

THE
QUANTUM
VALUE CHAIN
REPORT

DECEMBER 2023

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DR V K SARASWAT, CHAIRPERSON, QETCI

CHAIRMAN'S MESSAGE

The Quantum Value Chain Report is an insightful exploration of the intricacies of the quantum technology landscape in India. At QETCI, our commitment to fostering the quantum ecosystem is unwavering, and this report is a testament to our dedication to understanding, enabling, and accelerating quantum advancements in our nation.

The motivation behind this report stems from a realization that unraveling the quantum ecosystem's complexities requires a thorough comprehension of its players, the supply chain elements, and the enabling and inhibiting factors. Approaching this challenge through the lens of regulatory environments and trade policies provides a unique perspective on the current state of the quantum ecosystem, paving the way for future possibilities.

Quantum technology is not merely a technological leap; it is a paradigm shift with the potential to reshape socio-economic and security landscapes globally. As we stand at the threshold of the post-quantum era, nations without comprehensive quantum missions risk falling behind. In India, the National Quantum Mission has laid the foundation for a technological revolution, promising substantial investment and support for various quantum aspects. The effects are already tangible - research institutions intensify their efforts, students and professionals up-skill, and



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a vibrant quantum ecosystem emerges with startups and tech giants actively investing in R&D.

This report is not just an analysis; it is a roadmap for India's quantum future. The anticipated outcomes are comprehensive - a deep understanding of our quantum ecosystem, insights into the supply chain, informed policy recommendations, accelerated opportunities, and much more. development, identification of international collaboration

As we unveil this report, it is crucial to note it is a snapshot in time, capturing the quantum landscape. However, the dynamic nature of the field necessitates periodic updates, to keep stakeholders abreast of the evolving quantum value chain in India.

I extend my gratitude to the dedicated team at QETCI, collaborators, and all stakeholders whose collective efforts have brought forth this invaluable resource. May this report guide us in creating a thriving quantum ecosystem that not only embraces the potential of quantum technology but secures India's position on the global technological map.

Together, let us embark on a journey of quantum exploration, innovation, and excellence!

PREFACE



REENA DAYAL
Founder & CEO, QETCI

When QETCI was established in 2021, the founders, including myself, were unequivocal about the organization's mission. Our primary objective was to expedite India's progress in quantum science and technology, positioning QETCI as a pivotal facilitator within the ecosystem. During our interactions within the ecosystem, constructive dialogues ensued, revealing valuable insights into the strengths and the weaknesses areas. Given the intrinsic self-deprecating nature of Indians when discussing matters internally, we gleaned considerable information on areas requiring improvement in the Ecosystem.

As our engagements deepened, encompassing discussions, laboratory visits, and interactions with startups, an analysis emerged. We came to recognize the presence of hidden strengths within the Indian quantum ecosystem, characterized by profound passion from individuals, remarkable research and technical capabilities, and avant-garde startups that stood on the global forefront. This revelation extended to the presence of world-class researchers and research insights.

While emotions and passion are commendable, we recognized the importance of objectively assessing the quantum ecosystem's reality to effect positive change. Although supply chain considerations held significance, we determined that adopting a value chain approach would prove more efficacious. Given the nascent and evolving nature of quantum technology, a pre-existing framework for the value chain was non-existent. Consequently, we opted to formulate a comprehensive framework before overlaying the Indian value chain onto it.

On a tangential note, I grappled with the query of what constitutes an adept quantum policy professional. The deliberation between a policy expert delving deeper into quantum or a quantum expert venturing into policy terrain lingered. Consequently, we initiated a quantum fellowship program, offering students or early-career individuals with a quantum education, an opportunity to engage in policy work. Padmapriya, our inaugural policy fellow, collaborated with me on the creation of this report.

We are gratified to have gained myriad insights during the report's development. Moreover, we are enthusiastic about its potential to inform data-driven decision-making, programme design interventions, and formulate policy recommendations that underpin the growth of the quantum ecosystem in India. An additional revelation from this exercise is the efficacy of transitioning quantum professionals into individuals versed in policy and policy research.

I am grateful to all the people at QETCI and those in the ecosystem who supported this endeavour. Your thoughtful consideration of this report and your feedback are requested. As is characteristic of the dynamic nature of quantum technology, the framework and analysis presented in this report remain subject to evolution, we acknowledge the need for continuous refinement.



PADMAPRIYA MOHAN
Quantum fellow, QETCI

When I was first accepted as a Policy Fellow at QETCI, I found myself at the intersection of two seemingly disparate worlds: the technical realm of quantum technology, which I was more comfortable with, and the complex domain of ecosystems, policy, and governance, which was completely foreign to me. As a student pursuing a masters in quantum science and technology, I discovered that while my technical background afforded me a distinctive vantage point that allowed me to critically assess whether developments in the ecosystem aligned with the realities of say, quantum hardware, it was not enough to explore the dynamic, multidimensional landscape that extends far beyond the laboratory. Without a doubt, the promise of quantum technology is immense, but these transformative possibilities are intertwined with societal, economic, and policy considerations that need to be thoroughly understood and analyzed.

In doing this project, I have been able to broaden my perspectives and develop a more well-rounded, holistic approach to technology. I had the privilege of interacting with a number of stakeholders from the industry, the government, and from academia, which solidified my belief in the importance of combining technical expertise with the breadth of interdisciplinary knowledge. This report is the culmination of my passion for both technology and policy.

ACKNOWLEDGMENTS

**WE ARE DEEPLY GRATEFUL TO ALL PEOPLE WHO PLAYED A ROLE IN THIS REPORT.
WE WANT TO SPECIFICALLY THANK**

1. Governing Board Members for their support to QETCI and to this report
2. Stakeholder Committee for setting the context of expectations from this report
3. Interviewees who spared valuable time to answer questions in groups or in 1:1 meetings at different stages of the primary research

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INTRODUCTION

MOTIVATION FOR WRITING THIS REPORT

Understanding the ecosystem for quantum technology in any country requires an analysis of the various players in the ecosystem, elements of the supply chain and all enabling and prohibiting factors that contribute to the technology's development. This view along with the lens of the regulatory environment and the policies that govern internal and international trade would enable an understanding of the current state of the quantum ecosystem and the possibilities for the future.

At QETCI, our mission is to enable and accelerate the quantum ecosystem in India. To achieve this mission, it is important to first understand the quantum ecosystem in its fine elements. When we looked at the description of the ecosystem as mentioned above it became clear that the approach that came closest was an understanding of how value flows in the ecosystem for quantum and its associated technologies, and then superimposing upon it the Indian context. To accomplish this improved understanding of the Indian landscape for quantum, we decided to do a value chain mapping exercise for the quantum ecosystem in India.

Quantum technology is widely believed to have the potential to change socio-economic and security status-quo across the world. Nations that do not have comprehensive

quantum missions will be left behind in the post-quantum era (the timelines in which quantum technology scales up to provide a distinct quantum advantage). In India, the National Quantum Mission has set the stage for the country's technological revolution. The mission, which has been in the making for a couple of years now, promises 6000 crore INR towards various aspects of quantum technology [1]. While there were a handful of groups all over the country working on quantum technology in the early 2000s, the projects started to receive funding only in the 2010s. In the 2015-2016 time frame, there was a fair amount of international activity around quantum. China announced that it had successfully demonstrated satellite quantum key distribution (QKD) in 2016. At around the same time, the Indian government initiated and launched the QuEST program, which dedicated funds and support to academics who wanted to pursue projects in quantum information, quantum computing, quantum communication, and quantum sensing [2]. Later the National Mission for Quantum Technology and Applications (NMQTA) was announced in 2020. Recently this was approved by the cabinet in 2023. This news has ignited a flurry of exciting activity within the country's burgeoning quantum ecosystem [3]. The ripple effects of the National Quantum Mission are already palpable. Across the country, research institutions are ramping up their quantum research efforts, and students and professionals from various backgrounds are up-skilling. Startups specialising in quantum hardware, software, and applications are mushrooming, while established tech giants are actively investing in R&D.

In order to fully harness the potential of such an investment, it is crucial for stakeholders to have a comprehensive understanding of how value flows within the ecosystem, what the key elements of the supply chain are, and what areas are key for international collaboration. The goal is a thriving Indian quantum ecosystem that is a favourable playground for Indian academics, industry professionals, government entities, and even international collaborators.

This project centres around a comprehensive value chain analysis of the quantum technology value chain, and is motivated by the need to design and develop policy that can help India not only embrace the potential of quantum technology, but secure her position on the global technological map. The objective is to recognise strength areas, identify weak links, and analyse the current state of the Indian quantum technology value chain. Only an in-depth analysis can provide insight into aspects such as manpower, standards development, international collaboration, and more. The table below summaries the objectives of the report and also sheds light on the scope and indicators of success.

1.1 KEY MILESTONES IN THE HISTORY OF QUANTUM TECHNOLOGY IN INDIA

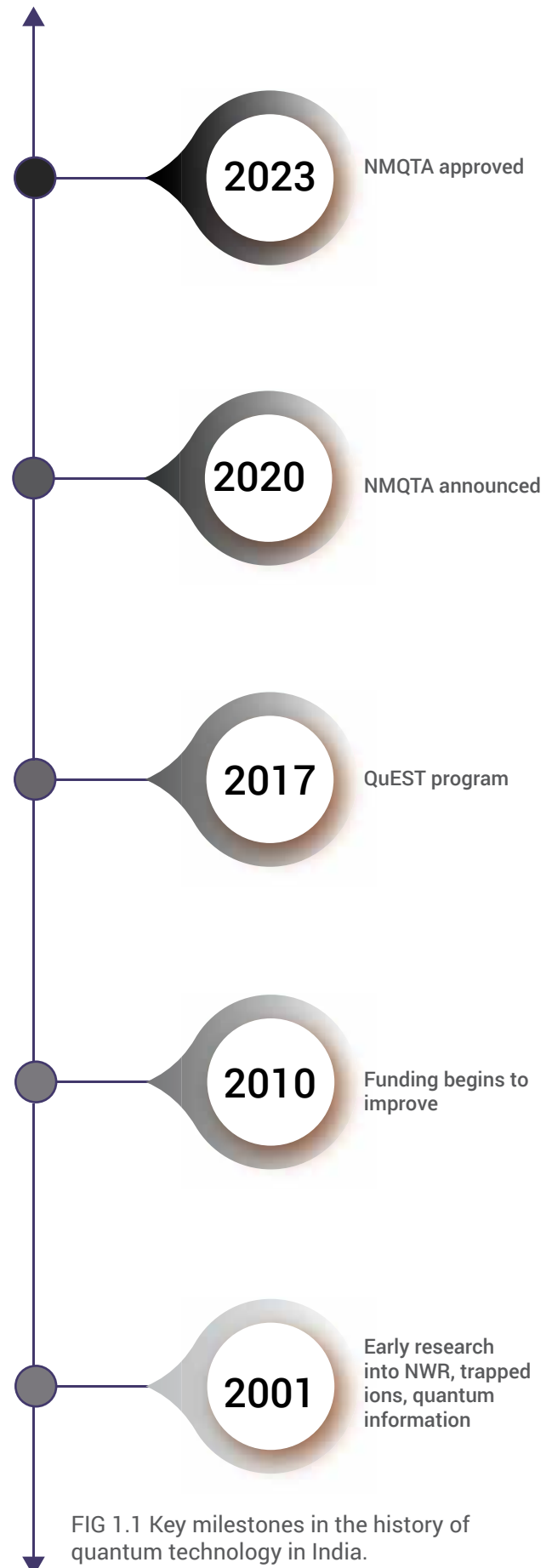


FIG 1.1 Key milestones in the history of quantum technology in India.

OBJECTIVES

The following is a list of outcomes expected directly from the report or through the influence of the report on the ecosystem, based on the leverage of the analysis and recommendations outlined in the report or through use of the report.

1.2 EXPECTED OUTCOMES OF THE REPORT

ANTICIPATED OUTCOMES OF THE REPORT	TIMEFRAME	INDICATOR
Comprehensive knowledge of the Indian quantum ecosystem and understanding of how value flows	Short term	1. Knowledge assessments of audience and impact analysis of the report 2. Better awareness among stakeholders
Understanding the key elements of the supply chain and derive key recommendations to make the supply chain stronger	Short to Medium term	1. Concrete changes in policy that affect the supply chain 2. More robust quantum supply chain 3. Mitigation of quantum becoming an export controlled technology
Informed policy design and development	Short to Medium term	1. Favourable changes in policy design and policy itself
Accelerated development of the Indian quantum ecosystem	Long term	1. Thriving Indian quantum ecosystem that is a favourable playground for Indian academics, industry professionals, government entities, and even international collaborators
Identify areas for international collaboration	Medium to Long term	1. New collaborations in quantum technology
Identifying strength areas of the value chain to create programs that can drive more economic value from those areas	Medium to Long term	1. Recognition of strong areas 2. Identification and dissemination of best practices 3. Reproduction of best practices
Identify gaps and weak areas for focus to be brought in, to strengthen them	Medium to Long term	1. Widespread analysis of problem areas 2. Allocation of funds to address weak links
Pointers and inputs to design more effective programs for workforce and skill building	Medium to Long term	1. Manpower retention in the country 2. Higher value for employment 3. More number of jobs in quantum 4. Increase in the quality and variety of quantum education 5. Increase in the number of publications and patents
New entities like industry consortia may be created, based on the insights derived	Medium to Long term	1. More academia-industry collaboration 2. More international collaboration 3. Larger, more complex quantum ecosystem
Inputs on any need for standards and regulations	Medium term	1. Development of better suited standards 2. Easy and widespread adoption of recommended standards

WHAT IS NOT IN SCOPE OF THE REPORT?

The report is a point-in-time report, most of the data collection and interviews were done in 2nd and 3rd quarter of 2023. Several aspects of the value chain have been dealt with generically to ensure that the general structure and definitions of the Indian quantum value chain are not time dependent. It is recommended that a revised version of the report be released every two years to keep the ecosystem and readers of this report updated on the state of the quantum value chain in India.

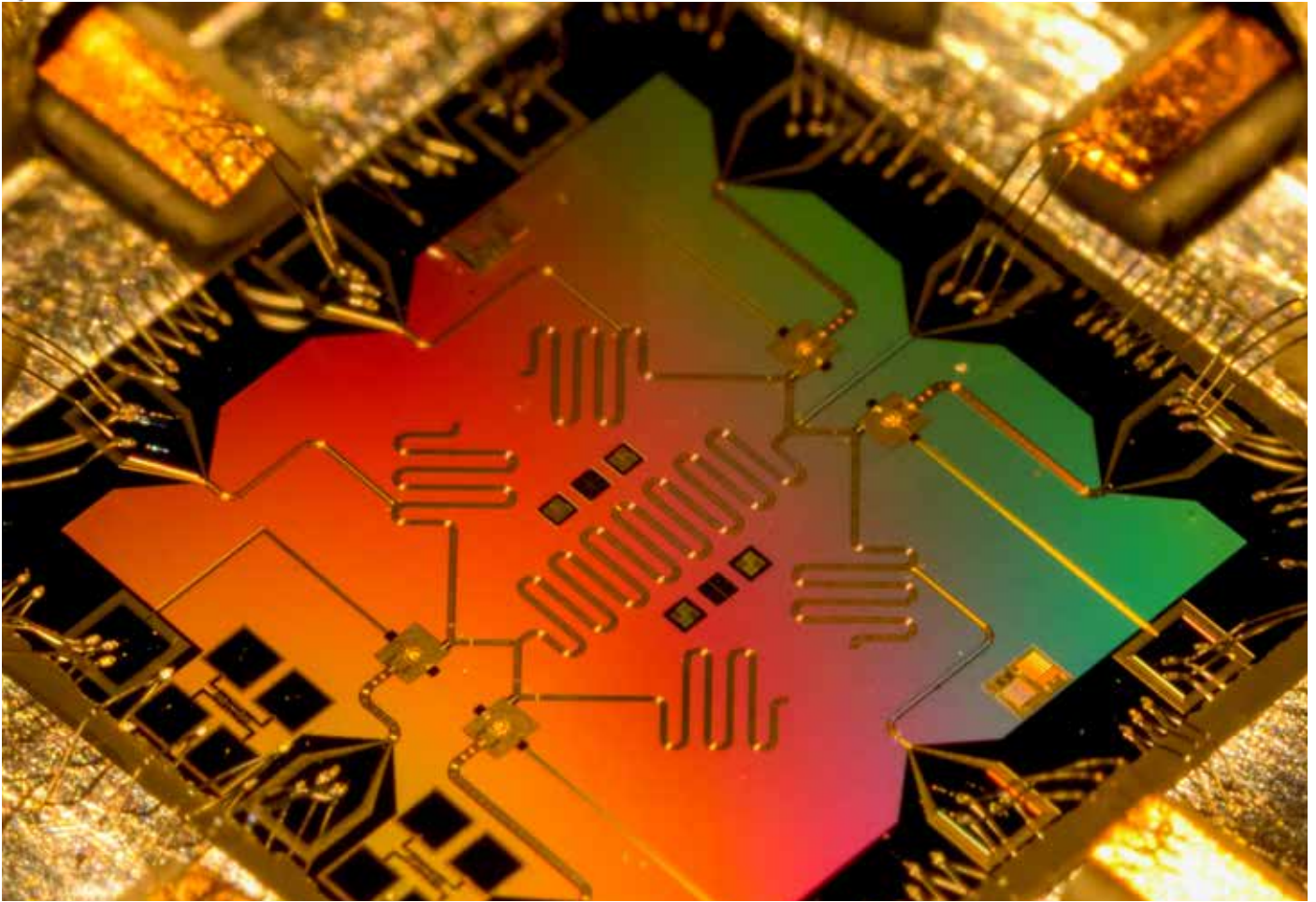
The report introduces the allied industries for quantum but does not include detailed stakeholder interviews of these allied Industries. Furthermore, a detailed supply chain for all possible quantum components and materials is not a focus.

While the international aspects of the value chain have been highlighted, the detailed extrapolation of these international value chain elements is not explored or elaborated in this report.



PROF. ARUN PATI
Co-founder and Director
QETCI

Even though theoretical research in Quantum Computing and Quantum Information has started some three decades back in India, on experimental front there was not much activity. To advance and foster both theoretical and experimental research in Quantum Technology, DST initiated QUEST program. It was kind of phase I of National Quantum Mission. This has really motivated all researchers to take a first step in making India Quantum ready.



METHODOLOGY FOR DEVELOPING THE QUANTUM VALUE CHAIN REPORT

The research process commenced with the introduction of the problem statement, which entailed a comprehensive examination of the quantum technology value chain in India. The project is motivated by a need for a thorough understanding of how value flows within the country's quantum ecosystem, what roles are played by direct and indirect actors, and what the dynamics of value creation are.

The phases of the project are illustrated on the opposite page -

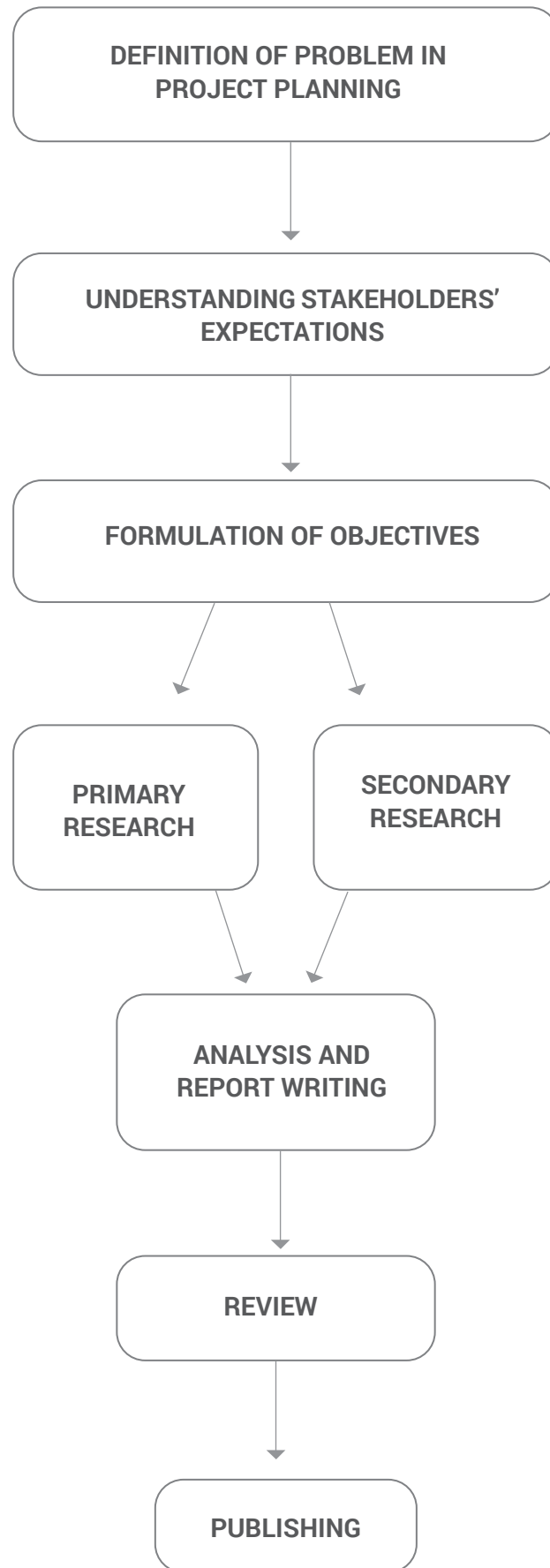


FIG 2.1 Phases of the value chain mapping exercise.

UNDERSTANDING STAKEHOLDER OBJECTIVES THROUGH A SAMPLE STUDY

A stakeholder committee was formed at this juncture and meetings were held to elicit from the stakeholders their expectations of the value chain report. The meetings were conducted on two separate days, with each meeting dedicated to a different set of stakeholders. The inputs received from the stakeholder committee were crucial in formulating the research objectives of the project.

The stakeholders invited were select individuals from Industry, Academia, and Government entities. Fig 2.2 shows the distribution of the stakeholders that attended the sessions.

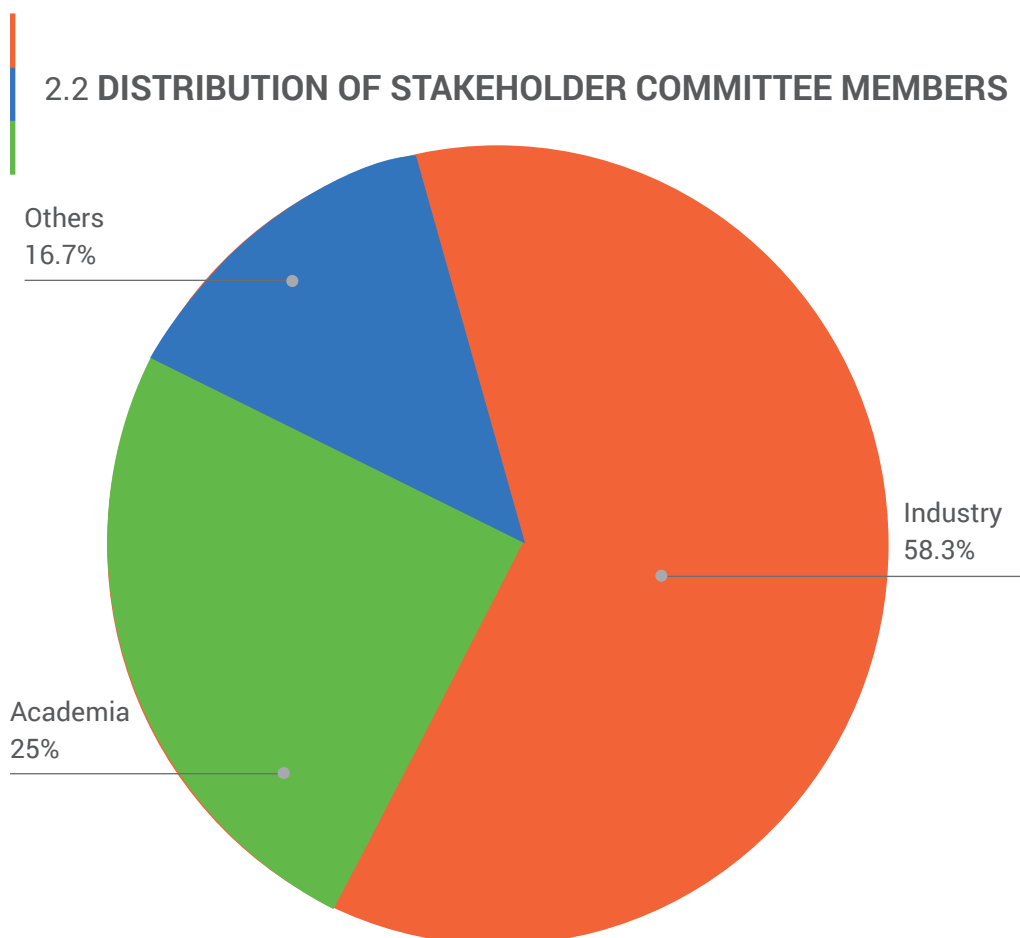


FIG 2.2 Distribution of Stakeholder Committee members.

Attendees from the “Other” category consisted of ecosystem-enabling entities and investors.

The meetings were divided broadly into four sections for discussion - Overview, Supply Chain, International Markets and interfaces, and Research and Development.

A preliminary assessment of the stakeholders’ relative interest in different areas of quantum technology is summarised in the next chart.

2.3 WHAT AREAS OF QUANTUM TECHNOLOGY ARE YOU MOST INTERESTED IN?

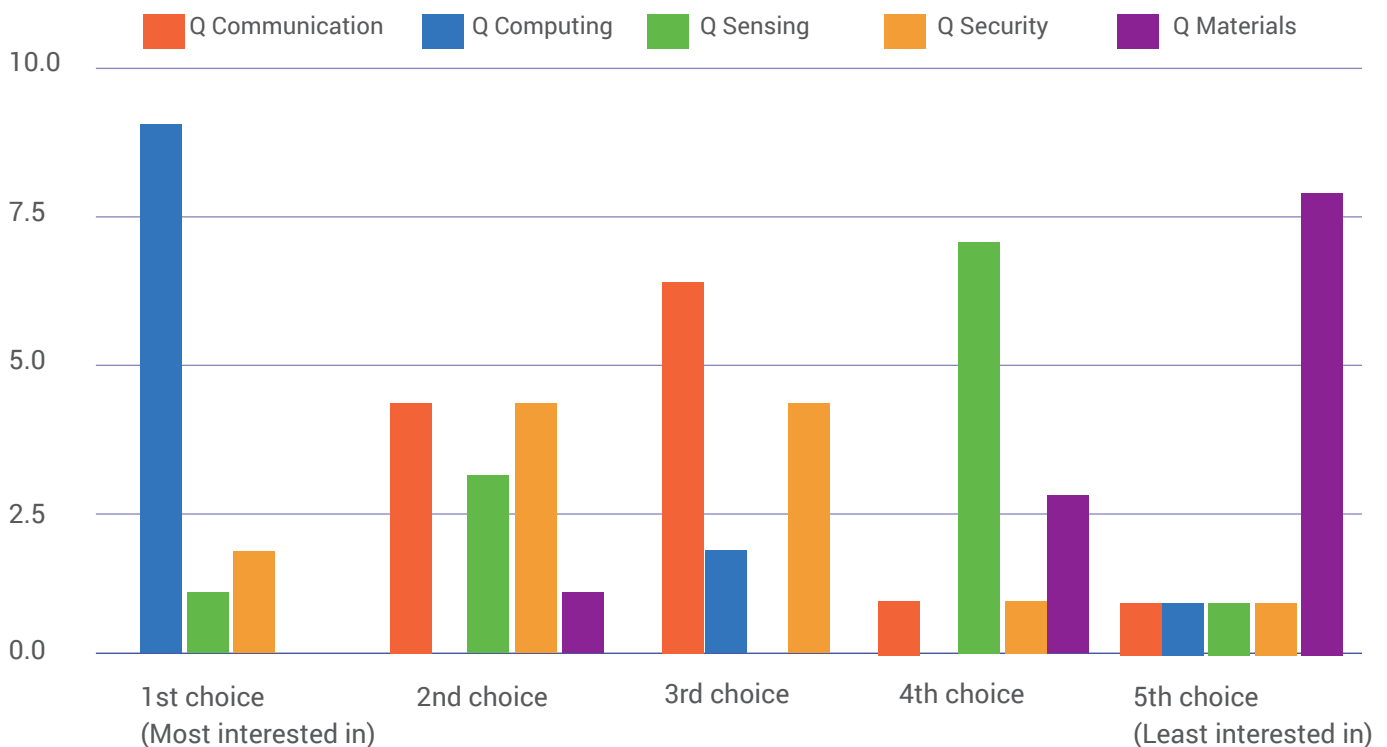


FIG 2.3 Interested areas of quantum technology.

Most attendees chose quantum computing as their highest priority. Quantum communication and quantum security are closely linked and are the second choices for most attendees. Quantum sensing is a popular fourth choice, with barely any interest in quantum materials.

When asked about the knowledge gaps that exist with respect to the quantum technology value chain, the following areas emerged -

- Current state of the supply chain
- Manpower and skilling
- Research and Development
- Start-up ecosystem
- International interfaces

These points were taken into special consideration while developing the outline and ToC of the report.

The second section of the stakeholder committee meeting was focused on the supply chain. There was general consensus about the value chain of India for India being as international and not just national, which was chalked primarily down to the inadequate state of quantum hardware initiatives in the country. Figure 2.3 illustrates the areas of the supply chain the stakeholders are most interested to learn more about.

2.4 WHAT ASPECTS OF THE QUANTUM TECHNOLOGY SUPPLY CHAIN WOULD YOU LIKE TO LEARN MORE ABOUT (Select Top 3)

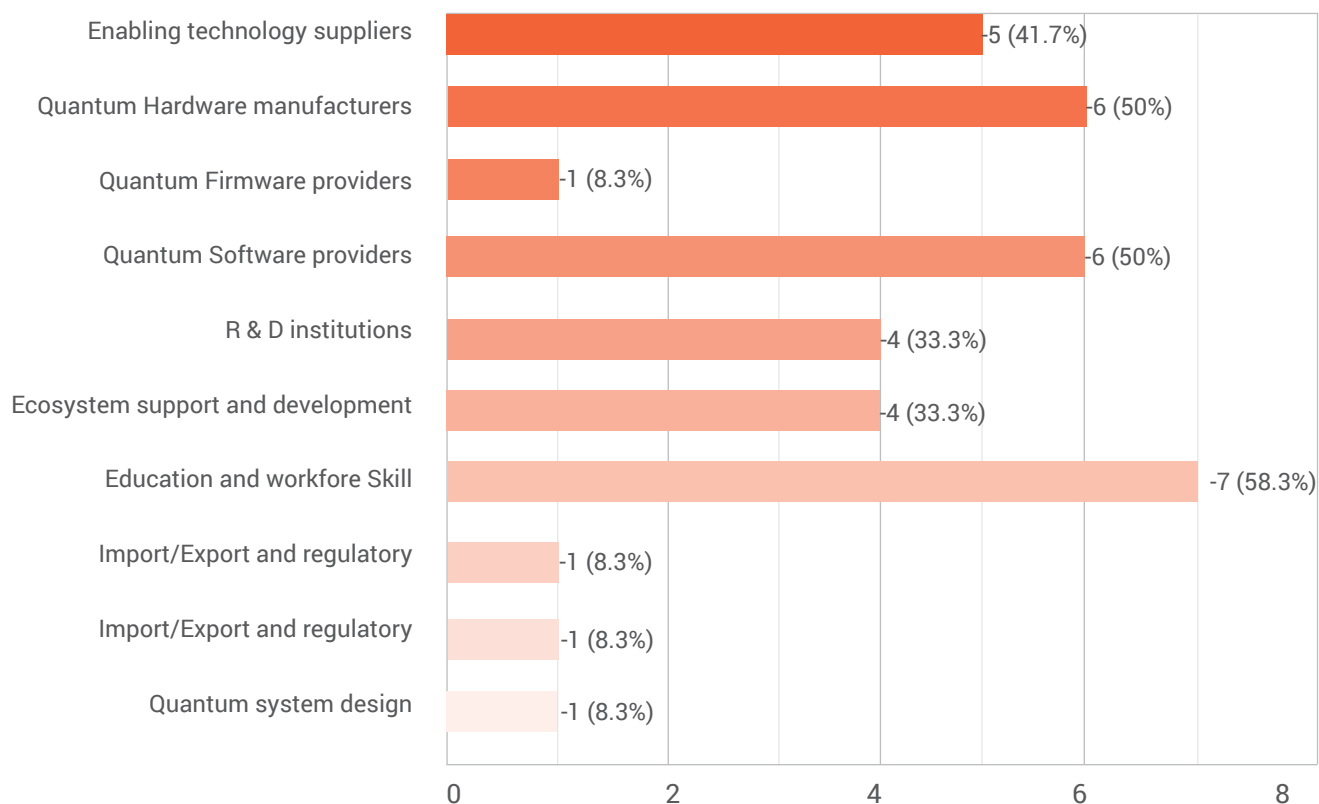


FIG 2.4 Aspects of quantum technology supply chain.

Different stakeholders had different priorities when it came to international interfaces and collaborations, as shown in fig 2.4. However, a fair share of them brought up intellectual property as a concern

2.5 FROM AN INTERNATIONAL COLLABORATION PERSPECTIVE, WHICH INTERFACES ARE OF THE MOST INTEREST/CONCERN TO YOU? (Select Top 2)

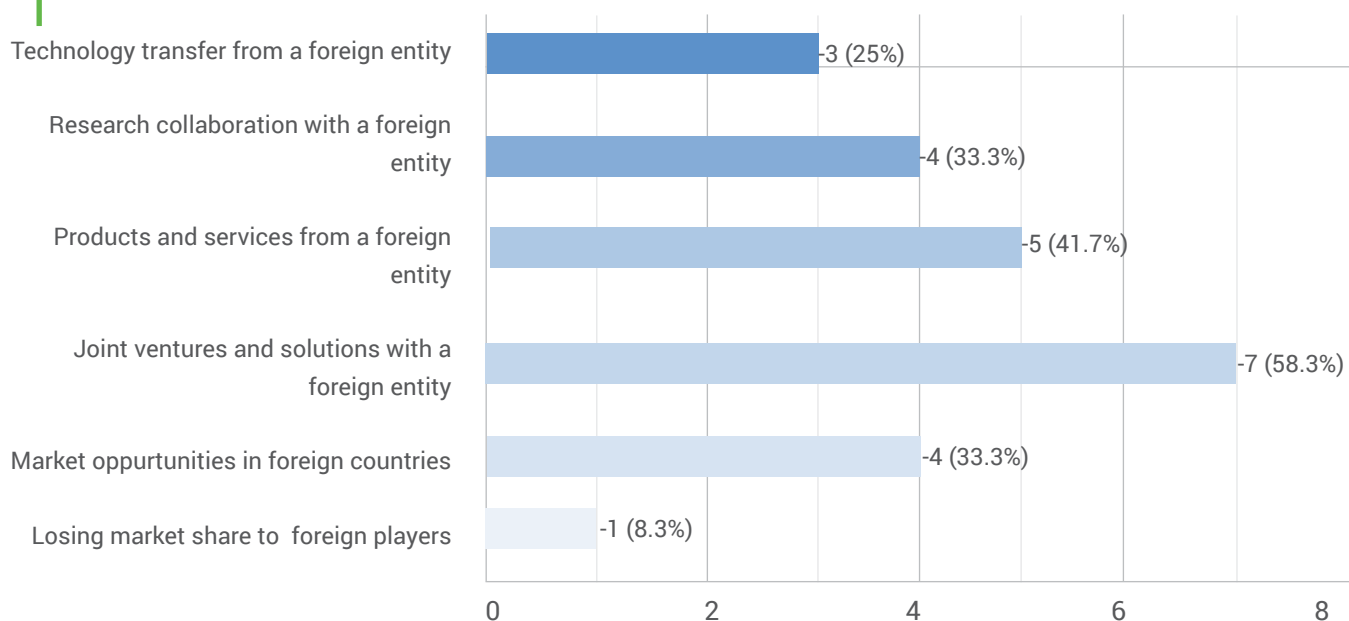


FIG 2.5 Interested interfaces from an international collaboration perspective.

The final prompt dealt with research and development of quantum technology in the country. In both meetings, the discussions converged to reiterate the neglected area of quantum sensing research in the past. The attendees were also asked which qubit modalities (apart from superconducting qubits and photonic qubits) they believe require most R&D focus according to them.

2.6 INTEREST OF STAKEHOLDERS IN QUBIT MODALITIES (APART FROM SUPERCONDUCTING AND PHOTONIC)

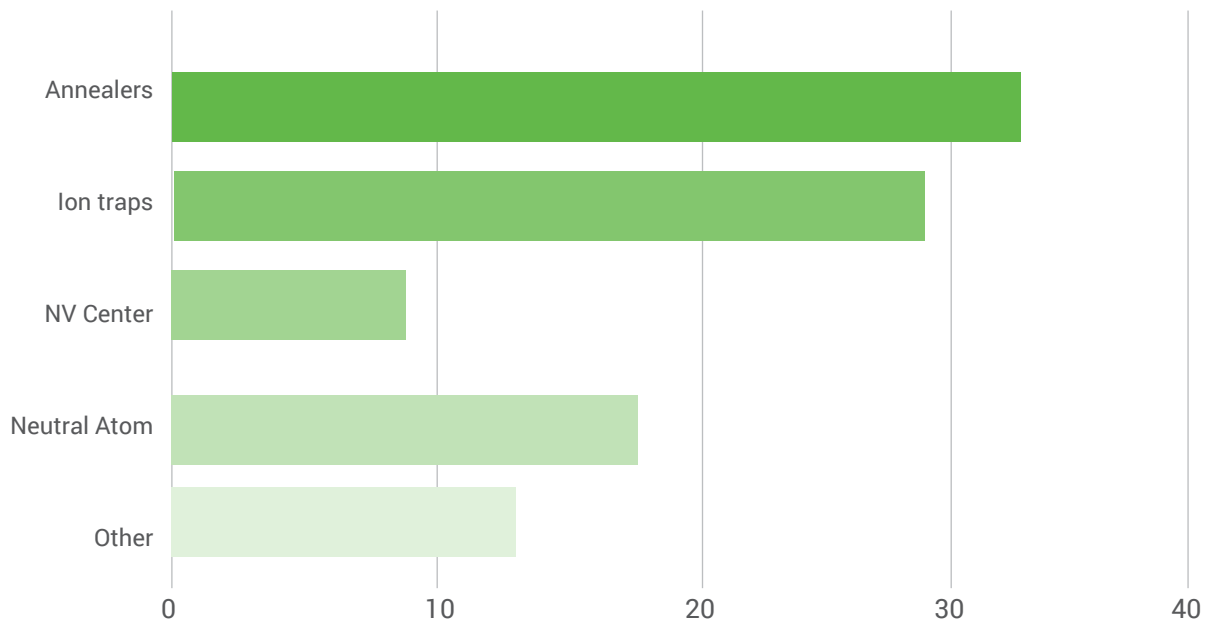


FIG 2.6 Interest of stakeholders in qubit modalities.

FORMULATION OF RESEARCH QUESTIONS

Based on the stakeholder expectations, a list of open questions to be answered was formulated. This was used to create questions for the 1:1 interviews and also identification of candidates for primary research.

PRIMARY RESEARCH

Interviews with several players from the Indian quantum ecosystem were conducted over the course of four months. The diagram below shows the distribution of the interviewees. A total of twenty three entities were formally interviewed. Inputs were also sought during several stakeholder group meetings and workshops.

2.7 INTERVIEWED STAKEHOLDER DISTRIBUTION

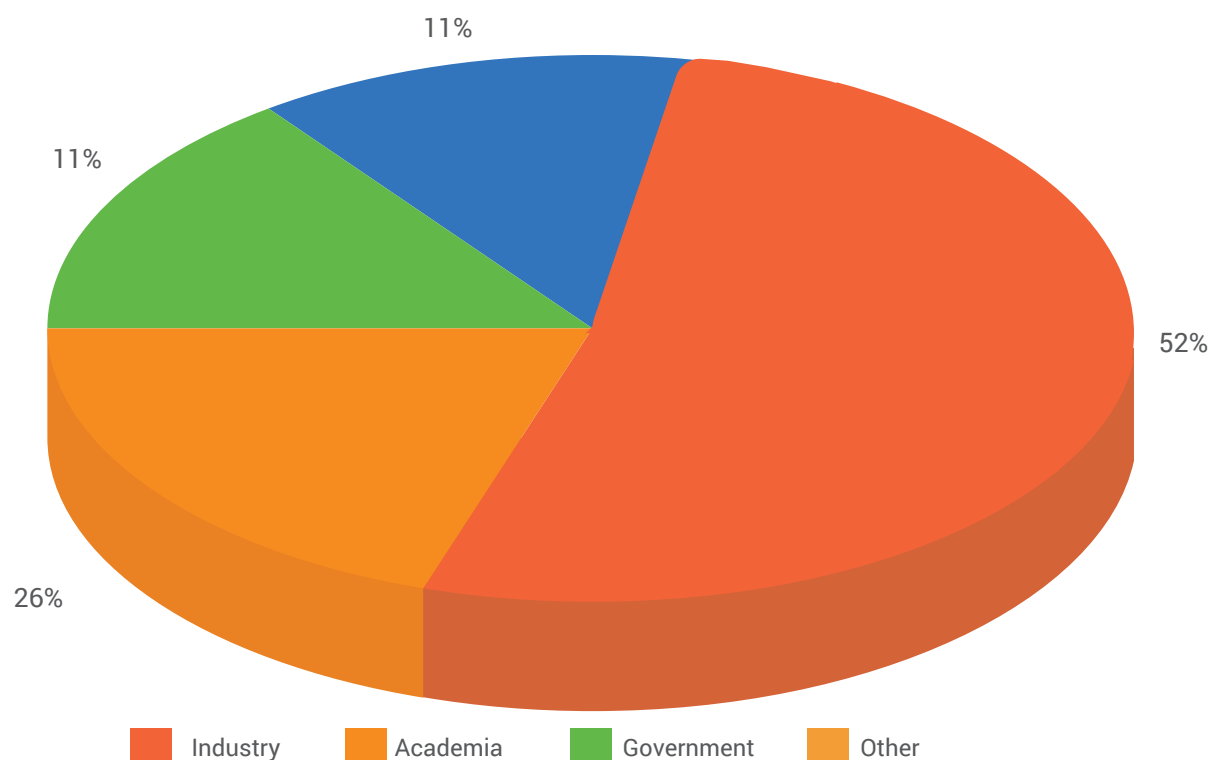


FIG 2.7 Interviewed stakeholder distribution.

STAKEHOLDERS INTERVIEWED 1-1

The four categories above were further divided into the following titles to study the flow of value within the ecosystem in the country.

Note that certain players satisfied the conditions of more than one title

- Educators
- Researchers
- Regulatory entities
- System Integrators
- Integrated System Providers
- Enabling technology providers
- Hardware providers
- Base software providers
- Algorithm developers
- Solution providers
- Investors and incubators
- Enabling government entities
- Ecosystem enablers
- End users

There were also 2-3 separate discussions with quantum start-ups, the insights from which are elaborated in chapter Quantum Startups. The interviews, discussions, and workshops regularly organised by QETCI were invaluable in developing an accurate understanding of the value chain.

The following table summarises some important figures associated with the project.

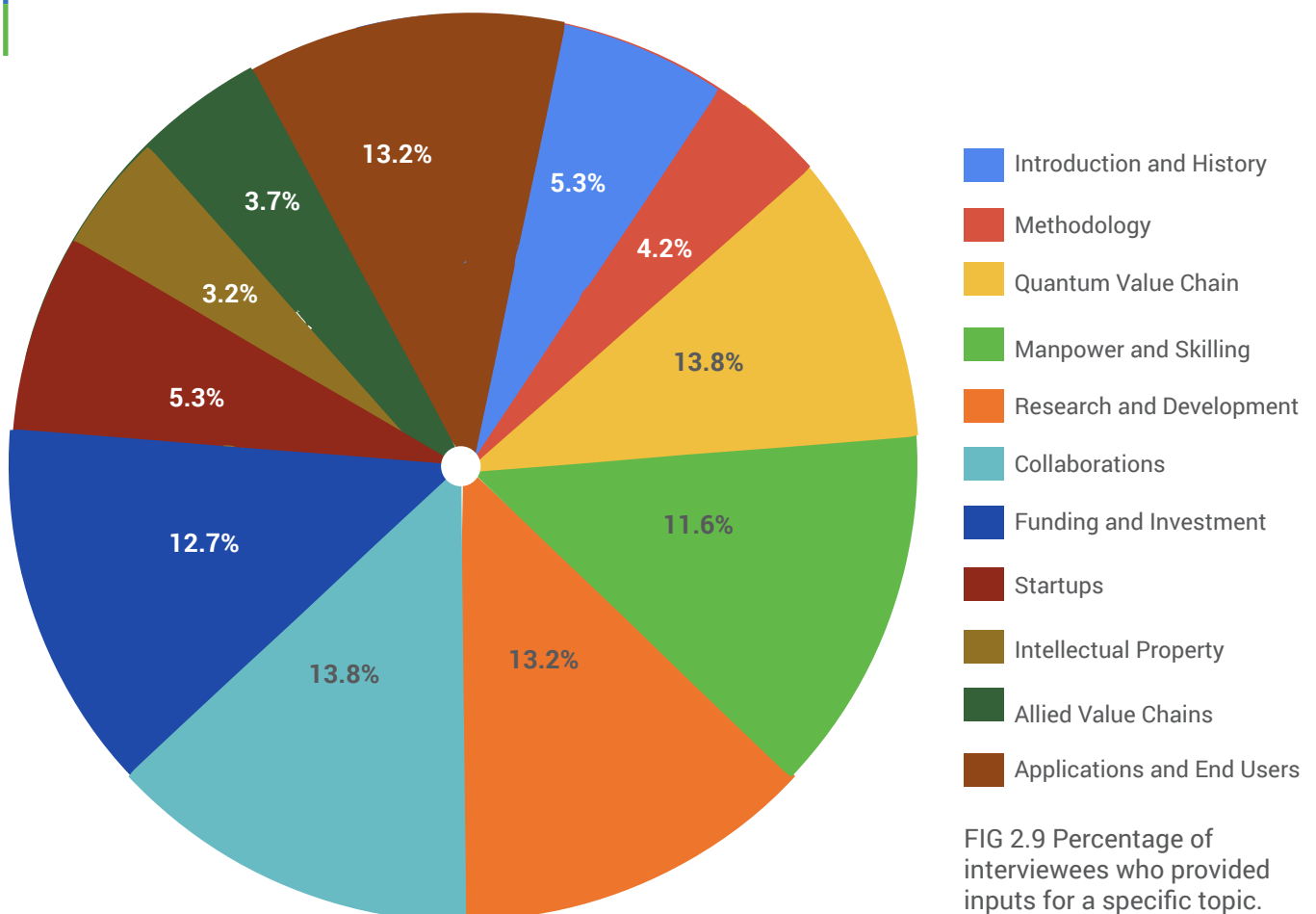
2.8 PRIMARY RESEARCH RELATED NUMBERS

Number of entities that showed interest in being associated with the project	22
Number of members in the Stakeholder Committee	12
Number of entities interviewed	25
Number of entities analysed - by primary or secondary research	62
Number of start-ups interviewed	10

FIG 2.8 Primary research related numbers.

Based on the area of expertise of the person and the part of the ecosystem that they represented, the input from various interviewees resulted in insights which have been included in the relevant chapter in this report. The following diagram shows the percentage of interviewees who impacted each chapter/topic

2.9 PERCENTAGE OF INTERVIEWEES WHO PROVIDED INPUT FOR A SPECIFIC TOPIC



We selected some of the most prominent people associated with the quantum value chain in India as Interviewees for this report . In order to understand the scope of impact of each interviewee on the report we prepared the following chart.

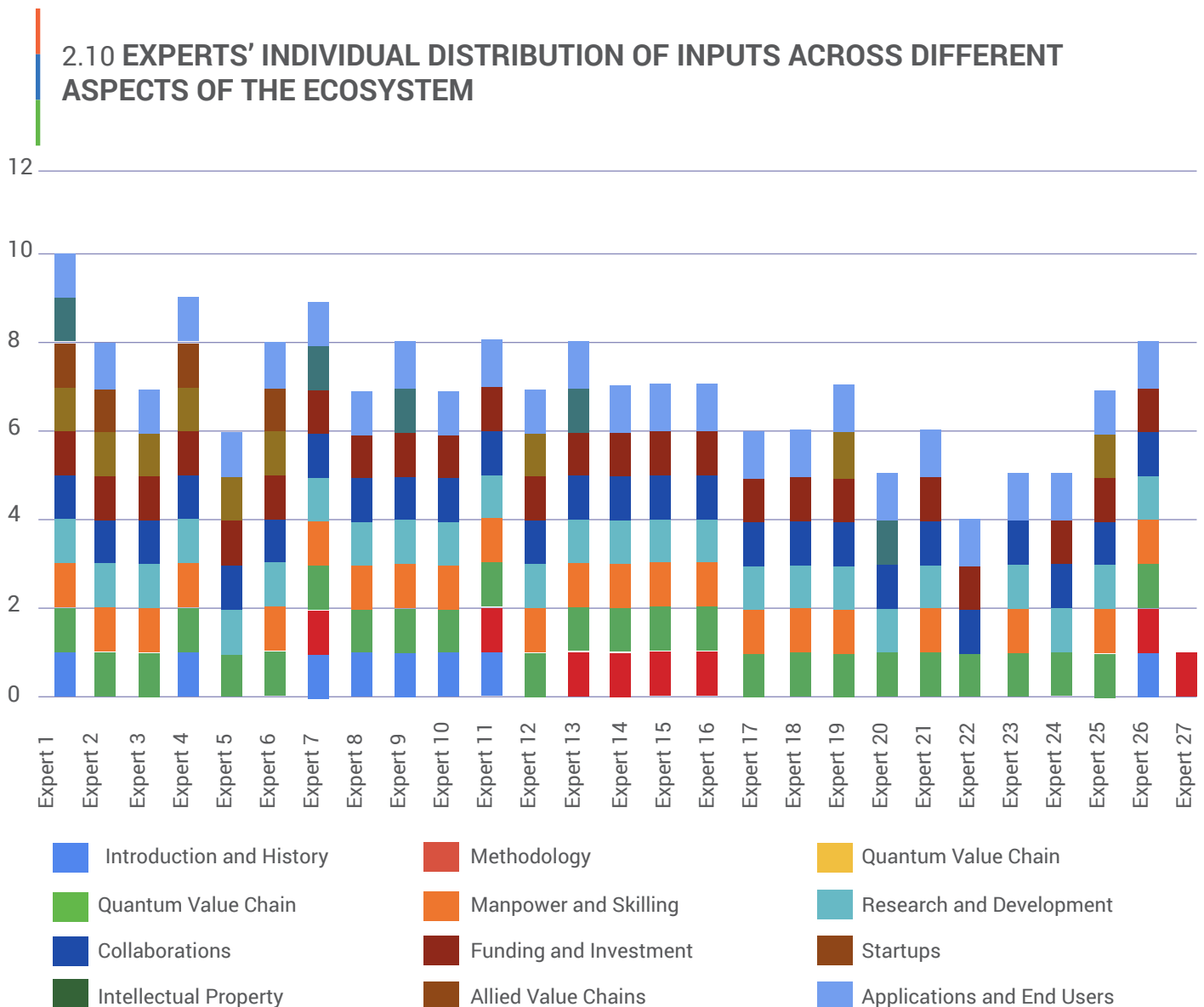


FIG 2.10 Experts' individual distribution of inputs across different aspects of the ecosystem.

Around 50 entities were contacted, out of which 25 entities were successfully interviewed. The actual number of people interviewed was 27. The 1:1 conversations with these individuals provided several insights which were helpful in accurately mapping India's quantum value chain. Below is a summary of some salient points gathered from the interviews.

- Quantum technology is emerging as a strategic area of international collaboration between governments.
- India has the second largest concentration of quantum talent globally, and therefore skilling efforts must be amped up to train the quantum workforce of the world
- The quantum communication industry in the country is

seeing significant interest from industry, academia, and government entities

- Intellectual property management is a critical point of consideration given the prominence of research in the current stage of quantum technology
- The space industry shares a close symbiotic relationship with the quantum technology ecosystem in India; areas like space based secure communication and sensing are prominent applications of quantum technology
- There has been an increase of more than 100 percent increase in the number of quantum technology related start-ups in India since 2021
- Semiconductor technology, electronics, and photonics ecosystem have an important influence on the development of the quantum technology value chain in India

It is acknowledged that the interviews themselves were not the only determining factor. For instance, considerations are made regarding the most suitable categorization of actors and the level of technological readiness, among other factors. The mapping of the value chain does not start from a blank slate, but rather from QETCI's existing knowledge of the ecosystem.

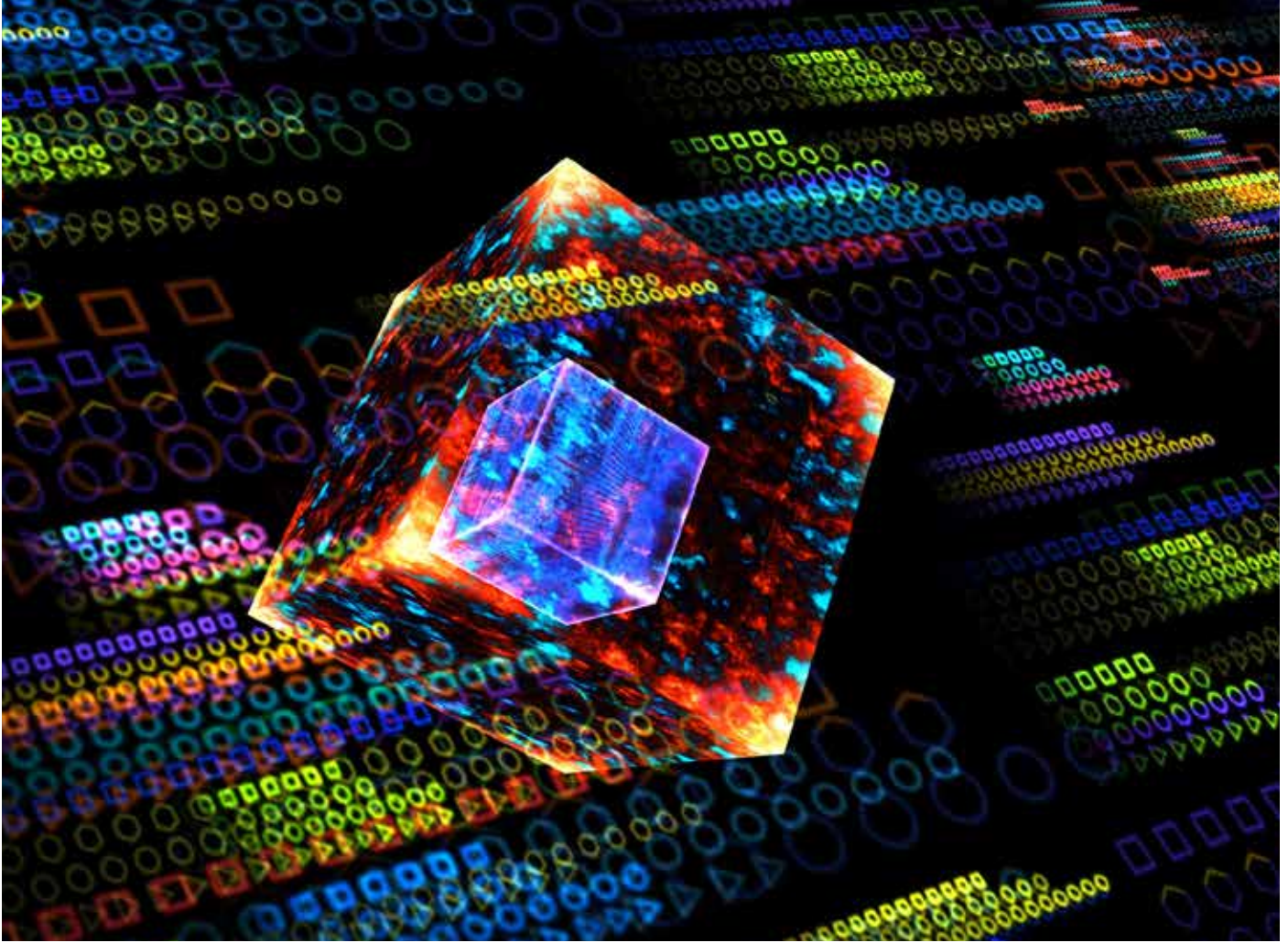
SECONDARY RESEARCH

The first step in creating the value chain diagram was the identification of actors, encompassing both direct stakeholders and indirect players, along with external influences. A survey calling for information was put out at the start of the project to identify entities involved in the Indian quantum ecosystem at various capacities. Once these players were determined, a flow map was crafted, graphically representing the value chain through interconnected boxes. Information pertaining to the relationships between these actors was also incorporated.

The collection of data was carried out through both primary and secondary research methodologies. An initial value chain map was formulated based on inferences drawn from secondary sources. Subsequently, it was adjusted and modified as necessary to reflect the insights garnered through primary research methods such as interviews, stakeholder meetings, and surveys.

The value chain report has two versions - one available for public access and the other sent to key stakeholders in the ecosystem.

Both versions of the report were reviewed by stakeholders, which included members from QETCI's Governing Board.



QUANTUM TECHNOLOGY

The roots of quantum technology lie in quantum mechanics, which was marked by revolutionary insights in the early 20th century. Pivotal results, such as Max Planck's groundbreaking work on energy quantization in 1900, and Albert Einstein's elucidation of the photoelectric effect solidified the quantum nature of light.

In 1924, Louis de Broglie proposed the wave-particle duality, suggesting that particles like electrons could exhibit both wave and particle characteristics. This concept gained experimental validation through the famous double-slit experiment, demonstrating the interference patterns of particles, conducted by Clinton Davisson and Lester Germer in 1927. Werner Heisenberg's uncertainty principle (1927) and Erwin Schrödinger's wave equation (1926) introduced fundamental uncertainties and mathematical tools to describe quantum behavior [1].

The development of quantum technology gained momentum with the advent of quantum computing. Richard Feynman's 1981 proposal to simulate quantum systems more efficiently using quantum computers sparked interest, and in 1994, Peter Shor formulated a quantum algorithm capable of factoring large numbers exponentially faster than classical methods, underpinning the threat to classical cryptography. Around the same time, quantum key distribution (QKD) protocols, such as BB84 by Charles Bennett and Gilles Brassard (1984), explored secure communication via quantum channels [2].

Experimental breakthroughs followed, including the realization of qubits in various physical systems like ions, superconducting circuits, and photons. Notably, in 2001, IBM demonstrated the first rudimentary quantum computer, initiating a race in quantum hardware development among tech giants and startups [3]. Achievements such as Shor's algorithm implemented on small-scale quantum devices showcased the feasibility of quantum computing's power [4].

Quantum communication also advanced with entanglement-based protocols and secure quantum key distribution (QKD) experiments conducted over long distances. China's Micius satellite launched in 2016, demonstrated entanglement-based communication on a global scale, highlighting the potential of a quantum internet [5]. Since then there have been several advancements in this space

There are three fundamental phenomena underlying quantum technology - entanglement, interference, and superposition [6].

QUANTUM ENTANGLEMENT

Two particles are said to be entangled when they become correlated in such a way that their states are interdependent, even when separated by large distances. Changes to the state of one particle instantaneously affect the state of the other, defying classical notions of locality. Entanglement is at the crux of revolutionary advancements in quantum technology, playing a pivotal role in quantum algorithms and protocols such as secure key distribution and quantum teleportation.

QUANTUM SUPERPOSITION

Another important quantum property is superposition, where a particle can exist in a combination of multiple states simultaneously. Creating superposition

states enables quantum systems to process and manipulate information in parallel states, which forms the foundation for quantum computing's exponential processing potential.

QUANTUM INTERFERENCE

This property is observed when quantum waves combine constructively or destructively, allowing precise control over outcomes and enabling applications like high-precision measurements and quantum information processing.

Together, quantum entanglement, superposition, and interference enable us to manipulate and exploit the non-classical correlations and probabilistic nature of quantum states, paving the way for quantum computing, communication, and sensing.

QUANTUM COMPUTING

A paradigm shift in computing technology, quantum computing capitalises on the principles of quantum mechanics to process and manipulate information. Unlike classical bits, quantum bits or qubits can exist in superpositions of states, exponentially increasing the potential computational power. These qubits can be entangled, establishing intricate correlations that enable parallelism and exponential speedup in solving certain problems. Quantum gates and interference operations exploit these properties to perform complex computations. However, the field faces challenges like decoherence due to the delicate nature of quantum states. Despite these challenges, quantum computing holds promise for tackling problems that are intractable for classical computers, spanning cryptography, optimization, material science, and more.

QUANTUM COMMUNICATION

Quantum communication leverages the principles of quantum mechanics to achieve unprecedented levels of security and information transfer. Quantum key distribution (QKD), a cornerstone of quantum communication, utilizes the properties of entanglement and the no-cloning theorem to enable secure key exchange between parties, guaranteeing the detection of any eavesdropping attempts. Quantum states, such as qubits encoded in various physical systems, are used as carriers of information, and their delicate nature ensures that any eavesdropping attempts would disrupt the states, providing a means of secure communication. Quantum repeaters are developed to extend the achievable communication distances, countering the effects of decoherence. While challenges such as channel loss and noise still pose obstacles, quantum communication shows immense promise

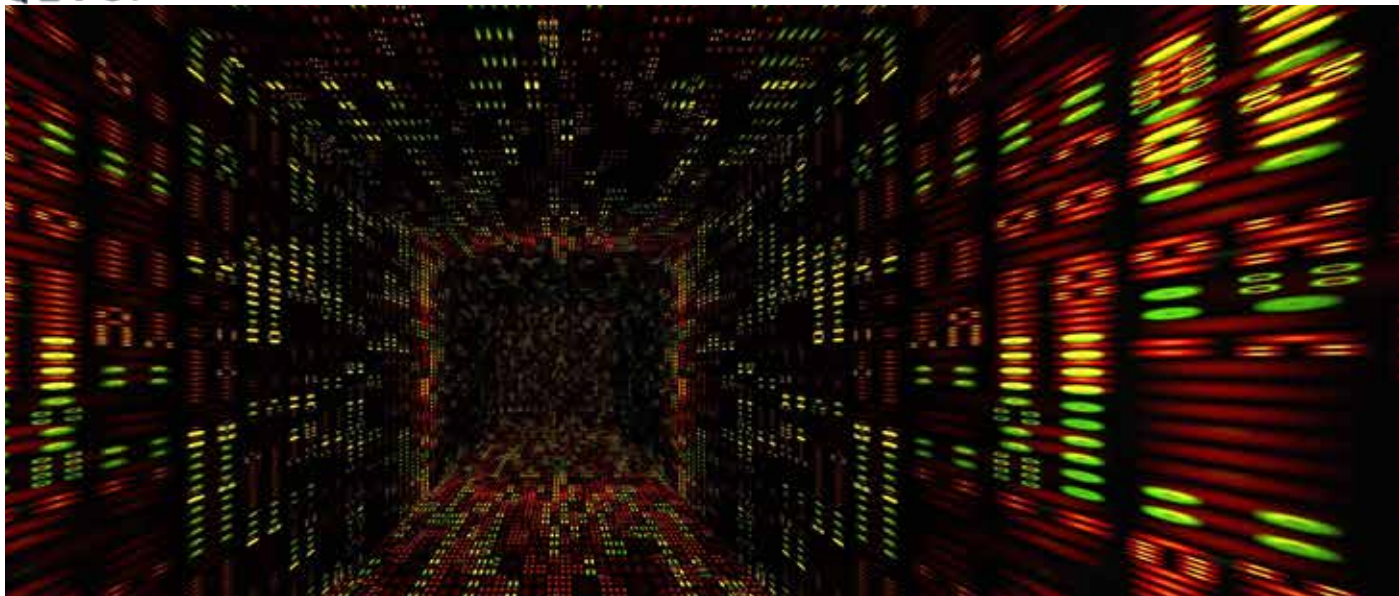
for establishing unhackable communication channels and has implications for secure data transmission and quantum internet development.

QUANTUM SENSING AND METROLOGY

Quantum sensing and metrology exploit the principles of quantum mechanics to revolutionize precision measurements beyond classical limits. Quantum entanglement and superposition underpin advancements in this field, allowing for enhancements in parameter estimation and sensitivity. Utilizing quantum states like squeezed states or entangled particles, quantum sensors can surpass the standard quantum limit, achieving measurements with reduced noise. Interference phenomena, such as Ramsey interferometry, are harnessed to increase the accuracy of atomic clocks and inertial sensors. Quantum-enhanced sensors have applications ranging from gravitational wave detection to magnetic field mapping, enabling new insights into fundamental physical phenomena. Nevertheless, challenges like environmental noise and system complexity must be addressed to fully harness the potential of quantum sensing in real-world scenarios, marking a significant stride in precision measurement capabilities.

POST QUANTUM CRYPTOGRAPHY

Post Quantum Cryptography (PQC) emerges as a response to the impending threat posed by quantum computers to classical cryptographic systems. Unlike the quantum technologies previously discussed, PQC does not directly harness quantum properties for computation or communication. Rather, it focuses on developing cryptographic algorithms resistant to attacks from quantum computers, which could efficiently solve problems like integer factorization and discrete logarithm that underlie many classical encryption methods. PQC explores alternative mathematical constructs such as lattice-based cryptography, code-based cryptography, and multivariate polynomial cryptography, exploiting problems that are believed to be hard even for quantum computers. This domain doesn't fit into the usual categories of quantum technology, as it pertains to safeguarding classical cryptographic infrastructure from the future advent of quantum computers, showcasing the interdisciplinary nature of quantum advancements.



INTRODUCTION TO THE QUANTUM VALUE CHAIN

VALUE CHAIN DEFINITION

Originally proposed by Michael Porter for individual firms, value chain analysis is an important tool that looks at the organization's activities that collectively contribute to the creation, production, and delivery of products or services, enabling insight into which activities create the most value and which ones may be outsourced [1]. The concept has since been extended to study national and international production networks [2]. A specific industry might be viewed as the movement of value between entities consisting of that ecosystem. The value chain now encompasses all vertical stages, from raw materials providers to end-users, as well as entities that inhabit the horizontal layers, like educators and government bodies. The mapping process provides knowledge of the roles, functions, and interconnections of the entities, and aids policy makers, researchers, and businesses to make effective decisions.

WHY VALUE CHAIN ANALYSIS

Performing a value chain enables a deeper understanding of the Industry and enabling entity dynamics, weak links, and areas for potential improvement. In the context of the quantum technology industry in India, a value chain analysis may be vital in recognising gaps, identifying growth opportunities, and navigating technical and non-technical challenges. Understanding the country's quantum technology value chain may also support policy formulation, which is critical to consider in the early stages of any emerging technology.

An alternative approach is the analysis of the supply chain, which, however, is limited and not encompassing all the factors that contribute to an ecosystem. The value chain may be thought of as a supply chain along with these ecosystem

dependencies and external interfaces.

We have developed and analysed the quantum technology value chain in India and used that to represent a full value chain framework. This has been done after a careful study via primary survey and secondary research.

The following are the key stakeholders identified as being elements in the Indian quantum technology value chain.

3.1 KEY STAKEHOLDERS

ENTITY	DEFINITION
Education Provider	An entity that creates and/or delivers educational content on quantum technology and associated domains
Researcher	An ecosystem entity that is engaged in research associated with quantum technology
Regulatory Body	A national entity that is responsible for creating, enforcing, and overseeing regulations and rules within the quantum ecosystem
System Integrator	An ecosystem entity that, without hardware capabilities of its own, provides base software and/or algorithms and/or solutions to the end user
Integrated System Provider	An ecosystem entity that may or may not develop indigenous quantum hardware, and provides it along with base software and algorithms to quantum solutions providers
Enabling Technology Provider	An non-quantum ecosystem entity that plays the role of providing technology that assists and enables the development of quantum technology (hardware).
Hardware Provider	An ecosystem entity that is engaged in the development of the hardware of quantum devices, like quantum computers, QKD devices, and quantum sensors
Base Software Provider	An ecosystem entity that develops firmware and control protocols for the underlying quantum hardware
Algorithms Provider	An ecosystem entity that works on quantum communication protocols, PQC schemes, or quantum computing algorithms for specific applications
Solutions Provider	An ecosystem entity that provides solutions by way of software products or consulting services to end-users interested in specific applications of quantum technology
Standards Body	An ecosystem entity that is responsible for the development of standards and regulatory recommendations associated with quantum technologies
Investor and Incubator	An ecosystem entity that provides financial support, mentorship, resources, and networking opportunities to quantum technology projects
Enabling Government Entity	A government entity that oversees and assists the development of quantum technology at various layers of the value chain
Ecosystem Enabler	An ecosystem entity that works closely with different stakeholders to enhance collaborations, mitigate challenges, and accelerate the ecosystem as a whole
End User	An ecosystem entity that is interested in the applications of quantum technology
Allied Value Chains	Value Chains from allied industries which add value to the quantum value chain

3.2 THE INDIAN QUANTUM TECHNOLOGY VALUE CHAIN

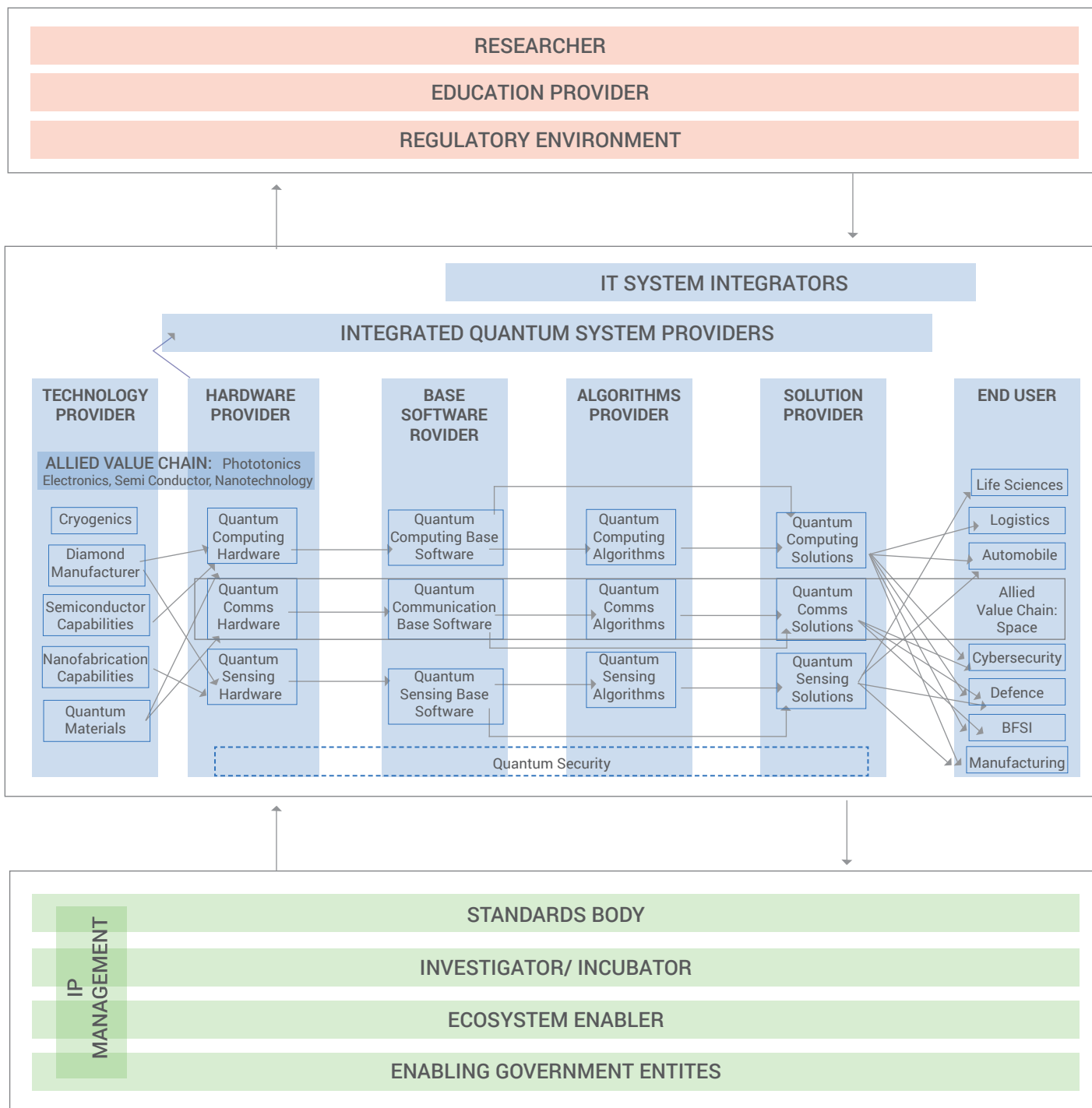


FIG 3.2 Quantum Value Chain Framework.

The above figure represents the quantum value chain in detail. The value chain can be studied in two parts

- The supply chain – The central big box in the above representation includes elements of the supply chain
- Some of the horizontal layers and additional elements which when included provide an overview of the

overall value chain and can represent non-supply chain ecosystem elements.

- The 2 together describe the way value flows within the ecosystem and also elements that provide value across the value chain
- This represents an allied value chain

Lets look at both of these in detail.

THE SUPPLY CHAIN

As quantum technology gains traction, there is a need for a streamlined supply chain that is robust and reliable. The specialised components and materials required for quantum technology are often challenging to produce and integrate, necessitating efficient supply chain management to ensure timely availability and quality. With precise manufacturing, stringent testing, and controlled environments being crucial, any disruptions or delays in the supply chain can hinder the development, production, and deployment of quantum devices.

The current supply chain for quantum technologies in India is outlined in the diagram below.

3.3 SUPPLY CHAIN FOR QUANTUM TECHNOLOGIES

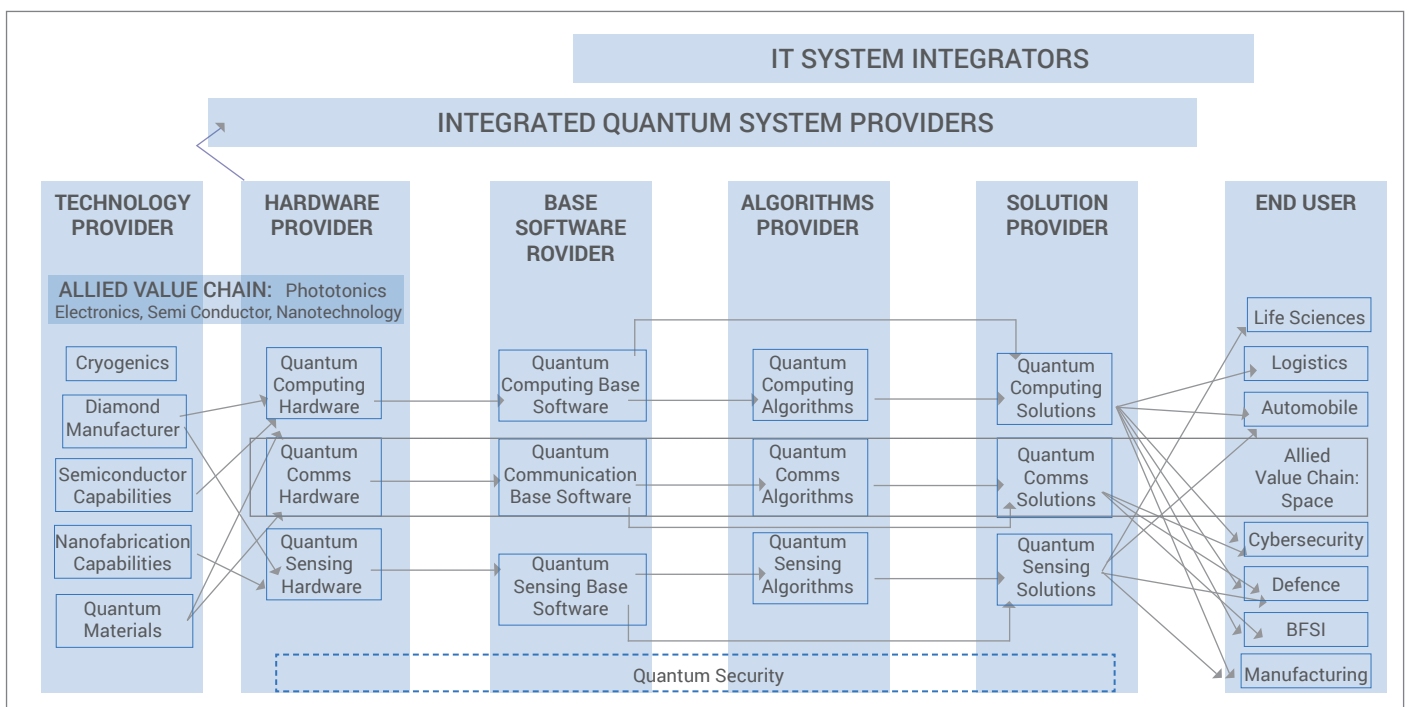


FIG 3.3 Quantum Supply Chain.

The Indian quantum supply chain is a mix of indigenous and international elements and while there are strength areas, there are gaps to be filled. At present, India is dependent on foreign sources for critical goods and services that build up the quantum ecosystem. Apart from limited exposure to supply chain risk, a localised supply chain lies at the heart of economic resilience and strategic autonomy. Moreover, being able to source most components from within the country allows scientists to speed-up and enhance their research. However, given India is not currently in a position to be completely self-reliant, alternative avenues must be explored to ensure that the rate of progress in quantum is not impacted negatively by the supply chain.

Currently, we do not have an adequate domestic supply of enabling technologies, which is a risk to the country's supply chain resilience. It is important to encourage and support enabling technology providers since that will reduce our reliance on foreign sources, which can be vulnerable to disruptions due to geopolitical issues, trade restrictions, natural disasters, or global supply chain shocks. Ensuring domestic supply of enabling tech will also reduce lead times and delays, and increase cost efficiency, which are problems that ail several quantum researchers in India.

However, we acknowledge that it is not possible to develop capabilities in all areas of enabling technology. Therefore, there is a need for strategy that does the following [3].

Monitor : sufficient alternatives exist within and outside India.
Response: monitor the situation and try to consolidate.

Increase : there are few suppliers of the component, although they are already based in (or can be replaced with an alternative supplier within) India.
Response : stimulate an increase in suppliers within India

Investigate: there are plenty suppliers, but they all reside outside of India
Response: investigate how to deal with the situation, e.g. by strategic investments to create an Indian ecosystem

Mitigate: few suppliers exist and there is little potential for finding a substitution within India
Response: mitigate this strategic risk, e.g. by pursuing alternative technical solutions.

India is fortunate to have leaders in certain enabling technologies, like synthetic diamonds and optical components. However, the majority of the customer base for such companies is international.

HARDWARE PROVIDER

Given the nascency of quantum technologies, the primary customers of any quantum hardware are mostly researchers based in academia and industry. Most hardware providers in India also work on base software, protocols and algorithms.

Quantum hardware providers may be classified broadly into the following categories -

- Quantum computing hardware
- Quantum communication hardware
- Quantum sensing hardware

Fig 3.4 indicates the distribution of hardware start-ups by the products they are working on. It should be noted that different start-ups are at different levels of maturity. Nonetheless, there is a dire need for more start-ups that work on quantum hardware. There is also a discrepancy in the numbers between sensing vs computing and communication, which needs to be addressed.

3.4 DISTRIBUTION OF QUANTUM START-UPS IN INDIA

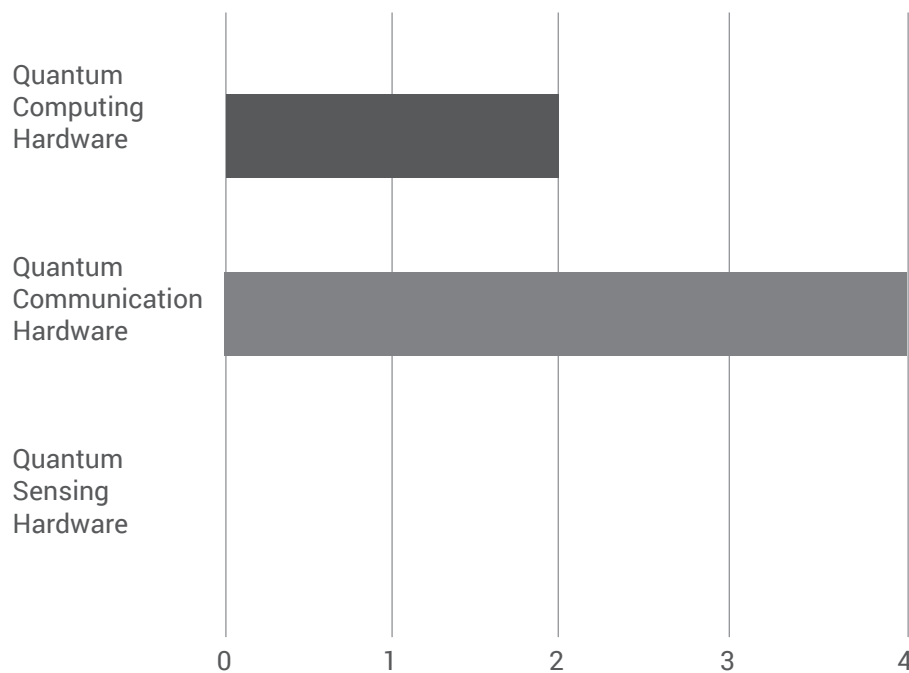


FIG 3.4 Quantum Start-Ups.

QUANTUM COMPUTING HARDWARE

The number of entities involved in developing hardware for quantum computing is quite small. The main hardware modalities being tested for quantum computers are photonics and superconducting circuits.

A survey conducted by QETCI revealed that certain entities are also interested in exploring quantum annealers and ion-trap based systems.

3.5 INTEREST OF ENTITIES IN QUBIT MODALITIES

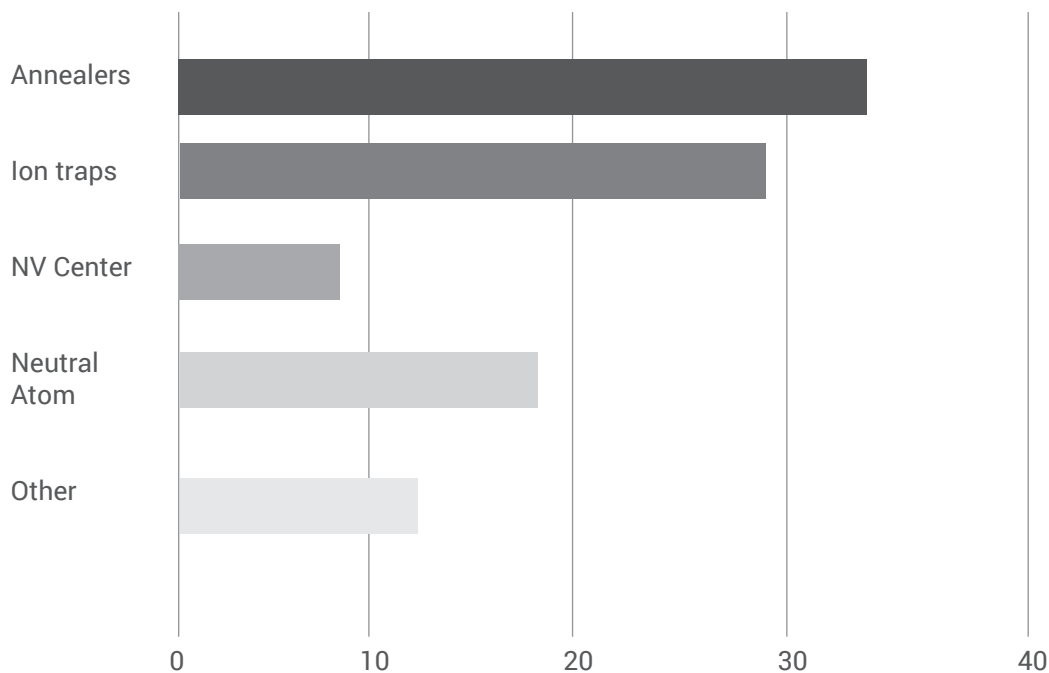


FIG 3.5 Qubit Modalities : Interest amongst interviewees.

Industry entities, from system integrators to solutions providers have indicated their interest in quantum annealing primarily because of its expected suitedness for quantum optimisation and machine learning problems, an important use-case for quantum computers.

Certain key characteristics in the strategy of hardware providers are as follows -

- Early engagement with software providers to ensure compatibility
- Creation of simulators for customers to use for testing
- Access of hardware via the cloud for seamless integration

The development of the quantum processor is only one part of the story; the control electronics required to manipulate qubits also requires careful attention. Currently, we lack companies specialising in quantum electronics, leaving companies focusing on quantum processors no choice but to import. A quantum computing hardware firm may need to spend anywhere between 70-100 lakh INR a year, especially

when setting up. The numbers go up drastically even further to enable full commercialization of the technology. However, collaborations such as CDAC's recent MoU with Dutch control electronics start-up QBlox can prove immensely valuable in developing a more complete ecosystem upon which core-quantum companies can thrive.

QUANTUM COMMUNICATION HARDWARE

Perhaps owing to a well-established electronics ecosystem in the country, the quantum communication hardware ecosystem, which relies mainly on photonics, seems more developed, with a relatively large number of entities focusing on developing indigenous QKD systems.

While there were early efforts in the 2010s, the transformational push for developing quantum communication hardware in the country was triggered perhaps by China's satellite QKD demonstration in 2016. In 2017, Raman Research Institute (RRI) launched the Quantum Experiment using Satellite Technology program, which demonstrated quantum communication at 50m and 300m apart in 2021.

Map showing the layout of the Quantum Internet with Local Access (QILA), demonstrating connecting from Chennai to Bengaluru to Delhi

3.6 MAP SHOWING THE LAYOUT OF THE QUANTUM INTERNET WITH LOCAL ACCESS (QILA), DEMONSTRATING CONNECTING FROM CHENNAI TO BENGALURU TO DELHI [4]



FIG 3.6 Map showing layout of the QuantumInternet in India

QKD CUSTOMERS AND APPLICATIONS

- Owing to its applications in security, the early adopters of QKD are government entities and armed forces.
- There is also some interest from domestic and international banks and NBFCs.
- Enterprise customers are mainly interested in Proof of concepts at the moment.

There is a push to develop network simulation tools, both in start-ups as well as academic labs. Simulation software is an important part of the value chain because it serves as a testbed and playground before the customer is ready to use real quantum hardware. Furthermore, the design and development of network simulators is a lot cheaper, making it a viable opportunity for Indian entities to look into.

QUANTUM SENSING HARDWARE

There are barely any entities that work in the production of commercial quantum sensors in India. This gap is worth addressing not simply because it exists, but also because focusing on quantum sensor hardware might prove to be a strategic win for India for the following reasons.

- Potential for low cost sensor development.
- Existing sensors market and large applications.
- Relatively low risk technology.

There are several academic labs involved in the quantum sensing hardware, mainly with NV Centre Diamonds.

A potential solution for addressing the gap in commercial quantum sensing could be supporting the emergence of quantum sensing start-ups from these labs. Globally, quantum hardware start-ups commonly emerge from research labs because of the need for substantial R&D efforts and expertise to bring quantum hardware from the conceptual stage to a practical, market-ready product.

Another viable alternative we might see are spin-off initiatives within existing engineering giants, like in the case of Bosch Quantum Sensing, which recently emerged from Bosch [5].

Quantum hardware providers also need to work closely with standards bodies to ensure interoperability, broader market reach, and adoption of their own products. By participating in standardisation efforts, they enhance their credibility and ensure the regulatory compliance of their products.

There are several challenges that ail quantum hardware providers in India. Some of them are listed below.

CHALLENGES

- Due to a high reliance on hardware components that need to be imported, hardware providers encounter delays in delivery times for equipment that are vital to their projects. There is quite a long turnaround cycle time - by the time contracts are fulfilled and equipment arrives, a lot has changed in the technology. As mentioned earlier, the supply chain is largely international and even prone to disruptions.
- Hardware providers also struggle with the complex processes and paperwork involved in customs. For instance, start-ups in this space have to track bills of entries, work with different banks for different favours, get clearances from various entities - all of which adds an unnecessary overhead to their already difficult endeavour. There have to be checks and balances to make sure that banks, courier companies, and all companies involved in the chain fulfil their compliances and their part of the job properly.
- An alternative is to source components locally, as much as possible. However, there are very few manufacturers in India for these specialised components; Indian companies rarely show up on the radar. Moreover, numerous hardware providers have complained of quality issues with Indian manufacturers. For instance, the quality and precision of the equipment required to setup an optical lab has to be of extremely high standards.
- Given quantum is a strategic technology, it is sometimes difficult to find the right partners abroad with the right security clearances.
- Quantum hardware is still in its nascency, and experts believe it will take decades before the technology is commercially viable. Investors need to be ready to play a long term game. Owing to the highly specialised nature of the hardware, use monetary investments are required, which are not easy to get.
- Defining a success criteria for Proof of Concepts in quantum hardware is difficult, given the technology is not yet mature. This makes customers and investors hesitant to work with and fund quantum hardware companies.
- The question of IP ownership deters collaborations, more so international ones, which are crucial to overcome the technical hurdles faced by quantum hardware technology.
- There are technical bottlenecks that hinder the progress of development in quantum hardware -
 - a. Scalability + NISQ era
 - b. Compatibility and integration with classical technologies
 - c. Development of standards



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KETHARAJU**
Co-founder & Director,
QETCI

The Quantum Technologies value chain report highlights a framework that has the potential to become a benchmarking method, enabling standardized assessment and comparison within the industry, fostering transparency and driving innovation in the quantum technology value chain.

- There is also a lack of talent and expertise, and this might be because of several reasons.
 - a. Quantum technology is a highly interdisciplinary field, which makes it hard to recruit ideal candidates.
 - b. There is a shortage of trained experimentalists in the country, and also a lack of research in experimental quantum technology.
 - c. Several young students and professionals interested in quantum technology are leaving the country for jobs and education abroad.

ALGORITHMS, SOLUTIONS, BASE-SOFTWARE PROVIDERS, AND IT SYSTEM INTEGRATORS

Among companies and start-ups, here is the division between entities working in quantum computing, quantum communication, and quantum security.

Most consulting companies are yet to specialise - the trend is that hardware providers also do base software. Most algorithm providers also are solution providers.

India has a very strong base of consulting and system integrator firms. Many of them are working in quantum consulting and solutions space, also developing specialized algorithms where required. The Indian quantum value chain does not have specialised companies for base software providers though.

The current entities in this space fall under one of the following categories. (Please note that these lists are non-exhaustive and ever evolving)

1. Indian and international software tech giants.

- Wipro
- TCS
- Mphasis
- Accenture
- HCL
- Infosys
- Tech Mahindra
- Harman International

These companies focus mainly on building services and solutions for clients.

2. Start-ups

- QKrishi
- BQP
- Quanta Computacao
- Artificial Brain
- QRD Labs

- Taqbit Labs
- Iota Aon Iq solutions
- PQubit Tech Solutions
- QBit labs
- QRace Quantum Research
- Accelaquant
- Entanglement Partners
- Quantum AI Global

3. Companies that do both hardware and software

- QNu
- Quanfluence
- QpiAI
- Qulabs

A more detailed view of the start-ups in quantum is in Chapter Quantum Start-ups.

INTEGRATED SYSTEM PROVIDERS

All current integrated quantum system providers are from outside of India as of today. The biggest international players in India include.

IBM

With a focus on quantum computing and quantum security, IBM offers quantum hardware through its IBM Q System One. They provide access to quantum processors for research and experimentation via the cloud. IBM also sells quantum computers to organisations for on-premises use. Along with hardware, IBM Quantum's Qiskit is also the most popular quantum software programming library [6].

Microsoft

Microsoft Quantum primarily focuses on the development of quantum hardware, such as topological qubits [7]. Devices from other hardware providers such as IBM and Quantinuum are also accessible via Microsoft Azure Quantum [8].

AWS

AWS provides access to quantum computing resources, including quantum hardware from partners like Rigetti and IonQ, through the Amazon Braket platform [9]. AWS also has the CQN initiative, to focus on quantum communication [10].

Technological leverage of international firms helps complete the value chain on one hand, yet on the other, it is important to be aware that quantum is strategic to nations and often subject to export restrictions driven by geopolitical considerations.

There are several advantages that come through the presence of international firms in the country and they are an integral



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and Information
Technology(MEITY)

MeitY is supporting the development of core and allied quantum value chains including hardware and software. It is actively fostering the development of diverse PIC technology platforms, including silicon photonics, through its self-sustainable R&D centers. PIC technology platforms are poised to revolutionize various sectors in the coming decade including room-temperature Quantum Technologies.

part of the quantum ecosystem and value chain in India.

Some examples of the Advantages are

- **Research collaborations** – e.g IBM's Quantum Network with IIT Madras and BQP [11]. AWS and Meity offer Quantum Computing Applications Lab (QCAL) together. [12]
- **Education** - Indian educators, researchers, and students are able to access quantum hardware via the cloud. This has enabled hands on experience with Quantum Computing to a larger section of students and industry members. Educational collaborations of various firms are also prevalent, like TCS, which is a part of the Microsoft Quantum Network, launched an education program with Microsoft Azure Quantum in 2022.
- **Local Hardware Innovation** - Access to hardware over the cloud gives us the opportunity to further research and resolve the bottlenecks in developing local hardware.
- There is also a need to ensure that there is space and opportunity for new national entities to be able to compete in a market dominated by large entities currently.

NON SUPPLY CHAIN COMPONENTS

Understanding the entities that inhabit the horizontal layers of the quantum technology value chain are vital to developing a complete picture of the state of quantum technology in India.

The insights associated with these entities are highlighted in other chapters such as Manpower, Standards and Development, Research and Development, and so on. Here is a brief summary of how these entities play a role in the value chain.

EDUCATORS

Unlike traditional industries, quantum education providers exist in industry and academia. Quantum start-ups have been especially active in educational outreach and skill development. A more detailed analysis is provided in the chapter - Manpower and Skill Development.

RESEARCHERS

Since quantum is still in the R&D phase, it is not surprising that researchers are present in various layers, as part of different kinds of entities. They also form a large part of the current customer base for quantum products and services today. This marks an opportunity for other entities in the Indian ecosystem to tap into the needs of quantum research labs and groups. The challenges specific to research elaborated in the R&D chapter.

3.8 NON SUPPLY CHAIN COMPONENTS

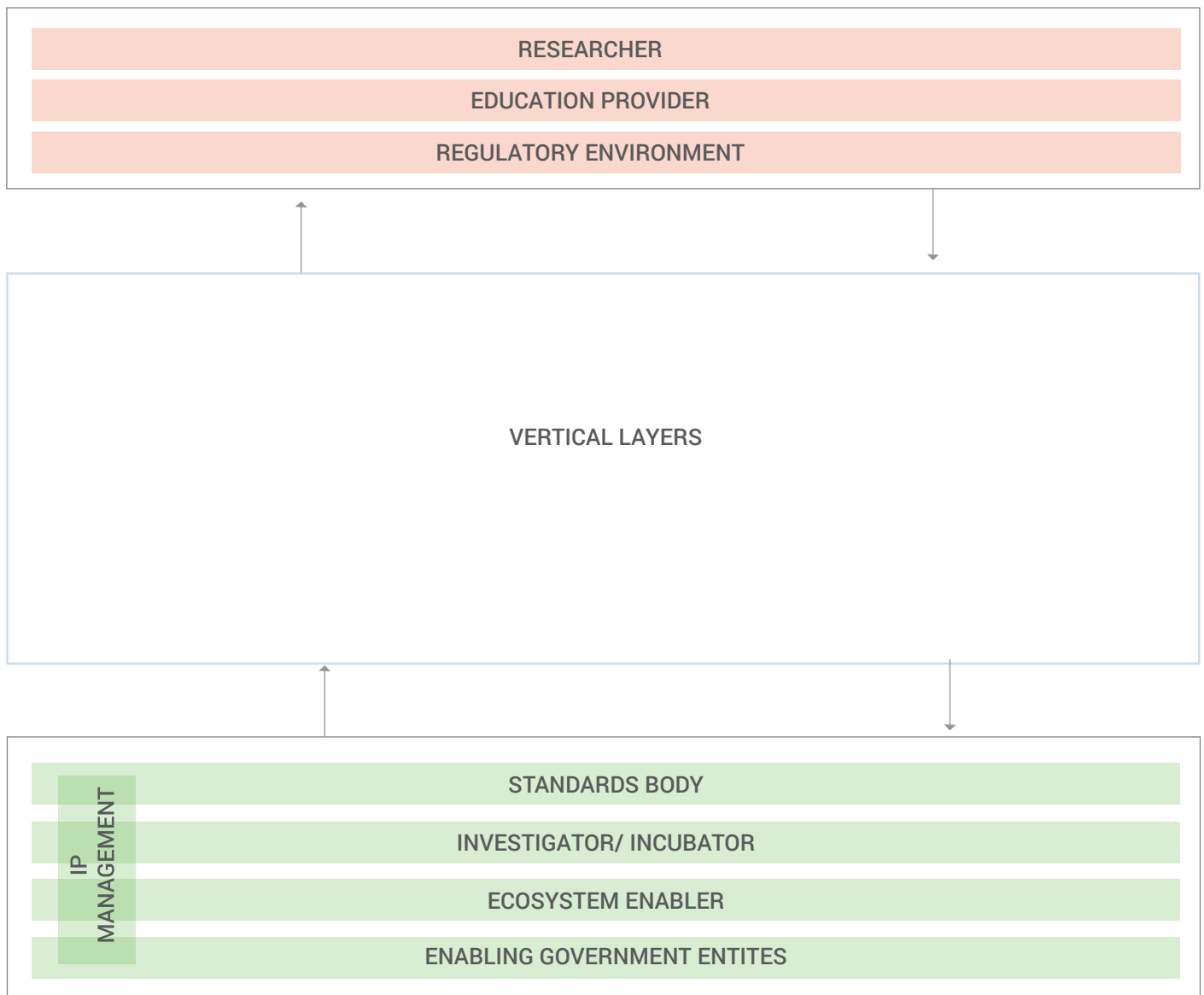


FIG 3.8 Non Supply Chain Components.

REGULATORY AND STANDARDS BODIES

Standards and regulations in quantum technology encompass a set of guidelines, protocols, and frameworks that define best practices, safety measures, and interoperability for various aspects of quantum technologies. Developing standards and regulations is crucial to ensure the safe, ethical, and effective development and deployment of quantum technologies, fostering trust and facilitating their integration into existing systems. More details in Chapter Standards and Developments.

INVESTORS AND INCUBATORS

Broadly, they are of 3 types.

- General investment funds that recognise potential but are risk sensitive, so they have a few quantum start-ups on their portfolio.
- Deep tech funds - mostly technology agnostic and invest in quantum.
- Quantum specific funds, which are fully focused on quantum.

Today India lacks specialized funds which are fully focused on quantum. It is recommended that the Govt drives this area by setting up a Quantum Fund in Public Private Partnership mode. Incubators like T-Hub and I-Hub are already focusing on supporting quantum start-ups.

ECOSYSTEM ENABLERS

These are entities that work with various elements of the Quantum Ecosystem and the quantum value chain and often play a catalyst or enabler role in driving market opportunity, provide policy recommendations and/or provide a collective voice of the industry. Entities like the Quantum Ecosystem and Technology Council of India (QETCI), Data Security Council of India (DSCI), SIA (Satellite Industry Association) are all examples of ecosystem enablers in India.

ENABLING GOVERNMENT ENTITIES

The National Quantum Mission in India is spearheaded by Department of Science and Technology (DST). Ministry of Electronics and Information Technology (MEITY) has several initiatives in quantum. Many other departments such as Department of Space, Department of Telecommunications and more in the Government have a focus on quantum. All of these entities are enabling entities supporting and nurturing the quantum ecosystem.

THE STATE OF THE QUANTUM VALUE CHAIN IN INDIA

The evaluation of the relative strengths of various elements within a National Value Chain are done by evaluating the results of the interviews and secondary research and applying that to the value chain Diagram by colour coding the value chain as follows.

3.9 THE CURRENT STATE OF THE VALUE CHAIN IN INDIA

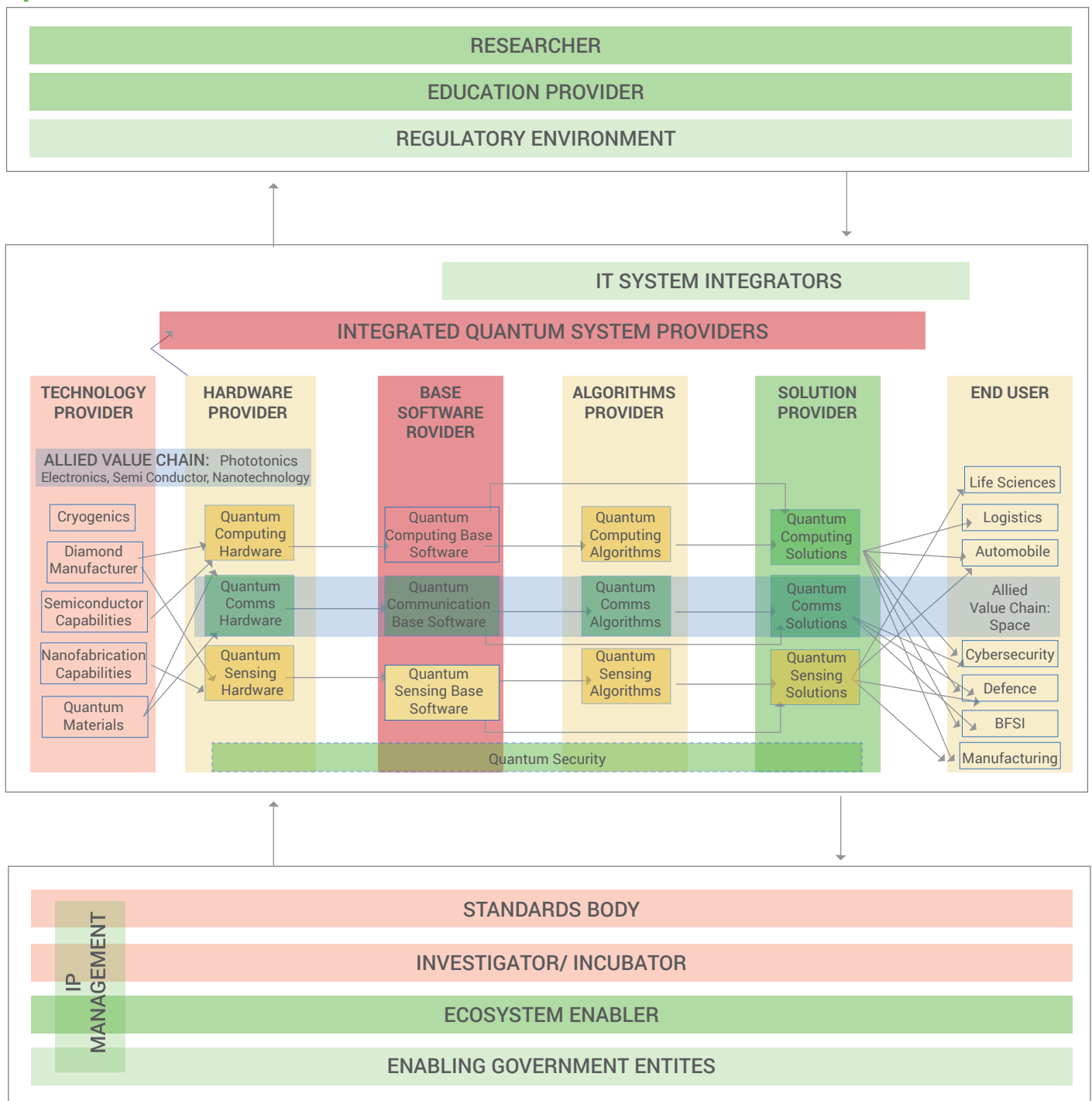


FIG 3.9 Current State of quantum value chain in India.

ANALYSIS

As we can see, there are various part of the value chain which need to be strengthened for enabling a cohesive flow of value in the ecosystem. This can be done through:

- Leverage of international collaborations for building cross border value chains.
- Have an action plan for indigenous development of capabilities for certain parts of the value chain.

SWOT ANALYSIS

A summary of the relative Strengths, Weaknesses, Opportunities and Threats is as follows:

3.10 SWOT ANALYSIS

STRENGTHS

- Strong system integrator and consulting players - Strong allied space sector
- Ecosystem enabler entities exist to bring together various stakeholders for collaboration
- National Quantum Mission is announced and Budgeted for
- Good presence in quantum communications and quantum security
- Strong engineering and scientific talent
- Rapidly growing deep tech startup base
- Strong educational and STEM focus

WEAKNESS

- No large Indian quantum computing hardware companies
- Delay in imports causes delay in research and development progress impacting both scientific research as well as start-up progress
- Weak links between academic research and commercial research
- Absence of deep investments by Indian conglomerates in quantum

OPPORTUNITIES

- Leveraging research POCs for driving commercial start-ups
- Close linkages with the semiconductor industry
- Geopolitical considerations
- Photonics integrated Circuits and Silicon Photonics focus of Meity
- Leveraging infrastructure and capabilities built from the Nano Mission and the semiconductor missions
- Possible synergies with the strong pharmaceutical and biotech sector in India

THREATS

- Nascency of the technology
- Varying levels of maturity
- Fragmented nature of the supply chain
- Scarcity of suppliers
- Standardisation
- Geopolitical considerations
- Quantum computing requires deep pockets and can only be picked up by large conglomerates or when very high funding is available for quantum star-tups

A DEEPER ANALYSIS INTO SOME TOPICS

Opportunity: Close linkage with the semiconductor industry

The semiconductor technology supply chain is closely linked to quantum technology; it is an essential backbone to the quantum supply chain, and consequently a critical factor in its development. While they have distinct focuses, the semiconductor industry provides critical elements that contribute to the development and functionality of quantum technology. Both industries require highly precise and advanced manufacturing processes to create components. Semiconductor fabrication techniques often overlap with the production of components used in quantum systems [14]. In extension, there is also an overlap in suppliers which cater to both industries, like suppliers of optical elements and nanofabrication technology among others. There is a lot of opportunity for collaboration between the industries; quantum computers have the potential to impact the semiconductor industry in areas like materials discovery. Consequently, the semiconductor industry's research into advanced materials like superconductors can potentially benefit the quantum supply chain by providing suitable materials for quantum applications.

As quantum technologies mature, there is potential for hybrid systems where quantum components are integrated with classical electronic components. This convergence could involve both quantum technology and semiconductor supply chains working together to create integrated solutions, like in the case of 6G technologies [15]. The semiconductor industry has decades of experience in scaling manufacturing processes, and leveraging this to address scalability of quantum technologies as they move from research to commercialization will be key. India's National Semiconductor Mission and strong presence of NITI Aayog in the semiconductor start-up space via programs like Start-Up India [16,17] can be utilised to bring in special encouragement and benefits to start-ups in areas which are crucial to fill in quantum supply chain gaps.

Opportunity: Geopolitical considerations

An additional consideration is that of geopolitical factors and their influence on the global supply chain. Favourable relationships can provide access to critical resources and also reduce supply disruptions. Bilateral agreements play a crucial role, even for start-ups looking for market opportunities internationally. Another key focus of such inter-government collaborations is manpower and skill development, which is undoubtedly fundamental to a resilient supply chain. India must leverage its vast engineering talent pool to build stronger services capabilities related to quantum.

A focus of the recent Indo-US initiative on Critical and

Emerging Technology is to lower barriers to American HPC technology exports to India [18]. An effective import-export policy is crucial for managing the complex supply chains associated with complex technologies in India. Simplifying customs processes and regulations can streamline the movement of quantum components, shorten production times, and prevent bottlenecks. To develop such a policy, one that ensures the progression of technology does not suffer, a clearer understanding of Make in India and its balance with imports is imperative.

Threat: Nascency of the technology

There are unique challenges associated with the quantum technology value chain in India, making it distinct from traditional value chains. The nascency of the technology is one of the main reasons the value chain is disjointed, fragmented, and non-uniform across the world. Due to frequent innovations and the ever-evolving nature of quantum, there are constant shifts in hardware approaches. In quantum communication, traditional protocols like BB84 are making way for newer approaches like continuous variable QKD, which have different hardware requirements and performance characteristics. With a lack of established norms (difference in terminology, benchmarking, understanding of protocols - standardisation therefore IEEE, ISO, ITU etc), different research groups, companies, and organizations take diverse approaches to solve challenges. This diversity can lead to the development of unique methods, technologies, and components, further contributing to fragmentation.

Threat: Varying levels of maturity

Today, we are faced with varying levels of maturity of different technologies; certain hardware modalities are relatively more advanced and ready for commercialization compared to the others. Since some components might be more readily available than others, the supply chain is at a risk of becoming disjointed. Additionally, demand for products and services are uncertain, which makes it difficult for players to gauge market needs accurately. This results in the emergence of a concentration of entities that cater only to certain specific areas, which may be lopsided and unproductive in the long run.

Threat: Fragmented nature of the supply chain

Fragmented supply chains across the world create a global opportunity - This also presents an opportunity for Indian entities; specializing in portions of the global supply chain, and in areas like components for quantum R&D, quantum security related digital transformations, solutions in the intersection of quantum and space, quantum meteorology,

could help establish them in the global market. However, fragmentation now is not bad since it can result in exploration, innovation, diverse solutions. It is reflective of nascent stage of industry, and consolidation will soon start.

Threat: Scarcity of suppliers

Another obvious disadvantage is the scarcity of suppliers, which makes it a challenge to establish a comprehensive supply chain network. A limited supplier base could mean high dependence on a small number of entities and therefore the risk of bottlenecks. This is especially painful for research, since they cause delays in critical inputs to the next stage of the experiment. From a market stand-point, such delays could also negatively impact the competitiveness of start-ups and companies. While there are suppliers for certain components present within the country, they are limited and are not of high quality.

Lack/Delay in Standardisation

Since quantum technology is still majorly research focused, there is limited investment in scaling up production and standardizing processes. Standardization is crucial for creating an efficient and cohesive supply chain. Bodies like Telecom Standards Development Society of India (TSDSI) and TEC are working with industry and academia to develop standards for quantum technology. In emerging fields, the lack of established industry standards can result in differing practices and approaches, which can cause a fragmented supply chain. Standardization in the semiconductor industry, for instance, has enabled companies to tackle scalability and compatibility issues with relative ease.

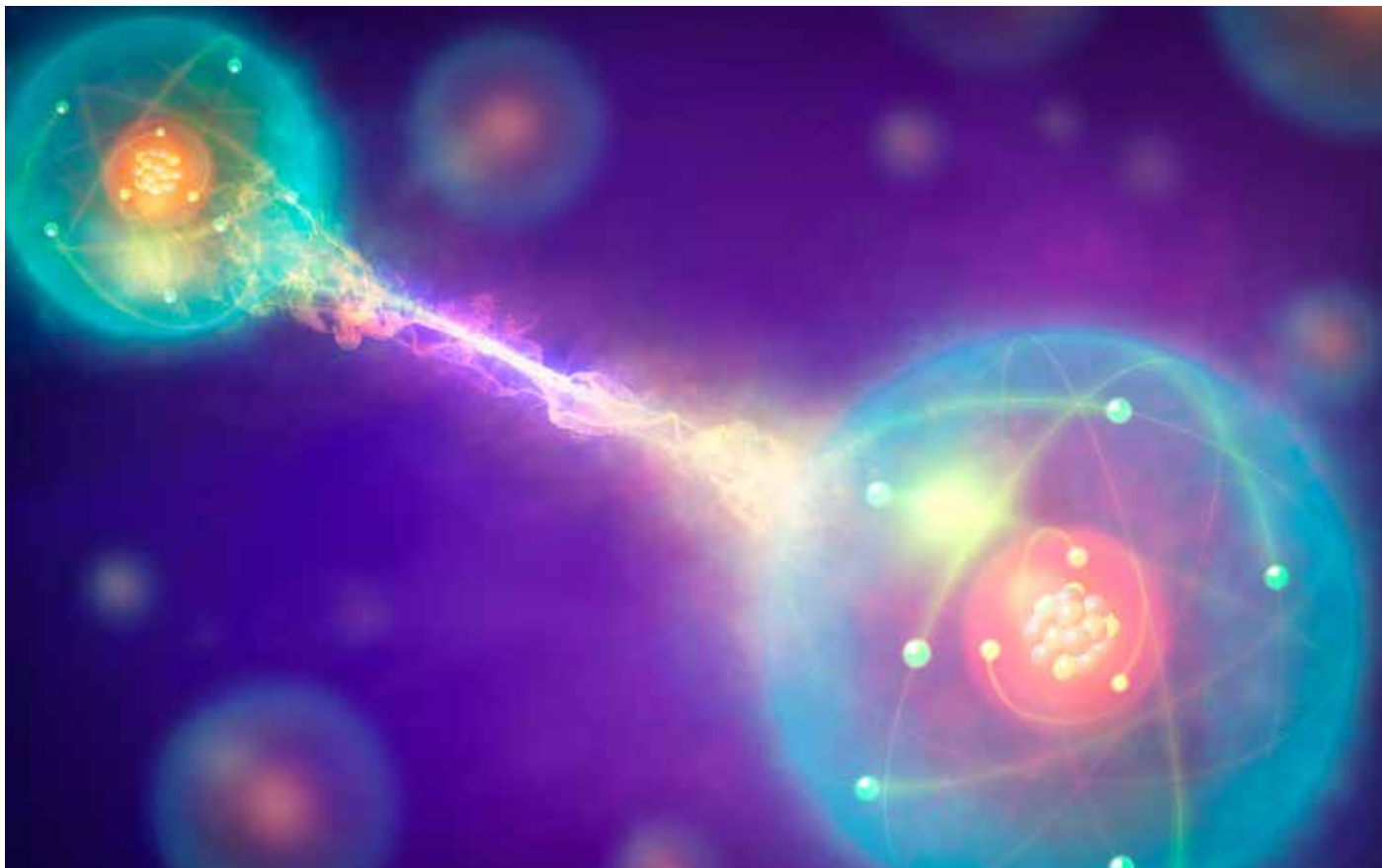
Geopolitical Considerations

Not so favourable geopolitical circumstances may also prove fatal for the emerging technology of quantum. For instance, the Wassenaar Arrangement regulates the transfer of dual-use technologies, including some quantum technologies like post-quantum cryptography. Stringent controls can impede the global distribution of quantum components and devices, affecting the efficiency of the supply chain. This is true even in the case of trade restrictions, embargos, and regulatory hurdles. A well-developed policy might be crucial in mitigating potential disruptions to the supply chain.



MR. NIKHIL MALHOTRA,
Chief Innovation Officer,
Tech Mahindra

The IT Services sector is critical to ensure the quantum value chain is enhanced by delivering value to its customers and society. The services sector would not directly get involved in fundamental research on hardware, their role however would be more translational research. How can quantum computing and other facets play a part in solving customer challenges be it security, quantum machine learning, deep sensor integration etc. as a big part of value chain delivered via the services industry.



QUANTUM AND ALLIED INDUSTRIES

Quantum Computing, Communications, Sensors, and Materials are not just part of an isolated quantum Value Chain but have interfaces with other industries. The most notable of these are the semiconductor, materials, and the electronics Industry. Supply chain components of these industries are important suppliers for the quantum industry as well. On the other hand, industries like the space industry have a very deep overlap with the quantum industry. The quantum value chain becomes a value adding element to aspects of the space industry value chain. At the same time elements of the space industry are part of the quantum value chain as well.

Given that quantum is our next generation information technology; across quantum computing, quantum communications, quantum sensing, quantum materials and quantum security we will see a gradual diffusion of all things quantum across Industries over a period. This is very similar to how the classical computing that we use today is an integral part of all businesses. Every business is impacted by technology as we know today. We will see the same in quantum. However, this is a projection of the perceived future.

At present we may consciously chose to focus on the more immediate short term and next 10 year projection , based on which the industries are gearing up.

The semiconductor industry is one of the bedrocks for the digital technology (computing, communications and sensors) that exists today. The future of any new technology becomes easier to unfold, if elements of the existing infrastructure capability can be utilized for the purpose of this.

The Interuniversity Microelectronics Centre (IMEC) based in Belgium, announces in 2022 that they were close to realizing a 300 mm CMOS process for developing high quality qubits based on superconducting technology. Efforts and milestone achievements like this provide hope that existing semiconductor infrastructure and process investments would have continuity with a technology like quantum.

On the materials front, several materials like GaAs, SiGe, and Si and their isotopes are good options for superconducting qubits.

If we examine photonics based development, there is a tremendous possibility of leverage of existing technology of Photonics Integrated Circuits (PICs) as well as silicon photonics capability that already exists. These capabilities are relevant for photonics based quantum computing, quantum communication and sensor development as well. India has traditionally had a stronghold on photonics with research and development funding and efforts spanning several decades from the past. This is an area of focus for India and possibly the place from where India can emerge as a leader in the quantum ecosystem of the world.

The components and parts and designs for quantum often require working at nanoscale , and hence nanotechnology capabilities are an important part of enabling further growth and development in the quantum area.

As a part of the Nanotechnology Mission, nanotechnology Centres of Excellence were set up by DST across the country. The Ministry of Electronics and Information Technology supported several projects across the country. There were cross agency and lab efforts spreading across DRDO, MEITY, DST, ISRO.

The Quantum Internet will use Satellites for enabling connection of local ground based networks across long distances, thus enabling a quantum Internet of sorts.

4.1 NATIONAL LABS / INSTITUTIONS / UNIVERSITIES INVOLVED IN NANOSCIENCE AND NANOTECHNOLOGY ACTIVITIES

LABS	INSTITUTIONS	UNIVERSITIES
DST: ARCI, IACS, SNBNCBS, CENS, INST, ARI and JNCASR DRDO: SSPL, DMSRDE, DMRL, NMRL, HEMRL, NPOL, ACEM and DLJ CSIR: ICT, NPL, NCL, INST, NIIST, CLRI, CGCRI, NIIST, IMMT, AMPRI, IITR, CSIO, CEERI, CECRI, CFTRI, CMERI, IMT, IIIM, NAL and NML ISRO: VSSC and Semiconductor Complex Mohali UGC: UGC-DAE Consortium (Kalpakkam, Mumbai, Kolkata, Indore), IUAC, CGC-Anna University Campus DAE: BARC, IGCAR, RRCAT, IOP, FCIPT-IPR, TIFR, SINP and NCBS MeitY: C-MET (Hyderabad, Pune, Thrissur) • DBT: ILS, CIAB and NABI CAR: CIRCOT, CIFE, CIFA and NIASM MNRE: NISE and SSS-NIRE MoFPI: IIFPT and NIFTEM ICMR Labs: Regulations on nanotechnology and handling of nano-materials Government-recognised Semiconductor Technology and Applied Research Centre (STARC)- formerly SITAR, Bengaluru Government-recognised Gallium Arsenide Enabling Technology Centre (GAETEC), Hyderabad	IISc Bangalore NITS (Rourkela, Trichy, Warangal, Calicut, Bhopal, Nagpur, Jaipur, Allahabad and a few newly established NITS) IITS (Kharagpur, Kanpur, Mumbai, Madras, Roorkee, Delhi, Guwahati and a few newly established IITs like Indore, Ropar, Gandhinagar, Patna, Bhubaneswar, etc) IISERS (Kolkata, Pune, Mohali, Bhopal, Trivendrum and Berhampur) IIST (formerly BESU/BEC), Shibpur, West Bengal	Central universities like Jawaharlal Nehru University, Delhi University, Pondicherry University, Allahabad University, Tezpur University, University of Hyderabad, CU-Jharkhand State universities like Jadavpur University, Calcutta University, Madras University, Bangalore University, Mysore, Karnataka University, Bharathiar University, Bharathidasan University, Alagappa University, Osmania University, Madurai Kamraj University, Anna University, Utkal University, Sambalpur University, North-Orissa University, Mumbai University, Shivaji University, Andhra University, TERI, SV University, Punjab University, University of Rajasthan Leading private universities like SASTRA Deemed University, VIT Deemed University, SRM Deemed University, Sathyabama Deemed University, Amity University, Amrita Deemed University, Karunya Deemed University, Periyar Maniammai Deemed University, Hindustan Deemed University, Annamalai University, BIT Mesra, BITS Pillani

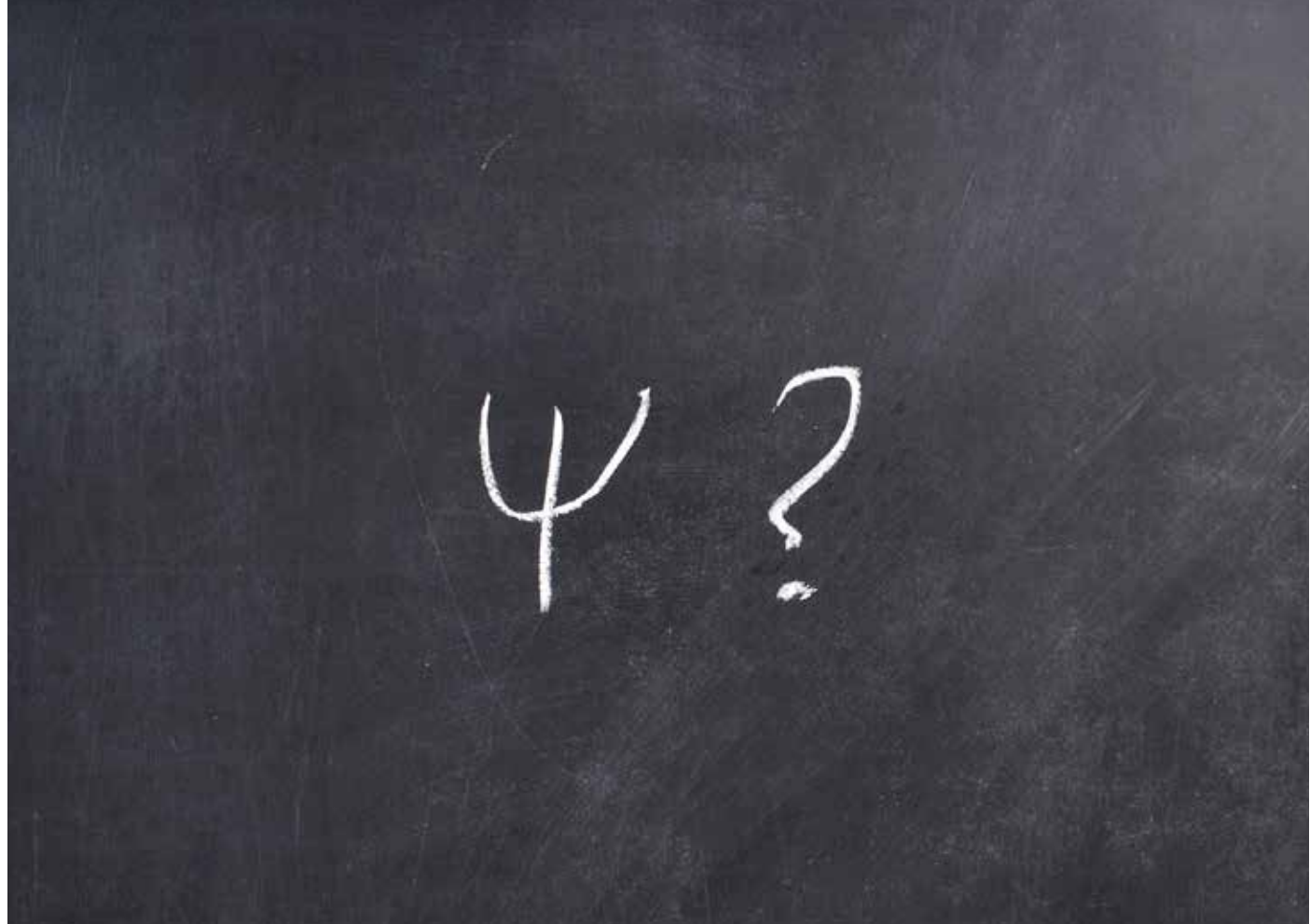
QUANTUM AND SPACE

There is a fair amount of overlap of value chains for Quantum and Space

- Space based secure communications system is an important area of application of quantum technology in Space.
- Time standards and frequency transfer based applications leveraging quantum and Space and providing global Availability
- Quantum sensing applications in Space. Both for earth monitoring and sensing (related to climate change studies, earthquake prediction and monitoring etc) and for applications in space telescopes
- Space is a great environment for studying the fundamental laws of physics, so setting up quantum physics labs in space would help drive essential science development forward

(**Reference**: Quantum Technology in space, Rainer Kaltenbaek et al, 10th Sept 2020)

Raman Research Institute announced in February 2021 the first successful demonstration of free space communication. Since then there have been significant developments in QKD technology by Raman Research Institute.

A chalkboard with the handwritten text "Ψ?" in white chalk. The chalkboard is dark and has some faint, illegible markings in the background.

RESEARCH AND DEVELOPMENT

THE IMPORTANCE OF AN R&D DRIVEN APPROACH

Taking an R&D driven approach to quantum technology is a strategic imperative that holds the key to an advanced quantum ecosystem in the country. Deliberate and systematic investments into quantum technology is a fertile ground for innovation due to its potential to revolutionize industries, and rigorous R&D efforts can lead to breakthroughs that have the power to disrupt and transform traditional technological paradigms.

A strong R&D focus is particularly crucial in overcoming the technical challenges that quantum technology faces. These bottlenecks, including error rates, qubit stability, and decoherence, require concerted efforts to develop effective solutions that are vital to transition quantum technology from the laboratory to markets. By investing in quantum R&D, governments, institutions, and industries position themselves at the forefront of the quantum race. This not only drives economic growth through the creation of new industries and markets, but also establishes India's strong foothold in the global quantum ecosystem.

INDIAN R&D EFFORTS

The QuEST program was instrumental in consolidating and accelerating pre-2016 research efforts in the area of quantum technologies [1]. Not only was it the first initiative that promised structured funding to researchers and academics, but it also garnered attention on the international stage, positioning India as a key player in the global quantum ecosystem. While QuEST laid the groundwork by focusing on research and development, the National Quantum Mission extends its scope to encompass various dimensions of quantum technology's integration with the industry [2].

Although research has not always been a priority for Indian industrial entities operating in other technologies, it is encouraging to observe that players in the quantum ecosystem are investing significant portions of their budget into R&D. It is not only academic or government organisations that are taking the charge, but also several start-ups that have cutting edge labs.

5.1 QUANTUM LABS AND GROUPS IN INDIA



FIG 5.1 Quantum labs and groups in India.



PROF. URBASI SINHA,
PROFESSOR
Light and Matter Physics,
Raman Research Institute

The success of the National Quantum Mission will require an efficient alignment of various factors including smooth flow of funds, timely project reviews, human resource development as well as availability of high end components and products that will enable the quantum technology development. Currently, we face tremendous challenges in timely execution of projects as indenting and procuring components takes months, most of them being imported. We need to ensure that we emphasise indigenous development of allied technologies to help with the overall mission objectives being achieved on time. Having said that, we also need to realise that maturity of such development takes time and abruptly making import arbitrarily difficult is definitely not the solution. We need gradual and efficient development of allied technologies so that our supply chain becomes self sufficient in the long run.

The National Quantum Mission has been especially fruitful in incentivising the creation of new labs and groups working on quantum technology across the country.

5.2

INSTITUTE	FOCUS AREAS
IIT Madras	    
IIT Bombay	    
IISc	    
PRL	    
IISER Pune	    
CDAC	    
TIFR	    
IMSc	  
Pondicherry University	   
IISER TVM	    
IIT Tirupati	    
Amrita Vishwa Vidyapeetham	    
SRMIST	  
IIIT Hyderabad	    
IIT Dharwad	  
RRI	    
PPISR	    
NMIT	
IISER Bhopal	  
IIT Mandi	   
IIT BHU	
IIT Indore	 
IIT Patna	   
IIT Jodhpur	    
IIT Bhuvaneshwar	
IIT Ropar	   
IIT Roorkee	   
TCG Crest	  
IIT Guwahati	   
IIT Delhi	    
IIT Kanpur	    
IIT Kharagpur	    
HRI	  
IIST	

INSTITUTE	FOCUS AREAS	Legend:
DYSL - QT	    	 Quantum Computing
IIIT Kottayam		 Quantum Communication
CR Rao AIMSCS	 	 Quantum Sensing and Metrology
Mahindra University		 Quantum Security
		 Quantum Materials

The table merely depicts the presence of some research related to the area. Not duration or number of researchers

It is interesting to note that some of these groups, like those at Mahindra University and IIIT Kottayam, have arisen from collaborations between industry and academia.

Notable points from secondary research are -

- Global investments in quantum R&D. As per a report by Quereca the worldwide quantum investments have exceeded USD 38.6 Billion in 2023.
- India's total investment for quantum R&D including NQM, QuEST, National Cyber Physical systems (IHub - IISER Pune) will cross USD 1 billion.

The future of the R&D landscape looks promising, given the number of entities getting involved, however, the level of activity and focus remains insufficient. These investments often pale in comparison to those made by leading nations at the forefront of quantum research, which currently operate at a scale and scope much larger than what we have in India. Although the National Quantum Mission has allocated substantial funding on a national scale, the extent of direct impact on individual projects remains comparatively modest. This disparity arises due to the inherent complexities of resource distribution and project selection. Albeit not straightforward, a potential solution to streamline funding and resource allocation would involve prioritising certain areas of research based on their immediate strategic importance to the nation. For instance (quantum bio vs cybersecurity). Whether we really need to work on a large quantum computer. Choosing races and battles.

Developing a strategy to identify and then allocate a larger proportion of money, expertise, infrastructure to priority areas can ensure critical R&D thrives.

Another approach that goes hand-in-hand with sub-domain prioritisation is identifying projects that can operate with smaller funds. While large-scale quantum endeavors understandably require substantial resources, quantum sensing, an area that more efforts have gone into recently, can potentially give immense returns with modest investments. Achievements of the Indian Space Mission, like the recent Chandrayaan 3,

have demonstrated the nation's prowess in conducting world-class research and engineering at a fraction of the cost of global counterparts [3]. India has the potential to replicate this success in the domain of quantum sensing.

The classical sensors market in the country is vast and relatively mature, and can prove to be a springboard for quantum sensors [4]. The commercial applications of quantum sensing and metrology are ubiquitous too, attracting a large number and variety of customers.

Another cost-effective area of interest is classical simulation that is fundamental to the progress of larger quantum technology solutions. For instance, to plan, study, and implement vast quantum communication links, researchers would first need to simulate the network. Developing tools for problems like these present an opportunity to the Indian entities, especially because of the kind of manpower we have that is skilled in software development.

A fundamental challenge that ails Indian R&D severely is the lack of collaboration between experimentalists and theorists. Indeed, this problem is neither specific to quantum science and technology, nor to India. The disconnect between theory and practice is especially hindering a field like quantum technology, which is inherently complex and multidisciplinary. Lack of collaboration may also lead to inefficient resource allocation; experimentalists might invest efforts in pursuing ideas that lack theoretical grounding, wasting time and resources on unproductive avenues. Overall, technological progress stagnates, and there are several missed opportunities at the intersection of theory and experiment. Designing funding programs and grants that explicitly require interdisciplinary collaboration might accelerate the integration of theorists and experimentalists. Other avenues might also be useful, such as joint academic positions and appointments that span both theoretical and experimental departments, collaborative workshops and seminars, and establishing research centers with a structure that promotes experimentalists and theorists working side by side.



QUANTUM START-UP ECOSYSTEM IN INDIA

The number of quantum start-ups in India has been steadily growing. Around the beginning of 2021 there were only a handful (less than 10) of quantum start-ups in India, with several of them focused on education. Fast forward to early 2023 and the number has risen to 20+.

These companies are working in areas like quantum computing, quantum communications, quantum security, quantum sensors, solutions, consulting and education and outreach.

The following graph shows the concentration of these companies in specific areas.

6.1 QUANTUM STARTUPS IN INDIA- AREA OF OPERATION

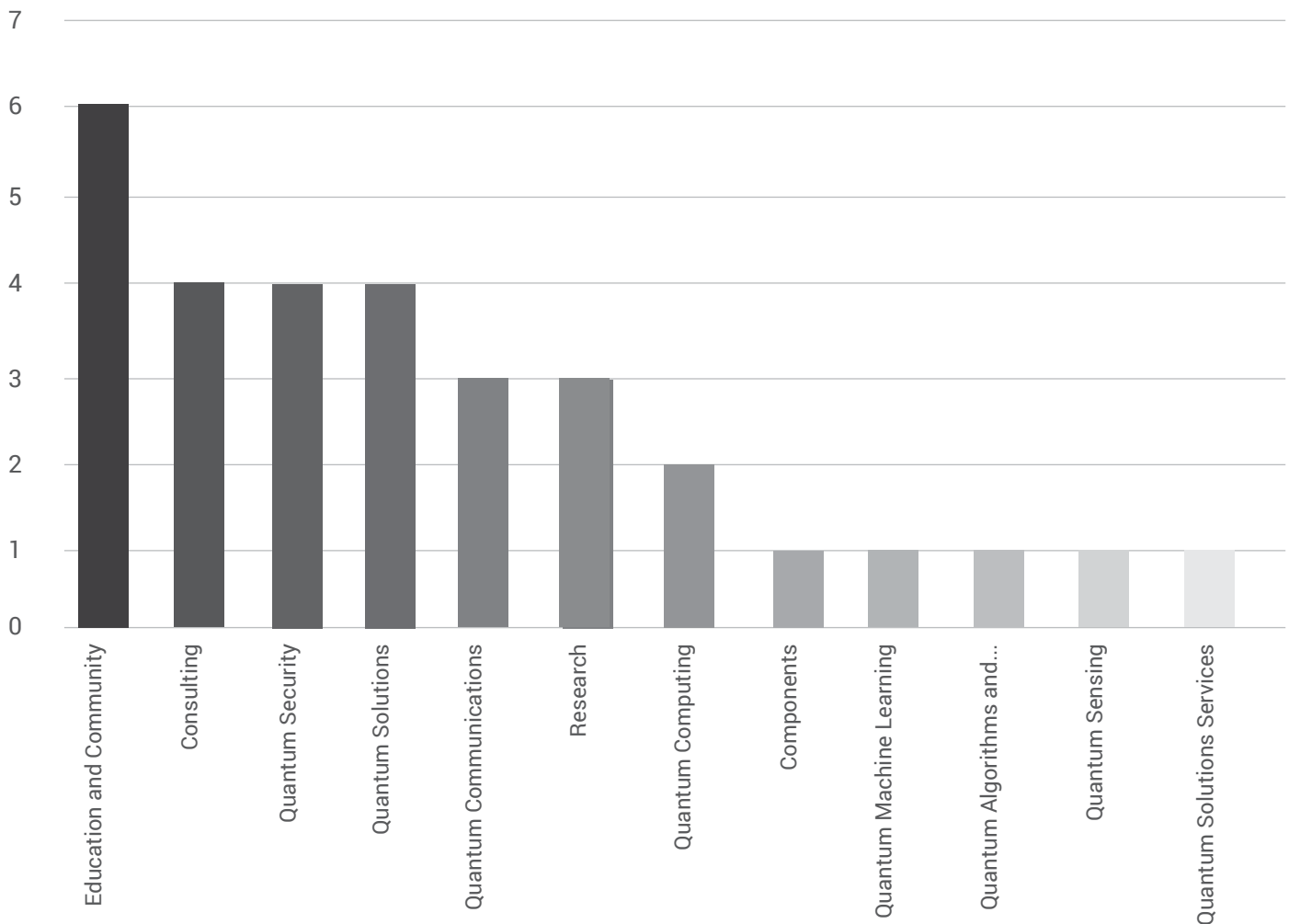


FIG 6.1 Quantum Startups, Area of Operation.

The education and community focused companies were the first to come into being in the ecosystem. Given that quantum is an evolving and less understood area, there is a need for quantum firms focused on education. The same is true for consulting firms. As end user Industries try to understand the what and how of leveraging quantum technology for their industry, there is a need for expert consultation.

The next segment of operations is areas that directly impact end users. Quantum communications, quantum security and quantum solutions are areas where we have seen more startups get formulated in the last 2 years.

WHERE DO THESE FIRMS FIT IN THE QUANTUM VALUE CHAIN

INDIAN QUANTUM START-UPS IN THE VALUE CHAIN

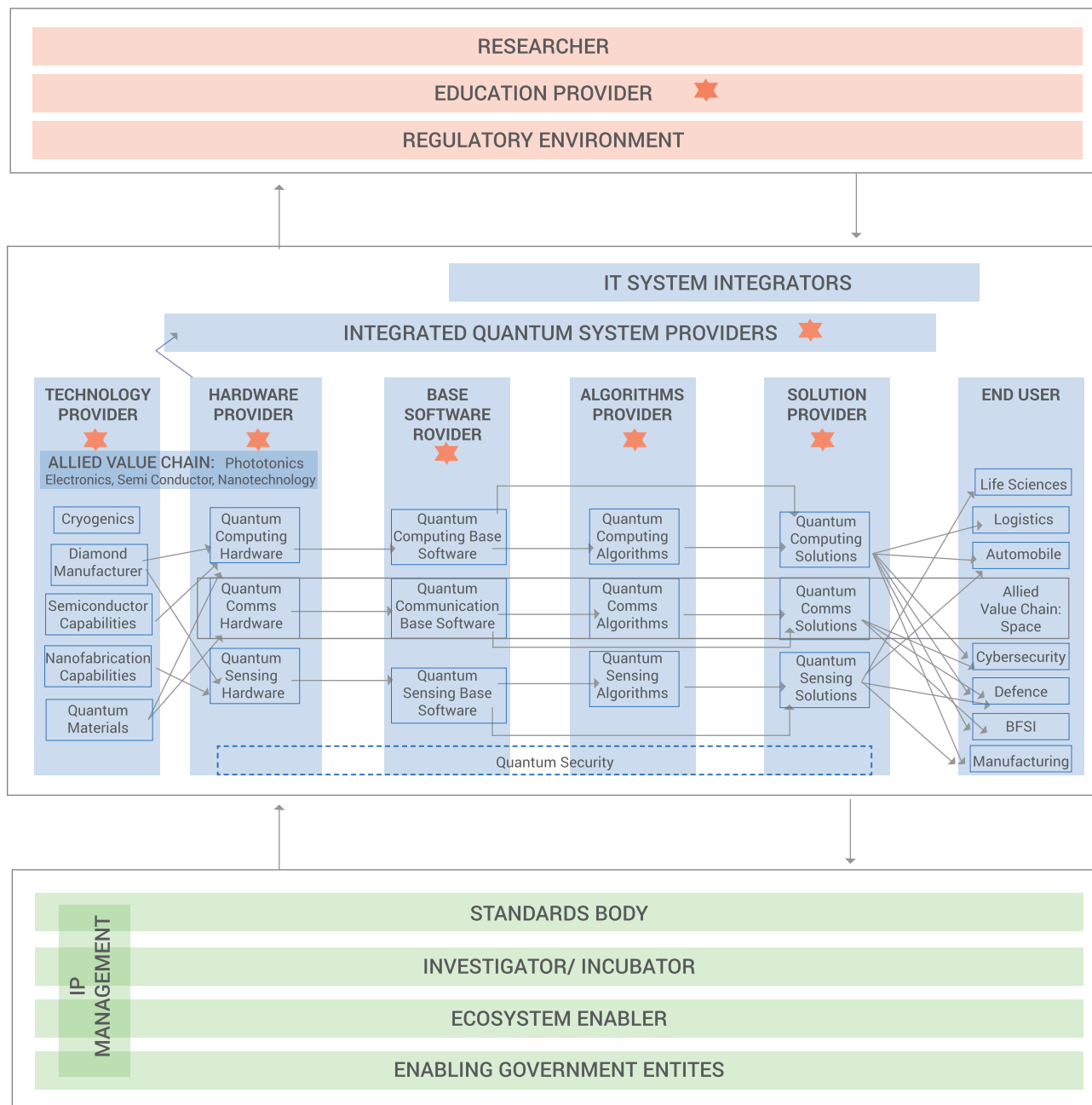


FIG 6.2 Indian quantum start-ups in the value chain.

★ Presence of quantum start-ups.

LOCATION SPREAD OF QUANTUM STARTUPS

The new start-ups seem to be emerging all across India, however we can see hot spots at Bengaluru, National Capital Region and Hyderabad. Some more salient points about startups and locations:

- Bengaluru startups are a mix of hardware and software and solutions focused with both the quantum computing start-ups being based out of

Bangalore.

- NCR quantum start-ups are largely focused on software and solutions.
 - Chennai is incubating start-ups headquartered at several locations, although there are some Chennai based quantum start-ups as well.
 - Hyderabad start-ups are hardware and software focused, with focus on quantum communications, quantum memory, quantum AI, quantum security
- The remaining start-ups are spread around India.

New Opportunities for growth into hot spot is in
Chennai, Mumbai/Pune region

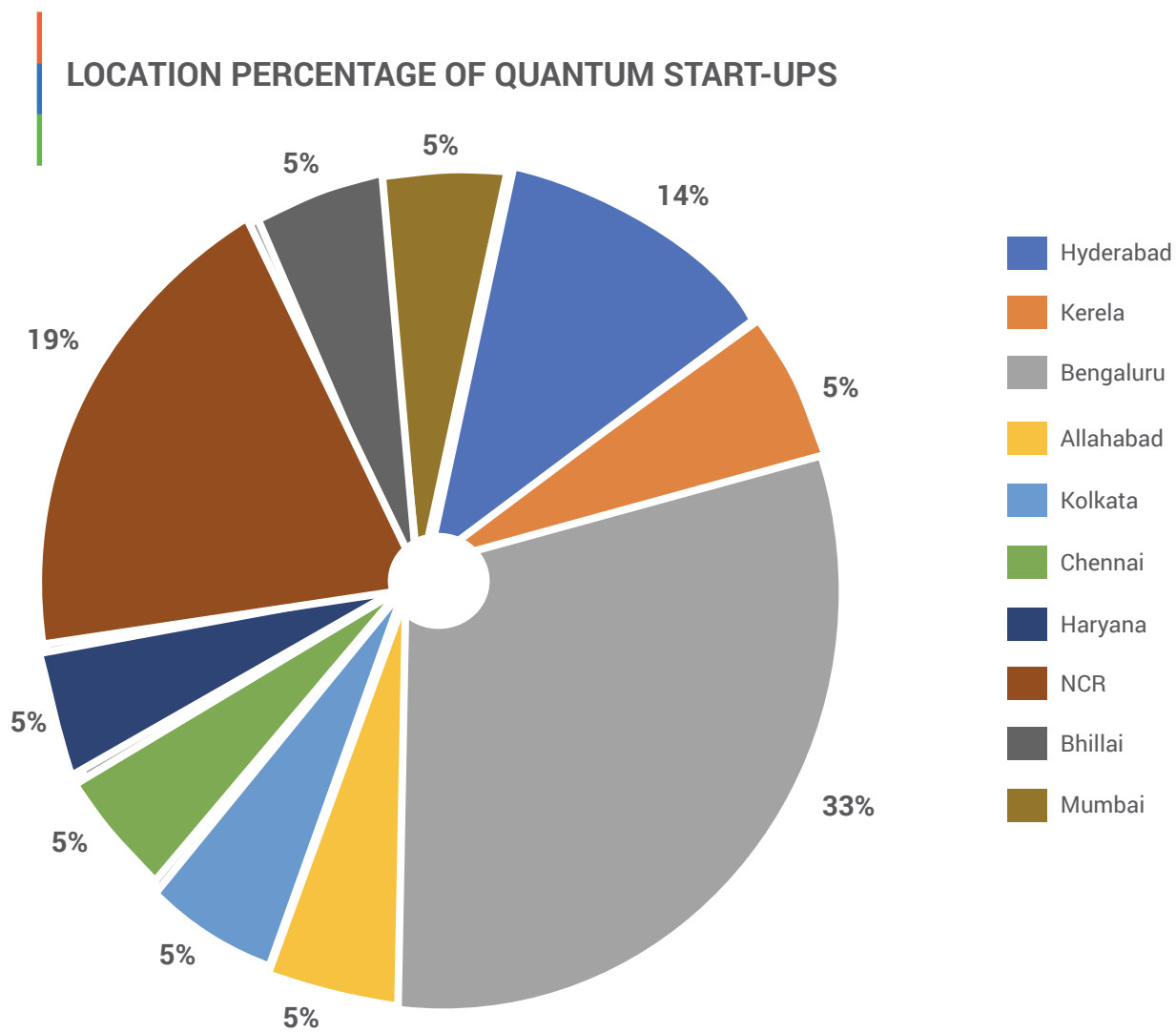


FIG 6.3 Location percentage of quantum startups.

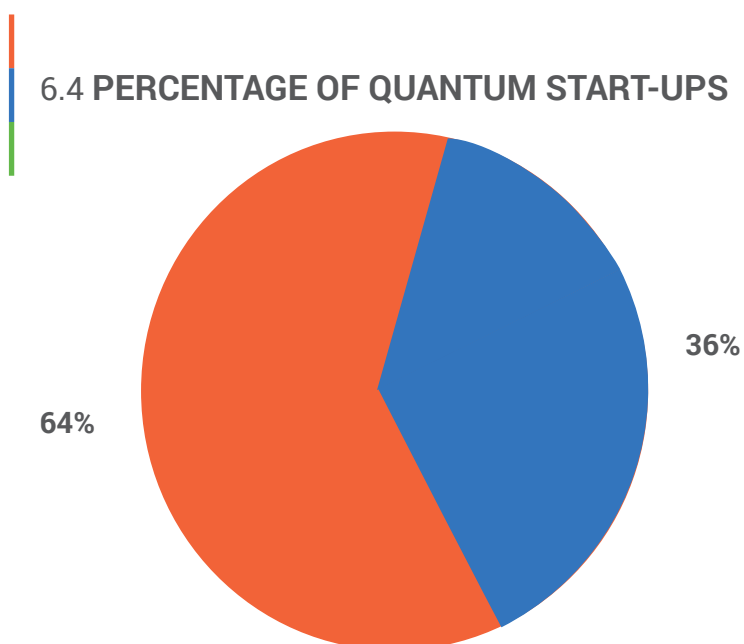


FIG 6.4 Percentage of quantum startups.

The ratio of software and hardware start-ups in the Deep Tech space is very heavily shifted towards software.

So we asked the startup founders in India on what are the challenges that exist for quantum start-ups in India

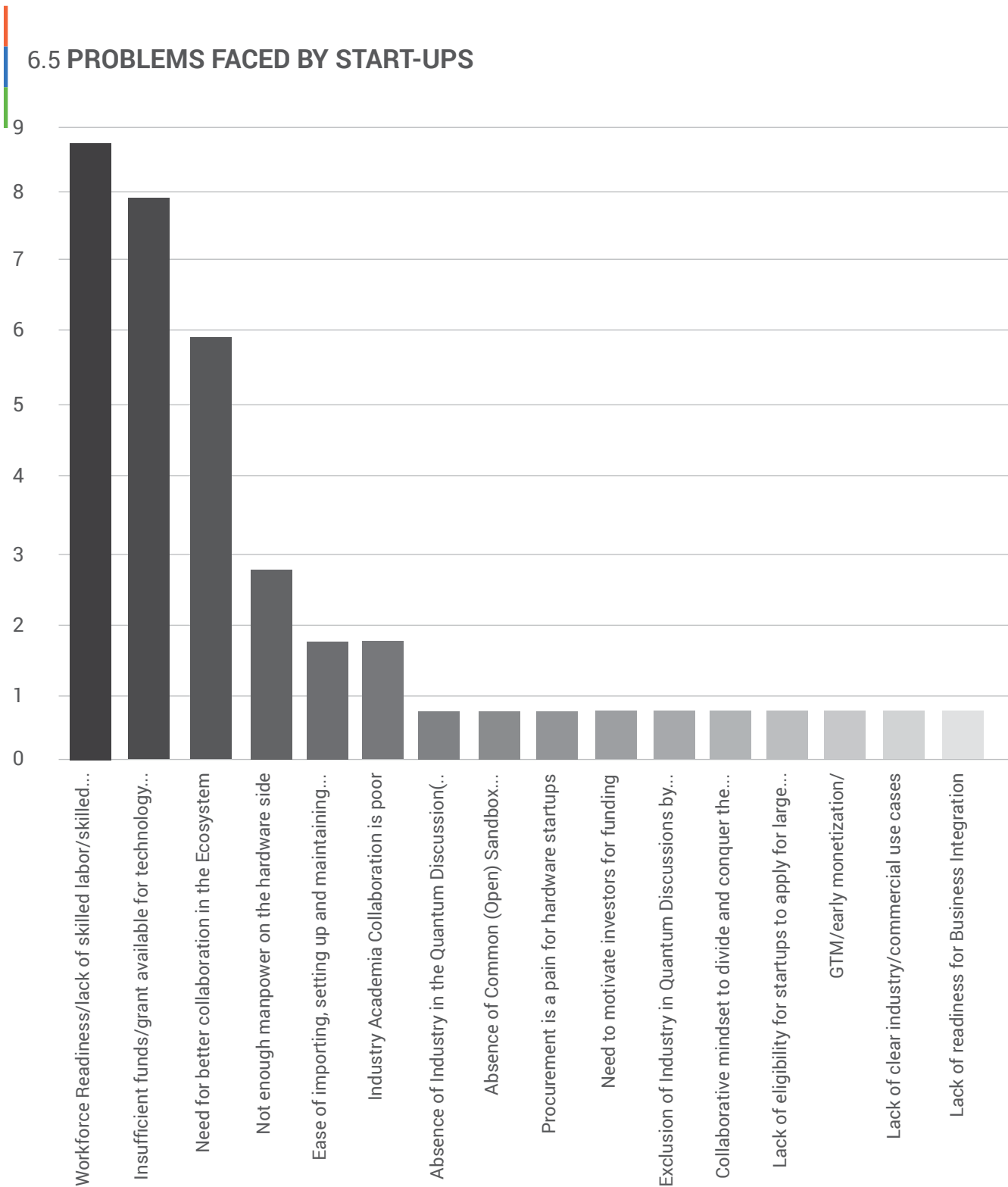


FIG 6.5 Problems faced by start-ups.

The 3 topmost concerns are around:

- Skilled workforce
- Insufficient grants or funds. Ticket sizes for Deep Tech need to be bigger and hence this is a challenge. Also difficult for individuals to pool in personal wealth to kick start a quantum hardware startup as an example
- Better collaboration is needed in the ecosystem, on all fronts - industry academia, amongst academia, amongst industry.

The lower number of people with hardware skills and capability came out as an additional area of concern. This correlates with the data that only 36% of the startups in India are hardware based.

6.6 ECOSYSTEM ASPECTS FAVORABLE FOR QUANTUM START-UPS

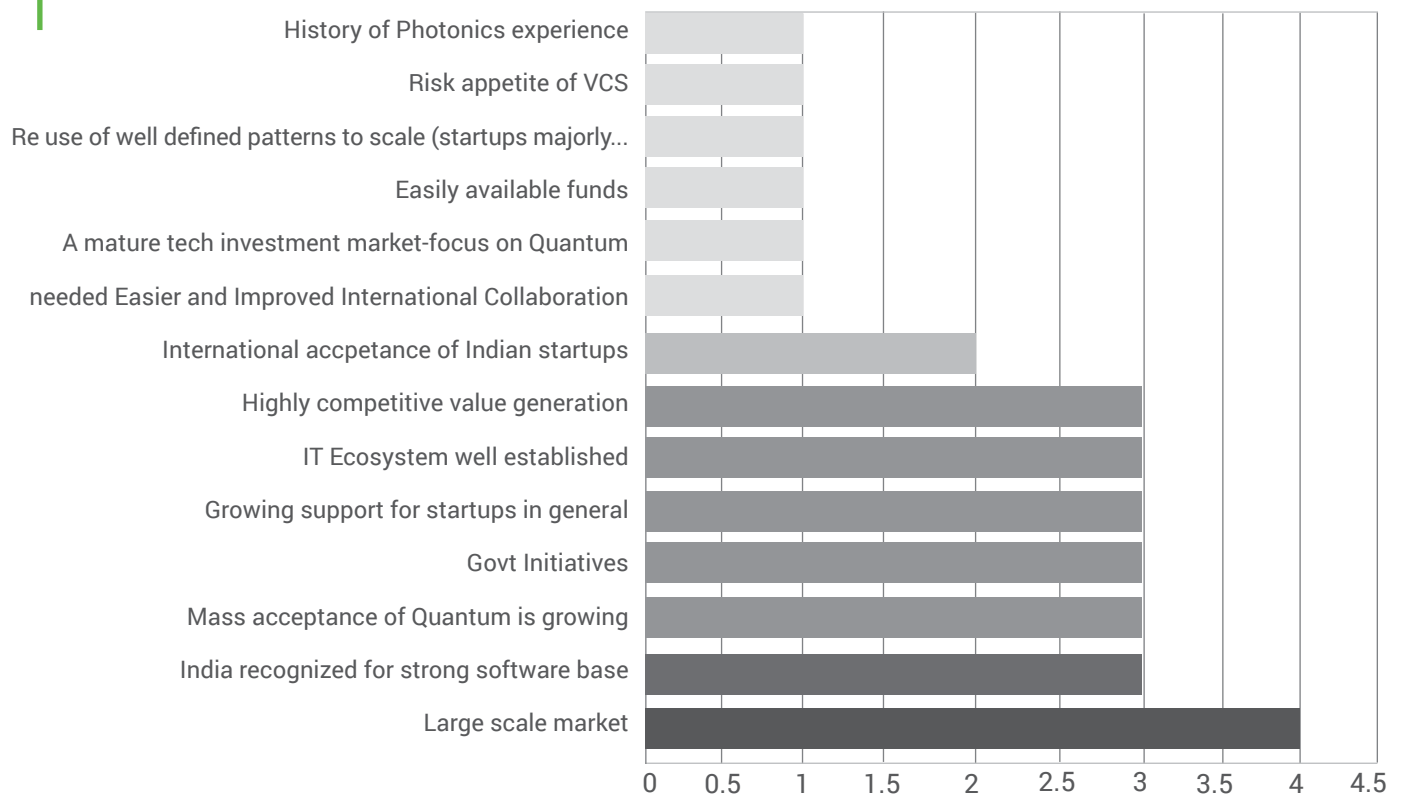


FIG 6.6 Ecosystem aspects favorable for quantum start-ups.

The large scale potential market in India was viewed as the most favorable aspect of the ecosystem. The following areas were found to be equally favourable by many participants

- International acceptance of Indian start-ups.
- Highly competitive value generation by the Indian entities.
- IT ecosystem in India is well established.
- Several Govt. Initiatives in quantum.
- There is growing support in India for start-ups in general and tech start-ups.
- The acceptance for quantum has grown significantly in the last few years.
- India is recognized as a strong software base.

WHERE IS THE OPPORTUNITY FOR QUANTUM STARTUPS

- Quantum security.
- Electronic components - optical interconnects
- Photonic integrated circuits.
- Quantum sensors - design, development, and packaging
- NV center diamond based quantum ecosystem for small scale computing and sensors.
- Quantum materials.
- Quantum solutions for pharmaceutical, biomedical applications, healthcare.
- Quantum solutions for BFSI sector.
- Quantum sensing and communication solutions for aerospace sector.

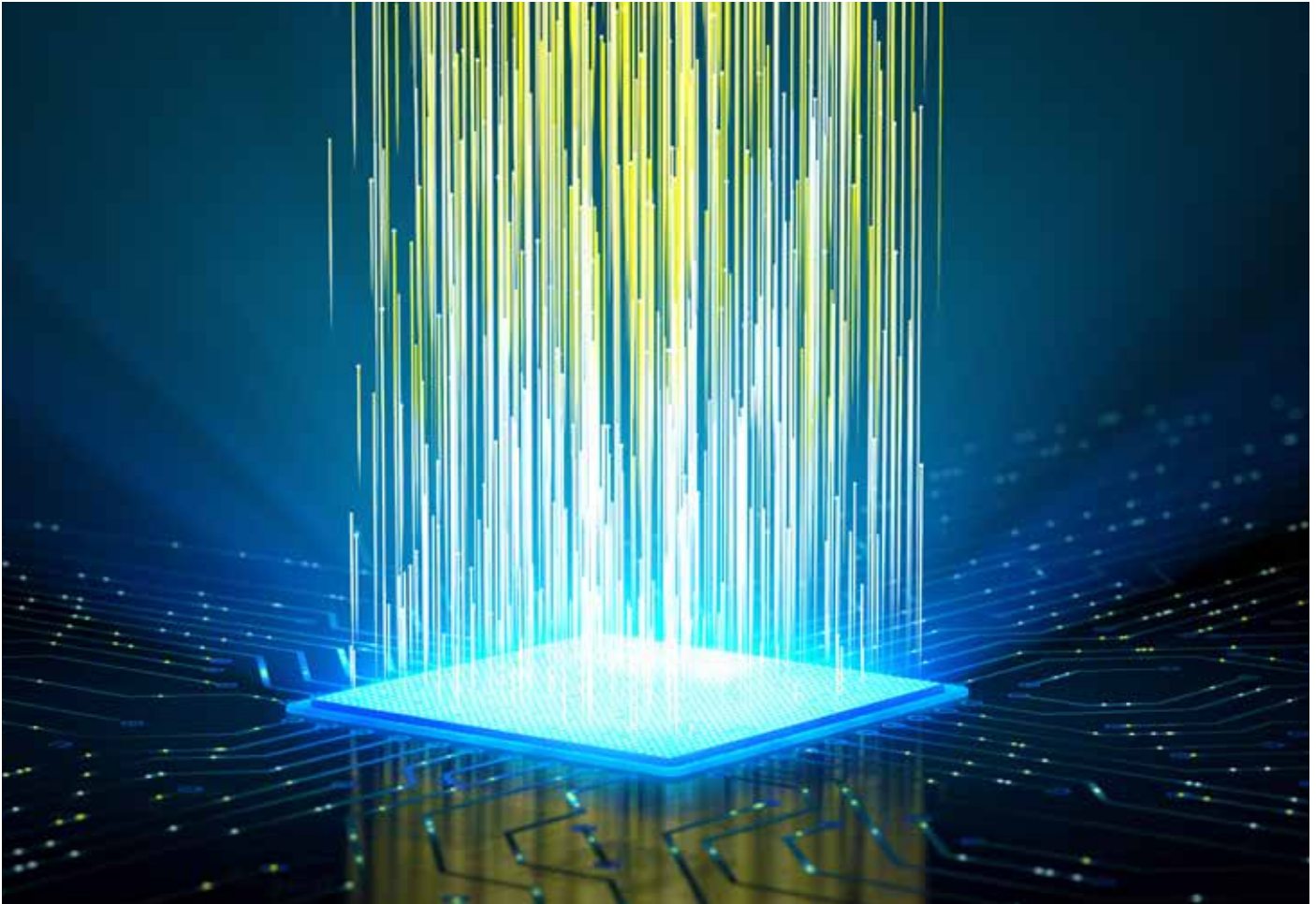
OPPORTUNITIES FOR THESE EMERGE FROM THE FOLLOWING SCENARIOS

- Applied research happening in the associated spaces - PoC is done by the research team and then commercialized.
- Core capability emerges from an allied sector - silicon photonics leveraged for quantum photonics.
- End user domain being strong in India with strong innovation focus - market area.
- Non-negotiable area for national security - market opportunity needs to be created.



SHYAM MENON
Co-founder,
Bharat Innovation Fund
and Infuse Ventures

"We believe the ecosystem and support for Quantum computing startups in India are growing and expect to see globally disruptive and competitive solutions from these startups making it an interesting area for deep-tech VCs to focus on in the coming years"



APPLICATIONS AND END USERS

Quantum technologies are sought out by different industries for various applications. In this chapter, we briefly summarise the following use cases, specifically for quantum computing.

QUANTUM COMPUTING IN HEALTHCARE

Quantum computing can facilitate precise and swift patient diagnoses, promote individual well-being through personalized interventions and treatments, and enhance the optimization of insurance premiums and pricing [1].

Challenges.

- **Data privacy and security concerns:**

Healthcare organizations may hesitate to adopt quantum technology based solutions due to concerns about safeguarding sensitive patient information.

- **Integration with existing systems:**

Seamless integration with current healthcare IT systems, such as electronic health records (EHRs), is crucial. Compatibility issues could hinder the smooth assimilation of quantum solutions into established healthcare IT ecosystems.

- **Regulatory compliance:**

The highly regulated healthcare industry may face concerns about compliance when integrating quantum-based solutions. Healthcare organizations must navigate regulatory complexities to ensure that quantum solutions align with standards related to data privacy, ethical considerations, and patient safety.

QUANTUM COMPUTING IN FINANCIAL SERVICES

Quantum computing exhibits promising applications in the financial services sector, particularly in areas such as targeting and prediction, asset trading optimization, and risk profiling [2].

Challenges.

- **Data privacy and confidentiality:**

Quantum computers' ability to process vast datasets quickly raises concerns about maintaining the privacy and confidentiality of sensitive financial information. Financial organizations must implement stringent measures to protect against potential breaches of client information and financial data in the quantum computing era.

- **Market disruptions:**

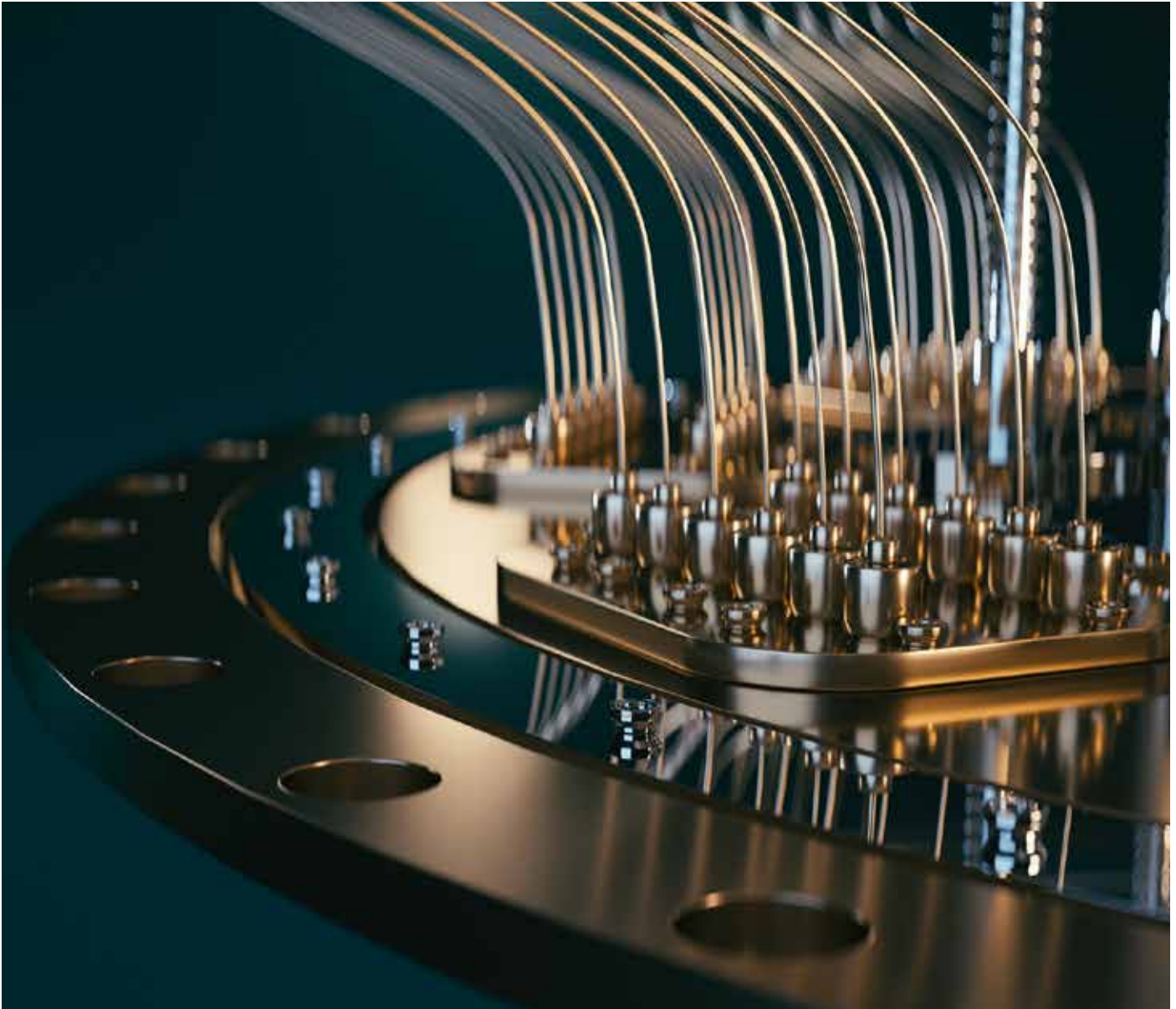
It can be expected that not all organizations and companies in the world of finance will adopt quantum solutions at the same pace. Organizations, along with regulatory entities, will need strategies for managing the potential disruption to the financial markets that are likely to be brought about by the non-uniform adoption of quantum solutions.

Leaders in numerous global companies have begun recognizing the profound impact quantum technologies can potentially have. A 2021 survey by Classiq [3] revealed that 98.6% of respondents viewed quantum computing as either a necessity or crucial for advancing technological performance. Additionally, 89% agreed that their companies should establish a dedicated budget for quantum computing. Despite this consensus, only 61.9% reported having financial plans in place for quantum readiness. This gap is often attributed to the early stage of quantum technologies, which are still far from achieving scalability and fault tolerance. Nevertheless, the state of the industry ecosystem is equally vital in determining the adoption of any emerging technology.



**DR. DURGA PRAKASH
DEVARAKONDA**
Managing Director
-AI, Digital Platforms
and Innovation, Carelon
Global Solutions

Quantum computing certain to transform healthcare, quantum-based AI machine learning is already outperforming classical AI models. Quantum computing can revolutionize the healthcare system through modern ways of enabling on-demand computing, redefining security for clinical data, accurately predicting chronic diseases, and expedite drug discoveries



MANPOWER AND SKILLING

The rapid advancement of quantum has created a pressing need for a skilled workforce that can adequately harness the potential of the emerging technology. As India strives to establish herself as a leader in the domain, investing in skilling and manpower development has become crucial.

Several educational institutes in India have been offering courses in and associated with quantum technology for years now. These include not only the premier IITs in the country, but also IIITs and other second tier colleges in Bengaluru, Pune, Chennai, and Delhi. More recently, certain institutes have come out with dedicated professional degrees in quantum science and technology, like the MTechs offered by DIAT [1]. The presence of quantum CoEs and research labs or groups in these

universities also contributes positively to their students being exposed to quantum. Today, there are more than 50 quantum related labs and groups in Indian universities, and they run several beginner to intermediate skilling programs like seminars, workshops, summer and winter schools, conferences, and talks to benefit students interested in the field [2].

An interesting phenomenon in the space of manpower skilling in quantum is the active participation of start-ups and companies in educational outreach. Some companies have their own quantum computing learning platforms and courses, like Qkrishi's Qkrishilearn and Qulabs' QuAcademy [3,4]. To this end, companies also partner with educational institutions, like Tech Mahindra with Mahindra University, Harman International with BITS Pilani, and Artificial Brain with Christ University [5,6,7]. It is interesting to note the participation of tier 2 institutes in such educational collaborations, highlighting the fact that quantum educational outreach is not limited to premier universities. Tech giants also play an important role in the skilling of the workforce; TCS, for instance, offers a TCS Quantum Lab on Microsoft Azure Quantum [8].

There are hundreds of wonderful free and open source resources online, for individuals from all backgrounds and levels of education, to begin exploring quantum technology. Intermediate level courses on Quantum can be completed on platforms such as edX (eg Introduction to Quantum Computing for Everyone | edX), Coursera (eg : Introduction to Quantum Information | Coursera) and FutureLearn (eg : Quantum ComputeArchitecture (futurelearn.com)). For study on the fundamental physics underlying quantum technology, the Feynman lectures are widely considered to be the best resource. Platforms like NPTEL and MITOCW are also immensely valuable to both beginners and intermediate students.

While all of these avenues exist, perhaps the most popular introductory resources in India are IBM's Qiskit's textbook and summer school, and QWorld's QBronze and QSilver workshops [9].

This presents an opportunity to develop indigenous content more suited to the Indian student community, in terms of approach, but even in terms of language. Qkrishi leads an initiative to develop content in Malayalam, Tamil, and Hindi [10].

It should be noted that most of these educational outreach programs exist mainly for those interested in

quantum computing, rather than communications and sensing. This trend is true even internationally. It may be concluded, hence, that the entry barrier for someone to begin exploring is much lower for quantum applications (not hardware) than for quantum communication and sensing. Considering the rapid pace with which quantum communications is advancing in the country, the lack of many quantum communication educational initiatives could easily be addressed.

Industry entities actively engage in quantum education to address the challenges they encounter during the recruitment process. One significant hurdle is the scarcity of experienced professionals with expertise in quantum technologies. The interdisciplinary nature of quantum science requires a diverse skill set, making it essential to provide opportunities for professionals to upskill and reskill in this field.

One effective strategy for recruitment in quantum start-ups and companies is the absorption of talented individuals after internships. These organizations often provide in-house training programs to equip interns with the necessary skills and knowledge specific to quantum technologies and their applications.

Another approach adopted by Indian tech giants involves engaging current employees in quantum-related activities on a part-time basis, leading to potential full-time transitions into quantum tech roles. This approach allows companies to leverage the existing talent pool within their organization and upskill employees to meet the demands of the emerging quantum ecosystem. As employees acquire knowledge and expertise in quantum tech, they can gradually transition to full-time quantum roles within the company. This transition is facilitated through mentorship, project assignments, and on-the-job training.

Keeping with the international trend, there are also a fair share of education and outreach start-ups and NGOs in India. Some of these operate exclusively online, like QuantumGrad and QIndia, the latter of which is a sister organisation of QWorld, a quantum education collective that is popular around the world. Quantum computing India, more info from QIndia

QETCI, in collaboration with the Telangana government and TASQ, offered a 2-week module session with a broad introduction to quantum technologies and the careers options that are available to students. AICTE, which was a partner for this project, works closely in



MR. KANISHKA AGI WAL
Head, Amazon Web
Services, Service Lines for
India & South Asia

India is uniquely positioned to skill a large Quantum workforce, one that not only understands the theoretical aspects of quantum computing but is also able to extend it to practical applications, via easy access to Quantum computing on cloud. At AWS, we are already working with our partners to offer Quantum computing courses for practitioners and students, in our endeavour to support and grow India's quantum computing workforce

the development of curriculums in schools all over India helped identify a quantum curriculum suitable for high schoolers and also conducted a faculty development program for teachers. A question being debated by quantum educators today is whether or not it makes sense to introduce quantum at the high school level. While doing so might contribute to the evangelisation and awareness about quantum technologies, certain groups also believe it would be too early since students of that age do not have the right scientific maturity to grasp the counter-intuitive fundamental physics or the mathematics required to understand quantum technology. Nonetheless, the popular QubitbyQubit program, which has partnered with companies like Microsoft and researchers from MIT, Oxford etc, brings quantum computing and information science to students, starting from high school, at no cost [11].

Given quantum's interdisciplinary nature, hands-on training is highly valued, which is perhaps why hackathons have become extremely popular in the quantum education space. Hackathons play a vital role in skilling the quantum workforce by providing a platform for hands-on learning, collaboration, and innovation. By bringing together industry sponsorships, experienced researchers as mentors, and students from varying backgrounds and levels of expertise, hackathons like the QETCI's Quantum Science and Technology Hackathon (2022) play an immense role in helping individuals make effective career starts [12].

Key stakeholders from the Indian industry and academia agree that one of the biggest impacts of the recent announcement of the National Quantum Mission is the awareness and publicity it brings to quantum technologies. Indeed, there are a large number of students and professionals, not just interested in, but also attitudinally well positioned to become a part of the quantum workforce India requires. As illustrated in fig 7.1, India has the second highest concentration of quantum technology talent. However, the same study ranks India as 8th in the number of quantum technology relevant publications made in 2022. This discrepancy highlights the need to focus on not just the magnitude, but also the quality of skilling efforts.

7.1 TOP 10 COUNTRIES WORLDWIDE 2021, SORTED BY H-INDEX RANK

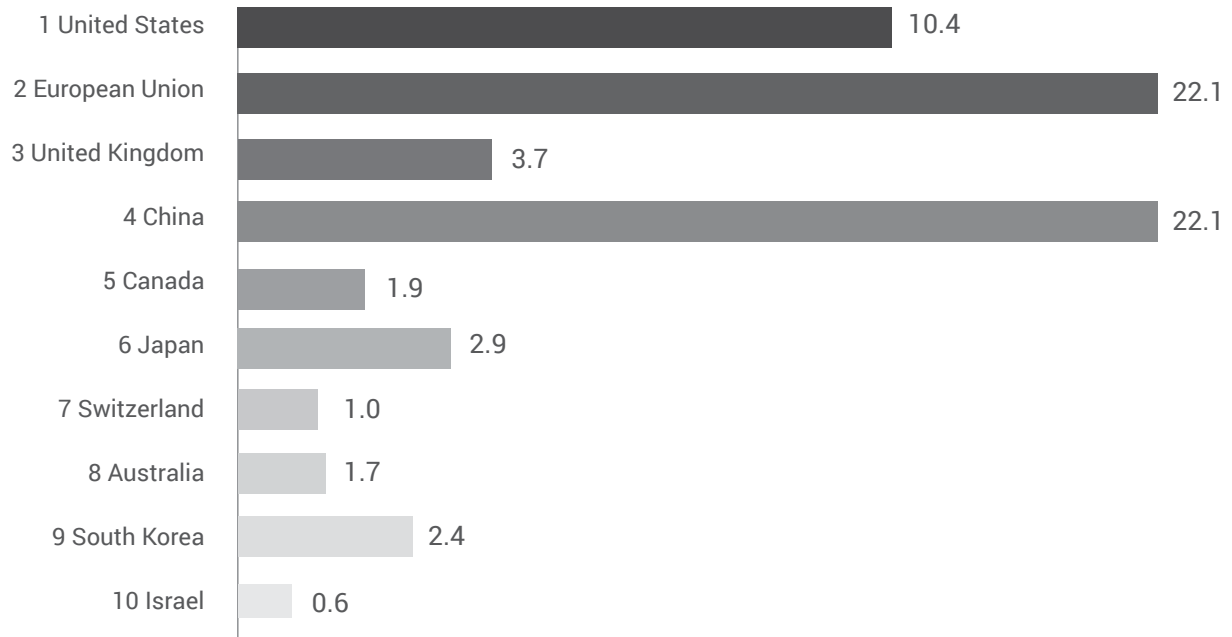


FIG 7.1 Top 10 countries worldwide 2021, sorted by H-index Rank.

7.2 ABSOLUTE NUMBER OF GRADUATES IN QT-RELEVANT FIELDS 2020

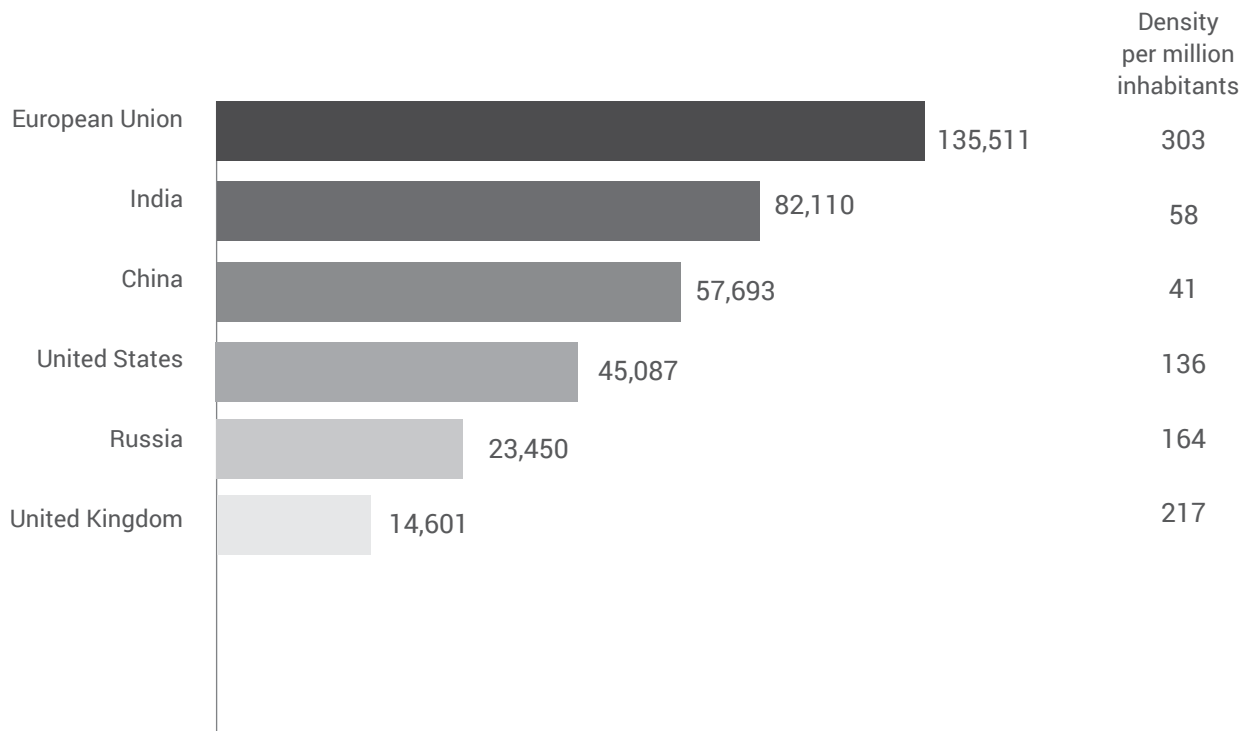


FIG 7.2 Absolute number of graduates in QT-relevant fields 2020.

The above figures are sourced from McKinsey's Quantum Technology Monitor (McKinsey & Company) 2022 [13]

Additionally, there have to be adequate opportunities for talented individuals who wish to work in quantum technologies. A frequently highlighted issue here is the retention of talent; several skilled students and professionals, potential researchers for the country, move abroad to better equipped labs and groups. There is a global competition for acquiring talent, and India is unable to hold on to individuals who are highly sought out abroad. Here, it might be useful to take a look at the design of the Indian Space Program and the attractive employee benefits and job security offered by ISRO. Taking an approach inspired by this might help with talent retention in the Indian quantum ecosystem.

There are several other challenges when it comes to skilling the Indian quantum workforce. Chief of these is the inherent complexity and interdisciplinary nature of quantum computing, communication, and sensing. Quantum physics is widely considered as difficult, the fundamentals are not believed to be easy to grasp. Consequently, quantum technologies are usually shrouded in a veil of mystery, and considered a subject only for the academically elite and brilliant. Quantum technology is a relatively new field, leading to a shortage of experienced and skilled experts. The demand for quantum educators far exceeds the current supply. The field is also rapidly evolving, which poses a challenge to keeping the workforce up-to-date with the latest breakthroughs and bottle-necks. [13]

All of the above challenges, however, are common around the world. An issue that affects India disproportionately, compared to other countries leading in quantum tech, is that quantum hardware for education is often expensive and needs to be imported. Lab work in all three subdomains of quantum are crucial to understand the fundamental way in which quantum devices operate.. For instance, a lab course in QKD for a moderately sized class of graduate students could require several tens of photon sources, detectors, specialised FPGAs, optical fibre, and more. With the current state of enabling technology suppliers in India, many of these components have to be imported, which can be prohibitively expensive, making it challenging for educational institutions to acquire and maintain such equipment for educational purposes.

Some short-term and rather limited solutions to this is for educational institutions to access hardware via the cloud, and to focus on theory and simulations more than experimenting with real hardware. But neither

of these approaches will fill the much needed gap for experimental learning and education.

The lists below are not exhaustive.

7.3 LIST OF INSTITUTES WITH SPECIFIC QUANTUM COURSES

UNIVERSITY	KIND OF COURSE
Bennett University, Greater Noida	Specialization
BITS, Pilani	Electives
VIT, Vellore	Electives
SRM University, Chennai	Electives
NMIT, Bengaluru	Electives
MKSSS Cummins College of Engineering for Women, Pune	Electives
Dhirubhai Ambani Institute of Information and Communication Technology, Gandhinagar	Electives
SVKM's NMIMS Mukesh Patel School of Technology Management & Engineering, Mumbai	Electives
IIT, Hyderabad	Electives
Indraprastha Institute of Information Technology, Delhi	Minor

LIST OF PUBLIC UNIVERSITIES THAT OFFER QUANTUM COMPUTING AND RELATED COURSES

- IIT, Madras
- IIT, Bombay
- IIT, Delhi
- IIT, Jodhpur
- IISc, Bengaluru
- Defense Institute of Advanced Technology (DIAT), DU, DRDO
- Indian Institute of Information Technology, Kottayam
- Indian Institute of Information Technology, Dharwad
- Indian Institute of Space Science and Technology, Thiruvananthapuram
- Savitribai Phule Pune University, Pune
- Savitribai Phule Pune University, Pune
- Raman Research Institute
- IIT Kharagpur
- IIT Kanpur
- IISER Pune

GRADUATE LEVEL COURSES AVAILABLE

- IISc
- DIAT
- IIT Jodhpur
- IISST Thiruvananthapuram

STARTUPS FOCUSING ON QUANTUM EDUCATION

- Qulabs(QuAcademy)
- Qkrishi (Qkrishilearn)
- QuantumGrad
- The Quantum AI
- AiQyaM
- MyQuantum Technology Pvt Ltd
- QRD Lab

EDUCATIONAL COLLABORATIONS BETWEEN INDUSTRY AND ACADEMIA

- IBM and IITM.
- Tech Mahindra and Mahindra University.
- Qkrishi and IIIT Kottayam.
- Artificial Brain and Christ University.

APART FROM THIS AWARENESS AND EDUCATION SESSIONS ARE BEING DRIVEN BY

- Quantum Ecosystems and Technology Council of India(QETCI) – Awareness sessions targeted to cover multiple platforms and Technologies.
- Quantum India – Quantum Computing.
- Quetzal – targeted at undergraduate students and high school students , run by Shraddha Angiras who is a class 12 student.
- Quantum security related awareness by Data Security Council of India.



INTELLECTUAL PROPERTY MANAGEMENT

Technologies like quantum are developing at a rapid pace, and they have the potential to transform many aspects of our lives. They have the potential to revolutionise industries, improve our lives, and even solve some of the world's most pressing problems. These technologies are gaining increased attention from all stakeholders due to their rapid development and deployment. The shrinking timeline of technology deployment, coupled with the vast amount of data accessible through these technologies, and the potential for anonymous usage necessitates the formulation of guidelines and safeguard mechanisms from different perspectives. Quantum being a critical and emerging technology requires to leverage a robust intellectual property management system through a lens of commerce and self-reliance, Issues of national security and value creation in the Indian quantum ecosystem.

Intellectual property management is a strong value chain element in the quantum value chain.

Some of the opportunities associated with managing IP for quantum are.

Create new jobs: Quantum can create new jobs in a variety of sectors, including manufacturing, services, and healthcare.

- Solve problems: Quantum can be used to solve some of the world's most pressing problems, such as climate change and poverty.
- Quantum can be used to accelerate scientific progress and help other emerging areas like AI, Human Brain projects, space sector and communications infrastructure .

The efforts in IP Management rely on the following 3 pillars:

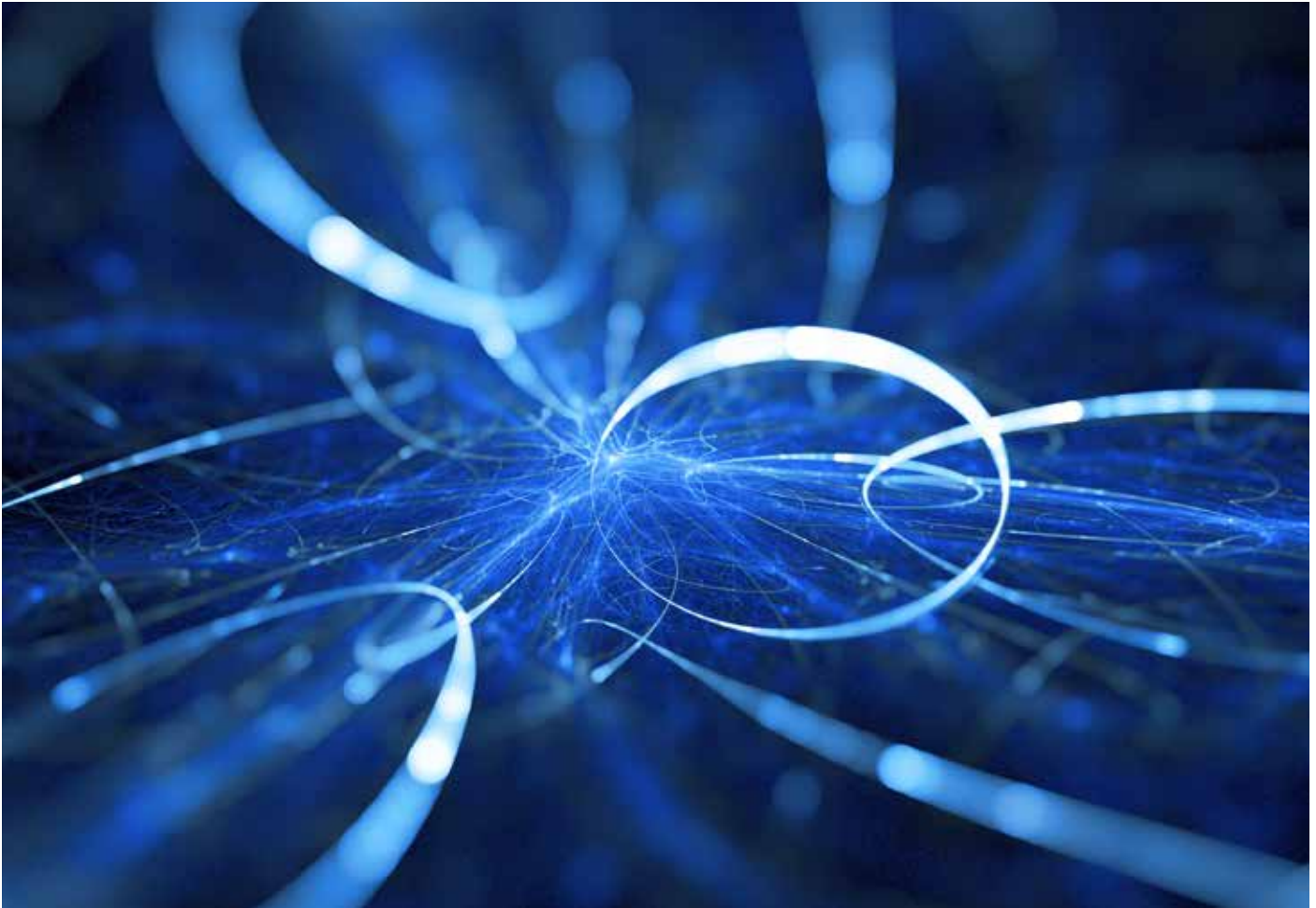
Policy : Policies that promote the development and use of quantum. The National Quantum Mission is playing a role in that.

Infrastructure : This includes Institutes like the National IP Cell associated with the office of the controller general of patents, designs and trademarks, which is part of the Department for Promotion of Industry and Internal Trade. This department is in turn part of the Ministry of Commerce and Industry, Govt of India.

Human capital : Human capital with necessary skills is needed to manage the IP associated with quantum. Several programs are being run by the IP Cell for training legal professionals on emerging technologies including quantum.

As per a paper titled quantum technologies : A review of the patent landscape by Mathew Alex, as of early 2021, India was 6th in the number of patents in quantum amongst the various countries focusing on quantum on earth.

A search on the Indian Patent System with the word quantum in abstract yields 993 patents in some stage of application, processing or granted. Out of these 231 were applied post January 2022. In the previous year (January 2021 to December 2021) this number was 137, and the year before this number was 77. This indicates the strong focus of quantum that is ramping up in India.



STANDARDS AND DEVELOPMENT

Standards and regulations in quantum technology encompass a set of guidelines, protocols, and frameworks that define best practices, safety measures, and interoperability for various aspects of quantum technologies. Developing standards and regulations is crucial to ensure the safe, ethical, and effective development and deployment of quantum technologies, fostering trust and facilitating their integration into existing systems.

As of now, the development of standards and regulations in quantum technology is in its nascent stage. Various countries and international organizations are initiating efforts to establish frameworks for quantum technologies. Organizations like the International Telecommunication Union (ITU), ISO (International Standards Organization), IEEE (Institute of Electrical and Electronics Engineer), the National Institute of Standards and Technology (NIST) and others are actively engaged in developing quantum-related standards [1]. Initiatives are underway to define common vocabulary, test methods, and security protocols

for quantum communication and computing. In India, organizations like BIS (Bureau of Indian Standards) and TSDSI (Telecom Standard Development Society of India) are working with other ecosystem entities to ensure the country's efforts are on par with global advancements. However, due to the fast-paced evolution of quantum technology, establishing universally accepted standards and regulations remains an ongoing and complex endeavor [2].

Developing standards and regulations for quantum technology is challenging due to the rapidly evolving nature of the field. Quantum technologies are not yet fully mature, and their characteristics differ significantly from classical technologies, requiring innovative approaches to address their unique challenges. Technical complexities, such as ensuring the security of quantum communication and defining metrics for quantum supremacy in computing, pose hurdles in creating comprehensive and effective standards. Balancing global consistency while accommodating cultural, legal, and economic differences is also a challenge.

The involvement of all ecosystem entities, including governments, academia, industry, and research organizations, is paramount for the development of standards and regulations. Quantum technology's interdisciplinary nature demands diverse perspectives to address technical, security, ethical, and policy considerations comprehensively. Collaboration among these entities ensures that standards are well-informed, widely accepted, and capable of accommodating the diverse applications and potential risks associated with quantum technologies.

Standards can promote interoperability, compatibility, and consistency within the quantum ecosystem. They also provide a forum where industry, academia, and government meet.

Good examples are ITU, IGPP, ISO and several standards from ETSI, IEEE and others. Development of use cases is crucial to develop standards that are focused on Interoperability, common understanding and are focused on the benefits for the end user. Development of standards may also need lots of users and test-bed implementations.

Participation in standard bodies is typically voluntary, and stakeholders from academia, industry, and research collaborate to create and update standards. Adoption of standards is often voluntary as well, although they can become de facto industry norms.

Eg: TEC, TSDSI, NPL, Quantum Nanophotonics Metrology Regulatory body, BIS are also working on developing standards.

CHALLENGES ASSOCIATED WITH STANDARDS DEVELOPMENT FOR QUANTUM

- The products are suffering from fragmentation of approaches and lack of uniformity – It is hard to develop common standards for technologies that are vastly different. For example - cold atom technology, photonics, topological systems and superconducting systems are very diverse in nature.
- We are in the era of evolution of quantum technologies. This is a rapid technological development and it is usually difficult to develop long lasting standards in such cases.
- The number of stakeholders is extremely diverse, since it is estimated that quantum computing and sensing will have applications across almost all industry verticals. Similarly, quantum communications will require standardization of protocols at all levels of the network. Handling the expectations of such diverse stakeholders is a long drawn and complex task.
- Quantum solutions are interdisciplinary in nature and it becomes important that at the time of the development of standards, people with skills from these interdisciplinary areas work together. This is often difficult since Quantum is seen as a difficult technology and people from other allied areas are hesitant to be deeply involved in cross skill areas associated with quantum.
- Quantum is a strategic tech linked with security and hence many areas that should ideally be a subject for standardization might get special treatment and remain very proprietary .
- Global coordination is difficult.
- Quantum technology requires massive investment in usecase proof of concepts, testbeds, user experience. Every nation may not be able to /willing to do the investments in this on a priority basis.
- Regulatory bodies may not have established frameworks for overseeing and regulating quantum technologies, making it unclear how standards will intersect with legal and compliance requirements.

There is a need for more industry to get involved in the standardisation process. There is also a need for more funds to be allocated to organizations and consortia developing standards.



MR. SAMEER MEHTA
Senior Vice President, Jio Platforms

In the imminent future of Quantum Computing, standards will emerge as the backbone, providing the essential framework that harmonizes innovation, fosters interoperability, and accelerates the development of quantum technologies. These standards will be the architectural pillars supporting the Quantum Value Chain, ensuring compatibility and propelling the quantum revolution to unparalleled heights.



COLLABORATIONS

Quantum technology is inherently collaboration inducing in nature. A typical project, either academic or industrial, requires the combined technical efforts of physicists, computer and electrical engineers, material scientists, just to name a few. Collaboration between experimentalists and theorists in quantum science and technology is crucial for advancing the field and realizing the full potential of quantum technologies. The models and algorithms developed by theorists guide experimental efforts, while experimental results are invaluable to validate theoretical interpretations. Similar collaboration exists between theoretical and experimental physicists focused on quantum physics. We can see evidence of such collaborations across the world. However, there is a need to collaborate more for accelerating development in quantum technologies. Although this is true globally, the situation needs more attention in India. The government might play a pivotal role in incentivizing joint collaborations

between quantum theorists and experimentalists, by funding initiatives for collaborative projects and research grants that require joint proposals, access to shared resources, joint workshops, and programs, and finally, recognition and awards for successful joint projects. It is important to note that project appraisal mechanisms need to be brought up to international standards.

ACADEMIA-INDUSTRY PARTNERSHIPS

An important partnership for enabling successful commercialization of great research is academia-industry partnerships. Academic researchers bring expertise in quantum theory and experimental techniques, while industry partners provide resources, practical insights, and potential commercialization pathways. These collaborations also serve the purpose of skilling and education. Some examples of collaborations in India are Harman International with BITS Pilani [1], Tech Mahindra and Mahindra University [2], Christ University's MoU with Artificial Brain [3] and IIT Madras with IBM [4]. Several partnerships of this nature allow access to quantum computing resources via the cloud, like AWS with IIT Delhi, and Microsoft with IIT Roorkee and IIIT Hyderabad. IIIT Hyderabad has a partnership with Synergy Quantum. There are also collaborative efforts present to build an indigenous quantum computer; TCS is partnered with TIFR, Mumbai, which is home to India's first quantum computer. IQTI of IISc, which recently graduated its first batch of MTech students in Quantum Technology, saw an impressively high placement rate, with students going to companies like Fujitsu, TCS, and MathWorks. Consequently, IISc's IQTI is also launching a subscription-based Industry Partnership Program (IPP) [5]. Industry Partnership Programs are extremely valuable to both parties involved. Industry partners can commercialize quantum technologies developed through collaboration, leading to potential products and services. They are also key in helping with funding and access to equipment, as well as validating and testing academic research in real-world settings. This last point is crucial in addressing scaling, compatibility, and reliability concerns associated with quantum technology. On the other hand, industry entities get access to a large talent pool and early access to IP. Some Industry Partnership Programs (IPP) are also international in nature; Qulabs is the first Indian start-up to become a partner with the Engineering Research Centre (ERC) at the Centre for Quantum Networks (CQN), based in the University of Arizona [6].

PUBLIC-PRIVATE PARTNERSHIPS(PPP)

An emerging trend in the quantum ecosystem is that of government and private company collaborations. In some cases, governmental bodies like the navy and railways

are customers to quantum technology companies or start-ups. More common is the phenomenon of public and private sector entities coming together to jointly invest in quantum research and development. PPPs often involve government funding or support, which encourages collaborations between academia, industry, and government agencies. TCS, TSDSI, QNu Labs, among other entities are deeply involved in developing standards for quantum communications in India [7]. A frequently brought up point of concern when looking for collaborations is the lack of awareness or information about what other ecosystem players are working on. A simple issue like this could result in an ultimately fragmented and inefficient value chain. To prevent this, efforts will have to be made to consolidate efforts and energy spent on quantum technology related projects. This would need to refer to a documented value chain for quantum in India.

It is not uncommon for foreign companies to collaborate with the Indian government, as in the case of Quantum Computing Applications Lab (QCAL), a collaboration between the Ministry of Electronics and Information Technology (MeitY) and Amazon Web Services (AWS) [8], or for Indian companies to collaborate with international governments, like the Danish government's collaboration with Artificial Brain, which has an Indian office [9].

PARTNERSHIPS WITHIN THE INDUSTRY

Companies in quantum computing often look for partnerships that allow them to create solutions and products that address all aspects of the stack. This is reflected in Boson Q Psi's membership to IBM's Quantum Network [10]. Similar to industry-academic partnerships, most inter-company collaborations in quantum computing are motivated by the requirement to access quantum hardware. Most quantum software start-ups in India have tied up with international hardware providers like AWS Braket, Microsoft Azure Quantum, and IBM Quantum. Another example of this is Tech Mahindra's partnership with IQM, Finland [11]. Collaborations between industry entities are also based on the use cases of interest. For instance, Tech Mahindra has recently partnered with BQP to collaborate on simulations in the automobile industry [12]. For start-ups like BQP, having channel partners like Tech Mahindra may assist them with their go-to-market strategy. However, a common complaint when it comes to engaging with big companies is the delays that happen in decision making. Consequently, many collaborations in the quantum ecosystem are soft commitments rather than definite contracts. The state of quantum technology and its current maturity are also reasons for smaller and fewer collaboration initiatives.

INTERNATIONAL COLLABORATIONS

In certain cases, quantum technologies may have direct or indirect implications for national security, such as in the context of secure communication, cryptography, and other critical infrastructure. An associated challenge is that there may be export control of certain technologies and hence international collaboration may get impacted with such restrictions. The other issue is that of intellectual property protection since there is a lot to consider when it comes to defining knowledge sharing and technology transfer strategies. Mechanisms for conflict resolution and equitable sharing are the bedrock of any successful international collaboration.

The focus of international collaborations like the U.S-India initiative on Critical and Emerging Technology [13], The Australia-India Cyber and Critical technology partnership [14], The India-UK research and Innovation agreement [15], or the QUAD program, is strongly technology-oriented where the mutual advancement of quantum technologies plays a vital role. For instance, during the US-India bilateral meeting, there was discussion of a joint Indo-US Quantum Coordination Mechanism [16]. Such initiatives are vital to the overcoming of technological bottlenecks in quantum. Owing to the extent to which supply chains for quantum technologies are international, it is not surprising that many Indian companies are interested in joint ventures with foreign entities. Collaborative research projects are also an area of interest for Indian entities. However, it should be noted that we are at a risk of losing skilled manpower in exchange for the sophisticated knowledge base and resources offered by these international collaborations. Hence, retention of manpower must be an important area of focus when developing joint agreements.

If you look at the value chain concept, it becomes clear that no single nation will be able to develop the complete quantum value chain indigenously, so there is an opportunity to leverage international collaboration and build resilient value chains and supply chain across borders, to fast-track development.

India would benefit from international scientific cooperation. From the interviews conducted by QETCI of the biggest stakeholders in the Indian quantum ecosystem, it is clear that many entities are interested in starting joint ventures with foreign entities. The import of products and services from foreign entities is next on their list of concerns, which is not surprising, given how much of India's current quantum supply chain is international. Indian stakeholders are also keen about foreign market opportunities and research collaborations, as well as

technology transfer initiatives, although the latter is to a lesser extent.

The inclination for joint ventures is rooted in the Make in India policy of India. The interest in imports is based on the dependence of the supply chain for various parts and equipment used for research as well as development of quantum technologies and there is a need to make the import processes easier and faster in certain contexts. The following diagram represents the relative interest of various interviewee in different aspects of international collaboration.

8.1 INTERVIEWEE FOCUS ON INTERNATIONAL COLLABORATION

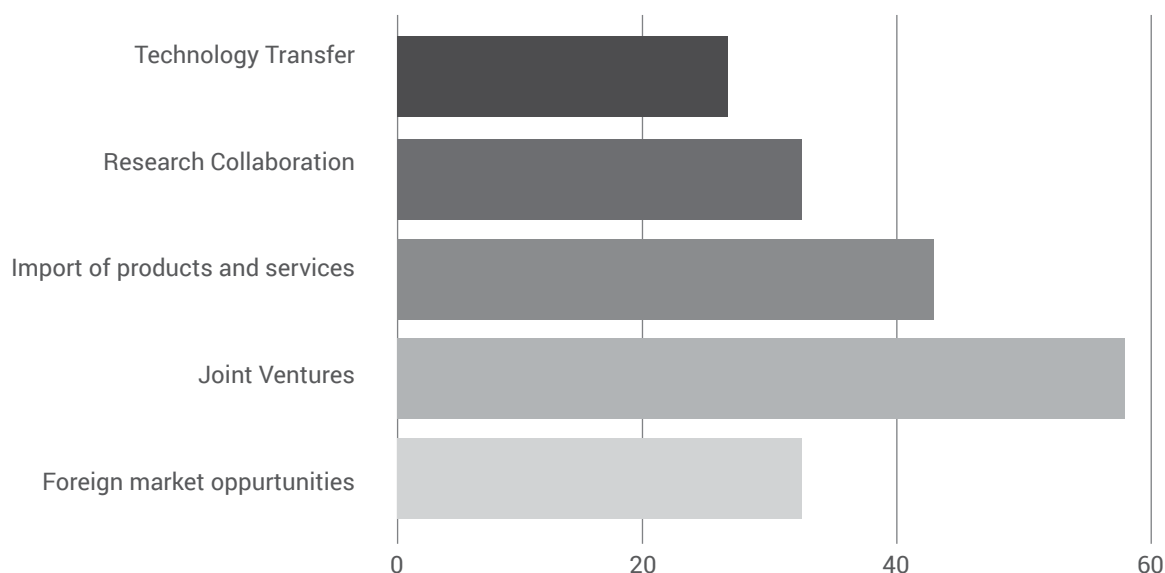


FIG 8.1 Interviewee focus on international collaboration.

An important question that needs answering is what India can bring to the table in such partnerships. Fortunately, there are several aspects, from expertise in certain niche areas of quantum science, to components that are vital to the supply chains of foreign quantum technology entities. Of chief importance is the contribution of skilled manpower to the global quantum ecosystem, which India is well positioned to continue to do. Today, we have many Indian students and professionals working in the quantum labs of academic institutions, start-ups, and tech giants worldwide. A recent report from McKinsey notes that India has the second largest concentration of quantum technology talent [17]. Already, India plays a vital role in the skilling of the quantum workforce of tomorrow, and this effort may be strengthened via joint international education projects. There are some unique capabilities in NV Diamond and diamonds for precision optical

electronics which are world class in India. Some of these products are already supplied across the world.

As with any other emerging domain, there are certain principal concerns when it comes to international collaboration in quantum science and technology. As mentioned earlier, the treatment of intellectual property, for instance, requires careful consideration and planning. It is vital to come together and reach a consensus on critical points like equitable distribution of benefits and conflict resolution.

The following diagram show the key focus areas of preference by interviewee with reference to intellectual property.

8.2 INTERVIEWEE FOCUS ON INTELLECTUAL PROPERTY WITH RESPECT TO INTERNATIONAL COLLABORATION

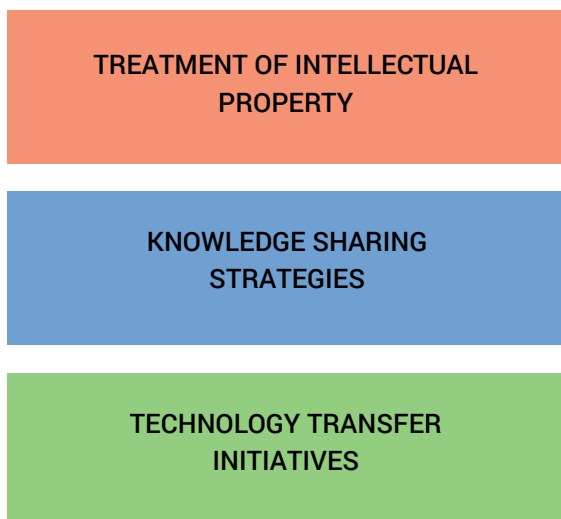


FIG 8.1 Interviewee focus on intellectual property with respect to international collaboration.

There is no doubt that we are on the cusp of considerable breakthroughs in the field of quantum technology. International collaborations, at the government, industry, and academic levels will be crucial in accelerating this imminent advancement.

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CONCLUSION

The Quantum Value Chain Framework and the mapping of India's current state on to the framework is just the beginning of the journey towards creating a conscious strategy for building a robust, inclusive, goal aligned value chain and supply chain in quantum. The exercise has given us insights which will help us build our strengths, address our weak areas, and also find opportunities for collaboration, both within the country as well as internationally.

This report is focused on the value chain and supply chain of the Indian quantum ecosystem. In the future, we aim to dive deeper into various other aspects of the quantum ecosystem, to develop a more holistic view of the state of the technology in the country. The following is a non-exhaustive list of areas we plan to explore in detail in future research -

- Industry-specific applications
- Investment landscape
- Ethical and societal implications
- Quantum security considerations
- Accessibility of quantum technology (particularly of quantum computing)
- Quantum policy landscape
- Quantum technology roadmap
- Quantum computing and Artificial Intelligence
- Quantum readiness status.

As the next step we will be using the value chain to make informed policy recommendations. We also have an opportunity to delve deeper into the intersection with Allied Value Chains such as semiconductor, photonics, nano technology, space and so on. Some of the elements of the current value chain can be expanded to see what would be most beneficial from an international collaboration perspective in specific bi-lateral and multilateral contexts.

