INDIA'S TECH STRATEGY: AN INTRODUCTORY OVERVIEW

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International cooperation and competition over critical technologies has assumed greater prominence in recent years, driven by emerging geopolitical frictions and rapid technological innovation.[1] In this context, India, the world's most populous nation and fifth-largest economy, has adopted a strategic approach to critical and emerging technologies. With the objectives of ensuring economic and national security, spurring economic growth and employment, and increasing its global competitiveness, India has taken several crucial steps. India has increased public investments and subsidies for manufacturing, it is seeking to improve its research and development (R&D) and education ecosystems, it has outlined new liberalized policies and regulations, and it is prioritizing technology agreements and standards in its diplomacy.

India's technology priorities include:

- Traditional strategic technologies (defense, nuclear, space, and dual-use technologies)
- Critical digital technologies (such as semiconductors, electronics, telecommunications, and digital public infrastructure)
- Emerging technologies (such as artificial intelligence (AI)/machine learning, quantum computing, and drones)
- Clean/green technologies and biotechnologies.

Taken together, these sectors present opportunities for deeper cooperation between India and its partners, including those in North America, Europe, Asia, and the Middle East. At the same time, India's strategic technology ambitions face several challenges in an increasingly competitive global landscape. To fully participate, India will have to continue to enhance its private industrial capacity; create the framework to compete more effectively for international investment, technology, and talent; and guard against supply chain vulnerabilities and economic security concerns.

Figure 1: Summary of India's Technology Strategy

Objectives	Priorities	Processes
Economic and national security	**Strategic Technologies:** defense, nuclear, space, dual-use technologies	Investment and technology absorption in manufacturing
Economic growth and employment	**Critical Digital Technologies:** semiconductors, electronics, telecommunications, and digital public infrastructure	Policy and regulatory clarity and simplification
National competitiveness	**Emerging Technologies:** artificial intelligence, quantum computing, automation/drones, etc.	Investments in R&D, advanced manufacturing, and human resource ecosystem
Strategic international partnerships	**Clean/Green Energy and Biotechnologies**	Bilateral and multilateral diplomatic cooperation on standards, investment, training, exports, and supply chains

[1] Jake Sullivan, "Remarks by National Security Advisor Jake Sullivan on Renewing American Economic Leadership at the Brookings Institution," The White House, April 27, 2023, https://www.whitehouse.gov/briefing-room/speeches-remarks/2023/04/27/remarks-by-national-security-advisor-jake-sullivan-on-renewing-american-economic-leadership-at-the-brookings-institution/; "Economic Security Promotion Council," Prime Minister's Office of Japan, November 19, 2021, https://japan.kantei.go.jp/101_kishida/actions/202111/_00034.html; "Commission proposes new initiatives to strengthen economic security," European Commission, January 24, 2024, https://ec.europa.eu/commission/presscorner/detail/en/IP_24_363.

1. INDIA'S RENEWED QUEST

Domestic investments in strategic technologies have historically had transformative impacts on India's national security, economic prosperity, and global competitiveness. From the engineering innovations of M. Visvesvaraya to applied statistics at the Indian Statistical Institute (ISI) under P.C. Mahalanobis, and the development of a space program under Vikram Sarabhai, the Indian government has long aimed to develop a strong indigenous technology base that could contribute to India's economic development. The public sector was critical to this ambition, driving research and development as well as the production of key technologies. The Indian private sector has played an important role in many cases as well. For example, the earliest origins of India's nuclear program under Homi Bhabha can be traced to work under the Tata Institute of Fundamental Research (TIFR).[2]

This focus on home grown research and development held even in the 1960s, a time when India was much more resource constrained. The high-profile interventions until the 1960s by the Nobel Prize-winning Patrick Blackett, at the invitation of Prime Minister Jawaharlal Nehru, was intended to identify ways to improve India's scientific and technological capabilities.[3] In due course, strategic technologies including atomic energy, space, and electronics were identified as critical to both civilian and military applications and India achieved some success in the development of rockets for the space program as well as missiles. India's technology aspirations continued into the 1980s when India sought to upgrade its defense and supercomputing capabilities.[4]

Despite some successes, India did not fully develop an innovation ecosystem that effectively combined efforts in education and training, research and development, technology scale up, and advanced manufacturing. Significantly, India's efforts were not bolstered by a robust high-technology manufacturing base. While India's nuclear and space programs made considerable progress after the 1980s, domestic electronics manufacturing did not take off. India's early efforts at manufacturing semiconductors were met with setbacks first in the 1980s and later in the mid-2000s.[5] R&D – including in critical defense industries – was often hobbled by a growing dependence on license production of imported technology without necessarily securing the accompanying technological transfers, a challenge that persists in some areas to this day. Even in successful cases of technology transfer, economies of scale and lower costs could not always be leveraged. Furthermore, India's institutions of higher education lost some of their global competitiveness for research even as they continued to produce large numbers of trained engineers. In total, 770,000 Indian students studied abroad in 2022, with particularly high outward mi-

[2] Indira Chowdhury, *Growing the Tree of Science: Homi Bhabha and the Tata Institute of Fundamental Research*, (Oxford: Oxford University Press, 2016).
[3] Robert S. Anderson, "Patrick Blackett in India: Military Consultant and Scientific Intervenor, 1947-1972 Part One," *Notes and Records of the Royal Society of London*, Vol. 53, No. 2 (May 1999), 253-273.
[4] Arun Sukumar, *Midnight's Machines*, (New Delhi: Viking, 2019).
[5] Andreas Kuehn and Trisha Ray, "Cutting-Edge Technologies in Developing Economies: The Case of India's Semiconductor Industry," in Francis Fukuyama and Marietje Schaake eds., *Digital Technologies in Emerging Countries* (Palo Alto: Stanford Cyber Policy Center, 2023).

gration by leading engineering students. India still spends only 0.7 percent of its gross domestic product (GDP) on R&D, as opposed to a global average of 1.8 percent.[6]

India's renewed focus on critical and emerging technologies has come about due to two main factors. The first involves the centrality of recent technological breakthroughs, their widespread commercial applications, and their growing importance to India's economic growth, social mobility, and national security. The lower cost and higher power of computing and better telecommunications networks, which have enabled transformations in digital security, cloud computing, artificial intelligence, and automation, can serve as a platform for another generation of economic growth and new military applications.

Technological disruptions are not restricted to the digital and computational realms. The lower cost of solar and wind energy production has made renewable energy sources competitive with fossil fuels. This is facilitating efforts to reduce greenhouse gas emissions and enhance energy security, while also increasing demand for improved battery technology, smart grids, and critical minerals. Breakthroughs in biotechnology are also underway, improving lives and productivity. While India's earlier approach to technology was primarily defensive, given international export controls, it is now increasingly seen as an opportunity to extend India's outreach.

The second reason for India's renewed emphasis on strategic technologies concerns shifting geopolitical realities. In particular, the military threat from China, evidenced in recent tensions along the India-China border has led India and other countries to diversify global supply chains. Concerns extend to China's efforts to dominate the development and production of semiconductors, solar components, batteries, and other advanced technologies, including through massive intellectual property theft and state subsidized production. In addition to the potential national and economic security concerns, there are macroeconomic implications: concerns about persistent trade deficits have contributed to the incentives to increase Indian exports. India now has a major opening to become a leading player in developing and manufacturing strategic technologies as firms seek alternatives. At the same time, the Covid-19 pandemic highlighted India's exposure to global supply chain disruptions, creating an impetus for the indigenous manufacturing of critical electronics (such as smartphones and laptops), defense supplies, and healthcare equipment.

Today, these technological and geopolitical dynamics are driving India's quest to create a robust domestic industrial base in important strategic technologies. Growing India's innovation system is now recognized as the most effective means to accelerate its economic development, increase its technological competitiveness, and ensure greater economic and national security.

2. NEW APPROACHES TO TECHNOLOGY POLICY

Unlike some countries, India does not have a single dedicated national-level technology policy. In practice, technology and innovation policies are variously designed and implemented by an assortment of government agencies. The Ministry of Defence, the Department of Atomic Energy, and the Department of Space are responsible for mature strategic technologies including nuclear energy, space policy, and weapons sys-

[6] Virginia Gewin, "Big Ideas: India's Drive to Stem the Brain Drain," *Nature*, December 13, 2023, https://www.nature.com/articles/d41586-023-03915-5.

tems. The Ministry of Electronics and Information Technology (MeitY) is leading efforts to develop India's semiconductors and electronics ecosystems. On emerging technologies, AI regulations involve the Principal Scientific Advisor to the Prime Minister, while the Ministry of Science and Technology leads on quantum and biotech policy. The Ministry of New and Renewable Energy (MNRE), Ministry of Mines (on critical minerals), and the Ministry of Power handle breakthroughs in clean and green technologies. These agencies often coordinate with the Ministries of Finance, Commerce and Industry, Education, and Environment, as necessary, while the Prime Minister's Office and Cabinet Secretariat, National Security Council Secretariat, and the Ministry of External Affairs often play critical coordinating and international roles. Despite the numerous agencies involved, the overall contours of India's approach to attracting and manufacturing strategic technologies is clearly discernible from a combination of domestic policies and international agreements and actions.

Financial Incentives and Subsidies: Production-Linked Incentives (PLI) are at the cornerstone of India's attempts to attract companies interested in alternatives to Chinese supply chains. These funds – as much of 50 percent of set-up costs for new investments in designated technology areas – are provided as reimbursements should manufacturers meet and scale up production targets.[7] The PLI scheme has so far directed unprecedented levels of public investment, approximately $26 billion, towards the manufacture of critical components, including for electronics, green technologies, biopharmaceuticals, and telecommunications.[8] Beyond PLI, specific national policies – such as the India Semiconductor Mission ($9-10 billion), the National Green Hydrogen Mission ($2 billion), and National AI Mission ($1.2 billion) – offer additional financial opportunities, although these funds are provided upfront.[9] For semiconductors, the government also developed a Scheme for Promotion of Manufacturing of Electronic Components and Semiconductors (SPECS) until 2024 to offer financial incentives on capital expenditure for fabs; advanced assembly, testing, and packaging; sub-assembly; and materials.[10]

Regulatory Certainty and Clarity: Additionally, the Indian government has begun to take steps to create regulatory certainty and clarity with respect to manufacturing, digital policies, drones, and space. These steps include regularly updating and streamlining the Defence Acquisition Procedure, a National Policy for AI in 2018, the Indian Space Policy 2023, Drone Rules 2021, and a National Geospatial Policy 2022.[11] Certain dedicated nodal agencies – such as the Indian Semiconductor Mission (in MeitY), National Quantum Mission (through the Department of Science and Technology, DST), and

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[7] "Guidelines for Modified Scheme for setting up of Semiconductor Fabs in India," Ministry of Electronics and Information Technology, May 29, 2023, https://d2p5j06zete1i7.cloudfront.net/Cms/2023/May/31/1685527229_Guidelines_for_Modified_Scheme_for_setting_up_of_Semiconductor_Fabs_in_India.pdf.

[8] Ministry of Commerce, "Production Linked Incentive Schemes for 14 key sectors aim to enhance India's manufacturing capabilities and exports," Press Information Bureau, August 2, 2023, Press Information Bureau, https://pib.gov.in/PressReleasePage.aspx?PRID=1945155.

[9] "National Green Hydrogen Mission," Ministry of New and Renewable Energy, Government of India, accessed on April 1, 2024, https://mnre.gov.in/national-green-hydrogen-mission/; Ministry of Electronics and IT, "India Semiconductor Mission," Press Information Bureau, December 21, 2022, https://pib.gov.in/PressReleasePage.aspx?PRID=1808676.

[10] Ministry of Electronics and IT, "Promotion of SPECS," Press Information Bureau, December 7, 2023, pib.gov.in/PressReleaseIframePage.aspx?PRID=1881407.

[11] "Defence Acquisition Procedure 2020," Ministry of Defence, Government of India, 2020, https://www.mod.gov.in/sites/default/files/DAP2030new.pdf; "National Strategy for Artificial Intelligence," NITI Aayog, June 2018, https://www.niti.gov.in/sites/default/files/2023-03/National-Strategy-for-Artificial-Intelligence.pdf; "Indian Space Policy 2023," Indian Space Research Organisation, 2023, https://www.isro.gov.in/media_isro/pdf/IndianSpacePolicy2023.pdf; Ministry of Civil Aviation, "The Drone Rules 2021," Press Information Bureau, January 28, 2022, https://static.pib.gov.in/WriteReadData/specificdocs/documents/2022/jan/doc202212810701.pdf.

National Green Hydrogen Mission (through MNRE) – have been established with mandates to create policy frameworks, initiate projects involving the private sector, offer single-window clearances, and support skill development. These agencies have also facilitated concerted efforts to get faster permits and clearances, streamline tax and customs procedures, and otherwise reduce costs to doing business.

Upgrading the Research and Development Ecosystem: Beyond financial incentives, India is also attempting to improve its research and development (R&D) ecosystem. India benefits from a technology ecosystem that is already valued at $227 billion and its universities produce the second largest number of STEM graduates in the world, the best of whom are highly sought after by other countries.[12] At the same time, while India produces a high volume of research papers, their citation impact is low and concentrated in only a handful of major institutions.[13] The replacement of the Science and Engineering Research Board (SERB) with a National Research Foundation boasting a $6 billion budget and clearer strategic mandate is intended to streamline grantmaking and support R&D.[14] Interest-free loans have also been proposed to incentivize private sector R&D.[15] This has been supplemented by the creation of sector-specific institutions, such as AI Centres of Excellence and proposed International Centres for Transformational AI.[16] Attempts are also underway to increase the number of patent officers to reduce processing times for applications and attract foreign universities to improve technology talent.

International Outreach: To complement domestic policies, India's international efforts include policies to shape global technology standards, incentivize foreign investment, facilitate technology transfers, and coordinate with other nations on developing resilient supply chains. These include attempts at entering into bilateral agreements to source investments and technology, secure supply chains, and develop standards. Multilaterally, India is increasingly involved in multilateral and other bodies to shape standards and norms, such as the Global Partnership on AI (GPAI). India is also interested in securing critical minerals and is starting to look at markets for technology products, both the export of manufactured goods and various technology services.[17] Some of the formal government-to-government mechanisms for accomplishing these objectives include the initiative for Critical and Emerging Technologies (iCET) with the United States, the Trade and Technology Council (TTC) with the European Union, and a supply chain agreement within the Indo-Pacific Economic Framework (IPEF).[18] India

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[12] Brendan Oliss, Cole McFaul, and Jaret C. Riddick, "The Global Distribution of STEM Graduates: Which Countries Lead the Way?" Center for Security and Emerging Technology, November 27, 2023; Ministry of Electronics and Information Technology, "IT/Software Sector," accessed on April 13, 2024, https://www.meity.gov.in/content/software-and-services-sector.

[13] "National Research Foundation: Detailed Project Report," The Prime Minister's Science, Technology and Innovation Advisory Council, December 2019, 5. Press Information Bureau, December 21, 2022, https://pib.gov.in/PressReleasePage.aspx?PRID=1808676.

[14] Sahana Ghosh, "Indian lawmakers greenlight National Research Foundation," *Nature*, August 16, 2023, https://www.nature.com/articles/d44151-023-00111-2.

[15] "Interim Budget 2024-2025: Speech of Nirmala Sitaraman, Minister of Finance," Ministry of Finance, February 1, 2024, 17, doc202421304701.pdf (pib.gov.in).

[16] "National Strategy for Artificial Intelligence."

[17] "The Minerals Security Partnership Continues to Expand with Norway, Italy, and India," U.S. Department of State, September 16, 2023, https://www.state.gov/the-minerals-security-partnership-continues-to-expand-with-norway-italy-and-india/.

[18] "Fact Sheet: United States and India Elevate Strategic Partnership with the initiative on Critical and Emerging Technology (iCET)," White House, January 31, 2023, https://www.whitehouse.gov/briefing-room/statements-releases/2023/01/31/fact-sheet-united-states-and-india-elevate-strategic-partnership-with-the-initiative-on-critical-and-emerging-technology-icet/; "India – EU Joint Statement 1st Meeting of the Trade and Technology Council," Ministry of External Affairs, Government of India, May 16, 2023, https://www.mea.gov.in/bilateral-documents.htm?dtl/36553/India__EU_Joint_Statement_1st_Meeting_of_the_Trade_and_Technology_Council; "Indo-Pacific Economic Framework for Prosperity Agreement Relating to Supply Chain Resilience," Office of Treaty Affairs, U.S. Department of State, November 14, 2023, https://www.state.gov/ipef-supply_chain-agreement.

has also entered into bilateral agreements to provide goods, services, and technological know-how, including with developing countries for digital public infrastructure.

3. INDIA'S TECHNOLOGY PRIORITIES

Financial incentives, policies and regulations, R&D and skill development, and international cooperation are reflected differently in the areas India has identified as technology priorities. While these sectors will naturally expand or evolve based on technological developments and shifting demand, a few trends are readily observable.

Defense, Space, Nuclear, and Dual-Use Technologies

Traditional strategic technologies, such as defense, nuclear, and space technologies, have had important military and dual-use applications almost since India's independence in 1947. These are, in many cases, more mature and critical for national defense, while also sometimes serving important commercial applications. Defense technologies have been at the vanguard of India's technology diplomacy. In the 1980s, India sought to bolster its military capabilities and access higher-end defense technologies. Following the India-U.S. Civil Nuclear Agreement, the Defense Trade and Technology Initiative (DTTI) was established to identify technologies for joint development with the United States, an effort that has not made much progress due to divergent priorities, mismatched capabilities, and onerous export control policies.[19]

Instead, these developments have been superseded by both private efforts at defense production in India and high-profile attempts that could potentially accelerate the Make in India initiative in defense. Make in India seeks to promote India's aerospace and defense industry by actively involving the public and private sector to increase export potential.[20] To accomplish this, India has attempted to facilitate clearances, including through continuously streamlining the Defence Acquisition Procedure so that it levels the playing field by reducing distinctions between public and private sectors while continuing to prioritize indigenization.[21] Some of the products of these efforts include joint ventures on artillery and missiles.[22] Efforts at standardizing and coordinating foreign and defense policies has resulted in a series of Indian "2+2" dialogues with other countries, including the United States, Japan, and Australia. Other major deals involve the production and maintenance of GE F-414 jet engines and co-manufacturing of MQ-9 drones.[23] Recent defense deals include tech transfers between private companies in the United States and India, facilitated by the two governments. India and the United States have also established INDUS-X, a government-supported initiative directed at facilitating early-stage cooperation between Indian and U.S. defense and space companies, including start-ups.[24]

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[19] "India-U.S. Defense Technology and Trade Initiative - Initial Guide for Industry," U.S. Department of Defense, July 14, 2020, https://www.acq.osd.mil/ic/docs/dtti/DTTI-Initial-Guidance-for-Industry-July2020.pdf.
[20] "Make in India Defense," accessed on April 13, 2024, https://www.makeinindiadefence.gov.in/pages/about-us.[15] "Interim Budget 2024-2025: Speech of Nirmala Sitaraman, Minister of Finance," Ministry of Finance, February 1, 2024, 17, doc202421304701.pdf (pib.gov.in).
[21] "Defence Acquisition Procedure 2020."
[22] Defence Research and Development Organization, "155 mm x 52 Cal Advanced Towed Artillery Gun System (ATAGS)," *Technology Focus*, Vol. 31, No. 4 (August 2023), 5.
[23] "Joint Statement from the United States and India," The White House, June 22, 2023, https://www.whitehouse.gov/briefing-room/statements-releases/2023/06/22/joint-statement-from-the-united-states-and-india.
[24] "Launch of the India-U.S. Acceleration Ecosystem (INDUS-X)," U.S. Department of Defense, June 21, 2023, https://www.defense.gov/News/Releases/Release/Article/3682879/fact-sheet-india-us-defense-acceleration-ecosystem-indus-x/.

In terms of nuclear technologies, bilateral civilian cooperation has stalled since the India-U.S. Civil Nuclear Agreement resulted in a waiver for India by the Nuclear Suppliers Group (NSG). India subsequently signed bilateral civil nuclear agreements with Japan, Russia, the United Kingdom, and France, among others.[25] But actual investments in India's civilian nuclear sector has been inhibited by India's nuclear liability law, high capital costs, popular pushback against nuclear energy, and the financial woes of major private nuclear companies. Attempts are now being made to take advantage of more recent technological advancements in nuclear energy, including possibly small modular reactors, subject to clarifications by the Indian government on nuclear liability.[26]

By contrast, India's space efforts have seen some significant changes in recent years. India's space program, led by the Indian Space Research Organisation, was driven originally by civilian and development applications. In recent years, the military aspects have grown, exemplified by India's anti-satellite test in 2019.[27] Perhaps more significantly, this sector has seen a growth in private industry since 2020. A result of this has been the Indian Space Policy 2023 which is intended to provide a regulatory framework, limit India's space agency to research and development, and designate an Indian National Space Promotion and Authorization Center (In-SPACE) for enhancing private space activities.[28] Although many space policies are not yet binding and lack regulatory clarity, recent years have seen a proliferation of private space companies, with about 190 new space tech start-ups.[29] The country's space economy is expected to grow from $8.4 billion in 2023 to $44 billion in 2033.[30]

International space cooperation, traditionally involving Russia, has extended to the Quad, involving India, Australia, the United States, and Japan. In 2023, a Quad Space Working Group was established to enhance situational awareness and provide earth observational data to countries in the Indo-Pacific.[31] Bilaterally, the U.S.-India Civil Space Joint Working Group (CSJWG) has enabled projects such as the NASA-ISRO Synthetic Aperture Satellite (NISAR), planned human spaceflight cooperation, and commercial partnerships between Indian and American firms.[32] India joining the

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[25] "Question 2814: Foreign Countries Having Nuclear Pact with India," Ministry of External Affairs, August 11, 2016, https://www.mea.gov.in/rajya-sabha.htm?dtl/27300/QUESTION_NO2812_FOREIGN_COUNTRIES_HAVING_NUCLEAR_PACT_WITH_INDIA.

[26] Ashley J. Tellis, "Completing the U.S.-India Civil Nuclear Agreement: Fulfilling the Promises of a Summer Long Past," Carnegie Endowment for International Peace, November 27, 2023, https://carnegieendowment.org/2023/11/27/completing-u.s.-india-civil-nuclear-agreement-fulfilling-promises-of-summer-long-past-pub-91043; Rituraj Baruah, "Govt plans sops for making small modular N-reactors," *Mint*, November 3, 2023, https://www.livemint.com/news/india/govt-plans-sops-for-making-small-modular-nreactors-11699032050249.html.

[27] "Frequently Asked Questions on Mission Shakti, India's Anti-Satellite Missile test conducted on 27 March, 2019," Ministry of External Affairs, March 27, 2019, https://www.mea.gov.in/press-releases.htm?dtl/31179/Frequently_Asked_Questions_on_Mission_Shakti_Indias_AntiSatellite_Missile_test_conducted_on_27_March_2019.

[28] P.V. Manoranjan Rao, ed., From Fishing Hamlet to Red Planet: India's Space Journey, (New Delhi: HarperCollins India, 2015); "Frequently Asked Questions on Mission Shakti, India's Anti-Satellite Missile test conducted on 27 March, 2019," Ministry of External Affairs, March 27, 2019, https://www.mea.gov.in/press-releases.htm?dtl/31179/Frequently_Asked_Questions_on_Mission_Shakti_Indias_AntiSatellite_Missile_test_conducted_on_27_March_2019; "Indian Space Policy 2023," https://www.isro.gov.in/media_isro/pdf/IndianSpacePolicy2023.pdf.

[29] Ministry of Science and Technology, "India has witnessed investment of over Rs.1,000 crore in Space Startups in last nine months," Press Information Bureau, December 17, 2023, https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1987449.

[30] Jagmeet Singh, "India Spurs Space Sector Investment with Raised Limits on Foreign Funding," *TechCrunch*, February 21, 2024, https://techcrunch.com/2024/02/21/india-space-foreign-direct-investment/.

[31] "Quad Leaders' Joint Statement," The White House, May 20, 2023, https://www.whitehouse.gov/briefing-room/statements-releases/2023/05/20/quad-leaders-joint-statement/.

[32] "U.S.-India Civil Space Joint Working Group Advances Bilateral Space Collaboration," U.S. Department of State, January 31, 2023, https://www.state.gov/u-s-india-civil-space-joint-working-group-advances-bilateral-space-collaboration/.

Artemis Accords has also opened up scope for considerable collaboration, including with the United States and its partners.[33]

The Digital Backbone: DPI, Semiconductors, Electronics, and Telecommunications

The digital revolution in India since the turn of the millennium has had transformative effects on the Indian economy and society. Unique biometric identification (Aadhaar), smartphones, and links to bank accounts (through a program called Jan Dhan Yojana) have made critical technologies vital to day-to-day life for over a billion people in India. India's embrace of digital public infrastructure (DPI) has transformed into a significant domestic policy priority with an increasing international character. DPI is essentially a framework for building digital systems that prioritize openness, scalability, and responsible governance to improve the delivery of public services without sacrificing innovation or private competition.[34] India's digital identity platform, its digital payments ecosystem (UPI), and the vaccine delivery system are some examples of how India has used DPI to modernize the provision of public goods. Notably, India is attempting to internationalize its approach to DPI. At the multilateral level, DPI was made a cornerstone of India's G20 presidency and advocacy at international development institutions.[35] At the same time, India has also been willing to directly advise and provide its DPI technology, especially to developing countries, and has signed several Memorandums of Understanding (MoUs) from Africa to the Caribbean with this objective in mind.[36] At the same time, while mobile payments, e-commerce, and digital welfare schemes have been transformative, they remain vulnerable to malicious foreign actors. The importance of cybersecurity in India's economic transformation has increased.

Another essential priority has involved the domestic assembly of electronic items, including mobile handsets. Electronics manufacturing has proved an early test case for India's PLI scheme and has begun to be reflected in the arrival of major manufacturers and assembling companies such as Apple and Foxconn and growing exports. Recent developments, not least supply chain shortages resulting from the Covid-19 pandemic and security concerns as relations with China have deteriorated, have provoked greater emphasis in India on indigenizing and securing its telecommunications infrastructure.

Semiconductor supply chain disruptions have multiple known vulnerabilities, and India's response has been manifested in the India Semiconductor Mission (ISM).[37] The ISM facilitates the development of a manufacturing ecosystem, including assembly, testing, and packaging units as well as fabs, along with associated physical infrastructure such as land, energy, water, and transportation. It is also meant to increase and improve the talent pipeline, enhance the R&D base, and improve regulatory and customs procedures to make Indian turnaround times more competitive. These steps have quickly

[33] "Quad Leaders' Joint Statement," The White House, May 20, 2023; "Indian, US space officials discuss human space exploration," "Joint Statement from the United States and India."
[34] Keyzom Ngodup Massally, Rudra Chaudhuri, and Rahul Matthan, "What is DPI? The Need for a Principle-Based Approach," Carnegie India, May 15, 2023, https://carnegieindia.org/2023/05/15/what-is-dpi-approach-pub-89721.
[35] Rudra Chaudhuri, "Decoding the G20 Consensus on Digital Public Infrastructure: A Key Outcome of India's Presidency," Carnegie India, September 1, 2023, https://carnegieindia.org/2023/09/01/decoding-g20-consensus-on-digital-public-infrastructure-key-outcome-of-india-s-presidency-pub-90467.
[36] Ministry of Electronics and IT, "India signs MoU with Colombia on sharing India's open-sourced DPIs," Press Information Bureau, February 16, 2024, https://pib.gov.in/PressReleasePage.aspx?PRID=2006634; Ministry of Electronics and IT, "India Signs MoU with Trinidad and Tobago on Sharing India Stack," Press Information Bureau, August 17, 2023, https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1949830.
[37] "India Semiconductor Mission," Ministry of Electronics and Information Technology, accessed on April 1, 2024, https://www.ism.gov.in/.

resulted in construction initiated for semiconductor fabs with a promised capability of 28 nanometers and upward, as well as several testing and packaging facilities, including in Gujarat and Assam.[38] Electrical, water, and transportation infrastructure, essential for semiconductor production, is already being built to scale, and is set to increase in capacity by several-fold over the next decade.[39] The additional investment incentives offered by several of India's states, such as Gujarat's Semiconductor Policy 2022-2027 are notable here as well.[40]

Semiconductors have also emerged as a key focus of India's technology diplomacy, including an MoU with the United States in 2023 and a feasibility review as part of the initiative on Critical and Emerging Technologies (iCET).[41] Similar semiconductor diplomacy has been a feature of India's engagement with Japan and the European Union, resulting in the signing of MoUs.[42] Some results with the United States have included Applied Material's establishment of a semiconductor center and Lam Research's announcement that it would train 60,000 Indians over the next decade.[43] Additional efforts with Israeli, Taiwanese, and European companies are already resulting in investment, training, and R&D.[44]

Another critical element of India's digital backbone is its growing telecommunications network. While India was behind the curve in the development and spread of its 2G, 3G, and 4G networks, it has a wide and growing 5G network today. Indian telecom companies are actively investing in foreign markets including that of the United States. Simultaneously, U.S. companies are conducting trials for an Open Radio Access Network (O-RAN) system in India.[45] For context, O-RAN networks have an open and interoperable architecture that enables disaggregated radio networks and non-proprietary components through industry standards. Cooperation on 6G has commenced with an MoU between America's Next G Alliance and India's Bharat 6G Alliance, to make India a "global supplier of IP, products and solutions of affordable 5G and 6G and other future telecom solutions."[46] The telecommunications sector has also been a beneficiary of about $1.5 billion in production-linked incentives. 5G, 6G, and ORAN network cooperation has also featured prominently in the Quad's CET Work-

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[38] Prime Minister's Office, "PM to participate in 'India's Techade: Chips for Viksit Bharat' and lay the foundation stone of three semiconductor facilities worth about Rs 1.25 lakh crore on 13th March," Press Information Bureau, March 12, 2024, https://pib.gov.in/PressReleasePage.aspx?PRID=2013949.

[39] Jerry Chen, "Modi Inaugurates India's First Commercial Semiconductor Fab in 30 Years," *DigiTimes Asia*, March 14, 2024, https://www.digitimes.com/news/a20240314VL201/india-commercial-fab-psmc-tata-group.html.

[40] Department of Science and Technology, "Gujarat Semiconductor Policy 2022-2027," Government of Gujarat, July 27, 2022, https://dst.gujarat.gov.in/Portal/Document/1_486_Gujarat_Semiconductor_Policy_2022_27_Brochure_2707.pdf.

[41] "FACT SHEET: United States and India Elevate Strategic Partnership with the initiative on Critical and Emerging Technology (iCET)," White House, January 31, 2023.

[42] Ministry of Electronics and IT, "Cabinet approves Memorandum of Cooperation between India and Japan on Japan-India Semiconductor Supply Chain Partnership," Press Information Bureau. October 25, 2023, https://pib.gov.in/PressReleasePage.aspx?PRID=1970782; "Commission and India sign agreement on semiconductors," European Commission, November 24, 2023, https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4380.

[43] "Joint Statement from the United States and India," The White House, June 22, 2023, https://www.whitehouse.gov/briefing-room/statements-releases/2023/06/22/joint-statement-from-the-united-states-and-india/.

[44] "Joint Statement from the United States and India," https://www.whitehouse.gov/briefing-room/statements-releases/2023/06/22/joint-statement-from-the-united-states-and-india/; Chen, "Modi Inaugurates India's First Commercial Semiconductor Fab in 30 Years,"; "Israel's Tower Proposes $8 bln Chip Plant in India," *Reuters*, February 11, 2024, https://www.reuters.com/technology/israels-tower-proposes-8-bln-chip-plant-india-report-2024-02-11; Cheng Ting-Fan, "Europe's Top Chipmaker Infineon Ramps Up Hiring in India and Vietnam," *Nikkei Asia*, January 26, 2024, https://asia.nikkei.com/Business/Tech/Semiconductors/Europe-s-top-chipmaker-Infineon-ramps-up-hiring-in-India-and-Vietnam2.

[45] "Joint Statement from the United States and India," The White House, June 22, 2023, https://www.whitehouse.gov/briefing-room/statements-releases/2023/06/22/joint-statement-from-the-united-states-and-india/.

[46] "Aims and Objectives," Bharat 6G Alliance, accessed on April 1, 2024, https://bharat6galliance.com/OBJECTIVES.php.

ing Group, including cooperation "on technical standards; 5G; horizon scanning; and technology supply chains."[47]

Early-Stage Technologies: AI, Quantum, and Automation

While the criticality of strategic and digital technologies is beyond doubt, a host of newly emerging technologies are also gaining in importance, with differing levels of commercial application. In these areas, India wants to play an important role in developing global standards. These areas include artificial intelligence (AI), quantum computing, and automation (including robotics and drones).

In 2018, India developed a National Strategy for AI, a policy document to "maximise the late-movers advantage."[48] Acknowledging that India was behind the curve on homegrown AI solutions, it is focused on leap frogging to meet India's needs while building foundational R&D capabilities.[49] In line with the 2018 National AI Strategy, the Indian government allocated $120 million toward creating three AI Centers of Excellence.[50] These centers will promote joint public and private AI research targeting health, agriculture and sustainable cities.[51] India has followed this initiative with the ambitious IndiaAI Mission under MeitY that directs $1.24 billion toward developing the national AI innovation ecosystem.[52] The initiative has an integrated approach to developing AI in India, combining investments in computational resources, entrepreneurship, academic research and technical skill development.[53] Diplomatically, India has stressed the creation of adequate safeguards, trustworthy and reliable standards in AI, and access to compute, including through the New Delhi Declaration of the Global Partnership on AI (GPAI).[54] Commercial applications in automation and drones has also witnessed remarkable progress. India's drone policy saw a liberalization in August 2021 to encourage R&D, testing, manufacturing, and operations in drones.[55]

Quantum technologies and their many potential applications remain in the early stages of development, and progress has been relatively limited. India's National Quantum Mission was established to nurture and scale up R&D. It has received approximately $740 million in funds for four thematic hubs (T-hubs) at major educational and research institutes for applied research in quantum computing, communications, and sensing capabilities.[56] Quantum technologies are not the only areas receiving such specialized attention: the Department of Science and Technology has three similar missions for interdisciplinary cyber-physical systems, supercomputing, and climate

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[47] "Fact Sheet: Quad Leaders' Summit," The White House, September 24, 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/24/fact-sheet-quad-leaders-summit/.
[48] "National Strategy for Artificial Intelligence."
[49] Ibid.
[50] Ministry of Finance, "Mission Karamyogi Providing Learning Opportunities for Government Employees to Upgrade their Skills and Facilitate People-Centric Approach: Finance Minister," Press Information Bureau, February 1, 2023, https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1895302.
[51] Ministry of Education and IIT Jammu, "AI Centres of Excellence (CoE) Make AI in India and Make AI work for India: Call for Proposal," November 18, 2023, https://iitjammu.ac.in/aicpmu/flyer.pdf.
[52] Ministry of Electronics and IT, "Cabinet Approves Over Rs 10,300 Crore for IndiaAI Mission, will Empower AI Startups and Expand Compute Infrastructure Access", Press Information Bureau, March 7, 2023, https://pib.gov.in/PressReleaseIframePage.aspx?PRID=2012375.
[53] Ibid.
[54] "GPAI Ministerial Declaration 2023: 5th Session of the Ministerial Council," Global Partnership on Artificial Intelligence, December 13, 2023, https://gpai.ai/2023-GPAI-Ministerial-Declaration.pdf.
[55] "Drone Rules."
[56] National Quantum Mission, Department of Science and Technology, accessed on April 1, 2024, https://dst.gov.in/national-quantum-mission-nqm.

change.[57] Internationally, India and the United States have established a Quantum Coordination Mechanism to facilitate links between academic institutions, industry, and government agencies in quantum technologies.[58] India is also part of the Quantum Entanglement Exchange – a U.S.-led initiative to exchange researchers.[59]

Clean/Green Energy, Critical Minerals, and Biotechnology

Although of high importance, developments in clean and green technologies and biotechnologies are often treated separately from other technology policy matters. Clean and green technologies are tied into India's larger energy transition and climate commitments. Meanwhile, international cooperation on biotechnology, despite Indian strengths, has been complicated by very different approaches to intellectual property and innovation. For India, health access as a developing country relies on low-cost pharmaceutical manufacturing of proven drugs. This contrasts with priorities in the developed world on cutting-edge innovation in novel and synthetic biotechnologies.

Green and clean energy technologies have received the most government funding through the PLI scheme after semiconductors. Much of this funding is directed toward two flagship initiatives: the National Green Hydrogen Mission and efforts to increase production of high-efficiency solar photovoltaic (PV) modules. The Green Hydrogen Mission intends to make India a global hub for the production, use, and export of green hydrogen and its derivatives.[60] The PLI scheme for solar PV modules is similarly designed to build a manufacturing ecosystem to reduce import dependence.[61] India has also benefited from foreign partnerships in its attempts to strengthen its renewable energy resilience: the United States' Development Finance Corporation, for example, has financed 11 gigawatts of cell and module manufacturing in India.[62] On electric vehicles, tax incentives are being altered to attract domestic and foreign manufacturers.[63] One area that has received somewhat less attention is bioenergy, where India's National Bioenergy Program provide financial assistance to help generate biogas, bioCNG, and energy from waste and residue.[64]

For a number of critical technologies, including battery storage but also electronics and semiconductors, the issue of securing critical mineral supply chains has risen in importance. In 2023, India's Ministry of Mines identified a list of 30 critical minerals and families after reviewing other countries' policies, evaluating India's prospects and vulnerabilities, and inter-ministerial consultations.[65] It followed up with revised poli-

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[57] Ministry of Science and Technology, "Cabinet approves National Mission on Interdisciplinary Cyber-Physical Systems," Press Information Bureau, December 6, 2023; "National Supercomputing Mission," Department of Science and Technology, accessed on April 13, 2024, https://dst.gov.in/national-super-computing-mission; "Climate Change Programme," Department of Science and Technology, accessed on April 13, 2024, https://dst.gov.in/climate-change-programme.

[58] "Joint Statement from the United States and India," The White House, June 22, 2023.

[59] "Fact Sheet: United States and India Elevate Strategic Partnership with the initiative on Critical and Emerging Technology (iCET)," The White House, January 31, 2023.

[60] "National Green Hydrogen Mission."

[61] Ministry of New and Renewable Energy, Production Linked Incentive (PLI) Scheme: National Programme on High Efficiency Solar PV Modules, accessed: April 13, 2024, https://mnre.gov.in/production-linked-incentive-pli/.

[62] "Building solar capacity in India," U.S. International Development Finance Corporation, accessed on April 13, 2024, https://www.dfc.gov/investment-story/building-solar-capacity-india; "DFC and Vikram Solar Sign Ceremonial Retainer Letter for ~ $200 Million Funding at COP28," U.S. International Development Finance Corporation, December 15, 2023, https://www.dfc.gov/media/press-releases/dfc-and-vikram-solar-sign-ceremonial-retainer-letter-200-million-funding-cop28.

[63] Ministry of Commerce and Industry, "Government approves E- Vehicle policy to promote India as a manufacturing destination for EVs," Press Information Bureau, March 15, 2024, https://pib.gov.in/PressReleasePage.aspx?PRID=2014874.

[64] Ministry of New and Renewable Energy, "Ministry of New and Renewable Energy initiates National Bio Energy Programme to utilize surplus biomass for power generation," Press Information Bureau, December 20, 2023, https://pib.gov.in/PressReleasePage.aspx?PRID=1885073.

cies for exploration and mining rights for most of these minerals, as well as parameters to determine costs. With few exceptions, such as silicon and chromium, India remains very import dependent on the bulk of critical minerals. This means that securing mineral supply chains – including at the upstream mining and processing stages – with international partners will be vital in the years to come.[66] India's joining the Mineral Security Partnership represents just one effort at coordinating with partners in this domain.[67]

Biopharmaceuticals have also received some state subsidies, with almost $2 billion going toward pharmaceutical manufacturing and smaller amounts toward medical technologies.[68] India's strengths in generic pharmaceutical manufacturing were tapped in belated efforts to ramp up vaccine production during the Covid-19 pandemic. While international collaboration has now shifted to broader health and drug-related cooperation, strategic efforts in biotechnology cooperation face challenges, including questions of intellectual property and securing active pharmaceutical ingredients.

4. CONCLUSION: POLICY CHALLENGES

Although India's technology strategy has assumed some obvious contours and momentum, Indian policymakers are conscious of several challenges they will face in the years ahead. One of these is that the Indian public sector has an inconsistent record in absorbing and mastering critical technologies by creating an ecosystem that both contributes to and is bolstered by private institutions (telecommunications being an important exception). In many areas, including defense, space, semiconductors, and telecommunications, the government is now making conscious efforts at encouraging private sector involvement and animating start-ups. A continued focus on Atmanirbhar Bharat ("self-reliant India") while leveling the playing field between public and private players in bidding, contracting, and regulations will improve the domestic competitive environment and help ensure delivery.

Second, while the ease of doing business in India has gradually improved, India is now competing with other international players in terms of exports, costs, technology, and talent. Like India, the United States and Europe are offering generous domestic subsidies and are similarly concerned about technology sovereignty. At the same time, India is often seeking to compete in different market segments, which in turn opens some room for some collaboration on investment, technology, talent, and supply chain resilience. Thus, in many areas, India is linking up with the United States, Europe, Japan, South Korea, Taiwan, Australia, and other advanced economies as key innovation partners. In addition to the attraction of increased resilience, costs, and trust, India may consider linking investment and technology from external partners with labor mobility provisions that facilitate access to Indian human resources, a key Indian advantage in global competition.

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[66] James Bowen, "Driving Critical Mineral Partnerships: The Emerging India-Australia Opportunity," Perth U.S.-Asia Centre, October 2023, https://perthusasia.edu.au/research-insights/publications/driving-critical-minerals-partnerships-the-emerging-india-australia-opportunity/.

[67] "The Minerals Security Partnership Continues to Expand with Norway, Italy, and India," U.S. Department of State, September 16, 2023.

[68] "Schemes for Pharmaceuticals Manufacturing," Invest India, accessed on April 14, 2024, https://www.investindia.gov.in/schemes-for-pharmaceuticals-manufacturing.

Despite the opportunities for international collaboration on technology, there remain challenges. Crucially, sunk costs, pre-existing supply chains, prior technological and human resource advantages, and resource disparities vis-à-vis China will have to be navigated. In other instances, India will find itself competing for investment with mid-sized emerging markets, such as Vietnam, Malaysia, Thailand, Indonesia, the Philippines, Mexico, and Morocco. India's R&D ecosystem, infrastructure, ease of doing business, subsidies, workforce, and market access will be benchmarked not against an India of the past, but against current competitors. This will require India to take further steps to improve infrastructure and education, leverage clusters and scale, increase export market potential (including through trade and supply chain arrangements), and continue to reduce frictions for domestic and international corporations.

Finally, India's technology ambitions will face vulnerabilities, whether disruptions to supply chains upstream or manipulation by malign state and non-state actors. This will require taking a variety of steps, from hardening software and hardware against attempts at interference to working to strengthen India's technological resilience. A variety of necessary policies might encompass securing critical minerals at the mining, processing, and manufacturing stages, as well as ensuring the free flow of commerce for exports. Building on its recent strides, India's strategic quest for technology will necessitate dedicated attention and resources for decades to come.

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