country's total energy supply. Given its continuing importance, India must invest in carbon capture, utilisation and storage (CCUS) technologies

and expand the Integrated Gasification Combined Cycle (IGCC) program. The Department of Science and Technology has recently launched an R&D Roadmap for CCUS. However, since a demonstration CCUS plant can cost nearly $500 million, collaboration with major coal producers, such as those in Australia, Indonesia, and South Africa, could help develop more affordable solutions. CCUS also offers the potential for producing clean liquid hydrogen. In January 2022, the Hydrogen Energy Supply Chain (HESC) Project in Victoria, Australia, achieved a world first by demonstrating the extraction of clean liquid hydrogen from Latrobe Valley coal via carbon capture, utilisation and storage.[21] India's coal power giant, NTPC, could integrate hydrogen production into its large-scale coal gasification plans, combining energy generation with the production of cleaner liquid hydrogen fuel.[22]

In the nuclear sector, India has yet to fully realise Homi Bhabha's 1950s vision of achieving 8,000 MW of nuclear capacity. As of 2025, 24 reactors generate 7,438 MW, accounting for just 3% of the country's total electricity. To accelerate nuclear capacity growth, the government must fast-track additional Pressurised Heavy Water Reactors (PHWRs). India could also expedite its collaboration with US Company Clean Core Thorium Energy for the development of thorium as an alternative fuel in reactors. The new HALEU (high-assay low-enriched uranium) technology, which blends thorium with a more concentrated type of uranium, can be used in the existing Indian fleet of PHWRs.[23]

Given India's substantial endowment of thorium reserves, it is imperative to fast-track the commissioning of the 500 MW Prototype Fast Breeder Reactor (PFBR) at Kalpakkam, Tamil Nadu, which is expected to become operational in 2026. The successful deployment of this reactor will mark a critical milestone in India's three-stage nuclear programme and pave the way for scaling up thorium-based fuel cycles.

A rapid expansion of thorium technologies—supported by targeted public investment, innovative public–private partnerships, and collaboration with advanced nuclear research institutions—could significantly accelerate India's transition toward a more secure and self-reliant energy future. If implemented with urgency and strategic additional investments, thorium-based nuclear power has the potential to be a true game changer, reducing import dependence, enhancing baseload capacity and strengthening long-term energy security.

In 2024, plans were announced to develop 300 MW Bharat Small Modular Reactors (SMRs) under a public–private partnership model, with ₹20,000 crore allocated in 2025.[24] India already operates 84 MW SMRs in submarines, and BARC has initiated three demonstration SMRs, with capacities of 200 MW, 55 MW, and 5 MW. To strengthen energy security, India should expedite collaborative projects with Russia, Japan, and France for the development of SMR technology over the coming decade. SMRs may not compete with large-sized reactors in terms of cost per MW of production, but they will be relevant for decentralised energy production in India. Civilian nuclear technology represents a key alternative for significantly reducing India's oil imports.

Batteries in EVs

With nearly 1.75 million EVs on Indian roads, more than 85% of lithium-ion batteries—the most critical component in their manufacture—are still imported. EVs also rely on permanent magnet synchronous motors, braking systems, sensors, and power electronics, most of which are dependent on imported magnets, leaving India around 90% dependent on external suppliers and highly vulnerable technologically.

The PLI scheme has provided strong momentum to domestic lithium-ion battery manufacturing, with major firms such as the Tata Group, Exide, Amara Raja, Ola Electric, and Luminous Power Technologies establishing gigafactories. Additionally, the government's decision to reduce GST on locally produced EVs and charging stations from 12% to 5% is expected to further boost domestic production and reduce import dependence. The EV industry must urgently expand downstream activities in the mining, processing, and supply chains of critical raw materials and explore alternatives to lithium-ion batteries to enhance self-reliance. 'It takes 682 times more water to extract one tonne of lithium versus one tonne of sodium. The sodium-to-lithium ratio in the Earth's crust is 23,600 parts per million (ppm) to 20 ppm. The natural abundance of sodium results in a significantly lower extraction cost.[25,26] There are solid-state batteries, which are safer

and can have higher energy density. Other emerging technologies with potential include graphene, zinc-based batteries and hydrogen-powered cars.

The National Green Hydrogen Mission, launched in 2023, involves schemes worth INR 19744 crores until 2030.[27] India has not yet achieved its ambitious goal of producing 5 million tons of green hydrogen per year, primarily due to slow project commissioning and infrastructure issues.[28] Benchmarking against global leaders like Chinese CATL[29] and BYD, India's investment in hydrogen and EV-related activities remains dismal, underscoring the urgent need for greater public-private R&D and innovation funding to build a robust indigenous EV and clean mobility ecosystem.

Are we Investing Enough in R&D?

Funding for S&T and research-oriented higher education has been a persistent challenge for India. One key indicator of national commitment to research is GERD as a percentage of GDP, which measures the total investment—by government, industry, and academic institutions—devoted to R&D relative to the size of the economy. Despite ambitious policy initiatives and the growing importance of technology-driven development, India's GERD as a share of GDP has remained relatively stagnant over the last three decades.

Public R&D

In the 1990s, GERD accounted for approximately 0.8% of GDP, but by 2025, it had slightly receded to around 0.7%. More than 50% of GERD is allocated to strategic sectors of atomic energy, space, and defence. The rest, spread across various sectors and programs, pose constraints in realising the objectives of these programs. The comparative growth of GERD/GDP for India and China is shown in Table 1. In terms of purchasing-power parity (PPP), India's GERD in 2023 is approximately US$ 71.3 billion, whereas China's figure of GERD stands at US$ 723 billion.[30] Further, while India's total R&D spending has grown in absolute terms over the past decades, the private sector's share of GERD has remained relatively low, hovering around 35–40%, compared to more than 70% in countries like China.

Table 1: R&D Expenditure as Percentage of GDP & S&T Output: India vs China (1990–2025)

Year	India GERD/GDP %	India S&T Output*	China GERD/GDP%	China S&T Output*
1990	0.8	10113	0.5	6407
1995	0.62	10907	0.7	9624
2000	0.74	21000	0.9	22702
2005	0.81	24000	1.3	36985
2010	0.82	60555	1.7	308769
2015	0.7	80195 (2013)	2.1	351526 (2013)
2020	0.64	149213	2.4	669744
2021	0.66	-	2.5	-
2022	0.7	-	2.6	-
2023	0.7	228174	2.6	932712
2024	0.65	-	2.7	-
2025	0.7	-	2.8	-

*Based on National Science Foundation (NSF) and Web of Science Data

Private Sector R&D

Historically, one of the key reasons for India's low GERD-to-GDP ratio has been the limited contribution

of the private sector to R&D spending. Globally, industry accounts for nearly 70% of GERD in countries such as South Korea, Japan, and across the OECD. In contrast, in India, the share of private sector R&D expenditure remained stagnant at around 25–30% from the 1990s until 2015 and has only marginally increased to 35–40% in recent years. As Naushad Forbes of the Confederation of Indian Industry points out, private R&D spending in India still amounts to a mere 0.3% of GDP, compared with a global average of 1.5%. This raises an important question, as Forbes argues: if foreign multinationals can leverage India's talent pool so extensively, why have leading Indian firms such as Reliance and L&T not made comparable investments in R&D?[31] The Office of the Principal Scientific Adviser study in 2023–24 on the state of private sector R&D in India reveals that out of 1,000 listed firms reviewed, the report was able to identify only the top 20 R&D-intensive companies for 2022 and 2023. The top 20 out of 911 Indian firms accounted for 71% of the country's total R&D expenditure in 2023.[32]

Timely Intervention

The chronic underinvestment in scientific research has long been acknowledged as a structural barrier to effectively linking India's S&T policies with its broader innovation and development goals. In response, the government has introduced several major S&T and R&D funding schemes in recent years. These initiatives mark a significant shift toward mission-oriented innovation and represent early steps toward bridging India's scientific and technological gaps.

Anusandhan National Research Foundation (ANRF) was created in 2023.[33] It was charged with disbursing US$6 billion to universities and laboratories over a 5-year period, with 70% of the funding coming from non-governmental sources and industry.[34] The overall budgetary provision for ANRF is INR 1 lakh crore, equivalent to approximately 11.34 US$ billion. The government, in its 2025 budget, allocated INR 20,000 million or US$ 235 million.

Research, Development, and Innovation (RDI) Scheme came into operation in July 2025, backed by a substantial budgetary allocation of ₹1 lakh crore (approximately US$ 11.34 billion).[35,36] The RDI Scheme is designed to catalyse private sector participation in high-impact, cutting-edge research and innovation, ensuring that the commercialisation of scientific breakthroughs is closely aligned with national development priorities.[37]

Vigyan Dhara scheme came into effect in January 2025.[38] The scheme is allocated INR 14,250 million, or approximately US$ 167.64 million.

Capacity Building and Human Resource Development Scheme[39], with a total outlay of INR 22770 million, was launched recently on 24 September 2025. It is implemented by the CSIR and will cover all R&D institutions and Universities across the country.

Towards Strategic Autonomy

In this evolving environment of new techno geo-politics, India must balance openness with self-reliance to safeguard its economic and strategic autonomy. This landscape underscores the urgent need to build robust indigenous research ecosystems, secure technological sovereignty and forge balanced international partnerships that safeguard national interests while sustaining innovation. In an era where critical technologies are increasingly being weaponised, technological sovereignty is no longer optional—it has become a strategic imperative. While India has already launched several vital initiatives across key sectors, the emerging geopolitical landscape demands a significant escalation of these efforts. The time has come to deepen investments, strengthen institutions, and accelerate the push toward genuine strategic technological autonomy.

<u>*R&D and Innovation*</u>: Several of the recently launched schemes are strategically designed not to rely solely on public expenditure but to use government funding as a catalyst for mobilising large-scale private investment. For example, more than 70% of the ANRF's projected ₹1 lakh crore budget is expected to be funded by industry participation. This, however, raises a critical concern: what happens if private funding does not materialise at the scale anticipated? India has launched nearly a dozen major

science, technology, and innovation missions to strengthen self-reliance in critical technology sectors. The present Indian government—unlike any previous administration—has earmarked close to ₹4.0 lakh crore for various critical technology missions over five years through public–private partnership models. However, benchmarking against leading innovation economies such as the OECD countries, Japan, South Korea, and China shows that India must sustain and significantly expand public investments in science, technology, and higher education research to remain competitive and realise its long-term technological ambitions. To make tangible progress in strategic missions and frontier technologies, the government should raise public R&D spending to at least 1.2% of GDP and simultaneously encourage the private sector to double its share from the current 0.3% to 0.6% of GDP per annum within three years, with a 10% increase per annum thereafter.

Public Procurement: In several missions aimed at building indigenous capacities in emerging technologies, the missing link is the creation of strong domestic demand. Taking a cue from China, the government could adopt strategic public procurement as a key instrument across sectors such as semiconductors, EVs, advanced batteries, and quantum technologies. Addressing this gap would not only support domestic industry in scaling up but also strengthen its ability to compete globally.

Research Intensity in Universities: The data on research output from universities indicate that this sector contributes approximately 70% of total publications but accounts for less than 7% of Gross Expenditure on Research and Development (GERD) in 2020. The low level of R&D effort and research intensity in Indian universities is closely associated with a relative stagnation or decline in the number of postgraduates and PhDs produced. The new capacity-building scheme in universities will address this problem, but not the research intensity of universities. Marginalisation of research funding and low intensity of research are not unrelated to the low level of innovation and university-industry relationships in universities.

'Triple Helix' Linkages: Systematic policy support and targeted funding for a select group of universities, such as IISc and the IITs, can play a pivotal role in fostering Triple Helix partnerships between science agencies, industry, and academia within the national innovation system. The IIT Madras model—with its innovation parks, spin-off firms, venture capital, technology transfer offices, incubators, and other supporting mechanisms—illustrates how focused efforts in just 10% of universities have become indispensable steps toward achieving strategic autonomy.

Start-ups and Venture Capital: Over the past five years, state intervention in the development of start-ups and venture capital in India has injected significant dynamism into the national innovation system. The country now needs to intensify its efforts in both sectors to sustain and accelerate this momentum in the years to come.

Achieving these targets would not only reinforce India's scientific and technological foundations but also bolster its economic resilience, enhance competitiveness, and secure greater strategic autonomy in an era marked by rapid global technological change and geopolitical uncertainty. By systematically strengthening research, innovation, and industry linkages, India can position itself to respond effectively to emerging challenges and seize new opportunities on the global stage.

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