Quantum Hardware Industrialization in India: A Policy Analysis Based on Stakeholder and Comparative Insights

A Thesis

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by

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Certificate

This is to certify that this dissertation entitled “Quantum Hardware Industrialization in India: A Policy Analysis Based on Stakeholder and Comparative Insights ” submitted towards the partial fulfilment of the Master of Science in Quantum Technology represents study/work carried out by Kishan Kumar Sarangi from Indian Institute of Science Education and Research Pune under the supervision of Dr. Kunj Shyamnarayan Tandon (I-HUB Quantum Technology Foundation) during the academic year 2025–2026.

Signature of Supervisor (Dr. Kunj Shyamnarayan Tandon) Date: 21-04-2026

Signature of Advisory Member (Dr. Sreejith G. J.) Date: 19 May 2026

Declaration

I hereby declare that the matter embodied in the report entitled "Quantum Hardware Industrialization in India: A Policy Analysis Based on Stakeholder and Comparative Insights " is the results of the work carried out by me at the Indian Institute of Science Education and Research, Pune, Maharashtra under the supervision of Dr. Kunj Shyamnarayan Tandon (I-HUB Quantum Technology Foundation) and the same has not been submitted elsewhere for any other degree.

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Abstract

Countries across the globe always focus on achieving economic strength, technological independence, and strengthening national security. In current geopolitical landscape, quantum technology has become very important for the above reasons. India is one of the fastest-growing economies. In quantum research also, India has made good progress; yet a clear gap still exists, and there will always be scope for improvement. One of the major challenges is moving ideas from the laboratory to the industrial scale in this domain. This thesis tries to understand those challenges.

To understand the challenges faced by the quantum hardware industry, the thesis follows a qualitative research approach. The approach follows two types of data collection, i.e., primary data collection and secondary data collection. The first method follows a format called KIIs (Key Informant Interviews), in which information is collected from stakeholders involved in the quantum hardware sector. It provides an evidence-based ground report based on the experiences of startups, academicians, VCs, and TTOs. The primary method provides a real picture of the sector, while the secondary method is based on comparative analysis of existing reports, articles, and white papers. It provides a global picture of different countries' ecosystems in quantum hardware. This list involves different European countries like the UK, France, Germany, Belgium, the Netherlands, and Finland. For domestic comparison, the automobile, pharmaceutical, and solar industries are used as case studies, and necessary lessons are drawn.

The findings reveal a few critical barriers. Regulatory and import-related problems, such as customs delays and heavy taxation on specialized components, cause delays in operational processes and increase costs. There is no shared infrastructure, including cleanrooms and foundries. This makes startups dependent on international infrastructure, which may affect rapid prototyping and IP protection. There is a mismatch between the funding requirements of deep-tech hardware startups and traditional venture capital life cycles, since deep-tech companies require substantial financing over more extended period than venture capital firms typically provide. Lastly, there are institutional barriers related to IP transfer and licensing, which impact the creation of academic spin-offs (ASOs). Overall, the thesis concludes that India's problem is not the lack of vision; it is insufficient implementation and development mechanisms. It

suggests that a systematic policy approach can help grow the sector in the long run. The focus should be on facilitating regulations, infrastructure sharing, government involvement as the first customer, and improved funding models for projects with long gestation periods. The entire research paper blends stakeholder consultation with policy analysis and can serve as a real-world template to build the quantum hardware ecosystem in India.

Acknowledgements

Completing this thesis on quantum hardware policy would not have been possible without the support of my mentors and peers. Primary credit goes to my supervisor, **Dr. Kunj Shyamnarayan Tandon**. He always provided guidance to me throughout this whole thesis journey and also connected me to the policy circle. My academic journey has been a rigorous and transformative experience in which **Dr. Sreejith G. J.**, who is also my thesis advisor committee member, has helped me a lot. In this thesis, all the primary research participants played a key role in providing practical insights into the industry. A detailed list of the names of the participants is mentioned in **Appendix B**. **Mr. James Johnson** (I-HUB QT Foundation), and my friends **Nikhil Sharma** and **Deepanshu Gupta** have helped me connect with a few key primary research participants. Thank you all for your help, guidance, and contribution.

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Chapter 1

Introduction

1.1 Importance of Quantum Hardware Technology

Quantum technology is becoming a strategic necessity for countries, as it can affect security, the economy, as well as technological independence. It has various applications in computing, communication, and sensing, which can be useful in areas like secure data transmission, defense, and advanced industries. Because of this, many countries are focusing on research and developing their own capabilities to control these technologies. In the future, quantum computers may be able to break current RSA encryption systems, which protect banking, military data, and communication networks. Also, quantum technology can improve security through different technologies such as Quantum Key Distribution in order to achieve highly secure communication infrastructure. Unlike software, quantum systems heavily rely on physical components. These components include cryogenic systems, precision electronics, and fabrication facilities. It is also a dual-use technology, which means it can be used for both military and civilian purposes. For example, a quantum sensor can be used for oil detection, submarine detection, and can also enable accurate navigation without GPS. So, progress in quantum technology heavily relies on hardware components, i.e., progress in quantum technology applications is directly proportional to the ability to design, build, and maintain these systems. Countries like the USA, European countries, and China have categorized quantum technology as a national asset. They are investing heavily in this domain and also controlling access through export policies. [1]

From a strategic perspective, dependence on imported quantum hardware creates risks because the supply of critical components is limited and controlled by a few countries and companies globally. Also, access to these components can be restricted due to geopolitical tensions and export controls. So, relying on these countries can create a hindrance to long-term development in quantum technology. India should focus on developing an indigenous hardware ecosystem. This can help achieve India's mission towards Atmanirbhar Bharat.

Although India is rich in research potential and talent, it lacks domestic competence in hardware design. This deficiency needs to be fixed immediately. In any case, India will not be able to decrease its dependence on foreign nations. As a result, India will fall behind in the race in the field of quantum technology.

1.2 The Quantum Hardware Industrialization Gap in India

India has a strong foundation in quantum research, especially in theoretical physics, quantum algorithms, and early-stage experimental work. These are supported by institutions such as IITs, IISERs, and other organisations. After the 1970s, India has made excellent progress in the IT sector, which is also called the IT revolution. In cities like Bengaluru, Hyderabad, and Pune, the IT ecosystem formed, and a lot of companies like TCS, Wipro, and Infosys not only strengthened the Indian ecosystem but also exported their services to other countries. However, not just in quantum hardware domain but also in nanotechnology and semiconductor manufacturing, the growth isn't as significant compared to China, the USA, and other European countries. The lacuna lies in the transition from theoretical expertise to physical product development i.e., the transition from laboratory research to industrial-scale hardware development.

The NQM has set a 2031 target for the development of intermediate quantum hardware spanning 50 to 1000 physical qubits.[3] The execution is hindered by a deficit in hardware engineering capabilities and manufacturing infrastructure. There is a term called Technology Readiness Level (TRL). It provides the formal scale for this gap between theoretical ideas and physical realization. Most work in India remains at early stages such as proof-of-concept (POC) and laboratory validation (TRL 1–3). However, commercial deployment requires reaching higher levels, i.e., TRL 7–9. The transition between these stages is referred to as the "Valley of Death". This phase requires high investment, infrastructure, and engineering support. Currently, these support systems are limited in India. As a result, many promising research efforts fail to move beyond the lab stage.

Fundamentally, quantum hardware is different from software-based technologies. India previously succeeded in the IT sector by building software on hardware developed elsewhere. However, in quantum technology, the physical technologies that act as the base of quantum technologies should be developed indigenously. In India, this base for developing hardware products is virtually non-existent. This creates a gap called the "Hardware Complexity Gap". This gap forces startups to rely on slow, expensive, and complex global supply chains.

Quantum systems require specialized components such as cryogenic systems, precision electronics, ultra-high vacuum chambers, and fabrication facilities. These systems are complex, expensive, and require long development timelines. The gap appears mainly in three physical domains:

a) **Cryogenics and Cooling infrastructure**: Superconducting quantum computers operate at milli-kelvin temperatures, i.e., colder than deep space. One of the major components is dilution refrigerators. This market is currently dominated by an oligopoly of European companies such as Bluefors (Finland) and Oxford Instruments (UK), with over 70% market share. Other key global players are Leiden Cryogenics (Netherlands) and Air Liquide (France). Although India has indigenous cryogenic capacities within ISRO (Indian Space Research Organisation) and the DAE (Department of Atomic Energy), there is negligible commercial-scale manufacturing of these systems.[4]

b) **Ultra-High Vacuum (UHV) Chambers**: Trapped-ion and neutral atom quantum computers require ultra-high vacuum chambers with extremely low pressure ,i.e., below 10^{-11} Torr. There are some Indian companies like Ranvac, NXTEK Yantra, Rudraksh Steel, and Ultrahivac that operate as fabrication service providers. But very few of them act as product-led Original Equipment Manufacturers (OEMs) and have the specialized testing infrastructure, such as highly sensitive permeameters or residual gas analyzers. But the numbers are limited. However, they do not certify to quantum standards, i.e., specialized magnetic shielding or low-outgassing materials for mK temperatures. As a consequence, Indian institutes are forced to import from global suppliers like Htc (Taiwan) or Kimball Physics (USA). This requires a timeline of approximately 6 to 12 months to obtain the product. [5][6]

c) **Precision Electronics and RF Components**: Quantum states can be manipulated by high frequency, ultra-low noise microwave electronics. These include Arbitrary Waveform Generators (AWGs), cryogenic amplifiers, isolators, precision optics, and specialized superconducting BNC cables. Since domestic product is limited, these components are imported. In many case, they are misclassified under general consumer electronics categories. This is also known as HS Code ambiguity, which leads to high custom duties and additional delays. In India there is no Quantum HSN code system, which means no single, 6-8 digit Harmonized System of Nomenclature (HSN Code) exists for quantum computing which creates the HS Code ambiguity. This increases cost as well as time required for hardware development.

Fabrication Constraints: Creating qubits requires semiconductor fabrication facilities with specialized materials and specific process nodes. These are different from standard CMOS technology. For example, superconducting qubits require materials like niobium or aluminium on silicon substrates, requiring multi-layer processes for high coherence of qubits. Also, for Josephson junction fabrication, precision oxidation is required. Currently, India's only Integrated Device Manufacturer (IDM) is the Semi-Conductor Laboratory (SCL) in Mohali, which operates at a 180 nm node and is being upgraded to 28 nm. However, without a dedicated quantum fabrication line, general upgrades may not support quantum-specific requirements. Standard fabrication lines may also face contamination risks when handling quantum materials.

Due to the absence of open-access micro-foundries, Indian startups are forced to follow a "fabless" model. This means they design chips in India, but they have to send their GDSII files (digital blueprints) to foreign foundries in Taiwan (TSMC) or France (Pasqal/Leti) to print the hardware. As a result, the iteration cycle increases from weeks to months and exposes Indian intellectual property and limits the ability to follow fast experimental cycles.

Import Dependency and vulnerability: Over-reliance on imported material poses strategic challenges. Many of the critical materials used in quantum technology are extremely scarce and regulated by governments. For instance, Helium-3 is necessary for dilution refrigeration, and it is a very scarce material. It is regulated by only a few countries, including the US and Russia. The cost of the material has soared tremendously over the years. India possesses enormous quantities of monazite sands; however, their processing facilities are highly constrained. For quantum-grade standards, the purity should be 99.9999%. India largely exports raw ore and imports processed oxides.

Quantum technologies are "dual-use" technologies, i.e., it is useful for both civilian and military purposes. Access to these components is often restricted by global export control regimes like the Wassenaar Arrangement (1996). So, this heavy dependency includes the potential risk of "kill switches" or hardware trojans embedded in foreign supply chains.

Capex Clash and Patient Capital Deficit: A quantum computer needs heavy CAPEX spending for its hardware over an extended period to become commercially viable. Quantum computing startups take 10-15 years of 'patient' money to develop. But this doesn't work in the case of Indian Venture Capital firms. Their model works on shorter timeframes. For example, they favor companies which have light CAPEX and fast scalability such as those in the software sector. Likewise, government grants focus only on early research activities and are inadequate for the development of hardware projects. This creates a funding gap in the mid-stage development phase, where prototypes need to be built and tested.

All these challenges are interconnected, and addressing them requires a coordinated approach. Further elaborated analysis based on stakeholder inputs is done in Chapter 4.

1.3 Problem Statement and Research Questions

India has a clear vision outlined by the National Quantum Mission (NQM). However, there are certain gaps between policy plans and the ground realities faced by hardware innovators.To understand the gaps, the thesis focuses on the following research questions:

a) What are the key operational as well as financial challenges that prevent quantum hardware startups in India, based on primary stakeholder inputs?

b) How do international policy frameworks, especially the European Quantum Flagship, support their hardware ecosystem? What lessons can India learn and implement in the short term as well as the long term?

c) What lessons can India learn from its past success in sectors like the pharmaceutical, automobile, and the solar industry?

1.4 Objectives and Scope of the Study

This study aims to develop a data-driven and practical framework to support the quantum hardware ecosystem in India. The primary goal is to understand the structural gaps between existing policies for quantum hardware research and the ground realities faced by startups in quantum hardware research. Based on the data, the study suggests necessary policy recommendations.

To achieve this, the study focuses on the following objectives:

a) To analyze the operational, infrastructural, and financial challenges faced by quantum hardware startups in India. The inputs include insights from startup founders, academicians, venture capitalists, TTOs from India as well as Europe. These can be categorized as primary research.

b) To analyze international policy frameworks, especially in Europe, and to understand how these frameworks support their quantum hardware ecosystem. This includes models such as the European Quantum Flagship, Quantum Delta NL (Netherlands), VTT (Finland), IMEC (Belgium), France, and the UK, from which necessary and relevant policies can be drawn.

c) To draw lessons from India's past successes in deep-tech sectors such as the pharmaceutical, automobile, and solar industries. This involves learning from how policy interventions like the 1970 Patents Act and PLI schemes supported these sectors.

d) To propose actionable policy recommendations for India in the short term (1–2 years) as well as the long term (3–7 years).

Scope and Delimitation:

The scope of the study is limited to the policy, economic, and regulatory aspects of quantum hardware development, which focuses on the hardware layer, i.e., cryogenic systems, UHV systems, fabrication, and control electronics. These areas are critical and the most capital-intensive.

The study does not focus on the technical comparison of different quantum computing types such as superconducting qubits vs trapped ions or photonics, instead, it treats the issues of the whole quantum hardware ecosystem as an industrial problem. The study is based on qualitative analysis using primary interviews and secondary research.

Chapter 2

Background / Literature Review

2.1 Key Pillars of Hardware Industrialization

The deep-tech industry, especially the quantum hardware sector, relies on key pillars that support its growth. These are:

(i) **Research & Development Funding**

(ii) **Tax Incentives**

(iii) **Skills & Workforce Development**

(iv) **Infrastructure Support**

(v) **Public Procurement Policies**

(vi) **Trade & Import-Export Policies**

(vii) **Intellectual Property Protection**

These pillars can be ranked by their importance. Evidence indicates that the most crucial pillar for the growth of the deep-tech ecosystem is "Research and Development (R&D) Funding". Countries that have made significant advancements in this area tend to foster a more vibrant deep-tech environment.

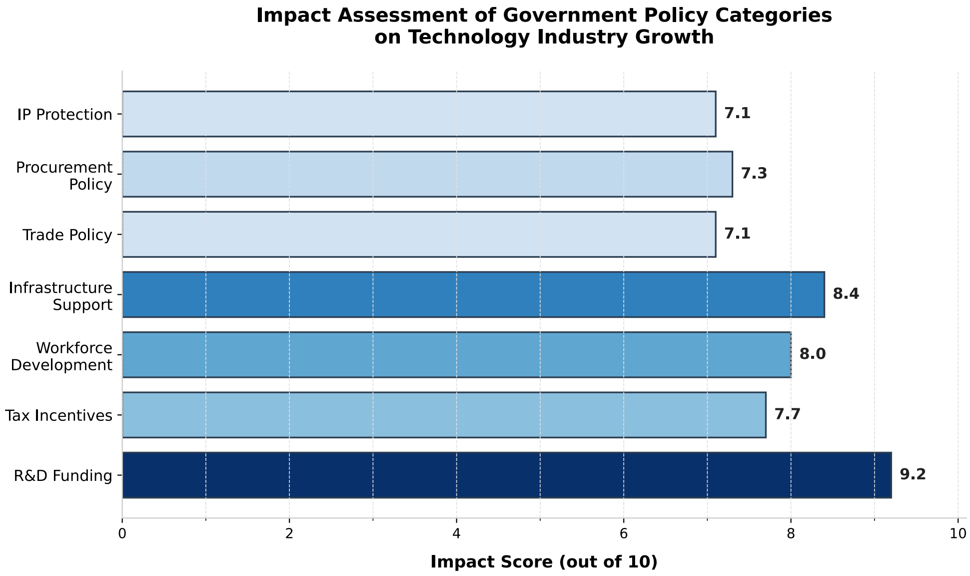

Figure 2.1: Impact of different policy pillars based on secondary research (score out of 10).

2.2 The Indian Quantum Landscape

2.2.1 National Quantum Mission (NQM) Overview

In April 2023, the Union Cabinet approved the National Quantum Mission, which shows India's vision for the deep-tech sector. The mission aims to seed, nurture, and scale up quantum R&D. The total budget announced was approximately Rs. 6003 crore from 2023–2031. The vision is that India should transition from a passive consumer to a global leader in quantum technologies.[3] (i) **Core Objectives**: The objective is to achieve time-bound milestones in four primary domains, i.e., Quantum Computing, Quantum Communications, Quantum Metrology & Sensing, and Quantum Materials & Devices. For quantum computing, the target is to develop intermediate-scale quantum computers, i.e., to achieve 20–50 physical qubits within 3 years, 50–100 qubits within 5 years, and up to 1000 qubits by 2031.

In the quantum communication sector, the objective is to establish a secure communication network, i.e., satellite-based Quantum Key Distribution (QKD) over 2000 km, and inter-city fiber QKD networks. It also aims to build advanced quantum networks utilizing quantum repeaters and entanglement swapping.

Similarly, in quantum sensing & metrology, the goal is to develop high-sensitivity sensors, including atomic magnetometers, gravimeters, gyroscopes, and high-precision atomic clocks for GPS-free navigation and medical diagnostics.

In the quantum materials & devices field, the creation of advanced quantum materials and devices that form the physical substrate for quantum computing is one of the major targets.

(ii) **Institutional Setups**: The NQM has followed a decentralized, hub-and-spoke model to execute the objectives mentioned above. Four **T-Hubs** (Thematic Hubs) have been established within the country, spanning 14 groups in 17 states. At IISc Bengaluru, the hub for quantum computing is hosted. Similarly, for quantum communication, quantum metrology & sensing, and quantum materials & devices, the hubs are hosted at IIT Madras (in collaboration with C-DOT), IIT Bombay, and IIT Delhi, respectively.

Apart from that, the NQM also supports projects and entities such as DRDO for secure communication and cryptography, SETS for post-quantum cryptography, and C-DOT. The mission also incubates over 50 quantum startups, aiming that at least 5 of them can reach global markets and generate revenue streams.

(iii) **Governance Structure**: The T-Hubs have been registered as Section 8 non-profit companies to provide agility to the mission. The intention was to bypass the rigid hiring and procurement rules, providing better financial and administrative autonomy that constrain traditional government departments. The central government has taken a lot of measures to nurture the ecosystem, but the state governments have not been far behind. States like Andhra Pradesh (Amaravati Quantum Valley) and Karnataka (Bengaluru) have been supporting the ecosystem by providing funding, land at low cost, and necessary support in collaboration with global players.

Through the Amaravati Quantum Reference Facility (AQRF), Andhra Pradesh has recently become the first state to operationalize an indigenous quantum system. The Karnataka government funds the Quantum Research Park (QuRP) at IISc via the Karnataka Innovation and Technology Society (KITS). Other states are also trying to support the ecosystem through different initiatives.[20][21]

The Telangana government plans to transform Hyderabad into India's first "Quantum City." The Tamil Nadu government plans to provide quantum computing education to engineering students through the "Naan Mudhalvan" upskilling platform.[22][23]

2.3 Global Practices: Comparative Ecosystem Analysis

2.3.1 The European Model

The European approach does not follow purely market driven model, but it also relies on strong government coordination. Strategic Planning, public-private partnership and long-term support are the primary focus areas.[24]

The EU's Quantum Technologies Flagship acts as the main framework, and over €1 billion budget has been allocated to it over ten years (2018-2028). To ensure real-world applications, the Flagship program follows a consortium model, which means, the funding is primarily allocated to joint proposals involving universities, startups, and industry players.

The European Innovation Council (EIC) Fund supports startups through "**Blended finance**". It offers non-dilutive grants (up to €2.5 million), equity investment up to €15 million and venture debt through the European Investment Bank.

Including national initiatives, total European public investment in quantum technologies exceeds $7 billion. The specific national models driving this ecosystem are detailed below:

(i) **The Netherlands**: The Netherlands follows a centralized model through Quantum Delta NL (QDNL), which is backed by €615 million from the National Growth Fund (2019–2028). It uses a hub-and-spoke structure. To avoid regional competition the structure connects five hubs, i.e., Delft, Amsterdam, Leiden, Eindhoven, and Twente.[4][25]

The strategy focuses on commercialization through projects, such as Quantum Inspire (Europe's first cloud-accessible quantum computer), a National Quantum Network (QKD deployment in the Rotterdam port as a living lab), and quantum sensing application.

The ecosystem strongly supports talent development. The government subsidizes more than 50% of Industry-Funded PhD programs costs and students split time between universities and startups. The research topics are aligned with industry needs, which creates a business-ready pipeline. The QuTech Academy supports education and training at different levels.

Easy infrastructure access is one of the key strength areas for the growth of Quantum ecosystem. So, the "House of Quantum" acts as a shared campus which provides access to cleanrooms, dilution refrigerators, and testing facilities at subsidized rates. It reduces the high upfront capital requirements.

One of the primary obstacles for startups to cross the "Valley of Death" without early dilution. The funding model focuses on patient capital. Programs like InfinityQD and the QDNL Participations Fund provide convertible loans, pre-seed grants, and equity support. These initiatives help the startups to cross the valley of death.

The "Innovation Box" reduces the tax on IP-derived profits to 9% and the WBSO scheme provides R&D tax credits on employee wages. This policy framework acts as strong tax incentive schemes.

Institutions like TU Delft and QuTech follow equity-based IP licensing instead of high upfront fees, which enables uccessful startup creation such as QuantWare, Q*Bird, Qblox, and Orange Quantum Systems. This is an excellent case of technology transfer.

(ii) **Finland**: Finland uses public procurement as a market-maker. The state-owned VTT Technical Research Centre acted as an "anchor customer" by contracting the startup IQM to build Finland's national quantum computer (scaling from 5 to 50 to 300 qubits by 2027) backed by a €70 million grant. This guaranteed revenue and market validation allowed IQM to later raise over $300 million in private venture capital.[26] [27]

Finland has built its quantum strategy on a historical legacy in low-temperature physics (originating from Aalto University in the 1960s). This environment fostered Bluefors, a company that holds a near-monopoly on the global market for cryogen-free dilution refrigerators.

Utilizing European tools, Finland secured a €35 million venture debt facility from the European Investment Bank (EIB) for IQM to finance fabrication expansion without heavy equity dilution.

Other startups like SemiQon raised €17.5 million in blended finance from the EIC Accelerator. To fund the Kvanttinova industrial park in Espoo, Finland uses the EU Chips Act. The industrial park is a piloting environment for microelectronics, which is supported by €79 million.

VTT is also a key partner in EU pilot lines (FAMES and NanoIC) in collaboration with France and Belgium, which ensures, startups have access to state-of-the-art fabrication.

The national innovation agency provides R&D subsidies, innovation vouchers, and specific internationalization support to scale businesses globally.

(iii) **Belgium**: Belgium's quantum ecosystem is built around the Interuniversity Microelectronics Centre (Imec) in Leuven, which is a nanoelectronics R&D hub. Annually, it receives around €108 million from the **Belgian** government. Imec follows a "lab-to-fab" model and uses standard 300 mm CMOS processes to scale qubit manufacturing, which helps solve the reproducibility issues seen in academic labs.

Belgium also offers tax incentives through the Innovation Income Deduction (IID). Companies can deduct 85% of income earned from intellectual property, which reduces the effective corporate tax rate to about 3.75%.

For early-stage startups, R&D tax credits are refunded in cash after four years. This acts as a non-dilutive funding source when companies are still pre-revenue. There is also an 80% exemption on payroll, which helps with withholding tax for researchers. This significantly reduces the cost of hiring scientific talent.

If we look into the infrastructure, Belgium is developing the BeQCI project to build its first national QKD network.

The Belgian sovereign wealth fund (SFPIM Relaunch) co-invests with the EIC Fund into hardware startups such as Swave Photonics. This provides additional capital support.

To help the startups further, the Wallonia Brussels Startup Launchpad (WSL) offers incubation, training, legal support, and access to funding networks.

(iv) **France**: France approaches quantum technology through the lens of strategic autonomy, launching a National Quantum Strategy with €1.8 billion in funding. It focuses on four pillars, i.e., Quantum Computing, Quantum Communications, Quantum Sensors, and Post-Quantum Cryptography.[28]

The ProQCIMA Program: The French Ministry of Armed Forces launched a €500 million defense procurement program. The aim is to acquire two universal quantum computer prototypes by 2030. They provided milestone-based defense contracts to selected startups (like Pasqal and Alice & Bob) .

The French state investment bank (Bpifrance) provides direct funding to startups and also co-invests with private VCs. This signals to the broader market that the state is financially committed to hardware scaling. This move help to de-risk the sector. Institutions like CNRS, Institut d'Optique, Collège de France, and Ecole Normale Supérieure, focus on theoretical and experimental research advancements.

(v) **Germany**: Germany has a €2 billion Action Plan (2022–2026) focused on applying quantum technologies to its existing industries, especially in manufacturing, automotive, and chemical sectors. It has also established the Munich Quantum Valley. This integrates institutions such as LMU, TUM, and the Max Planck Institutes. Apart from that, Germany has launched programs like Quantum Computing Initiative (QuIC), which involves partnerships with major companies like BMW, Bosch, and Siemens.

The EXIST Program is designed to support the vulnerable lab-to-fab transition, and it provides full salary support and a dedicated equipment budget for university spin-outs for up to 18 months. This allows founding teams to build their startup while remaining affiliated with national labs at zero cost to the company.

(vi) **The UK**: The UK identified immigration barriers as a important issue for deep-tech growth. It introduced the "Global Talent Visa," allowing institutions like the Royal Society to directly endorse skilled applicants and reduce bureaucratic delays. This policy helps attract top international researchers into the UK ecosystem.

The UK Quantum Skills Taskforce also recognized that PhDs alone are not sufficient to build an industry. So, it promotes specialized training and apprenticeships for technical roles., which includes technicians and cleanroom engineers who handle cryogenic systems and vacuum infrastructure.[29]

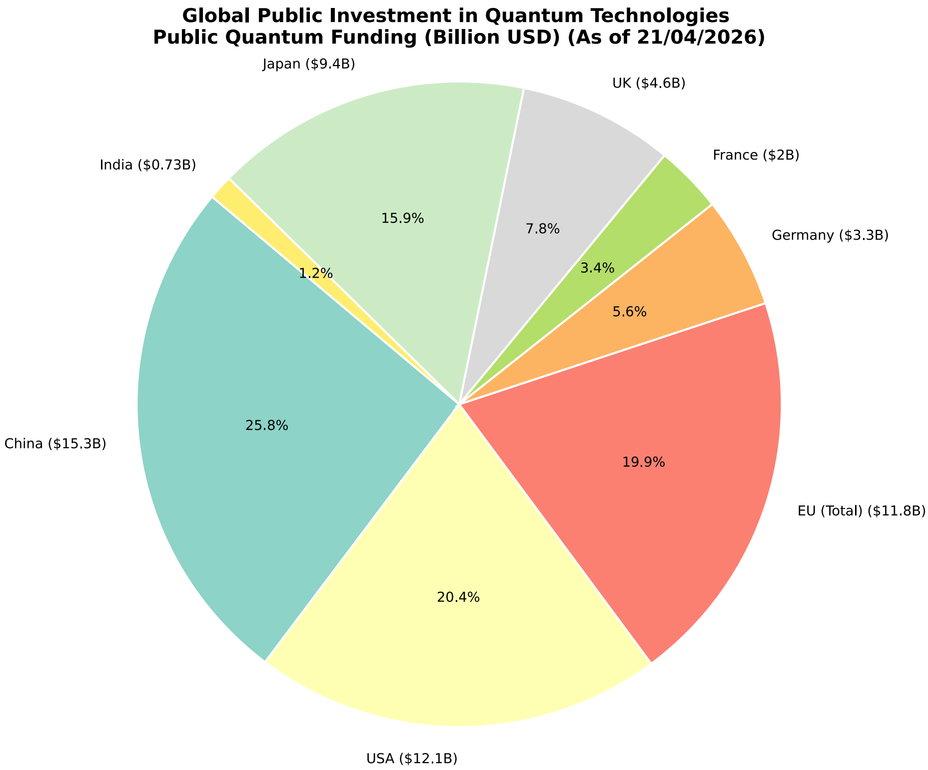

Figure 2.2: Public investment in quantum technologies (in billions of USD). Note:- The numbers changes time to time and the numbers are collected from various sources.

2.4 Domestic Deep-Tech Case Studies Analysis

2.4.1 The Pharmaceutical Industry

Strong policy decisions can help the deep-tech sector to grow globally, which is visible in the Indian pharmaceutical industry. Before 1970, India followed a product patent system. This allowed multinational companies to control drug molecules, which led to high medicine prices.

Following the 1970 Patents Act, there is a shift occurred. The act removed product patents for food and chemicals, including pharmaceuticals, and allowed only process patents. As a result, Indian companies could legally reverse-engineer drugs, develop new manufacturing processes, and sell generic versions in the domestic market.Firms like Cipla, Ranbaxy, and Dr. Reddy's built strong capabilities in chemical synthesis. Between 1970 and 2005, the number of manufacturing units increased significantly, and India became a global supplier of generic medicines.In 2005, India had to comply with international IP agreements and reintroduce product patents. However, the government added an important safeguard through Section 3(d) of the Patents Act. This section denies patents to new forms of existing drugs unless they show significant improvement in effectiveness, which prevents misuse of the patent system.

This provision was designed to stop "evergreening," where companies make minor changes to extend monopoly periods. It helped protect the domestic generic industry.

The lesson for deep-tech sectors is clear. Policy must directly address the main bottleneck—in this case, IP restrictions. When policies are aligned with sector needs, they can guide industry growth and create global competitiveness.

2.4.2 The Automobile Industry

The Indian automotive sector was tightly controlled under the License Raj before 1991. The output was restricted, entry was limited, and technology imports were controlled. As a result, a few firms dominated the market with outdated products.

In 1991, a turning point came following liberalization. The government removed licensing across vehicle segments and auto components, scrapped MRTP clearances, and allowed 100% FDI through the automatic route. This opened the sector to global competition and technology inflows.

To sustain growth, the government launched the Automotive Mission Plan (AMP) 2006–2016. It aimed to make India a global manufacturing hub, targeting a USD 145 billion turnover and a 10% GDP contribution.

Infrastructure policy focused on reducing logistics costs. The state developed auto parks and ensured "park-to-port" connectivity to support efficient manufacturing and exports.

Fiscal incentives were used to shape product design. Lower excise duty for cars under 4 meters with smaller engines pushed firms to develop compact, high-efficiency vehicles. This created a global niche; as a result, India became a major exporter of small cars.

However, the policy had limits. While vehicle exports grew strongly, the auto component sector lagged. The ecosystem deepened more at the final assembly level than in lower-tier supply chains.

The government also used regulatory forcing through Bharat Stage (BS) norms. In 2016, it mandated a direct shift from BS-IV to BS-VI by 2020, which compressed a decade of technological change into just three years. Without this push, firms would likely have continued with cheaper, older technologies. The regulation forced industry-wide upgrades and aligned Indian vehicles with global standards.

These are the lessons for deep-tech sectors, i.e., liberalization, infrastructure, incentives, and strict regulation can help to grow and transform a sector into a globally competitive industry.

2.4.3 The Solar Industry

The solar power moved from a costly technology to an important part of the energy system in between 2010-2024.

In 2010, the sector faced a clear viability gap. The cost of solar power was around 17.91 per kWh, while thermal power was available at 3–4 per kWh. This large cost difference created a situation where Discoms had no incentive to buy solar power.

The government responded through the Jawaharlal Nehru National Solar Mission (JNNSM). It introduced a "bundling" mechanism to make solar power financially viable. Under this mechanism, NVVN was appointed as the nodal agency. It combined expensive solar power with cheaper thermal power in fixed ratios and sold the bundled power at an average price that was acceptable to Discoms.

This solved a major problem. Solar developers got assured high payments, which made projects bankable. At the same time, Discoms were protected from high upfront costs.

Once the market stabilized, the government changed its approach. It moved from fixed pricing to reverse auctions, where developers competed by offering the lowest tariff. This triggered strong competition and innovation.

Solar tariffs dropped sharply, falling from around 12.16 per kWh in 2010 to 2.44 per kWh by 2017. As a result, scale increased rapidly. India's solar capacity grew from around 10 MW in 2010 to more than 70 GW by 2023.

The above case study provides a key lesson, i.e., the government can act as an early buyer to support new technologies. Once costs fall and the market matures, competition can take over and drive large-scale growth.

This chapters shows how necessary policy implementation and governmental support can help the industry to grow from a non profitable industry to a profitable industry.

Chapter 3

Methods

3.1 Research Philosophy and Design

The research method for technology policy requires a balance between scientific and practical industry understanding. This thesis uses a qualitative research method. It has already been elaborated in Section 1.4.

3.1.1 Justification for Qualitative Approach

The Indian quantum hardware ecosystem is at an early stage, and the number of active hardware startups is small. The quantitative methods such as surveys and statistical analysis may not provide an accurate picture of the issues faced by the quantum hardware industry. To avoid this, a qualitative method is used for analysis. The method includes inputs from stakeholders in the form of KIIs (Key Informant Interviews).

3.2 The Data Analysis Method

To ensure the validity of the findings, this research uses a triangulation strategy. This involves verifying information from three distinct sources:

1. **Secondary Policy Analysis:** Review of NQM documents, EU Flagship reports, differnt articles and historical data from the Pharmaceutical and Automobile sectors.

2. **Primary Stakeholder Interviews:** Direct insights from startup founders, academicians, TTOs and investors.

3. **Comparative Benchmarking:** Analyzing domestic realities against international standards like QuTech (Netherlands).

3.3 Participant Selection and Sampling

This study uses purposive sampling, i.e., to identify participants who can provide practical insights about the quantum value chain. There are total ten ($N = 10$) key informants were selected, categorized into three groups:

Table 3.1: Classification of Research Participants

Cohort Code	**Stakeholder Type**	**Primary Focus Area**
R2, R5, R6, R8,R9, R10	Hardware Startups	Quantum devices, Supply Chain, Import
R7	Venture Capitalists	Patient Capital, Risk Assessment
R1, R3, R4	Academicians/TTOs	IP Transfer, Lab-to-Fab Transition

3.4 Data Collection Protocol

Interviews were conducted using a semi-structured format, which allowed insights into different sets of questions specific to their domain. There are certain questions that were common for all respondents.

3.5 Thematic Analysis Procedure

The primary data was collected through online interviews. Some part of primary research data was also collected by circulating Google Forms. The analysis was done in three different stages:

- Finding the raw friction points (e.g., Customs took 3 months)
- Grouping them into broader themes like "Infrastructure Gaps" or "Regulatory Friction."
- Linking these themes to the policy recommendations in Chapter 5.

3.6 Ethical Considerations and Anonymity

Quantum hardware sector is competitive and sensitive in nature. Some of the participants requested anonymity, while others are credited in the acknowledgments. To get honest feedback regarding the limitations of the National Quantum Mission without fear of professional repercussions, this step was necessary.

Chapter 4

Results and Discussion

4.1 Analysis of Stakeholder Insights

The following table illustrates the mapping between the codes from the data collected through primary research and structural issues.

Table 4.1: Thematic Analysis of Interview Transcripts

Thematic Category	**Key Informant Observations (Raw Codes)**	**Frequency (N=10)**
Logistical Friction	Customs delays; Dual-use licensing confusion; High import duties on cryo-components.	8 / 10
Infrastructural Deficit	Absence of open-access cleanrooms; Outsourced fabrication; High CAPEX for testing.	9 / 10
Financial Misalignment	Lack of "Patient Capital"; Short VC fund cycles; Grant size vs. Prototype costs.	7 / 10
Institutional Hurdles	Rigid IP licensing at government labs; Lack of industry-academic consortiums.	6 / 10

4.2 Stakeholder Evidence: Startup Ecosystem Challenges

This section identifies the issues faced by different quantum hardware startup ecosystems based on the inputs provided by the startups through KIIs (Key Informant Interviews).

Startups working on developing quantum hardware face a complex and layered set of challenges. These are described below.

4.2.1 Severe Import, custom, and supply chain barriers

(i) **High Import Dependency and Financial Burden**: The thesis identifies that some startups have approximately 80–90% of their hardware components imported. The reason for this is limited domestic availability, only to standard electronics like PCBs and commercial off-the-shelf microcontrollers. So, startups are forced to import ultra-stable laser systems, acousto-optic/electro-optic modulators, dilution refrigerators, pulse-tube coolers, low-noise amplifiers, time-frequency standards (rubidium/caesium), UHV chambers, titanium sublimation pumps, ultra-pure alkali metals, and MSME-grade substrates. These specialized components face 18–28% customs duties, which inflate the total cost by 25–35%. Also, paying an 18% GST on R&D equipment with slow refund mechanisms adds a hidden financing cost.

(ii) **Unusable Duty Exemptions, Customs Misclassifications, and Compliance Risk**: While duty exemptions exist for scientific research, they are unusable for private startups. To get this duty exemption, they require a certificate from an institution head (designed for universities). Also, quantum components are not included in the approved exemption schedule, which forces startups to pay full duty and seek multi-year refunds. Research-grade dilution refrigerators should lie in the category of scientific instruments (HS 9027), but currently these are imported under consumer 'refrigerating equipment' (HS 8418). This doubles the duty. The laser systems are hit with a 15% Basic Customs Duty (BCD) on top of IGST because they are classified as industrial equipment, demanding industrial import permits. Private startups do not have these permits. As a result, on average, customs clearance takes 15–45 days. In an 8–12 month prototype iteration cycle, import delays alone account for 3–4 months of lost time.

4.2.2 Access to Capital and the "Valley of Death"

(i) **Timelines of Government Grants**: Government schemes (like DST, MeitY, DRDO TDF, NIDHI-EIR) take approximately 12–24 months from application to the first disbursement. To get a sanction letter, it takes around 6–18 months and an additional 3–6 months for the money to reach the startup.

(ii) **Private Investor Mismatch**: Quantum hardware commercialization requires 7–10 years of patient capital. Securing private VC/angel funding is a faster process compared to securing government funds. However, private equity prefers short-term returns, which is incompatible with the hardware sector.

(iii) **Grant Structure** : The iteration cycles of quantum hardware are quite unpredictable, but the disbursements are based on milestones, which indicates that the grant structure is poorly suited for hardware startups.

Apart from that, there is a lot of paperwork (audited accounts, incorporation certificates, utilization certificates) involved in the process. This eats up the founders' bandwidth and treats every technical failure as an audit event.

(iv) **Prototyping Funding Gap**: During the hardware prototyping phase (TRL 4–5), the capital requirement jumps by 5–10 times, but because the product isn't field-ready yet, equity investors retreat. Also, government grants are too slow to support product development.

4.2.3 Public Procurement Constraints

Exclusion from Government Tenders: For quantum sensors, government labs (ISRO, DRDO, NPL) are the natural first customers. Early-stage startups face barriers in procurement processes. Tenders on the GeM (Government e-Marketplace) portal require the lowest-price (L1) selection and field-proven deployment. Some startups face this issue despite positive technical discussions, i.e., they cannot get customers without field deployment, and they cannot secure field deployment without a customer.

4.2.4 Regulatory and Bureaucratic Friction

Quantum hardware development falls under multiple government bodies (DRDO, DAE, DoT, and MeitY) with no single-window clearance. Similarly, for emerging quantum technology, India's SCOMET list is poorly calibrated, which makes it difficult for startups to obtain fast-track export licenses. Also, there is no availability of clear guidance on what quantum sensors are permissible for civilian sales versus those restricted under defence rules.

One of the major issues that startups identified is unresponsive policymakers, i.e., government agencies show low to moderate responsiveness to the feedback of startups. Also, most of the policies by agencies are focused on metrics like patents filed or companies incorporated rather than tracking real technical progress like TRL advancement.

4.2.5 Talent Scarcity

India has a lack of trained talent who have hands-on experience in engineering tools in quantum optics and atomic physics. Very few relevant graduates are produced every year that are suitable for the ecosystem. The few skilled graduates that emerge from the system are recruited by international giants (IBM, Google, IonQ) and European labs before Indian startups can hire them, which is also known as "Brain Drain".

4.2.6 Intellectual Property Hurdles

It takes almost 5 to 7 years for the Indian Patent Office to grant a patent, especially in the physics and electronics division. There is no fast-track patent examination process for deep-tech startups, and there are no specialized patent attorneys in India who understand quantum hardware claims. For startups, filing international patents (PCT) is expensive.

4.2.7 Infrastructure Deficit

Long Queues and Missing Facilities: Startups face a 6–12 month waiting list to access cleanrooms and fabrication facilities at places like IIT Bombay or IISc Nanofabrication Centre. India has a lack of advanced shared facilities like a national UHV library, quantum photonics foundries, or rapid-access dilution refrigerators, which forces startups to take their fabrication needs overseas to EPFL (Switzerland), IMEC (Belgium), and CMC Microsystems (Canada).

Apart from all these major issues, startups also highlighted that the government takes a top-down approach rather than a bottom-up approach. The government is directly investing in assembling quantum computers. This neglects the foundational building blocks like wiring, high-speed electronics, and high-precision manufacturing.

4.3 Ecosystem Constraints: The Venture Capital Perspective

According to the inputs provided by VCs, this section analyses the issues faced by VCs in investing in the quantum hardware sector for the longer term, i.e.,more than 11 years.

4.3.1 Fund Lifecycle Mismatch

As discussed above, quantum hardware requires 12–15 years of long-term investments. However, there is massive pressure on VCs to return the principal investment to their Limited Partners (LPs) by the 5th or 6th year. Also, they must completely shut down the fund by year 11.

The current market lacks private LPs who want to invest funds for 14–16 years. Because of these strict fund lifecycles, VCs are forced to evaluate quantum hardware startups similarly to other deep-tech sectors. This means that the startup should generate revenue within no more than 2 years.

4.3.2 Primary Investment Risks

VCs face a compounding set of risks while evaluating the quantum hardware sector. This makes the hardware sector highly difficult to invest in. Long development timelines, high technical uncertainties, extremely high capital requirements, severe lack of market clarity, and talent constraints are some examples of the involved risks.

4.3.3 Infrastructure and Ecosystem Gaps

India's quantum hardware infrastructure sector isn't venture-ready. While the infrastructure is improving, VCs note that it isn't yet fully fit for broad-based commercialization, i.e., not strong enough to make the sector venture-ready. For VCs, trade and customs policies are important variables. If the policies create friction, they slow down the startup's iteration cycles. This will be enough to kill the startup's market competitiveness. Compared to the US or Europe, VCs note that there is a huge gap between lab progress and repeatable industrial scaling within strict timelines.

As there is friction surrounding capital, imports, exits, and execution, VCs view the quantum hardware sector as highly unpredictable for investments. India is currently an investable market for concentrated and thesis-driven bets. But, for quantum industries, it isn't an easy place for VCs to build a diverse portfolio. They also face highly constrained exit opportunities for deep-tech startups in India. They do not view Initial Public Offerings (IPOs) as a feasible exit pathway for quantum hardware companies. The only practical pathways to successfully exit and return money to their LPs are through corporate acquisitions and strategic pathways.

4.4 Institutional Gaps: The Role of Academia and TTOs

Limited financial support to set up laboratories, less access to fabrication and testing facilities, funding delays from public sources due to a lot of administrative work, and poor policy design for reporting success rather than enabling research, i.e., high demand for paperwork to report progress and financials, are some of the major hurdles which slow down quantum hardware research in academia. Similarly, TTOs (Technology Transfer Officers) find that systematic IP navigation sometimes becomes very difficult. Collaborations across different universities and managing IP rights make the process frustrating.

University researchers lack business insights and commercial vision, as at a fundamental level these are not part of their domain expertise, which creates struggles in translating lab research into real-world products. In India, there is a lack of framework for academia-industry collaboration. Especially, this collaboration aspect is very common in European countries. As mentioned in the previous sections, current education and training programs do not align with industry needs, creating a scarcity of human capital.

4.5 Summary Table of Issues Faced By Stakeholders

Table 4.2: Comparative Analysis of Structural Barriers by Stakeholder Group (Part 1: Capital & Infrastructure)

Issue Category	Startups	VCs	Academia/TTOs
Funding & Capital Access	Government grants take 12–24 months to disburse and require heavy paperwork designed for mature businesses. The milestone-based structure is hostile to hardware iteration. Startups face a severe "Valley of Death" funding crunch at the prototyping stage (TRL-4/5) when equity investors retreat and government grants are too slow.	Fund lifecycle mismatch is the biggest hurdle: VC funds shut down in 9–11 years, while quantum hardware needs 14–16 years to mature. Consequently, VCs demand clear revenue within 1–2 years. VCs need the government to co-invest (30-50%) and provide downside protection.	There is a fundamental lack of financial support to initially set up laboratories. Securing public funds involves tedious administrative processes and extremely long timelines. Heavy paperwork focuses on reporting financials rather than enabling real research.
Infrastructure & Supply Chain	80–90% of components are imported because India lacks a foundational base hardware ecosystem (e.g., cannot machine basic vacuum chambers). Startups face 18–28% customs duties, 15-45 day delays, and misclassification of scientific instruments as consumer goods. There are 6–12 month waiting lists for local cleanrooms.	The lack of shared national infrastructure keeps the sector from being broadly "venture-ready", making capital risk exceptionally high. Import dependencies and customs friction directly compress iteration cycles, which can slow startups down enough to kill their market competitiveness.	Absolute lack of state-of-the-art fabrication and testing facilities locally. Researchers are often forced to go to Europe or Canada for basic fabrication needs.

Table 4.3: Comparative Analysis of Structural Barriers by Stakeholder Group (Part 2: Market & Translation)

Issue Category	**Startups**	**VCs**	**Academia/TTOs**
Public Procurement & Market	Trapped in a procurement "Catch-22": Government tenders demand 3-5 years of profitability, MSME turnover, and field-proven deployments, locking out early-stage startups. Startups desperately need the government to be a first customer via Innovation Partnerships and Minimum Order Quantities (MOQs).	Government demand and public procurement are "extremely" important to create early markets. VCs view the government as the biggest future customer and emphasize that policies must incentivize domestic buying to reduce market risk for private capital.	Researchers desperately need government bodies or research institutes to act as "pioneer customers" to pilot and test early-stage innovations, but current structures do not support this.
Intellectual Property (IP) & Translation	The Indian Patent Office takes 5–7 years to grant patents and lacks an expedited track for deep-tech startups. Translating lab research to the market is blocked by conservative university licensing terms and strict conflict-of-interest rules preventing faculty from holding equity.	VCs face a highly constrained exit environment with no realistic Initial Public Offering (IPO) pathways. They must rely on strategic partnerships and corporate M&A for exits. They advocate for simpler cross-border IP rules.	Managing IP rights is made exceedingly difficult when collaborating across multiple universities or institutes. Researchers fundamentally lack business vision and require commercialization training to translate ideas.

Table 4.4: Comparative Analysis of Structural Barriers by Stakeholder Group (Part 3: Policy & Human Capital)

Issue Category	**Startups**	**VCs**	**Academia/TTOs**
Policy Focus & Bureaucracy	Policymakers falsely assume hardware operates on fast software timelines and that simple funding creates progress. Policies are designed around "vanity metrics" (patents filed, money spent) rather than tracking true Technology Readiness Level (TRL) advancement.	The immense daily friction around capital, imports, exits, and execution makes quantum hardware startups look highly unpredictable to investors. Policy must shift from being purely government-driven to actively attracting private capital.	The bureaucracy is described as a "mad circus" that can stall research for years. Researchers are penalized for doing high-risk research because they lack the total freedom to explore without being tied to restrictive guides.
Talent & Human Capital	Graduates have heavily theoretical knowledge but zero hands-on problem-solving skills with actual hardware. The talent pipeline is extremely thin (<50 grads/year), and the best minds face brain drain to foreign tech giants.	Talent constraints are listed as one of the primary risks when evaluating startups. However, VCs are optimistic that current geopolitical situations and international visa issues might drive home-grown talent back to India.	Current education programs fail to provide practical, hands-on training, resulting in a serious lack of capable engineers. Furthermore, Indian PhDs are treated as dependent students rather than independent engineers, stifling their decision-making abilities.

Chapter 5

Conclusion and Policy Roadmap

The chapter proposes policy recommendations based on findings from primary and secondary research.

5.1 Introduction to the Policy Roadmap

The hardware ecosystem requires structured policy-level interventions in order to make the shift from a research-heavy ecosystem to a self-reliant industry. It is a shift from 'knowing how' to 'scaling now'. The global quantum technology sector has already made the transition from scientific curiosity to geopolitical competition. So, indigenous growth is now becoming a necessity.

The necessary policy interventions have been categorized into three categories:

(i) Lessons from the European ecosystem (ii) Short-term policy interventions (iii) Medium-to-long-term policy interventions

5.2 Lessons From European Ecosystem

(i) **Industrial PhD and National Corps Program**: The Netherlands' Quantum Delta NL heavily subsidizes PhD researchers who work in both a university lab and a private startup. India should launch a "National Quantum Industrial Fellowship". This includes PhD programs (with a fixed number of seats) with competitive stipends or enhanced stipends for existing JRF and SRF PhD fellows, who must spend 50% of their time at an Indian startup or MSME or at an NQM Thematic Hub, as well as 50% in university labs. The startup provides the problem statement and mentorship, while the state covers the stipend. This will ensure startups get highly skilled talent. It will also provide opportunity to the fellows pursuing PhD to enhance their skills and become industry ready.

(ii) **Lab-to-Fab Foundries and Quantum Pilot Line**: Belgium's IMEC provides open access to 300 mm CMOS manufacturing, and Finland's Kvanttinova operates pilot lines for scaling. India should establish national quantum foundries and can offer subsidized, open access to cleanrooms, lithography, and cryogenic testing for private startups. It will reduce CAPEX barriers for startups. The government should carve out a dedicated "Quantum Pilot Line", which will support non-standard quantum materials (like superconducting niobium). The management of the Pilot Line can be done by an industry-academia consortium like IMEC.

(iii) **Government as a "First Buyer"**: Finland's VTT hired a startup, IQM, to build their national quantum computer. France's ProQCIMA program is paying five different startups to build prototypes for their military and government needs. Stakeholders suggest that the government should act as a first customer and also should introduce Minimum Order Quantity (MOQ) guarantees and Advance Market Commitments (AMCs). This will provide guaranteed revenue to startups and will also make them attractive for private investors.

(iv) **Venture Debt and Deep Tech Fund of Funds**: The European Investment Bank provided a €35 million special loan to IQM., which works like a credit line for startups.

To help the startups grow into a real business, the EU often uses 'blended finance,' which means they give companies a mix of free grant money for research and also buy a small stake in the company. Similar to this, India has already proposed the "Deep Tech Fund of Funds" in the National Deep Tech Startup Policy (NDTSP) report, but it needs to be fast-tracked.[30]

A Venture Debt Guarantee Scheme can also be helpful for hardware startups, which will provide loans for equipment. The purpose is to ensure patient, long-term equity capital into hardware-focused venture capitalists.

(v) **IP Retention**: The idea of a "Fiscal Magnet" focuses on retaining intellectual property within the country. India should introduce such policies to ensure that high-value innovations are not shifted abroad.

Belgium provides a strong example. The government offers up to an 85% tax reduction on income generated from intellectual property, which lowers the effective tax rate for innovators.

India should do the same. If we offer a low 10% tax rate on profits made from Indian-registered patents, startups won't feel the need to flip or move their headquarters to places like Singapore or the US just to save on taxes.[31]It would give them a huge reason to keep their patents and their factories right here at home.

(vi) **Quantum Technology for Policymakers**: The European Quantum Flagship provides dedicated programs called Quantum Technology Training for policymakers, patent officials, and government officials. It consists of monthly online training sessions and some offline sessions/visits for policymakers so that they can gain knowledge about the technical aspect related to the quantum industry. Apart from that, there is another program called QTIndu, i.e., a Quantum Technology course for Industry. The objective is to provide scientific rigor to policymakers without any complex mathematical jargon. These help policymakers bridge the gap between policy and the technical sector. India should also launch a similar kind of program for policymakers.

5.3 Short-Term Policy Interventions (2026–2027)

Government should take necessary policy interventions which doesn't require large investment or infrastructure development. These are as follows:

(i) **Quantum Green Channel**: The Ministry of Finance and the Department of Science and Technology (DST) should establish a Quantum Green Channel for imports. Government agencies (Director General of Foreign Trade) should make a list of critical quantum components, such as Helium-3, dilution refrigerators, and AWGs, with distinct HS codes to separate them from consumer goods. This will cut procurement time drastically.

(ii) **Equity-Based IP Licensing**: University TTOs need to abandon rigid and royalty-heavy licensing models and should focus on helping startups grow in the early stage. In the 1970 Patent Act, a similar approach was used. This helped the pharmaceutical industry expand in India. A practical way is to reduce royalty-based demands and take a small equity stake of 2–5%. If at a later stage the startup succeeds, then it will be beneficial for the institutions.

5.4 Medium-to-Long-Term Industrial Strategy (2028–2031)

In addition to necessary interventions in a short-time period, Government should think for a sustainable growth in a long run. Here are some policy recommendation as a long term vision:

(i) **Talent Development**: The government should introduce a 6-month industry internship in quantum hardware labs as a mandatory PhD requirement. Shared hardware teaching labs (laser systems, vacuum chambers, FPGA-based control electronics) at IITs should be funded and made accessible to students and startups alike. A dedicated Quantum hardware engineering MTech track with embedded industry projects should be designed. NQM should fund 100+ dedicated postdoctoral fellowships with a startup-deployment pathway similar to DARPA's Embedded Entrepreneurship Initiative. Quantum Hardware Bootcamps (3-4 months) should be established for re-skilling photonics, RF, and instrumentation engineers into the quantum domain.

(ii) **Quantum Production Linked Incentives**: Similar to the automobile sector, a targeted Q-PIL scheme must be established for domestic manufacturing of the secondary supply chain, such as cryocables, single-photon detectors, and specialized microwave electronics. This Q-PIL scheme must abandon standard volume metrics, as it operates on low-volume, high-complexity economics. It should offer 10–15% higher incentives on net sales.

(iii) **Metrics Measurement**: Instead of focusing on money disbursed and the number of grants sanctioned, the focus should be on real technological progress, i.e., TRL progression should be tracked by measuring the average TRL of funded startups at 12, 24, and 36 months post-grant. Annually, there should be a comparison of sensitivity, stability, and size-weight-power (SWaP) of Indian quantum sensors against international standard products.

(iv) **National Strategic Quantum Materials Reserve**: The Department of Atomic Energy (DAE) should stockpile a 5-year rolling buffer of Helium-3 and critical rare-earth minerals to prevent supply-chain weaponization. This should be accessible to NQM startups at a subsidized rate during a crisis.

The other long-term recommendations are listed in the section 5.2.

Table 5.1: Phase 1: Short-Term Policy Interventions (2026–2027)

Policy Intervention	**Mechanism**	**Implementing Agency**	**Target Outcome**
Quantum Green Channel	Distinct HS codes and zero-duty clearance for critical components.	Ministry of Finance, DGFT, DST	Eradicate demurrage delays and reduce hardware prototyping time-tax.
Equity-Based IP Licensing	Pharma-style tech transfer replacing upfront royalty fees with 2–5% equity.	Academic TTOs (IISc, IITs, IISERs)	Accelerate the transition of academic IP to commercial spin-offs.

Table 5.2: Phase 2: Medium-Term Industrial Strategy (2028–2031)

Policy Intervention	**Mechanism**	**Implementing Agency**	**Target Outcome**
Sovereign Fabrication Hubs	Open-access cleanrooms and the SCL Mohali "Quantum Pilot Line."	MeitY, DST	Eliminate the CAPEX barrier and "fabless trap" for startups.
Quantum PLI (Q-PLI)	10–15% value-based incentives + 25% Capex subsidy for manufacturing.	MeitY	Localize the secondary supply chain (cryocables, lasers, electronics).

Table 5.3: Phase 3: Long-Term Strategic Framework (2030–2035)

Policy Intervention	**Mechanism**	**Implementing Agency**	**Target Outcome**
Advance Market Commitments (AMC)	Pre-commercial procurement and L1-rule waivers for startups.	Strategic Ministries (Space, Defense)	Government acts as the "First Buyer" to unlock private VC capital.
Strategic Materials Reserve	Active stockpiling of Helium-3 and rare-earth materials.	DAE	Ensure strategic autonomy against geopolitical supply shocks.

5.5 Conclusion and Future Outlook

India's National Quantum Mission creates a genuine opportunity to build a globally competitive quantum hardware industry. The foundational science exists, the talent can be trained, and early-mover advantage is still available in quantum sensing. However, capturing this opportunity requires policies that match the actual timelines, risk profiles, and supply-chain realities of quantum hardware development, not generic deep-tech policies retrofitted from the IT sector.

The thesis provides consolidated data and recommendations using an evidence-based method. However, the scope of improvement will always be there. The challenges faced by different startups and academia are different. So, recommendations can be subjective. Hence, the number of primary research participants can be further increased over time. Policies always need to be updated from time to time with progress.

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Appendix A

Additional Derivations / Data

Table A.1: Impact Ratings of Policy Pillars By Stakeholders' response

Policy Pillar	GDQ Labs (Startup)	Quanastra (Startup)	Optical Sim Startup	Quantum Software Startup	Academia	Policymaker	VC (Seafund)	QuantrolOx (Industry Rep)
Research and development (R&D) funding	9	9	9	10	9	8	9	9
Infrastructure support	8	9	9	10	8	6	9	8
Trade and import-export policies	9	6	7	9	5	7	7	7
Public procurement policies	7	9	6	9	5	9	7	7
Workforce development and skills	7	5	7	10	8	5	7	8
Intellectual Property (IP) protection	7	7	7	10	5	8	7	6
Tax incentives	8	7	9	10	6	7	7	3

Appendix B

Primary Data Collection Participants

B.1 Profile of Research Respondents

List of stakeholders who contributed to the primary research.

Table B.1: Classification and Affiliation of Primary Stakeholders

Participant Code	Name	Affiliation / Organization
R1	Ms. Giulia Ferrini	Academic Expert
R2	Ms. Aishwarya Bhosale	Artificial Brain
R3	Ms. Amruta Gadge	SIIC, IIT Kanpur
R4	Ms. T. Theivasanthi	Academic Researcher
R5	Mr. Pranab Dutta	GDQ Labs
R6	Mr. Siddharth Singh	QuantrolOx
R7	Mr. Mayuresh Raut	Seafund
R8	Team Quanastra	Startup
R9	Anonymous	Indian Startup
R10	Anonymous	Indian Startup

Appendix C

Key Informant Interviews (KIIs) Questionnaires

C.1 Group 1: Startups

Questionnaire A: Policy Framework for Hardware Startups in India

1. From a policy perspective, what challenges have you faced while building a hardware based startup in India?
2. Which of these areas do you think have the highest impact on the growth of hardware startups in India?
   - Intellectual Property (IP) protection
   - Public procurement policies
   - Trade and import-export policies
   - Infrastructure support
   - Workforce development and skills
   - Tax incentives
   - Research and development (R&D) funding
3. If possible, could you rate each of these on a scale of 1 to 10 based on their impact?

Policy Area	1	2	3	4	5	6	7	8	9	10
Intellectual Property (IP) protection										
Public procurement policies										
Trade and import-export policies										
Infrastructure support										
Workforce development and skills										
Tax incentives										
Research and development (R&D) funding										

4. Are there any additional policy areas that you believe should be included in this list?

5. From a policy standpoint, how is startup funding supported by existing policies? Please elaborate: Was there a stage in your startup journey when funding became more difficult?

   How easy or difficult is it to access government grants or support schemes, and what are the main challenges involved?

6. At the current stage of your startup, what kind of support do you need most ?

   - Money
   - Infrastructure
   - Customers
   - Talent
   - Other: ____________________

7. Does public procurement in India affect your ability to sell or test your product? Please elaborate.

8. What is the typical timeline for funding approvals from public sources vs private sources?

9. How responsive are government agencies to stakeholder feedback?

10. What is the biggest challenge related to talent?

    - Lack of trained people
    - High cost of talent
    - Brain drain

- Visa / mobility issues
- Other: ____________________

11. Are current education and training programs aligned with industry needs? (Yes/No/Partially) Any suggestions on what should be changed specifically for Quantum Hardware technology?
12. Are IP and patent processes easy to navigate?
13. Compared to Europe, how supportive is the Indian ecosystem for hardware startups? Which European practice should India adopt first?
    - Faster funding
    - Shared infrastructure
    - Procurement reform
    - Tax incentives
    - Talent mobility
    - Other: ____________________
14. How easy is it to translate lab research into real products in India? What barriers do researchers face when working with startups or industry? What changes would help universities contribute more to hardware startups?
15. What percentage of your total hardware components are imported? What type of components are most commonly imported (optics, electronics, cryogenics, materials, any other)?
16. Have you faced delays or high duties due to unclear customs classification? Have research grade components ever been classified as commercial or consumer products?
17. Do customs duties and taxes increase your total project cost? Have you applied for any customs duty exemptions for research imports? If exemptions exist, how easy or difficult are they to use in practice?
18. How much faster could your work progress if import procedures were simplified? In your view, do current import rules discourage domestic hardware research? What changes would you suggest?
19. Has any government body ever acted as your first customer? Have you received any assured order or purchase commitment from the government?

20. Would a Minimum Order Quantity (MOQ) policy change your product development plans?
21. Are you eligible to participate in government tenders? Which tender conditions are hardest to meet? Should different procurement rules apply to research and innovation? What single procurement reform would help the most?
22. Do you have access to fabrication and testing facilities in India? If yes, are these facilities easy to access? If not, where do you go for fabrication or testing?
23. What facility is most urgently needed in India?
24. How does India compare with Europe in supporting hardware startups? What support mechanism abroad impressed you the most? Are tax and customs policies more research friendly?
25. Which European policies should India adopt?
26. What assumptions do you think policymakers make about hardware innovation that do not match reality?
27. Do you think current policies are designed more for reporting success or enabling real progress? How often are policies revised based on ground level feedback?
28. How should success in quantum or deep tech policy be measured? Are current metrics focused more on spending or outcomes? What indicators best show real technological progress?

Questionnaire B: Expert Interview: Quantum Hardware Ecosystem & Policy (Europe)

1. From your experience across India, Europe (TU Delft/QuTech), and now industry (QuantrolOx), what are the key structural differences in how the quantum ecosystem functions?
2. Among the following policy areas, which do you think have the highest impact on the development of a quantum hardware ecosystem?
    - Intellectual Property (IP) protection
    - Public procurement policies
    - Trade and import-export policies
    - Infrastructure support (cleanrooms, fabrication labs)
    - Workforce development and skills

- Tax incentives
- Research and development (R&D) funding

3. If possible, could you rate each of these on a scale of 1 to 10 based on their impact?

4. Are there any additional policy areas that you believe are critical but missing from this list?

5. At institutions like QuTech, how does research typically transition into startups or industry applications?

6. In your view, what are the biggest barriers in translating quantum hardware research into real products?
   - Lack of funding
   - Weak industry academia collaboration
   - Infrastructure gaps
   - Regulatory or policy barriers
   - Talent limitations
   - Something else (Please elaborate)

7. How easy is it for researchers to collaborate with startups or industry partners in Europe? Are there administrative or policy-related challenges that slow this process?

8. What changes would help universities in India contribute more effectively to hardware startups?

9. How is quantum hardware research and startup development typically funded in Europe? What is the balance between public funding and private/venture capital?

10. How does the timeline for public funding compare with private funding in practice? Do delays in fund disbursement affect research or startup progress?

11. In your opinion, is government funding alone sufficient for quantum hardware development? What role should private capital realistically play in India?

12. What is the biggest challenge related to talent in quantum hardware?
    - Lack of trained people
    - Insufficient experimental exposure

- High cost of skilled researchers
- Brain drain
- Something else (Please elaborate)

13. Are current education and training programs aligned with industry needs? (Yes/No / Partially) What specific changes are needed for quantum hardware training?
14. From a student's perspective, what skills are most critical to work in quantum hardware (especially experimental roles)?
15. How critical are fabrication facilities, cleanrooms, and shared infrastructure for quantum hardware development?
16. Do you think India needs centralized national facilities or distributed institutional labs?
17. What is the minimum infrastructure India must build to remain competitive in quantum hardware?
18. To what extent are quantum hardware components dependent on imports? Which components are most difficult to source domestically?
19. Do import regulations, customs duties, or delays significantly affect research or startup progress? What specific policy changes would improve this?
20. From your perspective, would a company like QuantrolOx be viable if it were based in India today? What policy barriers would it face?
21. Does public procurement play a meaningful role in supporting deep-tech startups? Should governments act as early customers in quantum technologies?
22. How responsive are policymakers to feedback from researchers and startups?
23. How does India compare with Europe in supporting quantum hardware development?
24. Which specific European policies or practices should India adopt first?
    - Faster funding mechanisms
    - Procurement reforms
    - Shared infrastructure
    - Talent mobility

- Industry-academia integration
- Any other

25. What assumptions do policymakers in India make about quantum hardware that do not match ground reality?

26. Do you think current policies are designed more for reporting success or enabling real progress?

27. If you were advising the Indian government, what would be your top 3 policy priorities for quantum hardware?

28. How should success in quantum technology policy be measured?

    - Spending vs outcomes
    - Publications vs products
    - Talent vs infrastructure
    - Any other indicators

29. Do you think India should aim to compete globally in quantum hardware, or focus on specific niche areas? Which niches are realistically achievable?

30. For a student in India today who wants to work in quantum hardware, what path would you realistically recommend?

C.2 Group 2: Venture Capital (VC)

Questionnaire: Policy Framework for Quantum Hardware Investment

1. From your perspective, how attractive is quantum technology particularly quantum hardware as an investment sector today?

2. Do you currently invest in deep tech or quantum startups?

    - Yes
    - No
    - Exploring

2a. If yes, what is your investment thesis in this space? If no, what prevents you from investing?

3. How do you evaluate a quantum hardware startup differently from a typical software startup?
4. What are the primary risks you associate with quantum hardware investments?
   - Long development timelines
   - Technical uncertainty
   - High capital requirements
   - Lack of market clarity
   - Talent constraints
   - Regulatory or policy risks
   - Other: ____________________
5. What kind of return expectations and time horizons do VCs typically have for deep tech investments like quantum hardware?
6. Do current policy frameworks in India align with these expectations? If not, where is the mismatch?
7. Among the following policy areas, which have the greatest impact on your willingness to invest in quantum hardware startups? If possible, could you rate each of these on a scale of 1 to 10 based on their importance for investment decisions?

Policy Area	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Intellectual Property (IP) protection										
Public procurement policies										
Trade and import-export policies										
Infrastructure support										
Workforce development and skills										
Tax incentives										
Research and development (R&D) funding										

8. Are there any additional policy factors that strongly influence investor confidence?
9. At which stage do you think quantum hardware startups face the biggest funding gap?

- Early stage (idea/prototype)
- Mid stage (technology validation)
- Late stage (scaling/manufacturing)

10. Do you think government funding schemes in India help reduce investment risk? Or do they create dependency without improving investability?

11. What kind of co-investment models (government + private capital) work best in deep-tech sectors?

12. How does the lack of infrastructure (cleanrooms, fabrication facilities) affect your investment decisions?

13. Would shared national infrastructure reduce capital risk for investors? In addition, is there an adequate enabling infrastructure for the success of the quantum industry in India?

14. Do import dependencies and supply chain issues impact the scalability of quantum hardware startups? How important are trade and customs policies in this context?

15. What do you look for in the founding team of a quantum hardware startup?

16. Do you think India has sufficient talent to build globally competitive quantum hardware companies?

17. How does talent mobility (e.g., international exposure, visas) affect startup quality and investment decisions?

18. Do you see a clear commercial market for quantum hardware in the near to medium term?

19. How important is government demand (public procurement) in creating early markets?

20. Should the government act as a first customer for quantum technologies?

21. How does India compare with Europe or the US in terms of investability in quantum hardware?

22. What specific international policy models have successfully attracted VC investment in deep-tech?

23. Which policies should India adopt immediately to improve investor confidence?

24. What are the biggest policy bottlenecks that discourage VC investment in quantum hardware in India?

25. Do you think current policies are designed to attract private capital, or are they primarily government-driven?

26. What are the top 3 policy changes that would make India more attractive for quantum hardware investment?

27. Are there sufficient exit opportunities in India for deep tech startups? What are realistic exit pathways for quantum hardware startups?

    - Acquisition
    - IPO
    - Strategic partnerships
    - Other: ____________________

28. How should success in quantum policy be measured from an investor's perspective?

C.3 Group 3: Academia

Questionnaire A: Policy Framework for Quantum Ecosystem (Europe)

1. From your experience in Europe, what makes the quantum research ecosystem work well?

2. Among the following policy areas, which do you think have the highest impact on the growth of quantum tech ecosystem in Europe?

    - Intellectual Property (IP) protection
    - Public procurement policies
    - Trade and import-export policies
    - Infrastructure support
    - Workforce development and skills
    - Tax incentives
    - Research and development (R&D) funding

3. If possible, could you rate each of these on a scale of 1 to 10 based on their impact?

4. Since your work is focused on fundamental research and training PhD students, I would like to understand how research funding is typically secured in Europe. Do research groups rely mainly on government grants, or are private, industrial, or collaborative sources also important?

5. What problems do researchers face that policy makers may not see? Do administrative rules ever slow down research or collaboration? Please elaborate.

6. In your experience, how does the timeline for public research funding compare with private or industrial funding? There is often a concern that administrative procedures can delay the release of approved funds. Do you see similar delays in the European research system?

7. Several companies working in quantum technology, including IBM and Google, have mentioned the shortage of skilled workforce in this field. In your view, why does this shortage exist? What kind of initiatives should governments and universities take to develop strong talent in quantum science and technology? And from a student's perspective, what should young researchers focus on to prepare for this field?

8. What skills do you think future quantum researchers will need the most?

9. Are current education and training programs aligned with industry needs? (Yes/No/Partially) Any suggestions on what should be changed specifically for Quantum technology?

10. In India, many recent initiatives appear to be more technology driven than focused on fundamental research. Do you observe a similar trend in Europe? How important do you think the balance between basic research and technological development is for the growth of the quantum ecosystem?

Questionnaire B: Policy Framework for Hardware Startups in India

1. From a policy perspective, what challenges have you faced while building a hardware based startup in India?

2. Among the following policy areas, which do you think have the highest impact on the growth of hardware startups in India?

    - Intellectual Property (IP) protection
    - Public procurement policies

- Trade and import-export policies
- Infrastructure support
- Workforce development and skills
- Tax incentives
- Research and development (R&D) funding

3. If possible, could you rate each of these on a scale of 1 to 10 based on their impact?

Policy Area	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Intellectual Property (IP) protection										
Public procurement policies										
Trade and import-export policies										
Infrastructure support										
Workforce development and skills										
Tax incentives										
Research and development (R&D) funding										

4. Are there any additional policy areas that you believe should be included in this list?

5. From a policy standpoint, how is startup funding supported by existing policies? Please elaborate: Was there a stage in your startup journey when funding became more difficult? In practice, how easy or difficult is it to access government grants or support schemes, and what are the main challenges involved?

6. What kind of support do you need most at the current stage of your start up?
   - Money
   - Infrastructure
   - Customers
   - Talent
   - Other: ____________________

7. Does public procurement in India affect your ability to sell or test your product? Please elaborate.

8. What is the typical timeline for funding approvals from public sources versus private sources?

9. How responsive are government agencies to stakeholder feedback?

10. What is the biggest challenge related to talent?

    - Lack of trained people
    - High cost of talent
    - Brain drain
    - Visa / mobility issues
    - Other: ____________________

11. Are current education and training programs aligned with industry needs? (Yes/No/Partially) Any suggestions on what should be changed specifically for Quantum Hardware technology?

12. Are IP and patent processes easy to navigate?

13. Compared to Europe, how supportive is the Indian ecosystem for hardware startups? Which European practice should India adopt first?

    - Faster funding
    - Shared infrastructure
    - Procurement reform
    - Tax incentives
    - Talent mobility
    - Other: ____________________

14. How easy is it to translate lab research into real products in India? What barriers do researchers face when working with startups or industry? What changes would help universities contribute more to hardware startups?

15. What percentage of your total hardware components are imported? What type of components are most commonly imported (optics, electronics, cryogenics, materials, any other)?

16. Have you faced delays or high duties due to unclear customs classification? Have research grade components ever been classified as commercial or consumer products?

17. Do customs duties and taxes increase your total project cost? Have you applied for any customs duty exemptions for research imports? If exemptions exist, how easy or difficult are they to use in practice?
18. How much faster could your work progress if import procedures were simplified? In your view, do current import rules discourage domestic hardware research? What changes would you suggest?
19. Has any government body ever acted as your first customer? Have you received any assured order or purchase commitment from the government?
20. Would a Minimum Order Quantity (MOQ) policy change your product development plans?
21. Are you eligible to participate in government tenders? Which tender conditions are hardest to meet? Should different procurement rules apply to research and innovation? What single procurement reform would help the most?
22. Do you have access to fabrication and testing facilities in India? If yes, are these facilities easy to access? If not, where do you go for fabrication or testing?
23. What facility is most urgently needed in India?
24. How does India compare with Europe in supporting hardware startups? What support mechanism abroad impressed you the most? Are tax and customs policies more research friendly?
25. Which European policies should India adopt?
26. What assumptions do you think policymakers make about hardware innovation that do not match reality?
27. Do you think current policies are designed more for reporting success or enabling real progress? How often are policies revised based on ground level feedback?
28. How should success in quantum or deep tech policy be measured? Are current metrics focused more on spending or outcomes? What indicators best show real technological progress?