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Assessing the Global and Local Landscape of 'Critical Technologies'

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Takshashila Internal Conference Compendium 2024-01
Version 1.0, January 2024

This document is a compendium of four Working Papers presented at the January 2024 Internal Conference organized by the Takshashila Institution on the theme, 'Critical Technologies'. The papers featured in this document cover four key aspects – a framework to identify and define critical technologies, an assessment of critical technology supply chains, policy approaches of various global actors towards such technologies, and India's policy approach in specific.

Recommended Citation:
Shambhavi Naik, Amit Kumar, Anushka Saxena, and Saurabh Todi, "Assessing the Global and Local Landscape of 'Critical Technologies'," Takshashila Internal Conference Compendium Document No. 2024-01, January 2024, The Takshashila Institution.

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Executive Note

Sarthak Pradhan

The term "critical technology" has gained prominence in the current geopolitical landscape. Various nations have developed criteria for what qualifies as critical technology. However, these criteria are vague, and do not inform on further policy steps. Consequently, policy responses vary.

In a pursuit to understand the current global and local landscape of critical technologies, the Takshashila Institution organised a conference on 17th January 2024. The conference explored questions around defining critical technology, its use in global public policy, its relevance to India and a potential way forward for India. This document is a compendium of the four working papers presented at the conference.

In the first paper, Shambhavi Naik examines the evolution of the term "critical" in public policy. She provides a framework for identifying critical technologies and driving further public policy actions. A more precise definition of critical technology would ensure targeted support for deserving sectors and prevent the dispersion of resources across numerous sectors.

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Amit Kumar's case study on Solar Photovoltaics (PV) delineates the factors contributing to China's dominance in Solar PV manufacturing. The study presents insights with potential applicability for other nation-states aspiring to gain control over a critical technology or its supply chain.

In her paper, Anushka Saxena does a multi-country assessment of critical technology definitions and the corresponding policy measures. The policy measures range from incentivising domestic players to become global leaders, fostering robust R&D ecosystems, and forming like-minded alliances to imposing sanctions and export restrictions. Though India has policies for sectors that should be deemed critical, it lacks a comprehensive critical technology policy.

In the concluding paper, Saurabh Todi addresses this question and reflects on the principles that should guide India's critical technology policy. The paper suggests that India's approach must be based on the current developmental stage of the technology in question and India's relationship with the current technology leader.

We welcome comments to build on and add to the ideas in this document. If you have any feedback, please get in touch with us at research@takshashila.org.in.

What is Critical Technology?

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Executive Summary

In the past few years, several countries have announced lists of technologies they deem critical for their national interests. These lists are a public signal of the priorities of the respective national governments and will shape further governmental action. Technologies deemed critical include artificial intelligence (AI), quantum, biotechnologies, and others. The criteria for identifying technologies as "critical" range from national security and economic prosperity to social cohesion. Yet, as more of such lists become publicly known, there is little clarity on what exactly is a critical technology and what governmental action it should elicit.

This paper proposes a framework to identify critical technologies and drive further public policy actions.

Introduction

In 2020, the US released an initial list of Critical and Emerging Technologies (CET) via the National Strategy for CETs. The goals of this list were to promote the national security base and protect the US' technology advantage. In 2021, the US White House released an Interim National Security Strategic Guidance, which defined three national security objectives: protect the security of the American people, expand economic prosperity and opportunity, and realise and defend democratic values. This revised prioritisation of objectives resulted in an expansion in the list of CETs that now included supercomputing, gas turbine engine technologies, nuclear energy, artificial intelligence (AI), financial technologies, biotechnology, etc.

Similarly, the UK's Science and Technology Superpower Agenda recognises science and technology as a major driver of prosperity and power in the country. It also highlights a perceived responsibility in delivering benefits of science to the global society. The UK identifies AI, engineering biology, future telecommunications, semiconductors and quantum technologies as critical for the UK.

In 2023, the EU commission recommended 10 technologies — advanced semiconductors, AI, quantum, biotechnologies, advanced connectivity, navigation and digital technologies, advanced sensing technologies, space and propulsion technologies, energy technologies, robotics and autonomous systems, and advanced materials, manufacturing and recycling technologies — as critical technologies for the EU countries to develop risk assessments. In a further advisory, the EU commission identified four of these technologies — semiconductors, AI, quantum and biotechnologies — as immediate risk areas.

Australia imagines critical technologies to balance three aspects of national interest — economic prosperity, national security and social cohesion. The technology fields include advanced manufacturing and materials, AI, advanced information and communication, quantum, autonomous systems, robotics, positioning, timing and sensing, biotechnologies, and clean energy generation and storage.

Japan defines critical technology as "important technologies in which Japan should maintain superiority and remove vulnerabilities in order to ensure Japan's security and realise the sound development of the Japanese economy. In October 2022, the Japanese government identified 20 technologies as critical fields: biotechnology; medical and public health technology; artificial intelligence and machine learning; advanced computing; microprocessor and semiconductor technology; data science, analysis, storage and management; advanced engineering and manufacturing technology; robotics; quantum information science; advanced surveillance, positioning and sensing technology; neurocomputing and brain interface technology; advanced energy and energy storage technology; advanced information, communication and networking technology; cybersecurity; space technology, marine technology; transport technology; hypersonics; chemical, biological, radiation and nuclear technology; and advanced materials science.

There is an underlying theme of identifying technologies of potential economic and technological advantage as critical. Most country-wise lists share technologies such as AI, biotechnology, quantum and semiconductors. Other sources such as the Australian Strategic Policy Institute (ASPI)'s tracker on critical technologies and a Brookings report on country views on critical technologies in the Indo-Pacific region (Table 1) also highlight similar technologies.

TABLE 1

Countries views on what are critical technologies

Technologies	Australia	Cambodia	Indonesia	Malaysia	Philippines	Singapore	Vietnam
Artificial Intelligence/ Machine Learning	x	x	x	x	x	x	x
Internet of Things (IoT)/Smart Grid	x	x	x	x	x	x	x
Quantum Computing	x	x	x	x	x	x	x
Blockchain	x	x	x	x	x	x	x
Cybersecurity	x	x	x	x	x	x	x
Cloud Computing			x	x	x	x	x
5G/Internet Connectivity	x	x	x	x	x		
Big Data	x	x			x	x	
Smart Cities				x	x	x	
Encryption			x	x		x	
Autonomous Vehicles	x				x		
Space Tech/Rocket Launcher/Smart Spaces	x		x				

Table 1: Country views on what are critical technologies (Table from '<u>A Critical Technology Standards Metric</u>'")

While there seems to be a consensus on what technologies should be included as critical technologies, there is no clear policy understanding of what constitutes a critical technology. More important, what policy actions should follow the identification of a critical technology.

This paper explores the evolution of the word 'critical' in public policy and posits that traditional strongholds of innovation such as the US or EU may be using this term to signal domestic priorities in the face of rising powers of innovation in developing countries. The paper then recommends that India's criteria for identifying a technology as critical needs to be more stringent and should include specific policy actions.

Evolution of the term 'critical' in public policy

The word 'critical' is often used in public policy in the context of minerals and other raw materials. In 1939, the US Congress passed the Strategic and Critical Minerals Act in response to an observed deficiency in natural resources of critical and strategic materials. The foreign dependency on materials was a specific observation made during the preceding war period, and the term "critical material" stemmed from the urgency of securing supplies in the face of the looming Second World War. The policy approach was determined to "decrease and prevent wherever possible a dangerous and costly dependence on foreign nations for supplies of these materials at times of national emergency."

The Act led to clear policy actions — either identification of alternative sources of minerals or stockpiling for use in a time of crisis. The term "critical minerals" is widely used today to refer to irreplaceable materials such as copper, lithium, and rare earths which are part of important components of technologies that fuel energy and electronic supplies.

The term "critical" has also been used in documents from defence departments in the context of military technologies that are crucial for national security. In this case as well, there is a clear deficiency of technology input that can lead to a defined problem, i.e., the inability to participate effectively in war and threatening national security. As with critical minerals, there are definite policy actions that can be done to alleviate the deficiency — such as investment in research on such technologies or acquisition of companies that own such technologies.

The purpose of creating a list of critical technologies is to guide government action — either through funding or regulations. These actions are broad. For example, making an investment in biotechnology can include a variety of mechanisms and topics, and therefore requires further data on market failures and existing measures to taking an informed policy action. Moreover, emphasis on these technologies can be made without explicitly calling them critical. Making such lists publicly available is a signal to other countries of domestic priorities and likely reflects an internal prioritisation of policy in response to increased international competition.

Term	Deficiency	Problem	Policy Action
Critical mineral	Minerals for equipment in war effort	Inefficient war effort	Stockpile or find alternative supplies
Critical mineral	Minerals needed for important technologies like clean energy or computing	Impact on lifestyle, and future-readiness	Stockpile, find alternative supplies, set up international partnerships
Critical defense technologies	Critical technologies for defense	Impact on national security	Research investment, technology acquisition
Critical technology	Unclear what is deficient, particularly when it is an emerging technology.	Unclear what would be the exact impact or crisis that the lack of technology would lead to	Risk assessments, investment, protectionism

Table 2: Summary of comparisons of the term critical in public policy contexts

While it may not be necessary for countries to signal their domestic priorities on an international platform, a framework to identify critical technologies may be useful in guiding national policy. The next section provides a framework for identifying critical technologies.

Framework for Critical Technology

In a 1994 paper, Bimber and Popper explored the use of critical technology as an organising principle for public policy. They recognised the lack of a definition of critical technology as a potential policy problem and suggested that any definition has to be policy-relevant, discriminating, and reproducible. They analysed four features that may be used as characterising properties of a critical technology — that is state-of-the-art, is necessary but not sufficient for national self-sufficiency, is a rate-determining factor for specific applications and is generic and pre-competitive. The paper concluded that only the last two features may be relevant as criteria for identifying critical technologies.

In this framework, a critical technology is a nascent technology, whose imagined benefits may be varied and may provide certain technological or economic advantage. An important facet of this perceived advantage is the possibility to patent and sequester technological progress and leverage technological supremacy to facilitate and consolidate global power.

The move from using critical to a physical material that is excludable to technology, which is neither pre-defined nor has to be excludable by nature, is likely an indicator of countries trying to maintain their competitive edge as technology becomes diffuse and widespread.

While creating generic lists and performing risks assessments and identifying broad investment areas may be of use to developed countries, developing countries with fewer resources for scientific development like India need more actionable policy recommendations.

The term critical indicates a threat to routine operations if the critical component is missing. The government identifying a technology as critical demands follow-up public policy action to build domestic competency. Thus, this paper proposes that a technology should meet three criteria to be deemed "critical":

1. **It should fill a gap or solve a problem with net benefit over existing solutions**

The technology should be able to solve a problem or provide a hitherto unseen advantage at costs proportionate to the conferred advantage. Costs in this case include both monetary costs for research and deployment, but also unintended consequences or risks associated with using emerging, untested technologies. Thus, there should be a clear articulation of the deficiency the new technology addresses.

2. The absence of the technology should threaten national security

A characteristic of criticality has to be that a crisis or problem situation would ensue if the critical technology were not appropriated. As seen in previous uses of the word “critical” the technology should be central to some form of domestic security. In contrast to previous uses, which have been primarily applied in the application of military and defense security, the scope of security has now expanded to account for current geopolitical challenges. For critical technologies, security may include:

A. National military security: Includes both international and domestic security

B. Health security: Includes nutritional security, sanitation, disease prevention and treatment, pandemic preparedness, climate change mitigation

C. Energy security: Includes securing supplies for India’s energy needs

D. Data security: Includes technology for the protection of personal data including personal identifiers, financial data, and health data.

E. Economic security

A critical technology has to feed into the mitigation of issues related to these security areas.

3. A critical technology requires governmental action in case of market failure

The identification of a technology as "critical" by the government requires the government to act on its development. Government can take several actions including risk assessments, investment in research, or acquisition of technology. However, the government should prioritise actions in areas of market failure, instead of spreading its resources across areas where the private sector or civil society can lead. Thus, government action should be driven by the nature of the market failure. For example, the private sector might not be willing to invest in research of an emerging technology with a high chance of failure. However, if such a technology is essential for India's security, the government should take necessary actions. These actions could include investment in research or collaboration with countries where such technologies are being developed.

This three-point framework will help prioritise technologies for the Indian government to focus resources on. Below are a few examples of technologies listed as critical, tested using this framework.

1. Gene drives for malaria alleviation

Gene drives is an emerging technology that modifies mosquitoes to not carry the malaria-causing plasmodium. This technology has been assessed to be important to health security by preventing vector-borne diseases. However, existing technologies such as fumigation, bed nets, and process changes to respond to cases of disease have been shown to eradicate the disease in Sri Lanka, Uzbekistan, and China. On the other hand, a risk assessment of gene drives demonstrates there are various potential unintended consequences. Hence, the cost of substitution of existing solutions with gene drives is high. Hence gene drive for malaria alleviation is not a critical technology for India.

2. Web conferencing

Web conferencing is a communications tool that is central to various aspects of national security. For example, web conferencing has been extensively used for patient-doctor consultations during and post-COVID, connecting patients even from remote areas to specialist doctors. The absence of these tools could impact health outcomes for these patients. However, web conferencing is available from several private players and there is no further need for policy action from the Government of India to appropriate web conferencing tools. With no clear market failure, web conferencing is not a critical technology for India.

3. Nuclear energy

Nuclear energy is a technology for clean energy that contributes to India's goals for climate change action. As a source of clean energy, it is not a direct comparator to coal. The high costs of setting up and running nuclear power plants have created barriers for private industry players. Thus, this technology is critical to India's future energy needs, and its delivery has seen market failures. This makes nuclear energy a critical technology requiring governmental interventions.

Conclusion

Creating lists of critical technologies is a good academic exercise to understand domestic priorities. However, a loosely defined critical technology list would lead to the distribution of resources across too many sectors, with each sector receiving marginal attention. It is therefore crucial that developing countries do not simply jump onto the bandwagon of creating such lists, but instead develop a framework for identifying and acting on critical technologies.

Critical Technology Supply Chains: a Case Study of Solar Photovoltaics (PVs)

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Introduction

Technology has always remained central to economic progress and sustainability. Of late, geopolitics has further amplified the salience of technology for nation-states, so much so that it has become integral to driving and anchoring geopolitical contestation among major powers in the last decade. As great power rivalry intensifies, ownership and trade of technology have become increasingly securitised with countries adopting several pathways to ensure either continued dominance or sustainability by mitigating dependencies and vulnerabilities.

However, not all technologies have garnered equal attention from these countries. Rather a subset of these, referred to by varying names — critical technologies, core technologies, high-technologies, among others — have hogged much of the limelight. It is because of their nature of application, whether existing, futuristic, or perceived, to national security and economy that a few among the larger pool of technologies have received much greater focus.

Although defining critical technologies may prove to be an arduous task, a broad consensus over a list of critical technologies is easier to reach. The ASPI critical tech tracker serves as a useful source that lists over 65 technologies it deems critical. These technologies are broadly classified under sub-heads ranging from AI, computation, biotechnology, space, and defence among many others.

One such important head is technologies underpinning clean energy. Clean energy technologies are critical to the survival and sustainability of the planet and mitigating climate change. The commitment to the idea of energy transition — from non-renewables to renewables, even as deadlines to achieve them might differ, is another reason that makes these technologies critical to human progress and its future. Thirdly, solar PVs and EV batteries are extremely employment-intensive industries adding to their criticality.

A relatively higher economic cost of switching to clean and renewable energy and the constant evolution of technology for better yield and efficiency are other factors that contribute to their criticality. The geopolitics has however ensured that countries that dominate these technologies (especially in the supply chain) have strategic leverage over their strategic competitors and rivals. Consequently, a battle is being fought among leading powers to control the technology and its supply chain.

This paper focuses on Photovoltaic (PV) cells within the larger pool of clean energy and attempts to map its supply chain and the extent of domination of the leading countries within each segment of the supply chain. The paper also offers plausible reasons behind the dominance of the leading countries.

Photovoltaic (PV) Cells Manufacturing

The PV manufacturing supply chain entails five broad stages or segments:

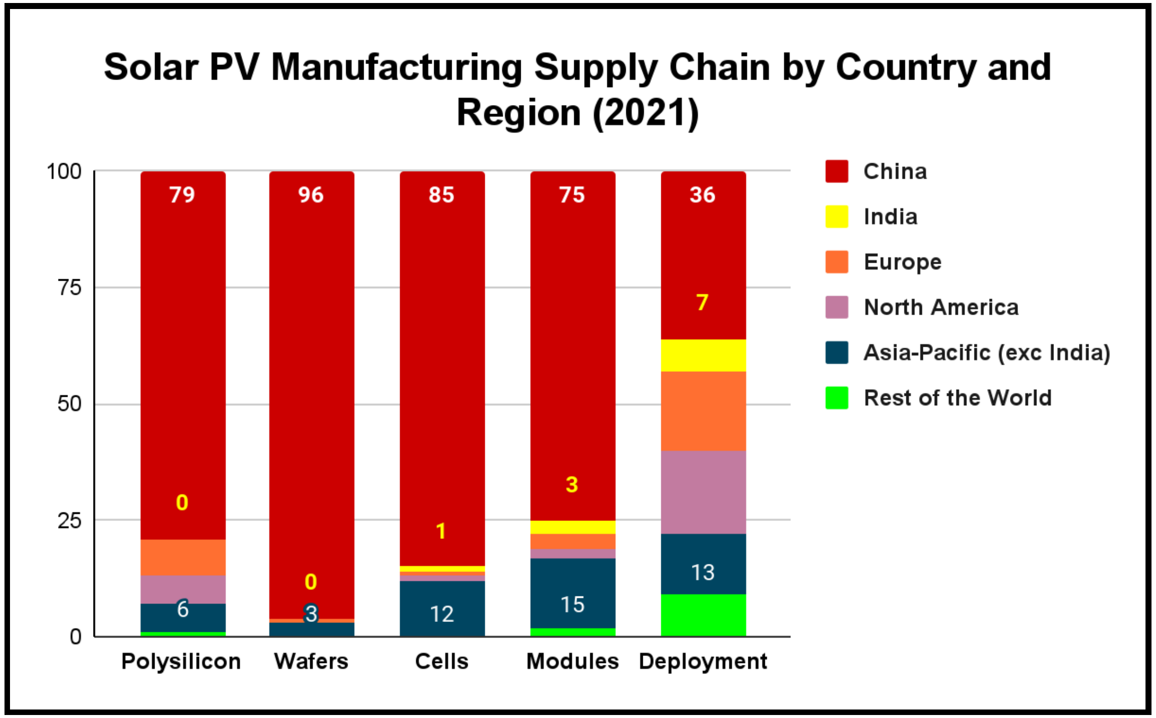
Stages	Key Processes	Description
Solar Grade Polysilicon	Silicon Purification	Silica quartz is used to produce metallurgical grade silicon (MG-Si) through carbon reduction which is then purified to attain Solar Grade silicon (SG-Si).
Ingot Pulling	Crystallite Ingot Growing Material Property Analysis Ingot Cutting	SG-Si is crystallised into ingots and doped with gallium (p-type) or phosphate (n-type) to cast massive monocrystalline silicon ingots (>300 kg each).
Wafer Slicing	Wiring; Pre-washing; Wafer Separation; Main Washing	Ingots are cropped, then sawed into wafers of 160-

	Wafer Inspection and Sorting	180 µm with diamond wire.
Cell Manufacturing	Wet Station; Diffusion; Chemical Vapour Deposition (CVD/sputtering); Screen Printing; Baking; Cell Transfer	The wafers are treated through chemical processes to obtain photovoltaic cells
Module Assembling	Cell Wiring (string); Layup (module assembly); Laminating and Sealing; Curing; Frame and Terminal Assembly; Module Transfer	The cells are laminated and connected to a multi-cell string. Several multi-cell strings are encapsulated, i.e. assembled with a sheet of glass, two foils of EVA resin, and a backsheet to make a module that is consequently framed and equipped with a junction box to form a solar PV module

Source: IEA, Becquerel Institute

China's dominance in the Solar PV Supply Chain by Sector

China has an oversized and overriding presence in each of the segments of the Solar PV manufacturing supply chain. The very first step entails the production of metallurgical-grade silicon – the raw material for solar PVs, of which 71% of the global production occurred in China in 2021. Russia, the US, Brazil, and Norway are the other major producers, each representing below 10% of the total production.



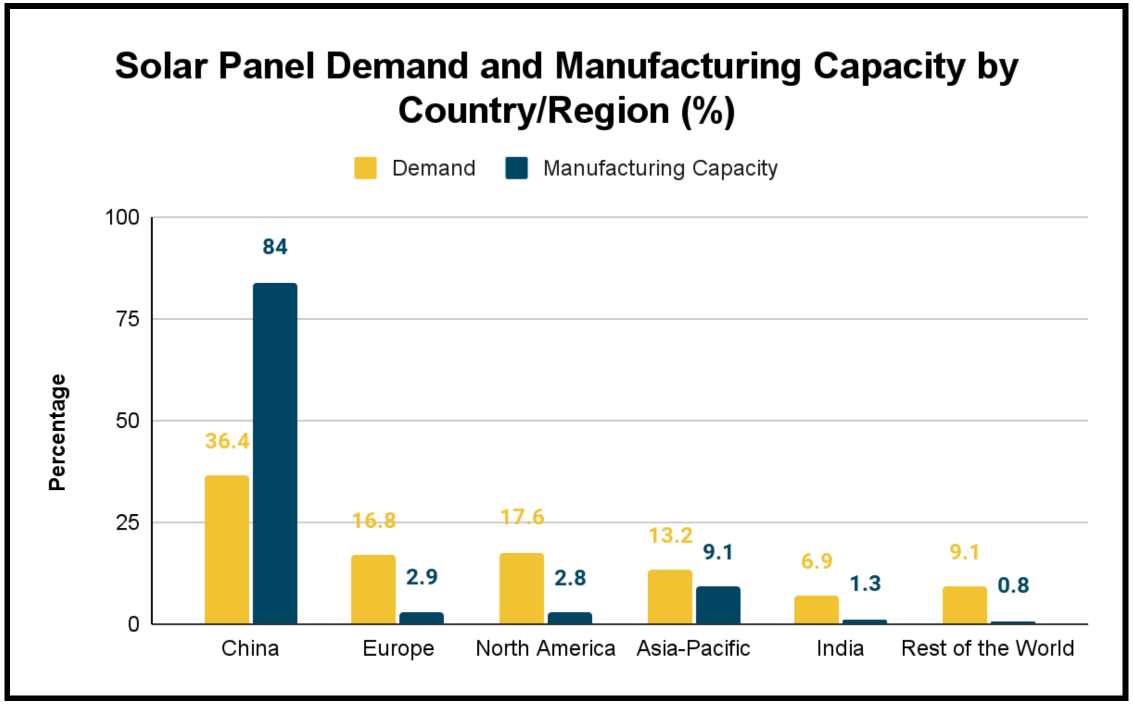
Source: IEA, "Special Report on Solar PV Supply Chain," 2022

According to estimates by the Becquerel Institute's report on *Building Resilient Global Solar PV Supply Chains (April 2023),* **polysilicon** production surged from 31 GW in 2012 to 224 GW in 2021. Of this, China accounted for 79% of the global production. The report informs that by 2021, Korean and Japanese production had almost vanished while European and North American production had stagnated.

The second segment comprises **wafer production**, which is almost exclusively located in China. Other Asian countries and Norway account for the remaining 2%. China's share in this segment has increased from 70% in 2012 to 98% in 2022.

In the next segment which constitutes **cell production,** China represents 86% of the total (estimated at 580 GW in 2022) production capacity while the rest of the world, mostly in the rest of Asia, accounts for the remaining 14%.

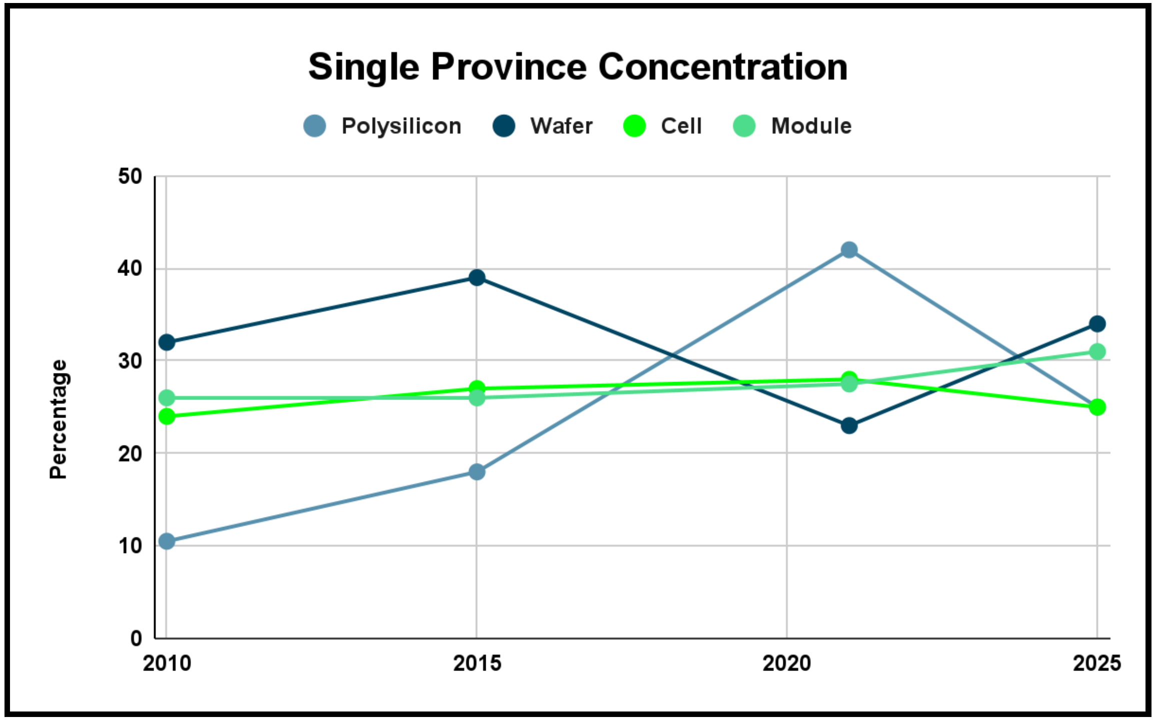
Module-manufacturing capacity is the most distributed segment of the solar PV manufacturing supply chain where China's share in the global total falls to 75% (2021). The Becquerel report, however, puts China's share close to ~80 in 2022. The graphic below shows the distribution of global demand and supply (manufacturing capacity) by country and region.



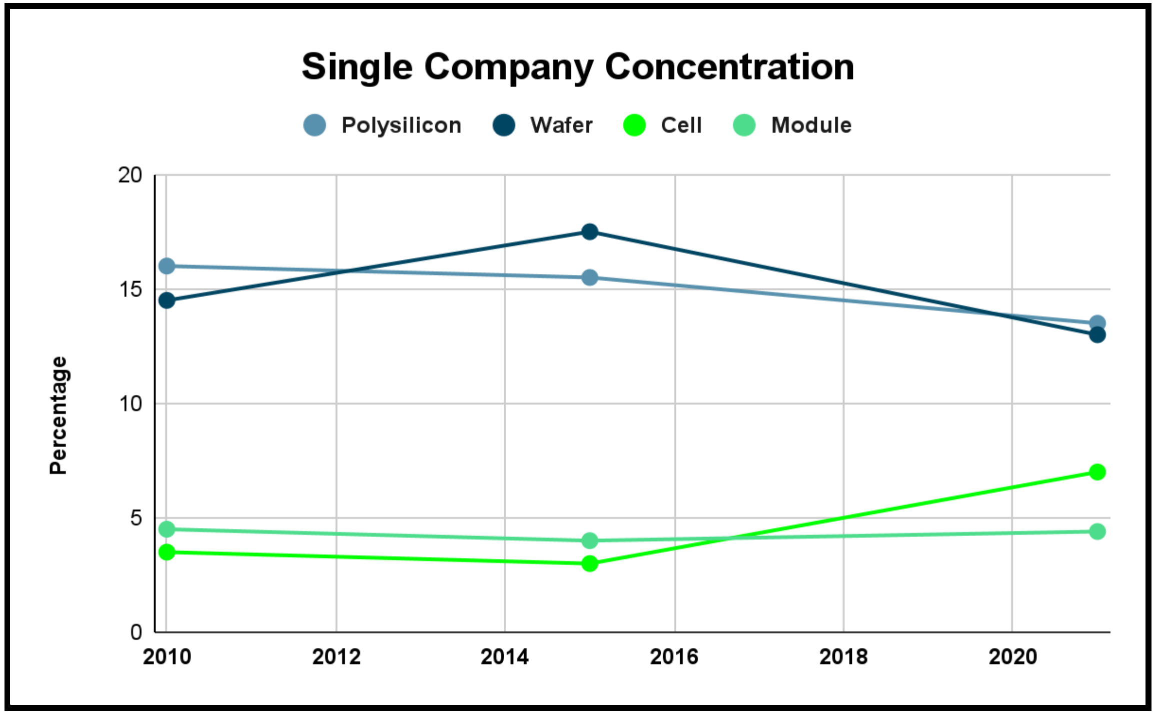
Concentration of Global Capacity by Single-largest Province & Plant in China

Based on the International Energy Agency (IEA)'s *Special Report on Solar PV Supply Chains (2022)*, around 42% of the world's **polysilicon production** capacity in 2021 was concentrated in China's Xinjiang province. Its largest polysilicon plant (also the country's largest) alone houses 14% of global production capacity. However, the province's share will likely decline as new polysilicon plants planned outside Xinjiang begin production.

Wafer manufacturing is comparatively more dispersed among Chinese provinces than polysilicon. Jiangsu, Yunnan, Inner Mongolia, Tianjin, and Jiangxi boast significant capacities in the provinces. China's single largest manufacturing facility accounts for 14% of global wafer production capacity.



Source: IEA, Special Report on Solar PV Supply Chains, 2022



Source: IEA, Special Report on Solar PV Supply Chains, 2022

Cell production is further distributed largely between three Chinese provinces — Jiangsu, Zhejiang, and Sichuan. China's single-largest facility accounts for a significant 8% of the global cell production.

Lastly, the Chinese province of Jiangsu alone accounts for 30% of the global **module manufacturing** capacity. At the facility level, China's single largest plant manufactures 4% of the global module production. Together, Vietnam, Malaysia, Korea, and India are home to 12% of the globe's module production capacity.

The larger trend suggests that China's overall share in each segment of the PV manufacturing supply chain will either remain more or less consistent (wafer and cell) or further increase (polysilicon and module).

Projection of China's Dominance Sector-wise in the PV Supply Chain (2021-26)

According to a study by Wood Mackenzie, China is set to continue its dominance in all segments of the solar PV manufacturing supply chain over the next two years. China's share is likely to peak in 2024 before returning to 2023 levels and sustain it till 2026.

Distribution of Revenue in PV Manufacturing by Country and by Segment

The chart below depicts the distribution of revenue generated by country and by segment of the PV Supply Chain. Here, too, China is the largest market generating ~50 % of the global revenue in the PV manufacturing value chain. Korea is the second largest market by revenue followed by Taiwan and Japan. Within the PV supply chain, the wafer-to-cell and cell-to-module segments generate the most revenue while the ingot-to-wafer and silicon production are the least revenue-generating segments.

Reasons for Chinese Dominance in Solar PV Manufacturing Supply Chain

China's invincible dominance can be attributed to five broad reasons:
1. Early Identification as a priority area and Policy Support – Investment
2. Control over Raw materials
3. Extremely energy-intensive nature of the PV supply chain
4. Minimal lead time
5. Rise of Integrated companies

1. Early Identification and Policy Support

China identified solar PV as a key industry as early as in 2001. Its 10th Five-year Plan (2001-05) envisioned expanding industrialisation of renewable energy technologies, including solar PV cells. This allowed for the introduction of central and provincial-level incentives for solar PV manufacturing. By the 11th Five-Year Plan, China identified that a lack of domestic capacity to produce polysilicon was posing obstacles to its expansion plans. At that time, China imported 95% of the polysilicon it used for PV manufacturing. In addition to imported polysilicon, China depended on imported manufacturing equipment. Consequently, China began promoting domestic production of polysilicon and equipment through grants, tax breaks, low-cost loans, and national funds. It also provided grant and tax incentives to encourage manufacturers to import technology and equipment from

Europe and the US. These incentives were discontinued after Chinese companies developed domestic capabilities.

Initially, solar PVs made in China did not have a market at home, and exports were the only option available to Chinese manufacturers. This forced them to improve their competitiveness and adopt vertical integration (in the supply chain) to reduce costs. The Chinese government also aimed to expand China's capabilities throughout the supply chain.

By 2007, China's dependence on polysilicon came down to 75-80%. In 2012, it imposed antidumping duties on polysilicon import from the US and South Korea. As a result, its dependency on imported polysilicon came down to 40% in 2014. Today, China accounts for 79% of the global polysilicon production. By this time, demand in China for solar PVs increased substantially and the domestic ecosystem was prepared to cater to it.

2. Control over essential raw materials (minerals)

The entire PV supply chain requires numerous minerals. China produces 35-65% of almost all of the selected mineral's global share, and this puts it in an advantageous position vis-a-vis availability and cost. No other country has a similar advantage in the production of the selected minerals that undergo the PV manufacturing process. Other countries do not consistently figure across all minerals as is clear from the following graphic.

3. Reliance on Coal in an Extremely Energy-intensive Manufacturing Process

The solar PV manufacturing supply chain is more energy-intensive compared to other industries. China, being the largest consumer of coal and exempt from any immediate or long-term commitment to phasing out usage of coal, heavily relied on it to fuel its manufacturing capacity. The usage of coal enabled China to keep the prices of solar PVs competitive in the global market which the developed world, despite access to capital, could not afford to beat. The advanced economies — the US, Europe, Japan, and Korea, bound by their commitment under climate change agreements to phase out usage of coal — did not have recourse to cheaper sources of energy. Over time, China-made solar PVs have pushed the cost down making it difficult for any of the advanced economies to compete with Chinese companies.

The above contrast is evident in the fact that while coal's share in global power generation stands at 36%, its share in fuelling electricity used for solar PV manufacturing rises up to 62%. In Chinese provinces such as Xinjiang and Jiangsu, where the majority of the solar PV manufacturing companies are situated, coal powers 75% of the province's electricity requirements.

4. Shorter Lead Time

'Lead time' refers to the time interval between the initiation of the facility and the first production. Across all segments, lead time in China is relatively much shorter than compared to the US or the EU. For both the EU and the US, the interval is 1-2 yrs in excess of China. Lead time in ASEAN countries is comparable to China. India too, except for the polysilicon segment, closely matches up to China.

5. Existence of Integrated Companies

The average profit margin in the PV industry is lower than compared to other critical technologies such as semiconductors. Volatility in profit has pushed a large number of companies out of business in the solar PV industry. However, vertically integrated solar industry manufacturing companies have consistently been profitable since 2014. This is so because they manage to compensate for the losses in one segment by making a profit in the other as opposed to some that remain active in only one segment of the industry. China has a larger number of medium-sized integrated companies (companies that manufacture in at least three segments; a medium-integrated company produces a minimum of 5000 MW in one segment) than any other country.

One more reason for India to target Solar PVs

Solar PV is one of the most employment-intensive sectors of all renewable and fossil fuel energy technologies. The IEA report estimates that the total number of jobs worldwide associated with manufacturing polysilicon, wafers/ingots, cells, and modules more than doubled in the last decade to nearly 600,000 in 2021. In 2021, over three-quarters of all solar PV manufacturing jobs were in China, followed by the Asia-Pacific region (14%, including India), Europe (3%) and the United States (1%).

In 2021, nearly 85% of the world's polysilicon manufacturing jobs were in China. Employment associated with wafers, cells, and modules is also the highest in China at nearly 80%, followed by Malaysia, Thailand, and Vietnam. In 2021, nearly 85% of all PV-related manufacturing jobs were in just these four countries. The employment figures in China are largely a result of its industrial policies and trade barriers. In 2010-11, China imposed anti-dumping duties on the import of polysilicon from the US and Korea, following which it witnessed a nearly 35% increase in polysilicon jobs between 2013-14.

Global Policy Approaches to Critical Technologies

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Introduction

Critical technologies have become central to the contemporary geopolitical landscape, and various countries around the world have undertaken a host of policy measures to define and analyse critical technologies, drive indigenous growth and curb competition in the field, and create collaborative supply chains. This paper assesses the policy responses of three key entities in the field of critical technologies — the US, China and the European Union — under three categories: defining, industrial policy, and outward-looking policy approaches.

At the outset, four common motivators behind industrial policy approaches to critical technology dominance emerge:

- Ensuring national security;
- Achieving economic security through global competitiveness of domestic actors;
- Peer pressure amidst intensifying geopolitical competition; and
- Protecting against concerns surrounding ethics, information security, and human rights.

The Decoupling Angle

Decoupling has become a keyword to describe the current global technological environment. As per an IMF Working Paper, 'decoupling' can be defined as "*the undoing of cross-border trade in high-tech goods and services—has been associated with concerns about intellectual property protection, data privacy, and national security concerns as well as a renewed attention to industrial policies.*" For many critical technologies, the verticals of their supply chain are distributed across the globe. For example, while the US has expertise in semiconductor chip design, the fabrication and packaging is concentrated in East Asia. One reason why the supply chain has materialised in this manner is on account of its economic cost and feasibility, based on the principle of competitive advantage.

In the past few years, because of a host of supply shocks induced by the COVID-19 pandemic, in addition to the competitive nature of technology geopolitics, there is an active policy effort to look inwards, boost domestic capabilities in critical technologies, and attempt to divert and re-shore some elements of a critical tech supply chain to friendly countries. In doing so, countries are attempting to 'decouple' themselves from a rival by either creating alternatives domestically or abroad, to align with dynamic foreign policy and national security goals.

This has become a key motivator behind some of the individual and multilateral policy measures of US, China, the EU, and other countries, discussed below.[1]

[1] Even though little emphasis has been paid to an actual assessment of the impacts of decoupling and high-tech-related industrial policy approaches by countries themselves, the IMF Working Paper lays down some insights for policymakers to consider. There are three broad, time-oriented impacts to consider. First is the short-term impact resulting in the immediate reduction of global trade flows, caused by the imposition of higher non-tariff barriers (NTBs) to eliminate the relative demand for high-tech imports, and compounded by domestic investment and consumption responses to the resulting permanent income losses restrictions. This will lead to losses for both parties at the two ends of the barriers. In the US and China case, for example, any restrictions on US's sales of chips to China will result in US firms losing an export market and employees losing income. For China, this may result in diversification but at a higher cost, and of course, disruptions in daily use and advanced requirements. Second is the long-term impact of sector misallocation, that is, the less efficient allocation of resources across sectors as trade is cut off between hubs and blocs. Third, is the combination of both impacts which will lead to challenges in global innovation and breakthroughs because of the losses caused by lower foreign knowledge diffusion on domestic labour productivity. For example, restrictions such as those on participation in 5G infrastructure or access to software and patents limit technological diffusion and spillovers through associated research and development and foreign direct investment.

1. United States

One of the first countries to define critical technologies in specifically the military sector was the US. As per a White House archive, in the 1920s, the US defined those technologies as critical to the military were those where "*dependence on foreign imports of certain materials was judged to be a vulnerability for the US military*." Subsequently, since the National Critical Technologies report was established in the 1990 Defense Appropriations Act, several critical technologies lists have been published. The National Critical Technologies Report, published under the Bill Clinton administration, for example, defines "criticality" in the broadest possible way – to "develop and further the long-term national security or economic prosperity of the United States." The Report further adds, that "*criticality is derived from the importance of the outputs of the system of which the technology is a constituent part, as well as from the significance the technology has for enabling that system*," thereby answering the question — "critical, but for what?"

Most recently, amidst the intensifying US-China technological contestation, the Biden administration unveiled the National Strategy for Critical and Emerging Technologies in 2020. Therein, C&ET are defined as those technologies that have been identified and assessed by the National Security Council (NSC) to be critical, or to potentially become critical, to the United States' national security advantage, including military, intelligence, and economic advantages. This list was expanded in the 2020 Strategy to 20, from the seven that the Clinton administration identified. The list was updated in 2022, and one technology (Advanced Conventional Weapons Technologies) was dropped. On the other hand, the other 19 were changed in language (for example, 'Aero-Engine Technologies' was changed to 'Advanced Gas Turbine Engine Technologies'), and expanded to include sub-technologies (for example, 'Distributed Ledger Technologies' from the 2020 Strategy was included as a sub-category in the newly phrased 'Finance Technologies' in the 2022 update).

1.1. Industrial Policy Approach of the US

A key example of an American inward-looking policy approach on critical technologies is the CHIPS and Science Act, to enable progress in its domestic semiconductor and microelectronics industry. In 2021, the US reportedly lost $61 billion in automobile sales due to a lack of availability of chips, which are mostly packaged and exported from countries based in East Asia. Its woes were exaggerated by ongoing tensions in its relations with China. To respond to the challenge, the US proposed the CHIPS and Science Act to empower its domestic chip industry to fill in for the demand external actors had so far been providing for. Promulgated in 2022, the Act empowers domestic firms in the US, through a monetary infusion of $280 billion, to become global leaders in chip design, fabrication, and the overall modernisation of the US semiconductor industry. Among other things,$13.2 billion has been set aside specifically to bolster R&D and workforce enhancement.

For the US, this drive for indigenous innovation in chips serves multiple purposes, including gaining competitive advantage in designing and manufacturing of both high-end and legacy chips, as well as enabling start-ups to innovate faster and at lower costs (especially through the new "chiplet" platform the US government is planning to create).[2] It also leads to the creation of strategies for the "secure" design and manufacture of chips wherever they are used for strategic purposes such as defence (a part of the Department of Defense Research and Engineering's Trusted and Assured Microelectronics project). Together, these purposes help the US gain a competitive edge in this critical technology over other countries like China and even allies like the Netherlands (ASML).

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[2] The Chiplet Platform, as explained by the US President's Council of Advisors on Science and Technology (PCAST) in a 2022 report, aims to enable start-ups and academic institutions to integrate their custom chiplet(s) with the National Semiconductor Technology Center-supported chiplet platform to demonstrate new innovations with dramatically reduced investment and time. Some of the push to enable domestic actors to gain advantage in chiplet design and fabrication comes from the US Department of Defense's State-of-the-Art (SOTA) Heterogeneous Integrated Packaging (SHIP) collaborative with Intel and Qorvo. The purpose of the programme is to provide Intel and Qorvo with the necessary funds (and strategic motivation) to develop prototype devices for DoD systems that will demonstrate enhanced capabilities along with size, weight, and power (SWaP) savings that can benefit the US military's warfighting capabilities. This example adds on to the understanding about US's national security-related policy prerogatives in boosting domestic chip capabilities.

The Act also sets aside $39 billion in semiconductor manufacturing incentives for domestic players. Such incentives are one of the oldest known policy responses to national shortcomings in global trade.

2. European Union

The European Commission has also adopted a risk assessment approach to identifying critical technologies, as per the recommendation on critical technology areas for the EU's economic security. Although the recommendation document recognises 10 technologies as critical for EU's economic security, four are referred to as having the "*highest likelihood of presenting the most sensitive and immediate risks related to technology security and technology leakage*" – Advanced semiconductors technologies; AI; Quantum; and Biotechnologies.

The aim and purpose of the EU's approach is to encourage member states to identify and analyse vulnerabilities according to their potential impact on the EU's economic security and the degree of likelihood that the negative impact of technological vulnerabilities materialises. The collective analysis of the member states, as the Commission recommends, should also take into account the value chain of the technologies, the evolution of risks as well as relevant technological developments, including any chokepoints and expected future chokepoints, a mapping of the EU's relative position in each technology, including key players and elements of the EU's comparative lead; the global interconnectivity of the ecosystem of the technology, including in research and the supply chain for the technology.

2.1. EU's Inward-Looking Policy

The EU has formulated its own Chips Act to bolster transnational domestic capabilities of the member states in semiconductor design and fabrication. Further, the EU has released a '2023 Digital Decade Strategy' to "*empower businesses and people in a human-centred, sustainable and more prosperous digital future*." That is the punchline, but the components of the strategy reveal multi-pronged goals for turning the EU into a critical tech powerhouse. The Digital Decade Strategy, for example, aims for Europe to have its first supercomputer with quantum acceleration by 2025, paving the way to being at the cutting edge of quantum capabilities by 2030.

To fulfil its quantum-related goals, a variety of policy measures are already underway.[3] One of these is the European High Performance

[3] The EU is placing an assertive focus on turning itself in the "quantum valley" of the world. Under Spain's presidency of the EU Council in the last year, the EU has issued a declaration on quantum tech, which argues that quantum technologies "are a high priority for the EU's sovereignty," and as per the June 2023 Economic Security Strategy of the EU, of the three tech-related immediate economic risks the EU faces, quantum is the first, followed by semiconductors and AI. Aside from the evident reasons for wanting to invest in quantum capabilities, from quantum optimisation to uses in AI/ML, the EU may also have a disproportionate emphasis on the tech for three reasons. One is that the EU has organically had a culture of research in quantum tech, and has been outpacing both China and the US in research on quantum since 2010. It has also seen a host of startups on quantum come up since that period (close to 70, as of 2021).

Computing Joint Undertaking (EuroHPC JU), under which the European Commission is now planning to build state-of-the-art pilot quantum computers. The sites for the pilot project to build these computers are located in Czechia, Germany, Spain, France, Italy, and Poland, and the investment totals €100 million, with 50% coming from the EU and 50% from 17 of the EuroHPC JU participating countries. Another is the Quantum Technologies Flagship instituted by the EU in 2018 to meet the challenge of the EU falling behind global competitors. It is a large-scale, long-term research initiative with a budget of €1 billion funded by the EU that brings together research institutions, industry and public funders, consolidating and expanding European scientific leadership and excellence in this field.

3. China

Chinese government documents do not carry the phrase "critical technologies," but rather the synonymous term they use is "core technologies" (关键核心技术). In a much more dramatic fashion than

Assessments are also being made as to how much more value quantum can add to the EU economy as a whole if leveraged appropriately. Second is that the EU wishes to make a space for itself as a leader in one of the key critical technologies amidst rising emphasis on chips and AI in both the US and China. Having a pre-existing culture helps shape geopolitical competitiveness goals. And finally, the EU genuinely understands the challenge of being a victim of economic coercion using quantum tech. The EU is also focusing on dealing with cyberattacks and human rights violations emerging from the use of Quantum capabilities, and from a values-based perspective, it wants to be prepared to tackle such threats.

that of the US or the EU, Chinese theory defines core technologies as those that "embody the national will, serve strategic needs, and are crucial for overall development." Further, "they hold significant importance in promoting high-quality development and ensuring national security. Conquering key core technologies is akin to obtaining 'national treasures,' while failure to do so is akin to endangering the 'lifeline of the nation'."

Further, as per a commentary published in the PLA Daily, the mouthpiece of the Chinese People's Liberation Army, an assessment of core technologies that gained significance in 2023 identified nine such key technologies – Generative AI Technology; Shipborne Unmanned Aerial Vehicle (UAV) Technology; Anti-Unmanned Aerial Vehicle (UAV) Technology; Military Robotics Technology; Quantum Information Technology; Hypersonic Weapon Interception Technology; Sixth Generation Fighter Jet Technology; Near-Space Aircraft Technology; and New Materials Technology. Most of these technologies are of a military nature, although they also have a host of dual use applications.

3.1. Industrial Policy Approach of China

China has articulated its policy on core technologies most prominently in the '2025 Make in China' Strategy and the revised 'Science and Technology Progress Law of the People's Republic of China' (revised

2021; w.e.f January 1, 2022). Instituted in 2015, MIC 2025 aims to help China skip the middle-income trap by installing technology-powered production as opposed to labour-intensive production and ultimately aid in the development of an "Internet Superpower." Similarly focused on building self-reliance in core technologies, the S&T Progress Law lays down three key policy prerogatives for achieving said self-reliance – "Promote research on key core technologies," "Strengthen corporate technological innovation," and "Increase the cultivation of scientific and technological talents." In a way, this is similar to the CHIPS and Science Act's emphasis on expanding domestic R&D capabilities, expanding competitiveness of domestic enterprises and enhancing sources of venture capital, and cultivating a generation of technology talent with specialised skillsets.

Further, each core technology has a strategy document assigned to it, which may not necessarily lay out the budget allocated, but lays down the key areas for expenditure. Subsequently, the Ministry of Finance and the National Bureau of Statistics respectively approve and release data on budget approved. For example, in the case of AI, China's seminal document is the 2017 'New Generation AI Development Plan'. Under this plan, China has laid down three main goals to be achieved by 2025 – "establishing a new generation of AI theory and technology system, as AI with autonomous learning ability achieves breakthroughs in many areas to obtain leading research results," "using AI in intelligent manufacturing, intelligent medicine, intelligent city, intelligent agriculture, national defence construction, and other fields, while enabling the scale of the AI industry to be more than RMB400 billion, and the scale of related industries to exceed RMB5 trillion," and "enabling the establishment of AI laws and regulations, ethical norms and policy systems, and the formation of AI security assessment and control capabilities."

Since then, Chinese spending on AI, especially basic and applied research, has varied every year, reaching a peak of 177 billion yuan in 2020, and declining to about 110 billion yuan as of 2022. The next step, in the path to Chinese self-reliance in AI as per the 2022 "Notice from six departments including the Ministry of Science and Technology on the issuance of the 'Guiding Opinions on Accelerating Scenario Innovation and Promoting High-Quality Economic Development through High-level Application of Artificial Intelligence'," is to actualise a national new generation artificial intelligence development pilot zone and the national artificial intelligence innovation application leading zone, using scenarios as a starting point to demonstrate capability and progress in commercial uses of AI.

Outward-Looking Policy Approaches: A Multi-Country Assessment

In the past few years, countries have readily deployed tools such as sanctions against non-friendly nations to boost its domestic national security agenda on the critical technology front, and have created partnerships with other nations that are pursuing mutual economic and national security-related goals. These partnerships have ranged from friend-shoring and supply chain diversification, to coordinated policy responses against a single actor. In addition to mutual economic and national security concerns, many of these endeavours are based around shared values.

The US has deployed some of its most wide-ranging sanctions against Chinese entities and government officials to curb China's technological advancement and hinder prospects of growth amidst growing authoritarianism and human rights violations in the country (which the US opposes from a values-based perspective). US's tech-related sanctions against Chinese entities have been mobilised under legal frameworks such as the Global Magnitsky Act of 2016, the Office of Foreign Asset Control's Specially Designated Nationals And Blocked Persons List, and most important, the October 7 (2022) and October 17 (2023) Export controls lists restricting China's access to specialised AI chips that can be used in Chinese military modernisation. Some leading Chinese firms such as Hikvision, Beijing Biren Technology Development Co., and Superburning Semiconductor (Nanjing) Co.

Ltd. are added to the Entity Lists under these legislative frameworks to align with the US's security and foreign policy objectives. These are mostly firms engaged in the development of advanced computing integrated circuits.

Further, as competition in high technology continues to take shape and intensify, countries such as the US, the Netherlands and Japan have similarly joined hands to restrict exports of sophisticated semiconductor materials like lithography tools to China. This is meant to mitigate their perceived vulnerability from China's rise as a global leader in high-tech, while also reducing the possibility that any "dual use" (civil-military) technology would reach China's hands. This is an example of a non-pre-existent coalition that came into being to align on a particular trade issue of mutual benefit and concern. The EU and US have also developed a Trade and Technology Council which is now coordinating policy approaches to critical technologies, and under its ambit, analysts have suggested that the two parties collaborate to jointly counter China's 'Digital Silk Road Initiative' (under the Belt and Road Initiative) by setting standards for transparency and openness, as well as the global promotion of digital rights as human rights.

The Quad countries (India, Japan, Australia and the US) have also partnered to create a Critical and Emerging Technology Working Group. Since its inception in March 2021 during the inaugural Quad Leaders' Summit, the Working Group has prepared various guiding documents for the Quad countries' partnerships on critical and emerging technologies, such as the September 2021 'Principles on Technology Design, Development, Governance, and Use' and the May 2022 'Common Statement of Principles on Critical Technology Supply Chains'. These documents lay down standards such as commitment to open technologies that enable freedom of expression and multi-stakeholderism in the development of critical tech, building tech to support and empower society, building trust and resilience in technology systems, and maintaining integrity and transparency of suppliers, vendors, and distributors. Subsequently, the Quad countries have attempted to adhere to these in their partnerships in the critical technology sector. For example, the Quad has partnered with the government of Palau to create sustainable and resilient Open RAN capabilities to modernise its national mobile network. Similarly, through its Advancing Innovation to Empower Nextgen Agriculture (AI-ENGAGE) Initiative, the Quad is identifying joint funding opportunities to encourage collaborative research between members on how to leverage the latest advancements in Artificial Intelligence to benefit farmers.

Conclusion

Overall, the global policy landscape pertaining to critical technologies has evolved to focus first on identifying and defining such technologies, and the values that each nation or entity wishes to approach them from. Next, there is a commonality in the inward-looking/ industrial policy approaches of each of the entities while approaching critical tech policy, which is, to incentivise domestic actors to outperform peers at a global stage, develop an excellent talent and R&D ecosystem, and gain a competitive advantage to protect economic and national security interests. The partnerships have focused on creating "like-minded" alliances that can articulate joint policy responses based on shared values and against a common perceived threat to economic and national security.

What Should India's Critical Technology Policy Look Like?

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Introduction

Critical technologies are considered crucial due to their importance for national security, economic prosperity, and social cohesion. These can include hardware, software, equipment, systems, and infrastructure. The concept of critical technology is often used in the context of defence, economic development, and national interest. The classification of what is critical and what is not depends on a country's security environment; therefore, different countries may see different technologies as critical.

For example, Australia defines critical technologies as "emerging technologies with the capacity to significantly enhance or pose risk to our national interests, understood broadly as comprising economic prosperity, social cohesion and/or national security."; Japan defines critical technology as "important technologies in which Japan should maintain superiority and remove vulnerabilities in order to ensure Japan's security and realize the sound development of the Japanese economy."; and the U.S. defines critical and emerging technologies as "advanced technologies that are potentially significant to US national security."

India's Current Critical Technology Policy

India has no comprehensive policy on critical technologies. There isn't a comprehensive list of technologies that can be classified as critical for India's national and economic security. This contrasts the Critical And Emerging Technologies List released by the National Science and Technology Council of the United States or The Science and Technology Framework released by the United Kingdom. The European Union recently recommended bloc-level risk assessment for identified critical technologies, and Japan has identified several critical technologies that it considers essential for its economic security.

The lack of a comprehensive approach to classifying emerging technologies as critical or not is a significant lacuna in India's economic and national security. There have been attempts to provide frameworks to consider what components must be factored in such a classification. One such prominent aspect is trade vulnerabilities. Furthermore, there is an ad-hoc approach to addressing this gap through bilateral initiatives such as the Initiative on Critical and Emerging Technology (iCET) with the United States and EU-India Trade and Technology Council with the European Union. It is also leveraging multilateral partnerships through initiatives such as the Critical and Emerging Technology Working Group with its Quad (Australia, India, Japan, and the United States) partners.

What principles India should follow while classifying which emerging technology is critical or not is beyond the scope of this paper. However, once such a determination is made, it is important to conceptualise technology-specific policies that can facilitate India's economic and national security.

What Should India Do?

While there may be some differences in classification between countries, certain technologies have such a significant and far-reaching impact that they become critical technologies for every major country (Table 1); it becomes critical for everyone. This implies that countries will seek to preserve their dominance in such technology while trying to prevent others from catching up to their level. Semiconductors, artificial intelligence, and quantum computing are some examples of technologies where governments worldwide are racing to preserve their dominance through various means.

Technologies	Australia	Cambodia	Indonesia	Malaysia	Philippines	Singapore	Vietnam
Artificial Intelligence / Machine Learning	✓	✓	✓	✓	✓	✓	✓
Internet of Things / Smart Grid	✓	✓	✓	✓	✓	✓	✓
Quantum Computing	✓	✓	✓	✓	✓	✓	✓
Blockchain	✓	✓	✓	✓	✓	✓	✓
Cybersecurity	✓	✓	✓	✓	✓	✓	✓
Cloud Computing			✓	✓	✓	✓	✓
5G / Internet Connectivity	✓	✓	✓	✓	✓		
Big Data	✓	✓			✓	✓	
Smart Cities				✓	✓	✓	
Encryption			✓	✓		✓	
Autonomous Vehicles	✓				✓		
Space Tech / Rocket Launcher / Smart Spaces	✓		✓				

Table 1: Countries' views on what critical technologies are | Source: Brookings Institution

India's critical technology policy will depend on specific technologies it labels as critical. Nevertheless, policymakers must consider the following **principles irrespective of an identified critical technology** while formulating policies related to critical technologies:

1. The policy should strengthen national security and promote the country's economic growth.
2. The overarching aim must be to develop indigenous capabilities wherever possible, keeping in mind India's comparative advantage. This could be in collaboration with a friendly country or with a partner country, or it could be a completely indigenous endeavour. However, this aim should not hinder India's active participation in global value chains.
3. Emphasis should be on participating actively in standards development organisations of an identified technology.
4. Emphasis must also be placed on removing vulnerabilities with respect to risky trade partners and major gaps in technology development ecosystem. This includes ensuring that dependence on our adversaries is minimised for critical technologies or their components.

Broadly, India's approach should be to expand and deepen cooperation with like-minded countries while ensuring strategic autonomy to whatever extent possible. India must strive to gain a competitive advantage in at least some aspects of global supply chains of identified critical technologies. In addition, efforts must be made to develop supply chain resilience to reduce the threat of economic coercion. This can be addressed by expanding the pool of trade partners and developing domestic capabilities. This approach is similar to that of Japan.

Critical Technology Policy Framework

For a decision on what kind of approach should be adopted for identified critical technology, the following questions need to be considered (Table 2):

1. Critical technologies can be divided into their primary R&D, manufacturing, and services components.

2. What is the technology's level of development or **maturity** in various aspects in the Indian context?

- **Non-existent:** The technology R&D capacity and/or manufacturing/services capacity does not exist. This implies that India is fully dependent on imports for this technology.
- **Nascent:** There is smaller capacity, either in universities or start-ups, but has not been able to scale up for mass use yet.
- **Significant:** There is significant capacity in India in terms of manufacturing or services. This implies that India is the major

producer for domestic and international markets. For R&D, it implies that India produces novel intellectual property for this technology and has human capital, which can help further develop and commercialise the technology.

- **Leader:** This implies that India is among the few countries with substantive R&D and/or industrial capacities, if not the only one.

3. If India's ecosystem for that specific technology is in the **non-existent or nascent** category, then who exactly is the leader in that domain becomes quite important.

- If the current leader or dominant force is an **adversary**, India must take steps to address that vulnerability. Building domestic capabilities across the board is the best option, but it may not be prudent or cost-effective for some other domains. Therefore, whenever necessary, India should bandwagon with its partners, who may have a comparative advantage vis-a-vis the current leader, to reduce this dependence. Geopolitical anxieties about US-China rivalry also play an advantageous role here.
    - India's decision to bolster domestic capabilities to produce Active Pharmaceutical Ingredients (APIs) was one such effort. India depended on China for more than 80% of its APIs, which are an important intermediate raw material for its pharma industry. The experience of COVID-19, where

India had to restrict exports of APIs to bridge the shortfall from China, highlighted this vulnerability.

- India's decision to incentivise foreign companies to manufacture semiconductors in India is an example of partnering with friendly countries to reduce dependence on an adversary. It also contributes to building an ecosystem that can be globally competitive in the near future. India may not produce the most cutting-edge semiconductors anytime soon but can be a viable supply chain alternative for larger-size semiconductors in the next few years.

- If the current leader is a **partner or a friendly nation**, then the focus should be to build co-dependence with the partner and become part of the global supply chains. It would ensure that India's limited resources can be allocated for more productive purposes or in sub-sectors where it has a comparative advantage.
    - India has been unsuccessfully trying to develop a fighter jet engine for decades. Despite pouring thousands of crores of rupees into its development, efforts have not borne fruit. This is a perfect example of India partnering with friendly nations such as the UK, the US, or France to co-produce jet engines using their proprietary technology. This does not mean that others would give away their prized technology, but indicates that India is willing to start with co-production and learn from that process to move up the

value chain in the course of time. The recent US-India deal for co-production of GE engines is an example.

- If the technology ecosystem is sufficiently diversified so that there is **no clearly identifiable leader** in that critical technology domain, efforts should be made to develop capacity domestically by leveraging India's comparative advantage in that specific domain.

4. Suppose India's ecosystem for that specific technology is in the significant or leader category. In that case, India should focus more on consolidating its dominance in that sector and, wherever possible, use export control measures to prevent adversaries from accessing Indian technology in case India becomes a global leader in such technology.

- The global semiconductor industry is an instructive example. The current technological landscape for semiconductors is diversified, with design and development happening in one country (India, US) and production in another (Taiwan), while machinery for semiconductor fabrication comes from a third (Netherlands). There are differences in the level of sophistication in the manufacturing of semiconductors between different countries (China, Japan, Taiwan, US). However, India has significant expertise in semiconductor design. All major semiconductor players globally have established design centres in the country. This expertise and lead should be tapped and expanded significantly. India has a competitive advantage in this domain, and it should ensure that this advantage is not lost. However, the lack of Indian companies owning any IP from this process is a gap that needs to be filled.

<table>
<tr><td rowspan="4">Level of Development of a Critical Technology</td><td rowspan="3">Non-Existent / Nascent</td><td>Is current leader an adversary?</td><td>Invest significantly in reducing vulnerability; bandwagon with partners to reduce dependence and build capacities from bottom up</td></tr>
<tr><td>Is current leader a partner?</td><td>work with partner to become part of supply chains</td></tr>
<tr><td>No clear leader</td><td>Develop domestic capacities based on comparative advantage and try to become a leader in the technology or a critical step of the supply chain</td></tr>
<tr><td colspan="2">Significant / Leader</td><td>Invest in bolstering domestic capacities and preserving dominance; increase representation in SDOs and incorporate safeguards in FTAs</td></tr>
</table>

Table 2: Critical Technology Policy Matrix

Specific Policy Proposals

India can take specific steps to operationalise the above principles:

1. India must see critical and emerging technologies as part of an ecosystem involving various ministries, public and private industry, academia and civil society. India should task the National Research Foundation and NITI Aayog with working with various ministries, science academies, industry organisations, and think tanks to develop a comprehensive critical technology strategy for India.

2. Once critical technologies are identified, India must ensure its participation in deliberations of major Standards Development Organisations (SDOs) related to identified critical technologies. This representation should be at the level of government, industry, academia and civil society, wherever applicable. Trade standardisation platforms such as the Indo-Pacific Economic Framework for Prosperity (IPEF) also provide an opportunity to economically integrate with other partners deeply.
3. To keep the focus on critical technologies, a certain percentage of annual R&D spend by the public sector should be exclusively earmarked for research on building capacity in critical technologies. This can be done through existing instruments such as the National Research Foundation or grants by state governments.
4. Given complex trade networks and economic interdependence, Indian policy should promote and support resilient supply chains for critical technologies. Active participation in initiatives like the Supply Chain Resilience Initiative (SCRI) provides an opportunity to become part of global supply chains.

Conclusion

The free flow of technologies and ideas has taken a backseat in a rapidly changing geopolitical landscape. The science and technology domain has become increasingly securitised, combined with economic and military power as a tool for power projection. In the shadow of US-China geopolitical competition, significant barriers have been erected that impede the free flow of technology. This poses a challenge for India, which is still looking to develop expertise and capacities in several important technology domains, many of which could be considered critical and bound to be closely scrutinised. At the same time, anxiety due to the rise of China places India at an advantage to capitalise on its large population and human capital to build capacities as a large emerging domestic market and also as an alternative to China. India's critical technology policy should seek to capitalise on both of these fronts and resist the urge to return to protectionist or isolationist policies regarding global trade and foreign investment.

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