In collaboration with
IBM and SandboxAQ

WORLD
ECONOMIC
FORUM

Quantum Economy Blueprint

INSIGHT REPORT

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Contents

Foreword

Joseph S. Broz
Vice-President, Quantum Growth and Market Development, IBM

The mission of IBM is "to bring useful quantum computing to the world" and "to make the world quantum safe". It is important that global users of this new technology embrace constructive values of scientific reciprocity and collaboration, fair trade, and honour the rule of law with respect to intellectual property and contractual agreement. As quantum technology matures and enters the era of utility-scale quantum computing, it becomes increasingly important for regional, national, and industrial consortia to develop strategies for using quantum capabilities that incorporate and support these values.

As of December 2023, 24 countries have some form of national initiative or strategy to support quantum technology development. Many of these governments explicitly acknowledge a need to guide the ethical, social, legal and economic implications of quantum technologies, including the impact on cybersecurity and the global financial system, blunt the potential for monopolization or militarization by certain countries or multinationals, and promote the active discussion of data privacy and equity. This blueprint outlines the key elements for establishing value-led strategies that are inclusive and supportive of democratic access to quantum computing resources. It provides guidance that enables the next step after adopting the established *Quantum Computing Governance Principles*. It allows policy-makers to put the core values and principles into practice by defining their implementation as part of a coherent regional or national strategy.

Jack Hidary
Chief Executive Officer, SandboxAQ

Quantum technologies can transform entire industries, advance human society and tackle some of our world's biggest challenges. The innovations these technologies will bring to healthcare, technology, energy production, finance, cybersecurity and more will benefit everyone and should be shared for the betterment of society, the sustainability of the planet, and the welfare of future generations.

SandboxAQ is proud to collaborate with the World Economic Forum on its blueprint for building national quantum ecosystems. SandboxAQ's mission is to help corporations, governments and research institutions harness the power of artificial intelligence (AI) and quantum technologies to deliver breakthrough solutions to unique and complex challenges. Quantum technologies go well beyond quantum computers to include quantum sensing, quantum networking, quantum-safe cyber and quantum simulation. Many of these areas are having an impact right now, well ahead of fault-tolerant quantum computers. AI and quantum tech are synergetic technologies. AI, for example, can pull signals out of highly sensitive quantum sensors that drive key applications in medicine and navigation.

It will take an orchestrated, global initiative to ensure that the benefits of AI and quantum technology are distributed equitably among nations to avoid the growing quantum divide. The World Economic Forum's vision for and approach to the democratization and globalization of quantum technologies will have a broad and long-lasting impact on the future of society.

Foreword

Jeremy Jurgens
Managing Director,
World Economic Forum

Unlocking the promise of quantum technologies and strengthening the efforts in developing real-world quantum applications requires close public-private collaboration in research and development and scaling globally. The Forum's Quantum Economy Network aims to encourage global collaboration and the sharing of knowledge, increasing the awareness of the potential of the technology and building readiness to mitigate cybersecurity risks. The Forum is committed to working with the ecosystem to advance the responsible innovation and commercialization of quantum technology. The *Quantum Economy Blueprint* provides a roadmap to build quantum ecosystems in an equitable manner to prevent a widening gap in quantum capabilities and access to quantum hardware and infrastructure, enabling the transition to the quantum economy. Each nation or region may adopt the various building blocks of the blueprint in a modular and phased manner, irrespective of which quantum technology they are involved in, based on the maturity level of their quantum strategy. We hope this blueprint will serve as a valuable starting point to self-assess, participate and harness the benefits of the quantum economy for a better future for humanity.

Preface

Kelly Richdale, Arunima Sarkar, Mira Wolf-Bauwens

Recent progress in the development and application of quantum technologies (QT) is eliciting increased interest from countries, regions and organizations. Notably they focus on quantum technology's potential to uncover solutions to problems that classical computers have not solved – and may never solve. The early adopter advantage we have with QT, which is still at a relatively early stage, helps us make decisions about how and where to explore – and hopefully reap – the benefits of QT. We can learn from the past and be proactive about making sure QT is being developed and deployed for the benefit of all. To do so, well-thought-through, scientifically sound and socioeconomically holistic QT strategies are needed.

This is what the *Quantum Economy Blueprint* intends to provide: a moment of reflection on already-existing quantum strategies. The abstracted dissemination of core elements of national and regional quantum strategies into building blocks enables others to learn from existing examples while also further developing the building blocks for individual successful strategies of QT and the respective ecosystems. As the authors, we hope that the core values specified below, among which inclusiveness and equitability, in conjunction with scientific rigour and global collaboration continue to underpin future efforts as we prepare for the quantum economy. This blueprint can play a part in enabling the equitable development of quantum ecosystems and be further refined as we learn from its piloting in various regions and nations. We would like to thank the Forum's Quantum Economy Network and all contributors to this initiative for their insights, experiences and feedback along the way.

Executive summary

This report disseminates key elements of existing national and regional quantum strategies and builds a blueprint that enables others to build their own strategy.

Quantum technologies, such as quantum computing, quantum sensing and imaging, and quantum communications and networking, are driving new opportunities across a range of industries and sectors. They are already impacting key areas of the economy, giving rise to new solutions to hitherto unsolved problems, new industry players and innovative business models.

The goal of this *Quantum Economy Blueprint* is to assist regions and countries in initiating, developing, supporting and commercializing their quantum technology (QT) initiatives in this new quantum economy. It can serve as a reference for policy-makers and government institutions, industry and academia to understand the different elements of building a quantum ecosystem, as well as to help them define which part of the quantum value and supply chain to occupy and which approaches best suit them to help accelerate the implementation. The blueprint enables understanding of the potential for new jobs and economic growth in the quantum economy, as well as areas for protecting economic security, business integrity and cybersecurity. The report also enables the development of strategies for responsible and sustainable QT development, deployment and use.

The report builds on the analysis of existing national and regional QT strategies. It disseminates the core elements of these strategies and – based on interviews with the different stakeholders involved in their establishment – abstracts from these existing strategies and distils their content in the form of overarching themes and detailed building blocks. It is suggested to map building blocks to a timeline, depending on a country's or region's state in the quantum journey. This helps to prioritize which building blocks the country or region should focus on in the shorter and longer terms, as well as to support the definition of their own quantum strategy.

In reviewing the building blocks and choosing a relevant approach, countries and regions will objectively consider their strengths and weaknesses, consider their social and economic identity and align with their long-term political and industrial goals. All countries and regions can participate in the quantum economy. They need not necessarily occupy the entire value chain or build complex quantum technologies, but they should consider participating in one form or another. This may involve supplying critical quantum or adjacent components, or it may mean training a local quantum-literate workforce.

Introduction

What is the quantum economy and why does it matter?

The impact of quantum technology (QT) will be far-reaching, potentially offering important opportunities across multiple industries, leading to advances in sectors such as healthcare, climate change, energy, communications, finance and others. Quantum physics allows a deeper understanding of the natural world. It is possible to harness the principles of quantum physics for different applications, such as quantum computing, quantum sensing and quantum communications and networking. There are significant technological developments and increases in funding every year. For example, quantum computing promises significant computational advances and the capability to solve problems that cannot be solved by classical computing alone. New quantum sensing technologies are being leveraged in diverse areas to deliver greater precision in measuring time, frequency, acceleration, temperature, rotation and magnetic and electric fields. This impacts multiple sectors of the economy and will unlock new industrial applications in healthcare, aerospace, electronics, geology, energy and many others. Quantum communications holds the promise of ultra-secure networking capabilities.

> **Quantum technologies will impact many critical industries and inspire new business models. Diverse technologies such as quantum computing, quantum communications, quantum sensing and quantum materials have given rise to new industry players and promising solutions for end users, greater sustainability and new solutions to hitherto unsolved problems. Some of these technologies are already being deployed and others are developing at a rapid rate. Quantum technology will eventually permeate and impact every key sector of the economy and take us into a period likely to be referred to as the 'post-quantum era'. This is collectively creating an economic impact and a distinctive economic ecosystem driven by quantum technologies, which we refer to as the quantum economy.**
>
> World Economic Forum Global Future Council on the Quantum Economy[1]

The quantum economy will be fuelled by disruptive, far-reaching innovation that ultimately filters throughout multiple fields and sectors. For example, a positive feedback loop could be formed as the discovery of new materials might enable advances in quantum computing capabilities. These advanced capabilities, in turn, could be applied to exploring more efficient and beneficial materials. While there will be benefits to these disruptions, risks, such as quantum computing's threat to cybersecurity, need to be managed.

The emerging quantum economy will be underpinned by entire value chain connecting producers to consumers in ways that go well beyond traditional quantum fields. There will be an inevitable crossover with existing supply chain networks for semiconductors, nanotechnology and integrated photonics, for example. No single nation can be expected to sustain all the elements necessary for a thriving quantum economy, and so progress will rely on international collaboration and the creation of international trade agreements specifically designed to facilitate the necessary flow of value across borders.

Need for a quantum blueprint: the risk of a "quantum divide"

The global quantum effort leading to research and innovation in quantum science and technology is continually rising, with current worldwide public sector investments exceeding $40 billion. Overall, the global QT market is projected to reach $106 billion by 2040.[2]

Disparities[3] in access to existing technologies have already created a digital divide: 2.9 billion people[4] are still offline and do not benefit from the digital economy. The growing global quantum divide between countries with established quantum technology programmes and those without will lead to significant imbalances in core areas such as cybersecurity, defence, healthcare, finance, manufacturing and more.

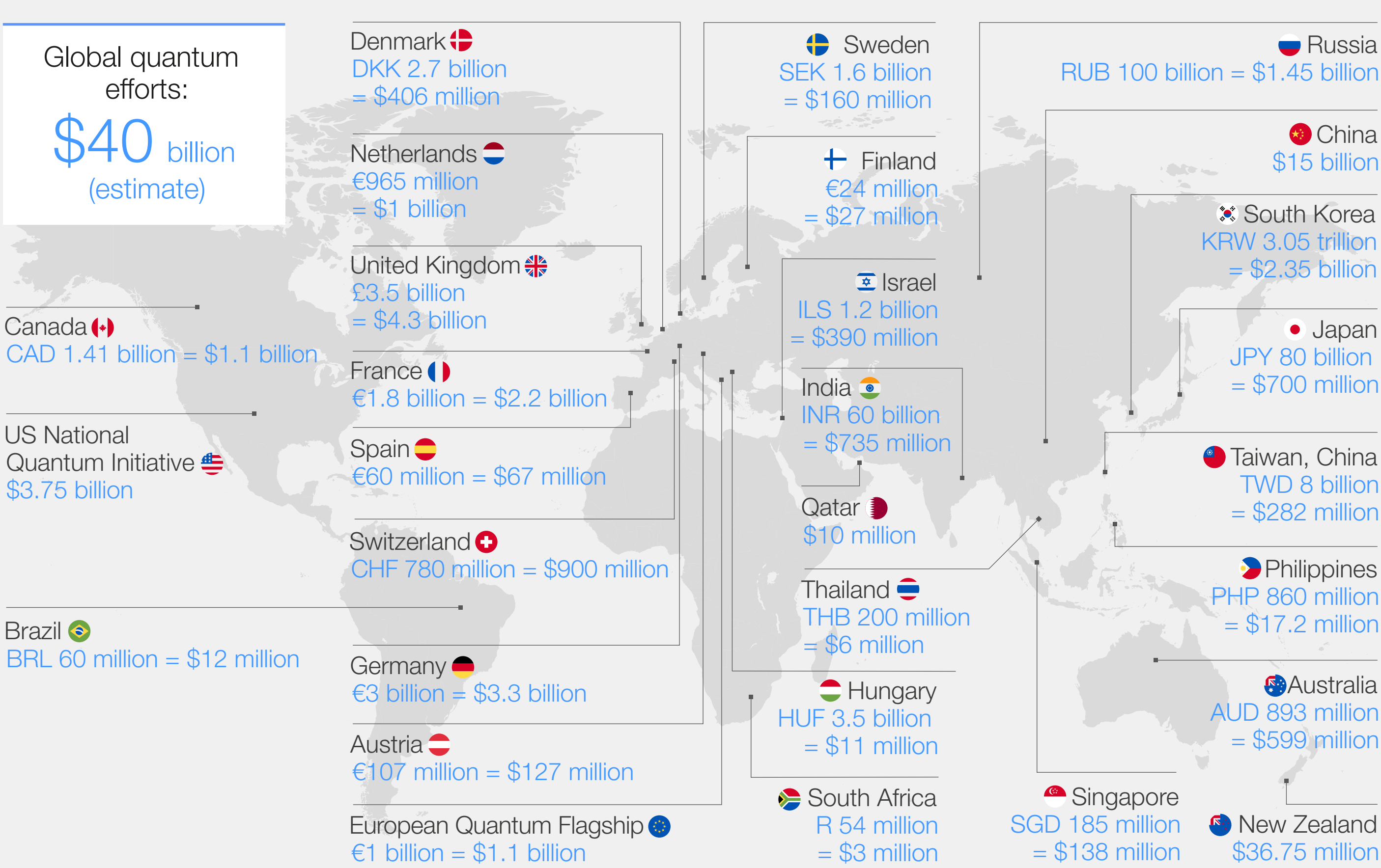
Unequal access to quantum technology has a negative impact on multiple levels, including on countries' ability to raise awareness and build a quantum-literate workforce, participate in research and development, and reap the benefits of QT.

There are also cybersecurity and geopolitical implications. This puts those countries whose quantum programmes are less developed in danger of falling further behind.

This report is based on an analysis of the main programmes and efforts around the world.

While a global ecosystem effort is needed to successfully develop and deploy quantum technologies, the current state of quantum efforts is concentrated in certain countries. Hence, this blueprint aims to provide a starting point and knowledge-sharing basis about key elements of a quantum technology strategy and best practices.

FIGURE 1 **Public sector investments in quantum technologies worldwide**



Note: Not exhaustive; timelines for funding vary by country.

Sources: "Overview of Quantum Initiatives Worldwide 2023", *QURECA*, 19 July 2023, https://qureca.com/overview-of-quantum-initiatives-worldwide-2023/; Department of Industry, Science and Resources, Australia; ETH Domain (ETH Zurich, EPFL, PSI).

In an attempt to outline the core values and principles governing the development and deployment of quantum computing, a previous report by the Forum, the *Quantum Computing Governance Principles*, serves as the core values, themes and principles in quantum computing.[5] While this current *Quantum Economy Blueprint* report focuses on all quantum technologies, it refers to the principles as guidance horizontally across diverse sectors and industries, and vertically for various stakeholders, from policy-makers to quantum engineers. Striking the right balance between generality and specificity is crucial for their utility.

The *Quantum Computing Governance Principles* end on a call to action. They ask regions, nations and collaborative institutions to put the principles into practice. It is for this stage that this *Quantum Economy Blueprint* is written.

Purpose of the *Quantum Economy Blueprint*

This *Quantum Economy Blueprint* creates a roadmap across academia, industry and governments to support regions and countries in their development and commercialization of their quantum technology initiatives, support and commercialize their quantum technology initiatives. It can therefore support policy-makers and government institutions, industry and academia with a blueprint for developing and growing a national quantum ecosystem. This blueprint can enable stakeholders to understand the potential for job creation, discover and accelerate areas for economic growth and protect their economic security, business integrity and citizens' privacy. The purpose of the blueprint also extends to enabling participation in scientific advancements through the development of

This report is primarily aimed at policy-makers, national applied research centres, centres of competence and excellence as well as various industry consortia and other quantum ecosystem enabling entities.

regional and national research strategies. Learning from existing strategies for the governance of quantum technologies contributes to ensuring the responsible and ethical development and use of such technologies. With the blueprint being a collaborative exercise based on sharing insights across sectors, regions and nations, it can contribute to spreading the benefits of the technology and related applications across regions, as well as to spreading a spirit of open science and collaboration. Nations, regions and industry initiatives should look at the entire research, development and manufacturing roadmap for quantum hardware and software to understand where they can best contribute for societal benefit and the global acceleration of quantum for all.

Not all countries or regions need to develop sovereign quantum computing or other quantum technologies hardware. A national or regional quantum strategy is, however, important to define one's position in the quantum supply chain, understand what parts of the technology are crucial to one's economy, and how to protect against some of the security aspects related to quantum technology. Furthermore, it is also essential to ensure access to critical technologies for researchers and academia, as well as becoming a critical supplier or part of the overall quantum value chain.

How to use the *Quantum Economy Blueprint*

This report is primarily aimed at policy-makers, national applied research centres, centres of competence and excellence as well as various industry consortia and other quantum ecosystem enabling entities. The blueprint also provides private enterprises and academia with mechanisms to engage with the different elements of the quantum economy.

The blueprint was co-developed over 18 months through a series of design workshops with members of the Quantum Economy Network, expert interviews with quantum strategy and policy-makers and an analysis of national and regional quantum strategies. The first scoping discussion was held in person at the Forum's Global Technology Governance Retreat event in San Francisco in June 2022, followed by three community workshops organized virtually in February 2023, July 2023 and October 2023, followed by a design workshop at the Quantum Economy Summit in Geneva in November 2023.

The blueprint is organized across nine themes, stemming from the *Quantum Computing Governance Principles*, each with a set of building blocks for consideration, as depicted in Figure 2.

FIGURE 2 | **Blueprint building blocks**

Source: World Economic Forum, *Quantum Computing Governance Principles*, 2022.

Phases of a quantum strategy

This report is designed to be relevant irrespective of the stage of one's regional or national quantum strategy. Each country may adopt the building blocks in a modular manner, irrespective of which quantum technology they are involved in, based on the maturity level of their quantum strategy or quantum activities. The following stages are differentiated:

1. Discovery: The country is in the discovery phase, with early quantum activity either in academia or industry.

2. Initial strategic considerations: Policy-makers and industry leaders are reflecting on a national or regional quantum strategy, but there is no structured responsibility yet.

3. Initial priorities defined: Policy-makers have defined the initial quantum priorities, and responsibilities have been allocated across ministries, federal departments or industry.

4. Strategy defined: There is a defined national or regional strategy that includes a funding plan but no implementation plan.

5. Strategy and implementation plan: This is the final stage where strategy, funding and the implementation plan are defined, detailed and in the process of execution.

The following mapping of building blocks to stages facilitates an understanding of which building blocks are most relevant at which stage. As discussed in theme 7 on cybersecurity, there is a time critical phase, which requires countries to adopt adequate regulations regarding upgrading to new cybersecurity requirements and adopting action plans for transitioning to quantum-safe cybersecurity.

FIGURE 3 | **Blueprint building blocks mapped to phases**

Different phases along the quantum strategy development and implementation journey

<table>
<tr><th>Phase / Themes</th><th>1
Discovery phase (QT early discoveries)</th><th>2
Initial strategic considerations (no structured responsibility yet e.g. no ministry tasked)</th><th>3
Initial priorities defined (responsibilities allocated e.g. ministry tasked)</th><th>4
Strategy defined, no implementation plan (including no funding plan)</th><th>5
Strategy and implementation plan (including funding plan)</th></tr>
<tr><td rowspan="2">Transformative capabilities</td><td></td><td>Self-assessment</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Value chain analysis</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Access to hardware infrastructure and supply chain</td><td></td><td>Long-termism and priority matching</td><td>Supply chain mapping</td><td></td><td></td></tr>
<tr><td></td><td></td><td>International nature of quantum supply chain</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="3">Adjacent supply chain capabilities</td></tr>
<tr><td rowspan="2">Open innovation and commercialization</td><td>Encouraging collaboration and pre-competitive environment</td><td></td><td></td><td></td><td>Public and private sector strategies</td></tr>
<tr><td>Trade strategies</td><td></td><td></td><td colspan="2">Technology transfer and commercialization initiatives</td></tr>
<tr><td rowspan="3">Creating awareness</td><td colspan="5">Multilevel public dialogue</td></tr>
<tr><td colspan="5">Educating decision- and policy-makers</td></tr>
<tr><td colspan="5">Awareness-building tools and methods</td></tr>
<tr><td rowspan="5">Workforce development</td><td colspan="5">Education initiatives</td></tr>
<tr><td></td><td></td><td colspan="3">Upskilling and cross-skilling strategies</td></tr>
<tr><td></td><td></td><td colspan="3">Global, regional and national talent pipeline strategy</td></tr>
<tr><td></td><td></td><td></td><td colspan="2">Public-private partnerships</td></tr>
<tr><td colspan="5">New job creation potential</td></tr>
<tr><td rowspan="2">National and economic security</td><td></td><td></td><td>Government defence investment priorities</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Geostrategic cooperation and protection strategies</td><td></td><td></td></tr>
<tr><td rowspan="4">Cybersecurity and privacy</td><td>Cyberthreat and risk analysis</td><td></td><td>Government regulations and directives</td><td></td><td></td></tr>
<tr><td colspan="5">Cybersecurity implementation and migration plans</td></tr>
<tr><td colspan="5">Cross-industry collaboration and awareness building</td></tr>
<tr><td>Privacy impact of other QT</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Governance, responsible innovation and standardization</td><td>Definition of common values</td><td></td><td colspan="3">Operationalizing responsible innovation</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Technology-enabling regulation</td></tr>
<tr><td></td><td></td><td></td><td colspan="2">Standardization strategies</td></tr>
<tr><td rowspan="3">Sustainability</td><td></td><td></td><td colspan="2">Strategies for sustainable QT</td><td>Energy consumption benchmarking strategies</td></tr>
<tr><td></td><td></td><td colspan="3">Incentivization strategies for sustainability use cases</td></tr>
<tr><td></td><td></td><td></td><td>Focus areas for positive impact on environment</td><td></td></tr>
</table>

For successful national or regional strategies, it is of key importance to embed the responsible governance of quantum technologies into these strategies.

Responsible governance and the *Quantum Economy Blueprint*

For successful national or regional strategies, it is of key importance to embed the responsible governance of quantum technologies into these strategies. This involves:

- Integrating the principles from *Quantum Computing Governance Principles*
- Taking foresighted, strategic decisions
- Ensuring responsible use and development through the respective binding principles and regulation which, in turn, enable responsible decision-making and action
- Ensuring interdisciplinarity
- Striving for greatest possible inclusivity (especially disciplinary and regional)
- Proactively integrating ethical and responsible practices from other domains.

Precisely how this can be done is specified in theme 8.

Understanding quantum technologies

Quantum technologies take advantage of properties of quantum mechanics to enable new ways to process, gather and send information, pushing the frontiers in application areas such as computing, sensing and communication.

Quantum computing

It is important to understand that the World Economic Forum makes the following technological assumptions regarding quantum computing (QC):

- It will be possible to build a useful, fully programmable universal fault-tolerant quantum computer.
- QC will make the computation of specific problems more efficient or precise.
- Quantum utility, where existing quantum computers can perform computations beyond the reach of brute-force classical simulation, has been demonstrated.

QC will accelerate computation towards solving specific problems currently deemed intractable with classical machines. The Forum adopts the community understanding of "quantum advantage", as the situation where quantum computer has a context-specific benefit over purely classical compute.

QC holds promise in a diverse set of highly complex problems that are currently inefficiently addressed by or intractable for classical computers. Such problems include but are not limited to:

– Simulation of physical systems, e.g. molecular reactions for material science, batteries, catalysts and drug discovery

– Combinatorial optimization and factorization problems, e.g. optimization of shipping routes and decryption of current public-key cryptography

– Quantum machine learning, e.g. neural networks and kernel methods.

Subsets of problems in these areas are believed to be more efficiently and more accurately solvable with quantum computers. The reason quantum computers are expected to outperform classical computers in these areas lies in the fact that quantum computers can – as the name suggests – harness the fundamental principles of quantum physics such as superposition and entanglement, giving rise to a new information-processing paradigm.

Currently, there exist multiple hardware technologies for quantum systems that can be used to implement the fundamental building blocks of a quantum computer – qubits. These include, among others, neutral atoms, trapped ions, superconducting qubits, photonic qubits, quantum dots and nitrogen vacancy centres. These hardware technologies vary in their maturity,[6] but researchers and engineers are exploring each of them to develop a universal fault-tolerant quantum computer. Achieving scalable QC with fault tolerance (active error correction during a computation) and giving measurable quantum advantage over classical computation is the long-term milestone for QC.[7]

Quantum sensors

Quantum sensors are instruments that use quantum properties, such as entanglement or interference, to detect positional or physical variations or provide highly accurate baseline standard measurements. They are capable of extremely high sensitivity in measuring acceleration, time, rotation and electrical or magnetic field changes. Quantum sensors thus have the potential to provide higher precision, speed and resolution than current classical sensors.

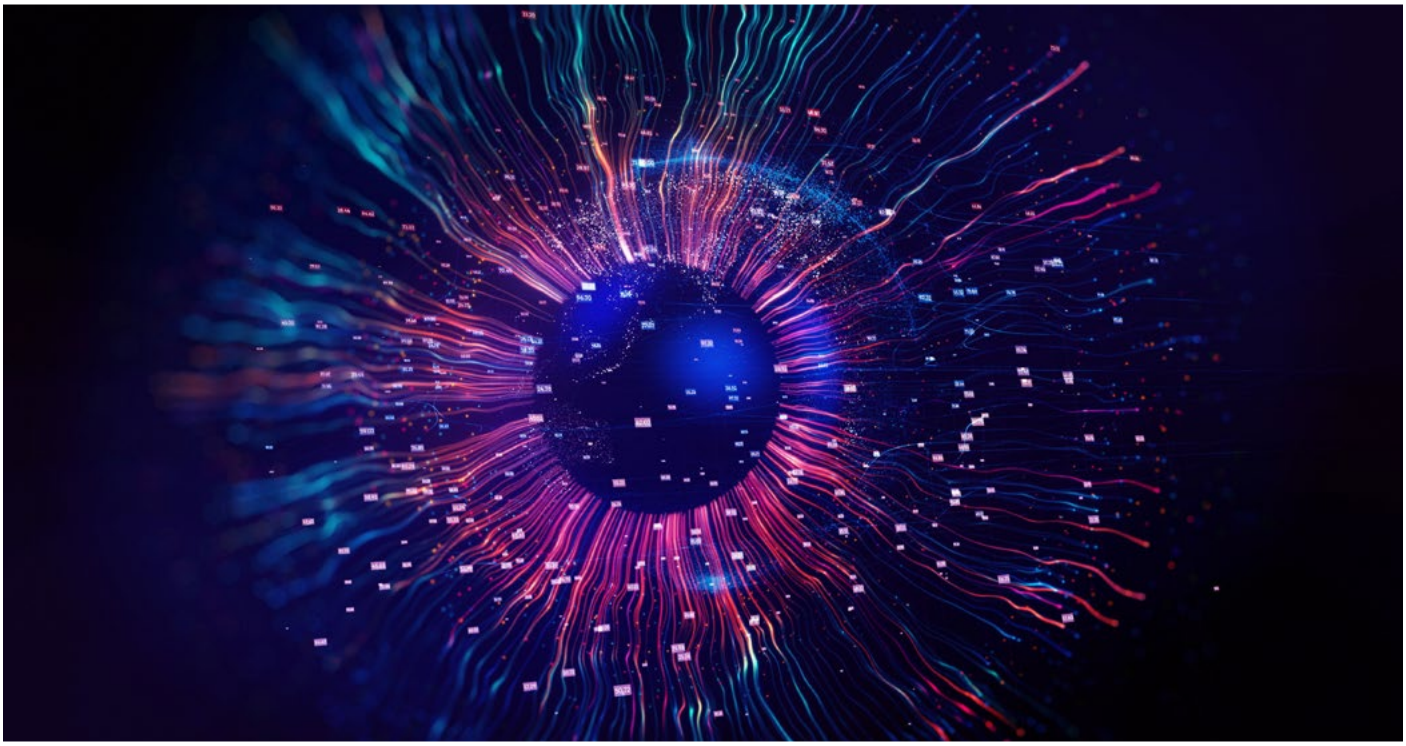
Applications include:

– Positioning and navigation via quantum sensors and atomic clocks in GNSS/GPS-denied environments

– Surveillance of underground construction and bunkers, and mineral and resource discovery through quantum gravity sensors

– Detection of metallic objects, such as mines or submarines, using quantum magnetometers to detect local magnetic anomalies

– Coordination of data transactions and energy networks via quantum atomic clocks



- Improved medical scanning based on the measurement of magnetic fields produced by electrical currents in the body (for example, magnetoencephalography or magnetocardiography)

- Measurement and monitoring of emission rates of greenhouse gases through optical lidar, spectroscopy and other methods

- Expanded and more sensitive communication based on quantum radio-frequency receivers.

Quantum communication and networking

Quantum networking allows the transmission of information in the form of qubits between quantum computers, sensors and memory. Quantum networking will allow the development of larger quantum computers from connecting smaller, modular systems of qubits and performing larger distributed computations between them. In addition, quantum sensor networks may enable precision metrology beyond what is possible with the best individual quantum sensors. Quantum communications is the use of quantum networking protocols for the purposes of establishing trusted communications links between sites. The quantum-mechanical nature of these links allows for, e.g. detecting eavesdropping attempts. Early practical versions of the technology include quantum key distribution (QKD) for cryptographic key establishment.

Applications include:

- Quantum cryptography, including quantum key distribution for secure cryptographic key establishment

- Quantum random number generators for improved randomness in cryptography

- Transfer of quantum sensor data for storage, computation, or quantum machine learning

- Quantum network repeaters for long-distance transfer of quantum-encoded information

- Quantum radio frequency receivers

- Networked quantum computers that realize large-scale and distributed quantum computation.

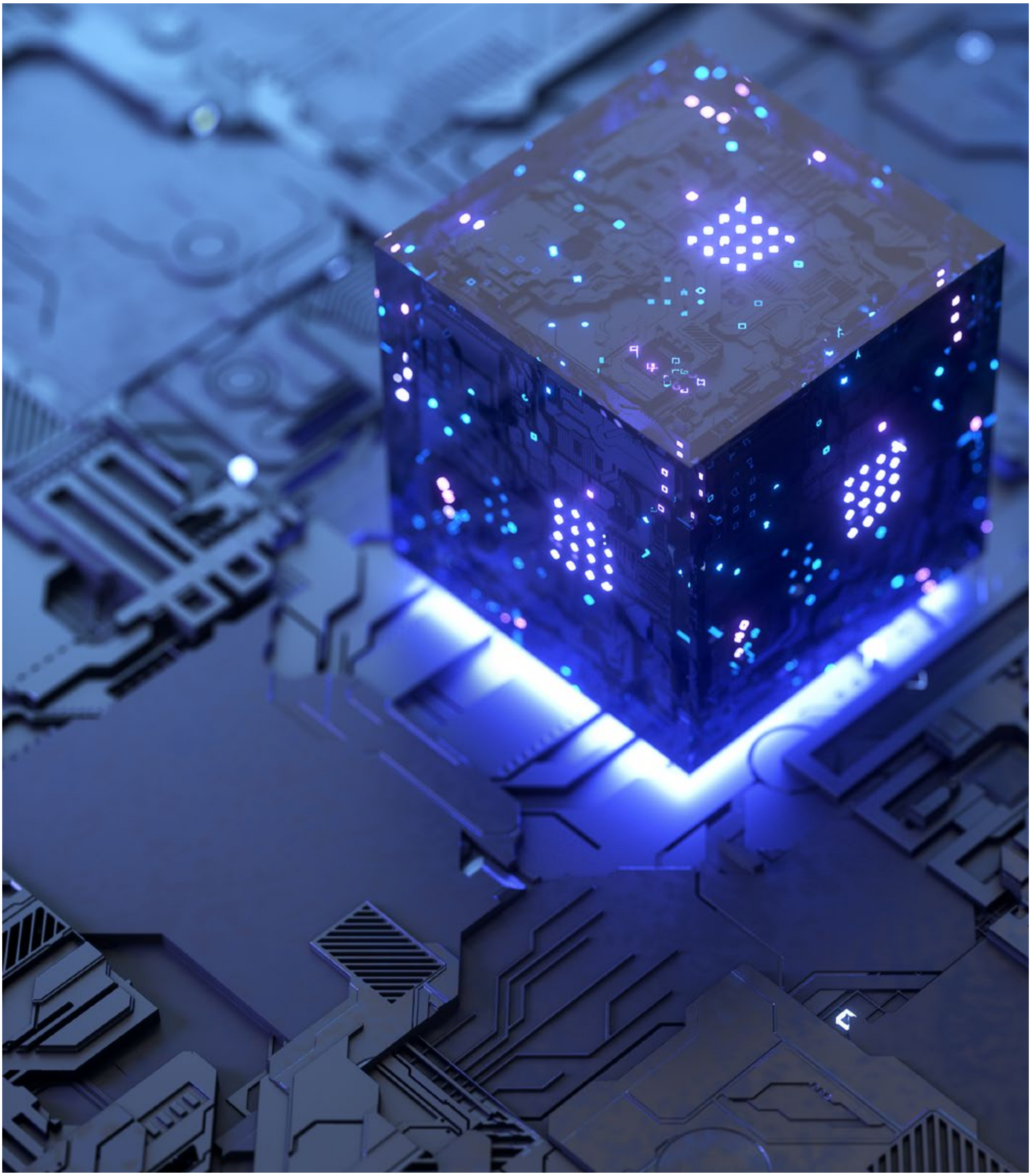
Future applications

The above applications of QT are examples only and are not an exhaustive list. In the early days of classical computing and sensing, researchers, developers and users had yet to learn of the many applications they would create as the systems evolved and became more powerful, smaller and energy efficient. There are likely many more applications that are yet to be discovered and thus research efforts are ongoing to identify them.

With these general considerations of QT in mind, the building blocks for a blueprint can be discussed. Following the building blocks, different approaches to implementing quantum strategies are discussed.

1 Themes and building blocks

Quantum strategy's building blocks, viewed individually or holistically, can be grouped into nine thematic categories for a complete approach.



1.1 Theme 1: Transformative capabilities

In order to gain clarity on a region's strongholds for quantum technologies, a national or regional self-assessment is a starting point.

The overarching goal of this theme is to harness the transformative capabilities of quantum technologies and their applications for the good of humanity while managing the risks appropriately. The following elements can enable the embedding of this goal in a national quantum strategy.

Building block 1.1: Self-assessment

In order to gain clarity on a region's strongholds for quantum technologies, a national or regional self-assessment is a starting point. This analysis is a basis of a later stage, national or regional strengths, weaknesses, opportunities and threats (SWOT) analysis. This analysis entails but is not restricted to understanding:

– State of research and academia, including the regional or national IP and patent landscape, and the state of research in quantum technologies

– State of the technology, including state of the industry working on quantum technologies and the state of quantum technology supporting industry

– The supply chain, based on a detailed supply chain analysis

– Government investments, partnerships and policies, including bilateral and multilateral collaborations

– Short- or long-term private investments

– Potential threats, including geopolitical conflicts, "brain drain" to other industries or countries and fears of cybersecurity readiness in the face of quantum attacks on encryption.

The self-assessment identifies priority areas to capitalize on (strengths and opportunities) or to proactively develop further (weaknesses) and develop mitigation strategies for (threats). This mapping further matches the developed vision for QT with general regional or national technology strategies.

Depending on which approach to building a quantum strategy is chosen, direct links to and communication between industry, academia and government is necessary, in order to coordinate stakeholder efforts. It also serves to influence technology-enabling and innovation-promoting policies and regulations can also be established on the basis of the self-assessment.

Furthermore, the self-assessment analysis can help to develop clear funding strategies. These range across technology areas and can closely be connected to the establishment of, e.g. centres of excellence.

Regarding the importance of a national self-assessment analysis, the following comment can be found in the Danish approach to developing their quantum strategy.

In Denmark, the Novo Nordisk foundation kick-started the quantum strategy and the Danish Government's strategy came after. Our focus was quantum in life sciences. We mapped the entire quantum space, examining strongholds in the Danish ecosystems. We interviewed trusted parties, and we also commissioned a third-party report from RAND Europe to make a deep investigation of strongholds for quantum tech in the life sciences.

Based on these reports and feedback, the Novo Nordisk Foundation formulated the strategy. We knew Denmark had an advantage, but we also knew that we had to act fast so as not to be overtaken.

Lene Oddershede, Senior Vice-President, Natural and Technical Sciences, Novo Nordisk Foundation

There is the possibility of commissioning an external party, such as RAND Europe. To start the reflection process, it is also possible to start with the suggested template for a regional or national SWOT analysis, such as the one that can be found in the appendix of this report.

Starting a quantum strategy with a national (regional) self-assessment allows stakeholders to harness the transformative capabilities of QT and their applications for societal good, while managing the risks appropriately.

Building block 1.2: Value chain analysis

A value chain analysis enables a fuller understanding of a current ecosystem. It is an analysis of the industry and enables seeing relationships and dynamics across an entire ecosystem. The value chain analysis also identifies the roles of different entities. It is important to develop a value chain in order to understand gaps, growth opportunities and possible challenges of economic, technical or social kinds. A QT value chain can contribute to informing a national or regional self-assessment.

CASE STUDY 1

Example from the Indian value chain

Quantum Ecosystems Technology Council of India (QETCI) has published the *Quantum Value Chain Report 2023 – India*, which introduces a quantum value chain framework for analysing the state of the quantum ecosystem in India.

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

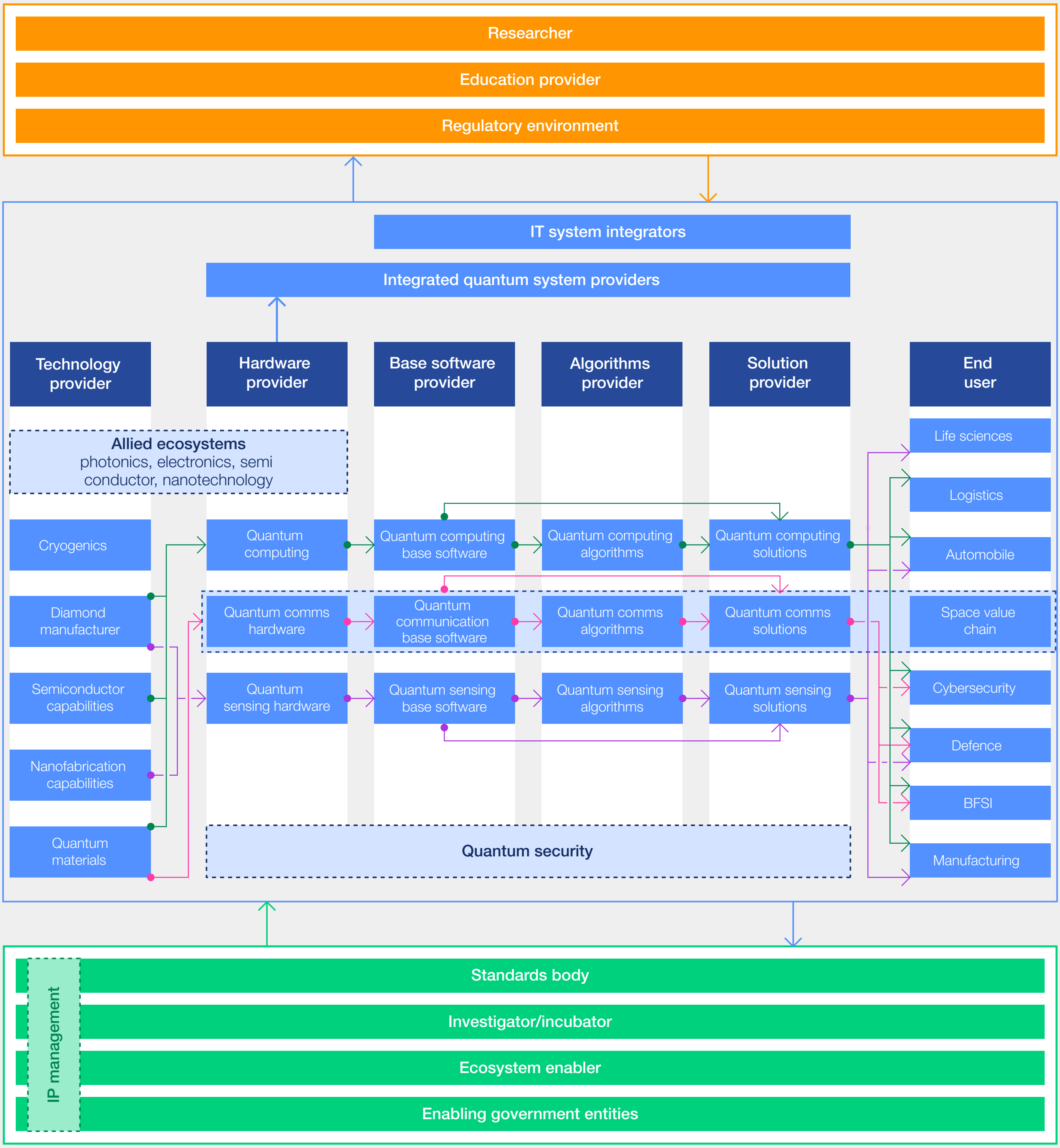
The following are the key stakeholders identified as being elements in the Indian quantum technology value chain.

TABLE 1

Entity	Definition	Entity	Definition
Education provider	An entity that creates and/or delivers educational content on quantum technology and associated domains	**Algorithms provider**	An ecosystem entity that works on quantum communication protocols, post-quantum cryptography schemes, or quantum computing algorithms for specific applications
Researcher	An ecosystem entity that is engaged in research associated with quantum technology	**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
Regulatory body	A national entity that is responsible for creating, enforcing and overseeing regulations and rules within the quantum ecosystem	**Standards body**	An ecosystem entity that is responsible for the development of standards and regulatory recommendations associated with quantum technologies
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	**Investor and incubator**	An ecosystem entity that provides financial support, mentorship, resources and networking opportunities to quantum technology projects
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 government entity**	A government entity that oversees and assists the development of quantum technology at various layers of the value chain
Enabling technology provider	A non-quantum ecosystem entity that plays the role of providing technology that assists with and enables the development of quantum technology (hardware).	**Ecosystem enabler**	An ecosystem entity that works closely with different stakeholders to enhance collaborations, mitigate challenges and accelerate the ecosystem as a whole
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	**End user**	An ecosystem entity that is interested in the applications of quantum technology
Base software provider	An ecosystem entity that develops firmware and control protocols for the underlying quantum hardware	**Allied value chains**	Value chains from allied industries that add value to the quantum value chain

Figure 4 represents the QETCI quantum value chain in detail.

FIGURE 4 | **The Indian quantum technology value chain**



The value chain can be studied in two parts:

1. The supply chain – the central big box (in blue) in the above representation includes elements of the supply chain.

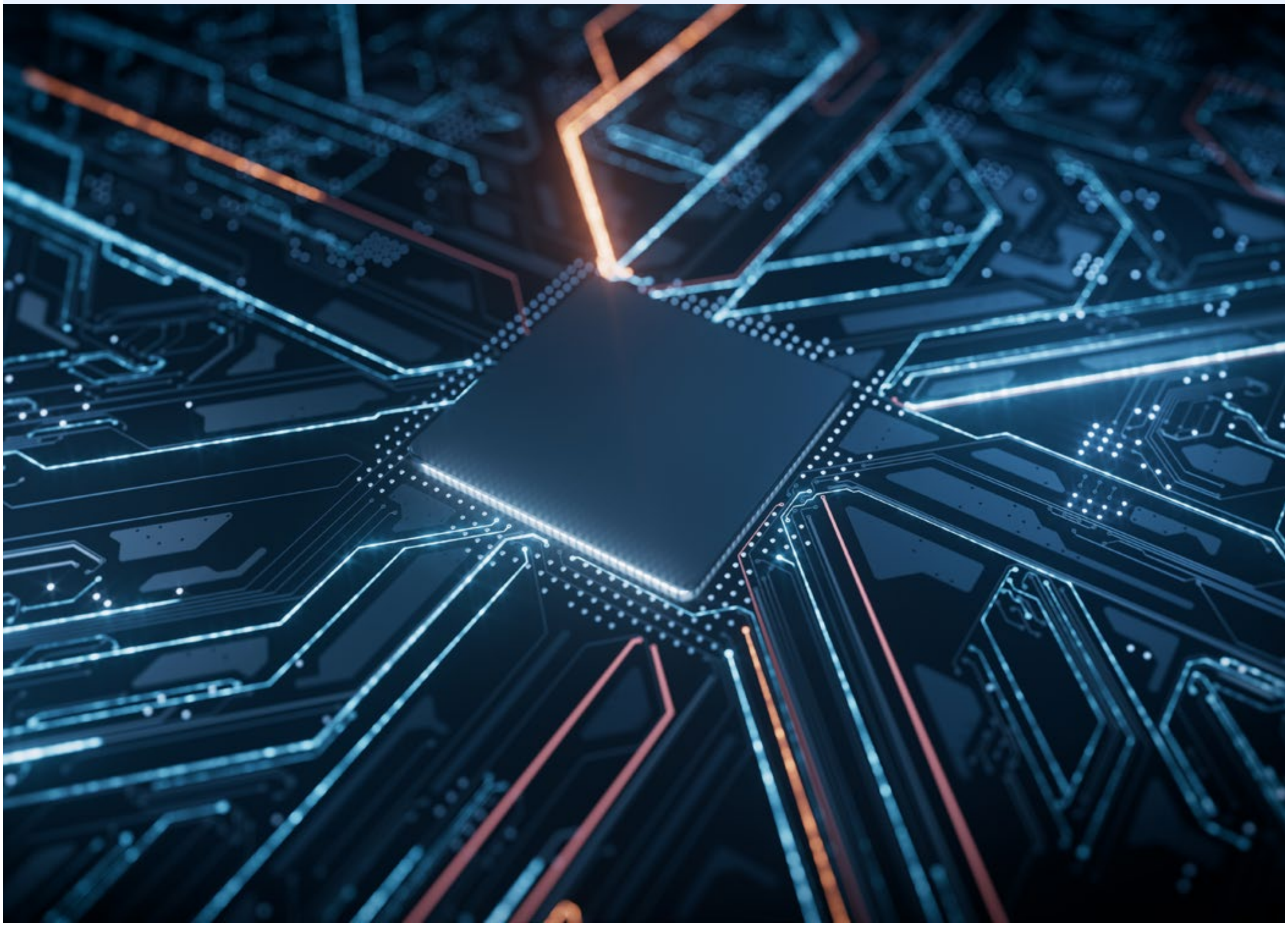
2. The horizontal boxes at the top (orange) and bottom (green) include horizontal sub-components and additional elements, which, when included, provide an overview of the overall value chain and represent non-supply chain ecosystem elements.

Source: QETCI, *The Quantum Value Chain Report 2023 – India*

> **We wanted to understand the quantum ecosystem in India in detail and we also wanted to be able to make interventions in the ecosystem and make policy recommendations using a data-driven approach. The value chain analysis turned out to be a great choice, because it not only shows the current state well, but it also provides insights into strong and weak areas and the role of allied value chains and has been very useful in all kinds of decision-making.**
>
> Reena Dayal, Founder and Chief Executive Officer, Quantum Ecosystems and Technology Council of India

This analysis provides insights into the different areas of the value chain, which in turn becomes an input to the quantum strategy for the nation.

The goal of this theme is harness the transformative capabilities of quantum technologies and their applications for the good of humanity. In order to do so it is necessary to understand where a region or nation stands with respect to QT. The self-assessment and a value chain analysis are a good start to doing so.



1.2 Theme 2: Access to hardware infrastructure and the supply chain

When considering QT hardware, it is paramount to think of the long-term implications of current (policy) decisions.

The goal of this theme is to ensure broad access to QT hardware and components. The strategies and actions here might differ for different quantum technologies as they may be at different maturity levels. This section is focused on key elements and, in particular, on components of a QT supply chain. Underlying these are national security considerations spelt out in more detail in theme 6 of this report.

Building block 2.1: Long-termism and priority matching

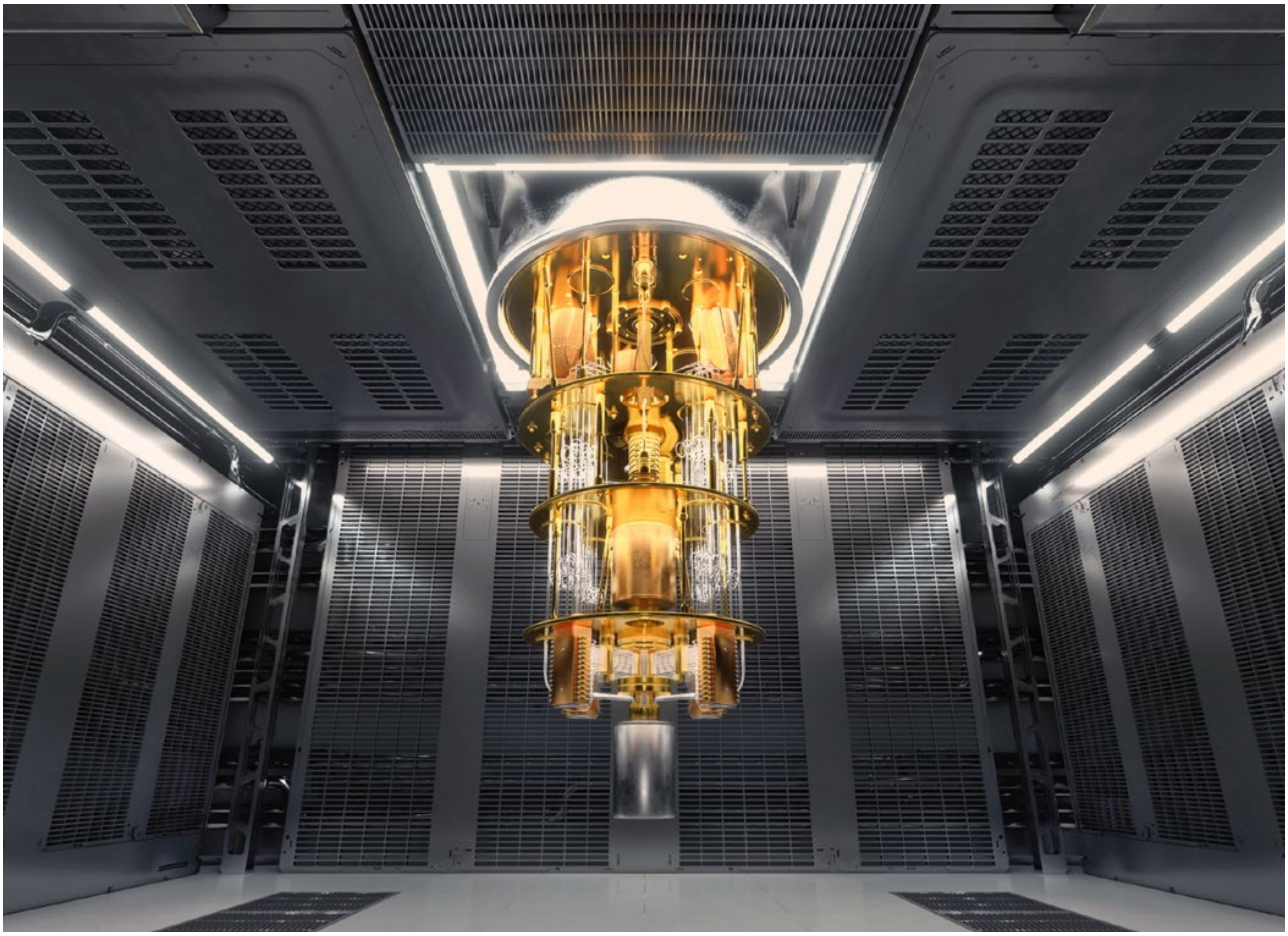
Long-termism

When considering QT hardware, it is paramount to think of the long-term implications of current (policy) decisions. In addition to considering the role of a region or nation in current quantum supply chains, it is crucial to establish a strategy that can safeguard long-term access to QT hardware or platforms, including funding to disadvantaged regions if necessary. Importantly, this does not require each nation or region to necessarily acquire or develop their own quantum computing systems since cloud access, e.g. to quantum computers and quantum-centric high-performance computing centres, is and will become more widely available.[8]

For other QT, such as sensing and communications, it is important for countries to ensure adequate long-term access to the necessary hardware components.

Priority matching

Investments in quantum hardware should be closely connected to the national and regional priorities identified in the self-assessment above. Thus, in deciding where quantum hardware needs to be built nationally or regionally, careful consideration must be given to where sovereign hardware is needed or where it is sufficient to be part of the supply chain as an importer or exporter. The considerations will differ across the respective technologies. Other concerns should also be investigated here, such as cloud access in the case of QC. This is linked to ensuring uninterrupted access to the highest quality systems and to questions on investing in or dependence on leading technology platforms while developing one's own platform.



Building block 2.2: Supply chain mapping

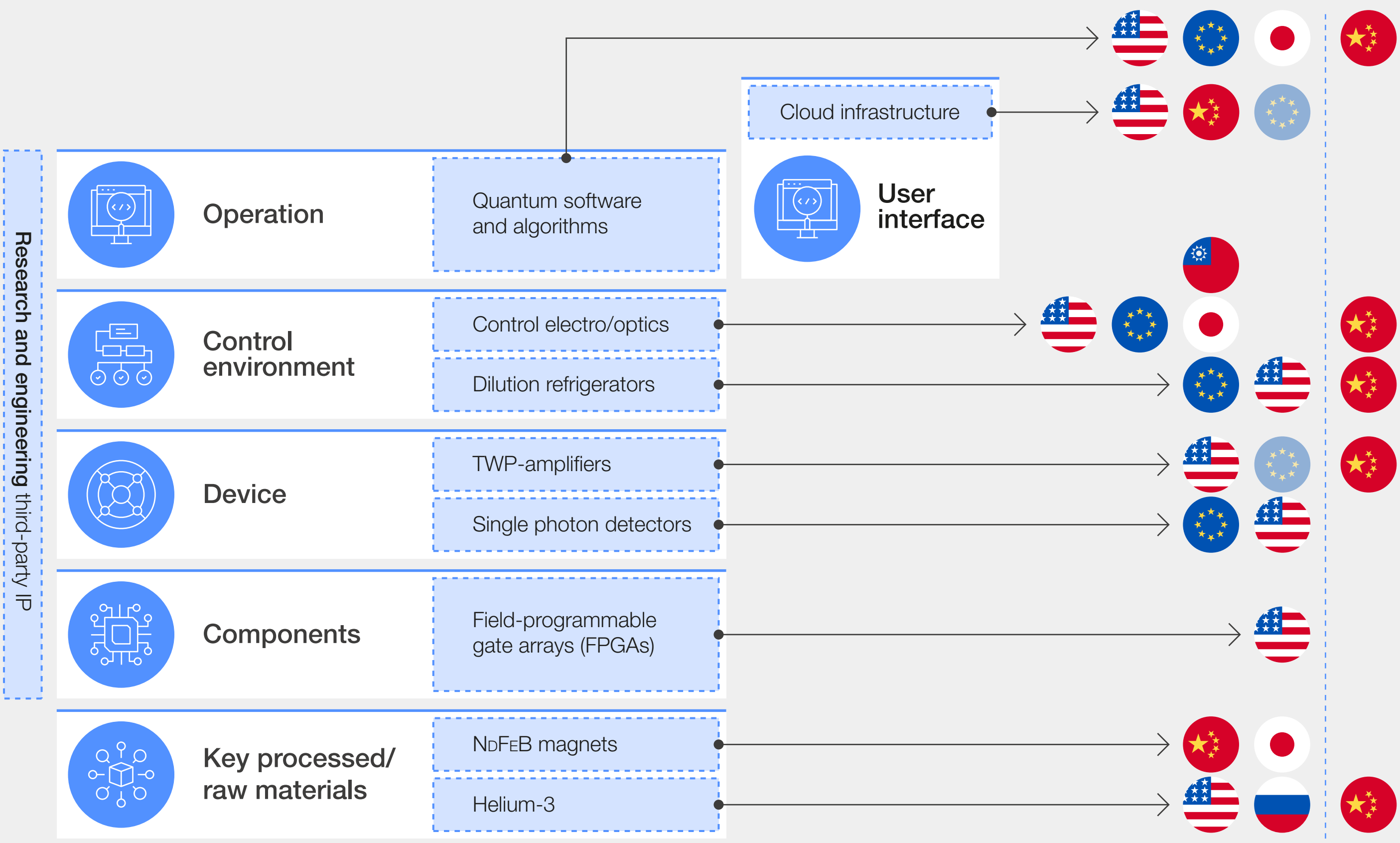
In order to know where the existing supply chain can serve to strengthen the quantum supply chain, supply chain mapping is required. Such a supply chain mapping varies, but typically entails the following key elements:

– Overview of the respective quantum technology stack: This is an overview of the type of components at different granularity levels. For example, a high-level starting point for QC can consist of key raw materials for hardware manufacture, individual components, devices, control environment and operational elements.[9]

– Component classification: This classification highlights which components are specifically relevant for QT and which are not (compare with the Quantum Economic Development-Consortium example in Figure 9).

– Analysis of local or regional availability of materials: As shown in the EU example in Figure 5, a quantum supply chain gains in potential when a layer of international availability is added (compare with the Quantum Delta NL example in Figure 6 or EU example for QT in Figure 5). Such mapping is particularly insightful from a policy perspective as a basis for reflections regarding international collaboration and trade, as in building block 3.2.

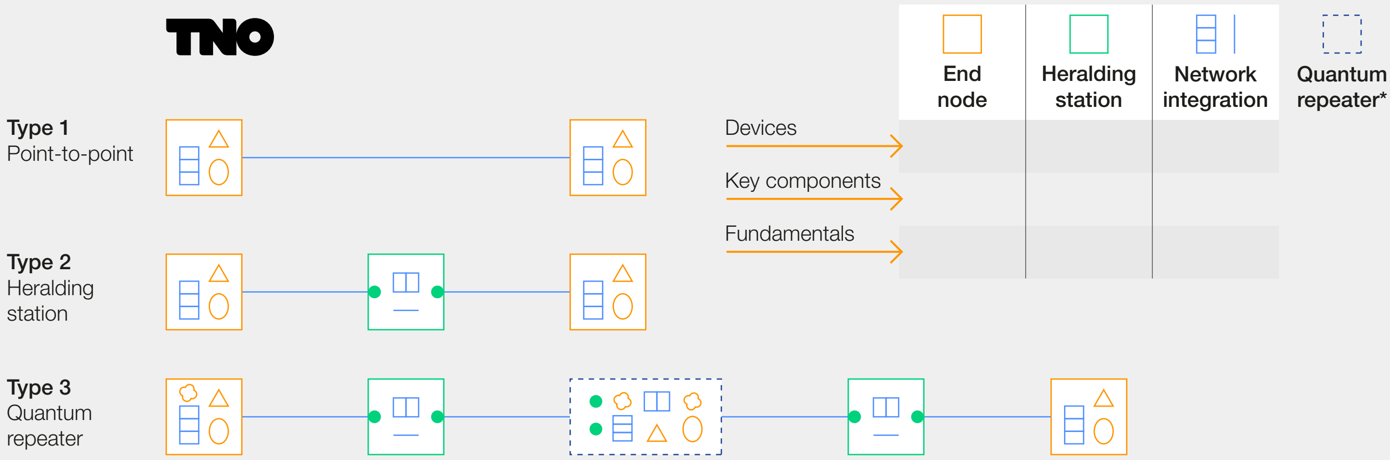
FIGURE 5 **Quantum technologies and supply chain example**



Source: Riekeles, Georg E., *Quantum technologies and value chains: Why and how Europe must act now*, European Policy Centre, 23 March 2023.

An example is the template ("canvas") for a quantum communications supply chain mapping suggested by Quantum Delta NL/TNO in 2023.[10] It is a breakdown of quantum networking architectures focusing on the required hardware elements.

FIGURE 6 | Quantum technologies and supply chains

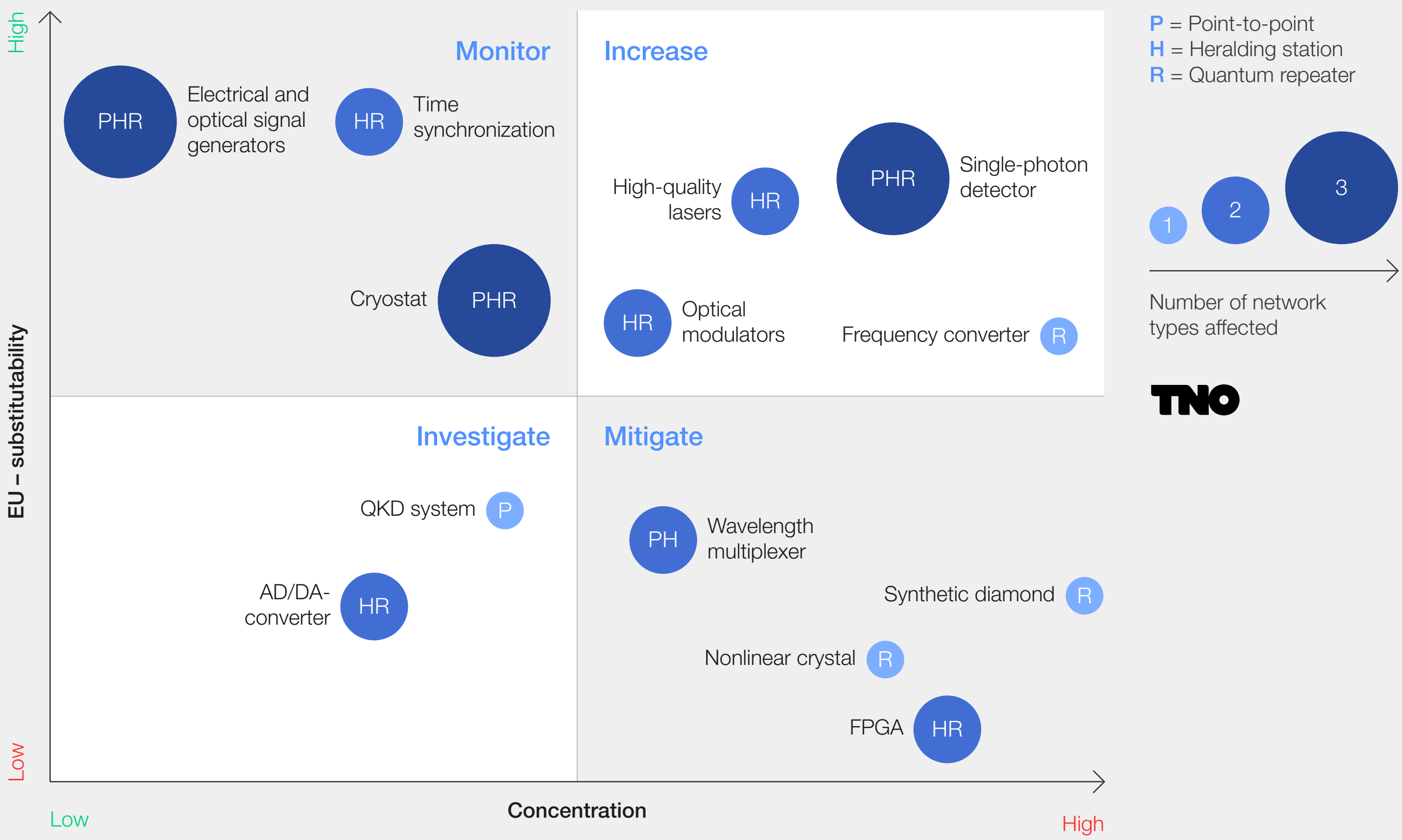


Supply chain canvas for quantum communication, for which a system breakdown structure for quantum networks based on hardware elements was used. *It is assumed that in terms of components, a quantum repeater generally consists of hardware elements that are also present in the end nodes and heralding stations.

Source: Quantum Delta, *Mapping the Supply Chains for Quantum Communication*, 2023.

When completed, this template can lead to a comprehensive overview of the different components underlying the quantum networking supply chain. The supply chain, which focuses on the availability of components in the EU, is mapped on the likeliness of substitutability of components within the EU (vertical axis) and on the concentration, which shows how many suppliers there are and their market share (horizontal axis).[11]

FIGURE 7 | Mapping the supply chains for quantum communication



Source: Quantum Delta, *Mapping the Supply Chains for Quantum Communication*, 2023.

Another example is from the Quantum Economic Development Consortium (QED-C) industry association document *Tracking the Global Supply Chain: A Framework for the Quantum Industry,* which is shown in Figure 8 in abstracted form.[12]

The QED-C set forth the following principles as suggestions to follow when building a quantum supply chain:

– Principle 1: Create a supply chain tracking approach that can be implemented in a practical tool.

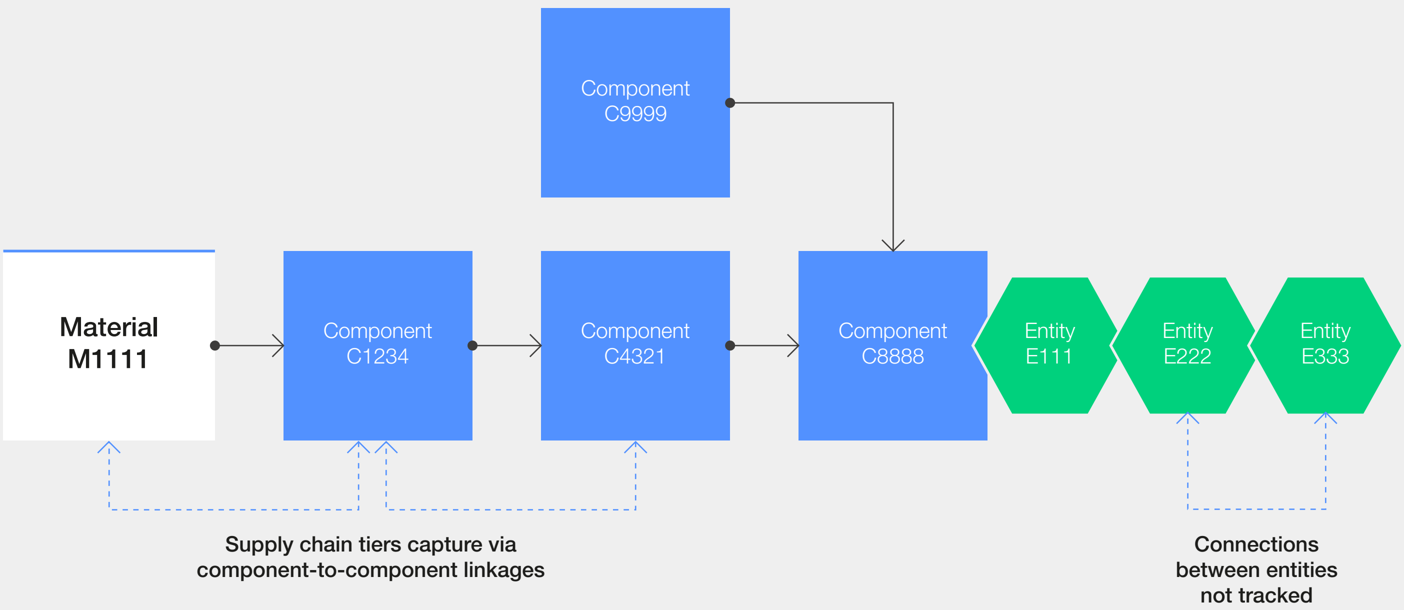
– Principle 2: Launch an initial proof-of-concept tool and expand its coverage and functionality over time.

– Principle 3: Maintain confidence in data to support adoption.

– Principle 4: Ensure data and tool security.

The QED-C supply chain framework is structured starting with a tracking of technology components and materials across the global supply chain. These are matched with the entities that produce them. As components and materials are often connected with one or more other components and materials and hence suppliers, different connections need to be drawn, as shown in Figure 9. It should be noted that this is one example of an approach. It can serve as inspiration for countries' own efforts but should be adapted to countries' own contexts.

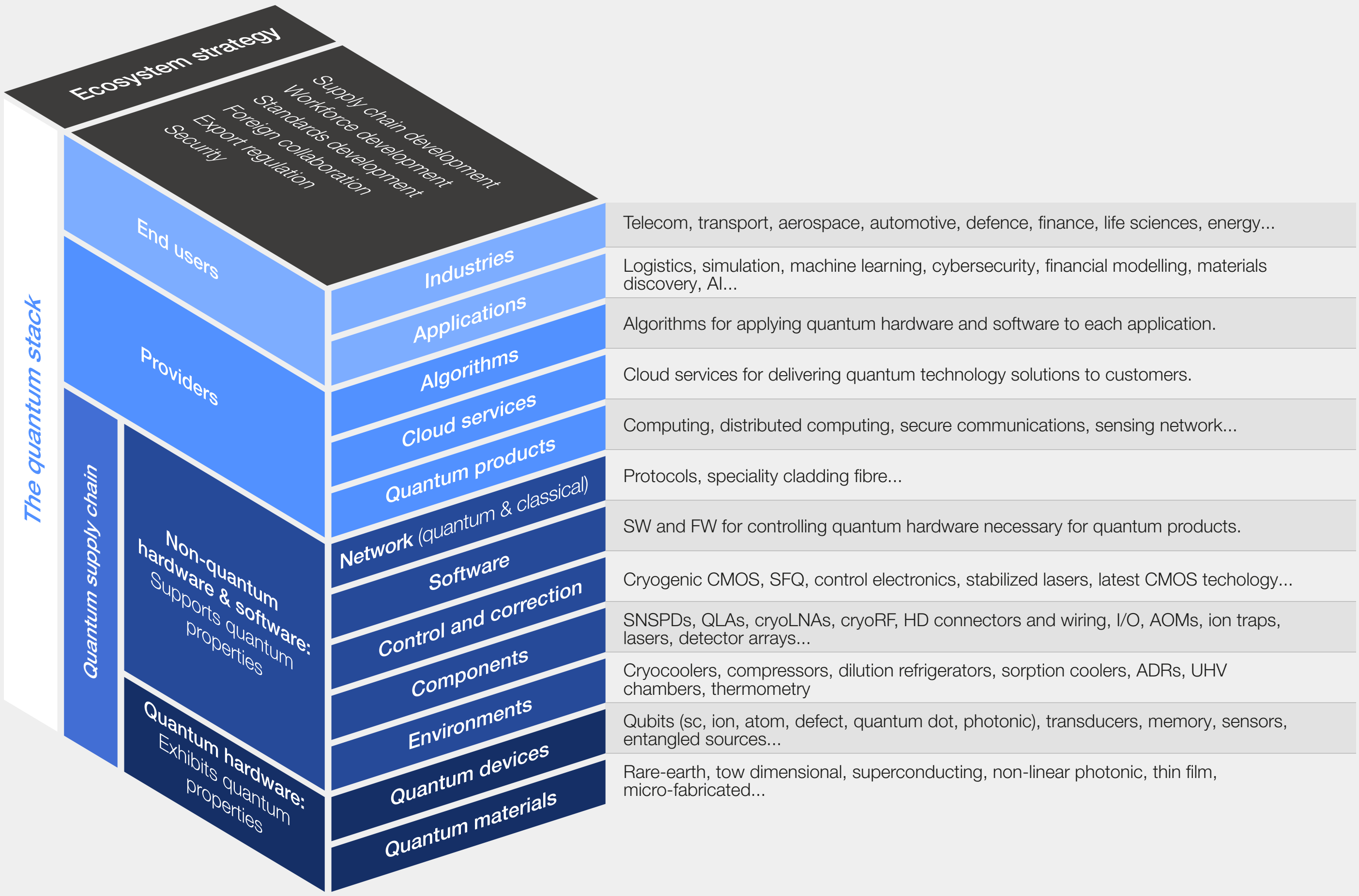
FIGURE 8 **Quantum supply chain tracking framework**



Source: QED-C, *Tracking the Global Supply Chain: A Framework for the Quantum Industry*, 2023, p. 4.

Another relevant element is to track the components across the quantum stack:

FIGURE 9 **Quantum stack listing tracked components and materials**



Source: QED-C, *Tracking the Global Supply Chain: A Framework for the Quantum Industry*, 2023, p. 7.

> **The supply chain that underpins the quantum sector – while still nascent – is already truly global. Based on a survey of 54 relevant UK companies, 85% are importing elements of their supply chain to develop quantum technologies. In the UK, 33 companies are a key part of this global supply chain.**
>
> UK Department for Science, Innovation & Technology, *National Quantum Strategy*, 2023.

The supply chain analysis should also entail a critical component analysis. It is important to note that non-quantum technologies such as cooling and lasers are also critical in the quantum supply chain. Governments, such as the United States government, have noted that access to such supporting technologies is crucial to efforts to support critical infrastructure.

Building block 2.3: The international nature of the quantum supply chain

Similar considerations on the supply chain are shared by other governments as part of their quantum strategy. It has also been noted that the global nature of the quantum supply chain may pose a challenge to access and supply.

> **Reliable access to resilient and trusted domestic and international supply chains is also essential for a successful Australian quantum sector. Quantum technologies use mass-produced components, such as semiconductors, which are in high demand across the world. They also need bespoke components that are available from single sources or specialist manufacturers. The Australian quantum industry relies on complex global supply chains for key materials and components. These complex global supply chains are vulnerable to disruption, resulting in unpredictable availability and costs. Australia could analyse future supply chain needs and identify areas where it can become a world leader, helping grow ongoing supply in the future.**
>
> Australian Government Department of Industry, Science and Resources, *National Quantum Strategy*, 2023.

As demonstrated above, the access to various hardware components and infrastructure has implications for the nature of national and regional quantum supply chains. This is important from the perspective of national security, as described in theme 6, but also for education and capability-building strategies.

To ensure wide access to quantum technologies, clear strategies for the supply and development of quantum hardware are necessary. A quantum supply chain mapping is a key element enabling such strategies. Particular attention must be paid to the fact that different quantum technologies are at different maturity levels, and it is important to have differentiated strategies for the respective technologies.

Building block 2.4: Adjacent supply chain capabilities

Countries can build on existing supply chain strength areas to create adjacent value-added capabilities in the context of the international quantum supply chain.

> **Participation in the quantum economy allows countries to focus on higher value-added sectors. For example, the supply of diamonds for nitrogen-vacancy (NV) diamond-based QT hardware may be coming largely from India. Currently, the preparation of the NV centres happens mostly outside India, with some promising efforts emerging to make this happen in India. This is a critical sector where India could develop their own high-precision production facilities to conduct this value-added activity locally. Another area where India could vastly contribute would be in the development of precision optics, optomechanics and allied quantum technologies**
>
> Urbasi Sinha, Professor, Raman Research Institute

1.3 Theme 3: Open innovation and commercialization

> Encouraging collaboration and fostering a precompetitive environment is essential for accelerated technology development and application realization.

The goal of open innovation is to ensure that collaboration is encouraged, especially in a pre-competitive environment, enabling fast and responsible development of quantum technologies and their applications.

Building block 3.1: Encouraging collaboration and a pre-competitive environment

Encouraging collaboration and fostering a pre-competitive environment is essential for accelerated technology development and application realization. For example, in the context of QC, a unified cross-national or cross-regional strategy should focus on creating or offering access to a fully functional QC infrastructure. This approach mitigates fragmentation, avoiding cannibalization. It can further the collaborative spirit of the scientific and technological endeavour necessary to be successful in the overall project of bringing useful quantum technologies to the world.

Drawing inspiration from successful open innovation strategies and commercialization models is recommended for the whole QT sector. This approach ensures adaptability to specific contexts and optimizes the overall development process. Careful governance considerations should underpin the considerations for open innovation and collaboration. These play a crucial role in ensuring ethical practices and responsible conduct for sustainable and impactful quantum technology development. These issues are discussed further in theme 8.

The strategies for open innovation include but are not limited to those listed in the following sections:

Building block 3.2: Trade strategies

A key area for furthering open collaboration is the way in which trade strategies are set up:

- **Open markets and trade barriers:** Evaluate and address trade barriers for QT, including a review of tariffs and export/import regulations.

- **Technology transfer and commercialization:** Promote initiatives and establish centres of excellence for technology transfer and commercialization.

- **National competence centres:** Build institutions focusing on encouraging international collaboration.

- **International collaboration rewards:** Institutionalize international-level rewards to incentivize collaborative research and projects.

- **Sharing/trusting code:** Establish a repository to share code for relevant use-case scenarios affecting society beyond individual organizations or communities (e.g. epidemics, cybersecurity, global catastrophic events).

Building block 3.3: Public and private sector innovation strategies

Public sector strategies

Public sector strategies and investments call for integrated approaches in order to be successful.

- **Connections to other industries:** Foster connections to industries in the QT value and supply chain.

- **Flagship projects:** Initiate flagship projects spanning geographies and industries.

- **Phased approach:** Implement a phased approach for understanding and exploiting both near and long-term opportunities.

Private sector strategies

Given the early stage of many of these technologies, private sector strategies are well advised in having a mid- to long-term horizon. Responsible investment strategies should underpin strategies in general.

1. **Venture capital (VC) and private investment for QT:** Encourage the involvement of venture capitalists and other private investors in QT initiatives.

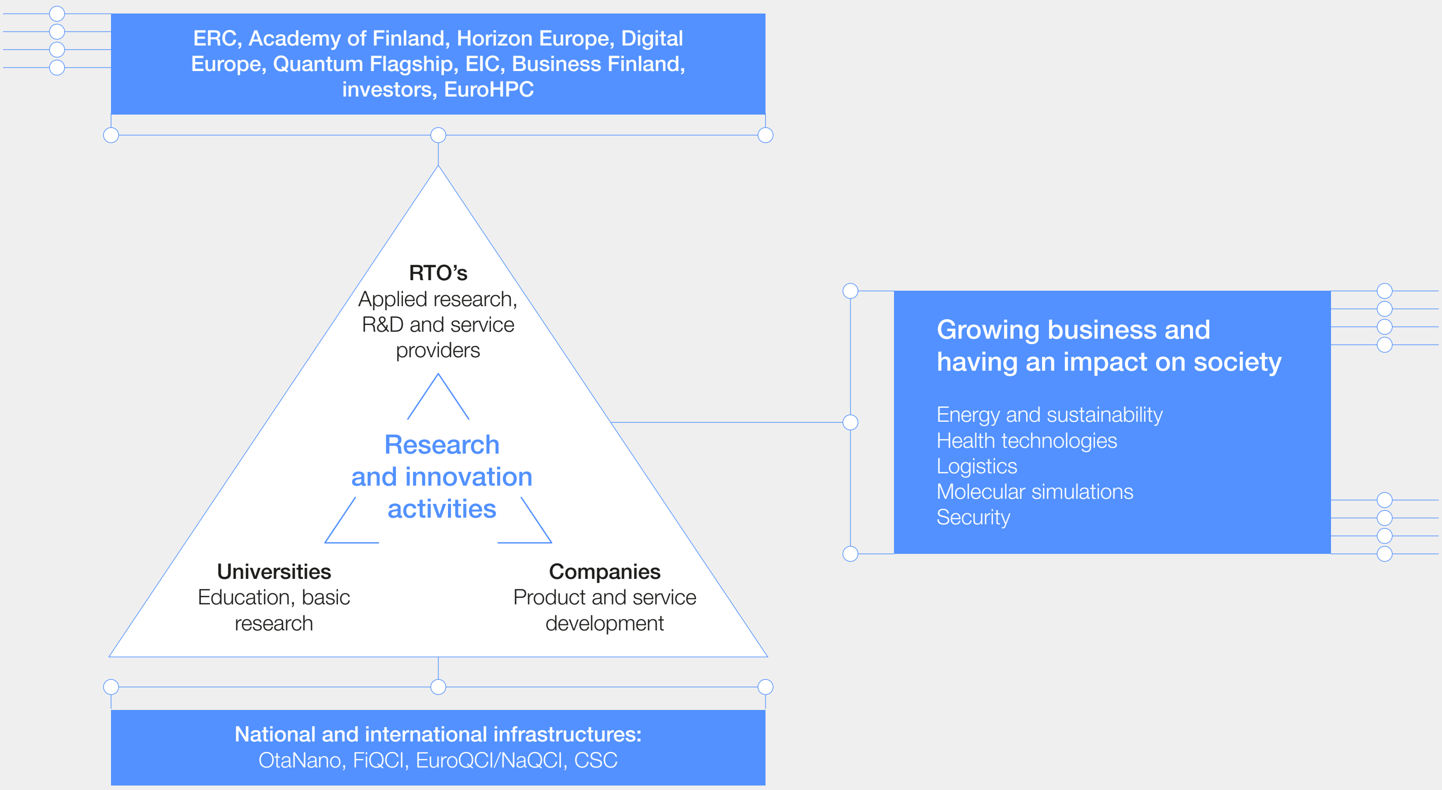
2. **Strategies for VC investment:** Develop strategies, including government funding, to enhance trust in QT and facilitate ease of investment.

3. **Long-term investment focus:** Private sector investment should, for the long-term (5-7+ years), be supported by family office funds, university funds and regional development funds such as Breakthrough Victoria in Australia.[13]

4. **Public-private partnerships:** Emphasize public-private partnerships and industry engagement, aligning with the focus of aligning with the focus of the QT strategy.

Figure 10 shows the interplay between the public and the private sectors, national and international infrastructures and different funding bodies in the Finnish strategy.

FIGURE 10 **Schematic illustration of the quantum ecosystem in Finland**



Source: Institute Q, *Finnish Quantum Agenda*, n.d., https://instituteq.fi/finnish-quantum-agenda/.

The Finnish example shows the interplay between research institutes, universities and private companies in the triangle, with the focus of their interplay being research and innovation activities. These activities and the interplay are influenced and enabled by different national and international funding bodies (top) and national and international supporting infrastructures (bottom). Together they aim at “growing business and having an impact on society” through the collaboratively made advancements in quantum technologies.

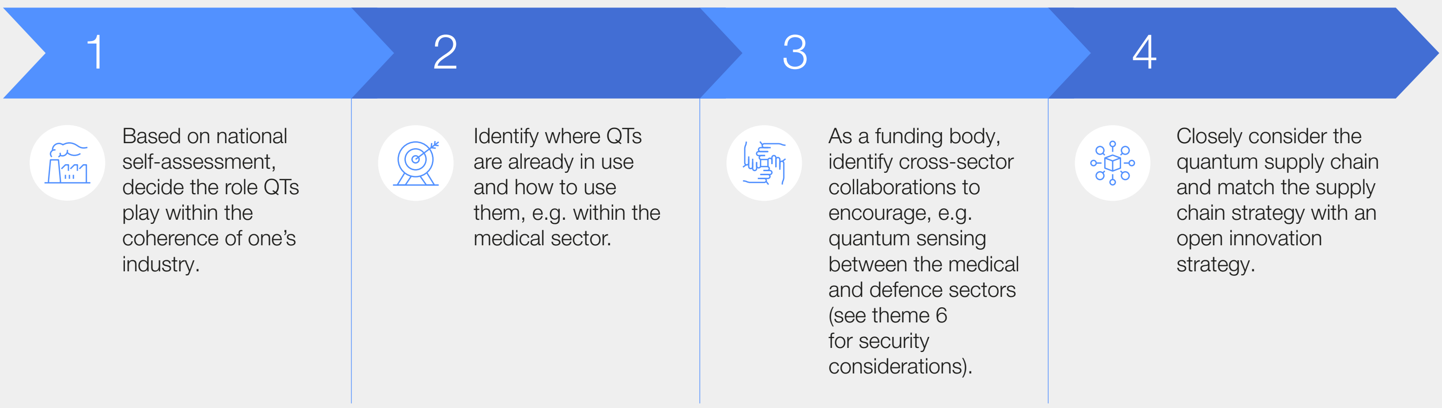
Building block 3.4: Technology transfer and commercialization initiatives

Decisions about technology and application areas to focus on should be informed by a national SWOT analysis and industry needs. Strong collaboration between industry, academia and funding bodies is required for best decisions. Successful strategies centre on the different focus areas to support, match and use existing national strongholds.

Another reason why open innovation can be key to a successful quantum strategy lies in the fact that not every country will have the funds and talent to create QC systems at the scale of the millions of qubits they will need. Cooperative cross-country agreements will be needed to ensure access to the systems useful for production work. Other complex QTs also benefit from open innovation approaches where the R&D or value chains span across borders.

The process to establish an open innovation strategy could look as follows in Figure 11.

FIGURE 11 **Process for establishing an open innovation strategy**



The following example from the UK shows how an open innovation strategy can be implemented across multiple sectors to drive and accelerate commercialization of QT.

CASE STUDY 2

Open innovation and commercialization in the UK National Quantum Strategy

It is still early days for quantum commercialization, with most quantum technologies in the research, development or early demonstration phase. Developing quantum products and services can be a long and challenging process, with the need for sustained investment and support before profits can be made. The UK understands commercialization as a truly collaborative endeavour over the next 10 years and beyond, spanning multiple sectors and requiring bold and innovative approaches supported by a diverse and thriving workforce that can drive the growing quantum industry.

In March 2023, the UK government committed to investing £2.5 billion over the next 10 years in the quantum sector through the publication of the UK National Quantum Strategy. This announcement builds on the successes of the National Quantum Technologies Programme, which for the past 10 years has mobilized over £1 billion of public and private investment to drive the development of the UK quantum sector.

This has led to the establishment of a thriving and collaborative quantum ecosystem supported by four research hubs. The hubs bring together experts from universities, national laboratories, business development and industry partners under the leadership of a single university to galvanize the development of specific technology areas: communications (University of York), sensors and timing (University of Birmingham), enhanced imaging (University of Glasgow) and computing and simulation (University of Oxford). Additionally, the National Quantum Computing Centre has been supporting multidisciplinary teams to work together to design, build and operate quantum computers through collaborative R&D projects across sectors. Its new state-of-the-art facilities are due to open in 2024.

The UK Commercializing Quantum Technologies Challenge fund drives collaborative innovation for new products across sectors, including healthcare, infrastructure, telecommunications, transport, cybersecurity and defence, based on advances in quantum science. Since 2018, it has delivered £174 million in public funding, supported by £390 million from industry, to support the commercialization of quantum technologies in 139 projects involving 141 organizations. This includes collaborative research projects, a programme of industry-led projects addressing specific challenges, a series of feasibility projects looking at innovative components and supply chain elements across the quantum sector, and an investment accelerator to support early-stage, spin-out and start-up quantum technologies companies in securing venture capital.

Additionally, the strategy outlines a series of flagship initiatives to support open innovation and commercialization, including missions, focused on galvanizing the community to achieve a particular outcome, and accelerator programmes, which drive development through enabling demonstration in real-world settings and to help move technologies up the readiness levels. In March 2023, the UK government announced an investment of £70 million into two short-term quantum missions. The aims of these are to:

– Demonstrate the advantage of a quantum computer over a classical one.

– Demonstrate mature proof-of-principle prototypes in position navigation and timing in environments that cannot be reached by traditional satellites.

"Additionally, the strategy outlines a series of flagship initiatives to support open innovation and commercialisation. These include: Missions focused on galvanising the community to achieve a particular outcome

– Accelerator programmes that drive development by enabling demonstration in real-world settings and to help move technologies up the readiness levels.

In November 2023, the UK Government announced five long-term quantum missions to galvanise technology development towards ambitious outcomes such as having UK-based quantum computers capable of running 1 trillion operations, adopting quantum sensors in the National Health Service, and deploying quantum navigation systems on aircraft, amongst others. These missions build on the two £70 million shorter-term missions announced in March 2023 on Position, Navigation and Timing and to demonstrate the advantage of a quantum computer over a classical one.

The government delivery agency, Innovate UK, has also launched two calls for a Quantum Network Accelerator Programme, two £10 million competitions to accelerate quantum network technologies by removing technological barriers to their commercialisation and adoption by focusing on their enabling components and systems".

Source: UK Office for Quantum, Department for Science, Innovation and Technology

This is one example of executing an innovation strategy, and in particular, the interplay between industry, research and government agencies. Governments can act as first procurers to signal confidence in QT. However, this depends on the state of technological development of the given QT, as it may not be possible to detail typical procurement specifications in the current state.

To conclude, it has been seen in the different existing national strategies that careful consideration of open innovation is of key importance. While a balance with security considerations is paramount, open innovation strategies can be key success factors, especially for resource-intensive quantum technologies.

1.4 Theme 4: Creating awareness

Widespread knowledge about QT and its impact across society can be achieved by creating a dialogue between government, academia and industry to create public education, awareness and avoid hype.

The goal here is to ensure widespread knowledge about QT and its impact across society. This can be achieved by creating a dialogue between government, academia and industry to create public education, awareness and avoid hype.

Building block 4.1: Multilevel public dialogue

Educational initiatives for creating awareness should span multiple levels, including boards and C-Suite, governments and policy-makers, as well as workers, interns, teachers and students. Such awareness-building programmes should be broad-based, focussing on the practical applications and benefits of QT rather than on the intricacies of the underlying quantum physics. They should also ensure to avoid hype. Some examples of awareness-raising initiatives are detailed below:

Year of Quantum 2025: An international partnership of major scientific bodies and academies is preparing a resolution for the 2023 General Conference of the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the 2023 General Assembly of the United Nations to proclaim 2025 the International Year of Quantum Science and Technology. This year-long initiative will celebrate the profound impacts of quantum science on technology, culture and understanding of the natural world. The year 2025 has been proposed for this international year as it recognizes 100 years since the initial development of quantum mechanics.

World Quantum Day: An initiative from quantum scientists from over 65 countries, aims at engaging the general public in the understanding and discussion of quantum science and technology every year on 14 April, a reference to 4.14, the rounded first digits of Planck's constant.

Centre for Quantum and Society: The Centre for Quantum and Society in the Netherlands facilitates a number of initiatives to better understand the societal implications of QT. One concrete example stemming from this initiative is the Exploratory Quantum Technology Assessment which is a roadmap to understanding the impact of QT uses.

Japan's Quantum Strategic Industry Alliance for Revolution (Q-STAR)[14] mission includes the aim to build a society where the use of quantum is for everyone: "By 2030, used by 5-10% of the population in major developed countries; in Japan, aim for a society where 10 million people use quantum technology".

Building block 4.2: Decision- and policy-maker education strategies

Awareness building for policy-makers and decision-makers at all levels of government and society is also critical as they are key constituents in the quantum economy. Initiatives, such as this report, are designed to help policy-makers map their countries' strengths to a developing quantum strategy, and to understand where their country could best participate in the quantum economy. This may be in building quantum hardware or developing quantum algorithms, in delivering critical parts of the supply chain, or in educating a skilled workforce to underpin their own and other countries' talent needs.

For example, EU Quantum Flagship[15] is offering a series of training sessions on quantum technology, addressing policy-makers at EU and national levels. The training is offered online and developed in the form of a monthly series.

Awareness building among policy-makers in countries that have not yet started the quantum journey is even more important and pressing.

> **There is a critical concern for Argentina, Brazil and other countries in the Global South related to the widening technology gap with developed countries, in spite of the fact that many countries in this region are scientifically and technologically mature. It is important to create awareness of this issue and to find ways to revert this trend.**
>
> Karen Hallberg, Professor of Physics, Balseiro Institute and Principal Researcher, National Council on Scientific and Technological Research (CONICET), Bariloche Atomic Center (CNEA), Argentina

Building block 4.3: Awareness-building tools and methods

Quantum offers a step change in capabilities impacting industry and society, and efforts are underway to unlock its full potential. Expanding the global use and understanding of quantum increases the benefits the technology will bring.

To this end, awareness building is emphasized prominently in national strategies. The European Flagship programme, has for example, an entire workstream dedicated to education and awareness-building, with programmes that address different types of audiences. The Netherlands have made "Quantum and Society" one of their four pillars on which the national quantum programme is built.

The Forum's Quantum Applications Hub

In support of awareness building, the Forum has also recently started the quantum applications hub, which aims to increase awareness among senior level industry stakeholders and policy makers. This initiative aims to shape a scalable and inclusive quantum ecosystem and launch a one-of-a-kind experiential platform to drive increased awareness and responsible adoption of quantum solutions. These goals will be advanced through two workstreams. The industrial workstream will bring flagship industry examples together within a global platform that enables access to success stories, research and applications for quantum technology. The societal workstream will accelerate quantum applications for the Sustainable Development Goals (SDGs) by developing collaborative partnerships and growing the ecosystem and launching an innovation challenge for the SDGs.

InstituteQ: Organization of the community[16]

In 2021, Aalto University, the University of Helsinki and VTT established a collaboration called the Finnish Quantum Institute: InstituteQ. The general mission of InstituteQ is to raise the readiness of Finnish society for the disruptive potential and implications that quantum technologies will have for society and the economy at large. By teaming up expertise and resources, the institute aims to carry, implement and mutually benefit from front-line research, education, innovations and infrastructures, forming a competitive edge in the quantum race. The work in Finnish universities and research organizations provides academic and technological research contributions on areas that are highly relevant to the development of the field in the long term. Altogether, close to 90 groups work in the areas relevant to this field, some with core activities and others with parallel activities supporting the field of quantum technologies. Via its strategic national role, VTT has taken significant steps towards building the national quantum innovation ecosystem. In 2021, several Finnish companies and VTT signed a memorandum of understanding (MoU) launching coordinated development of the business ecosystem on quantum technologies in Finland (BusinessQ). The membership is open to interested stakeholders with no financial or legal commitments. BusinessQ operates as an independent collective within the framework of InstituteQ, based on the common principles and expectations defined in the MoU. This is to make the membership as easy as possible to attract the wider business and other stakeholder communities.

> **Awareness building for policy-makers and decision-makers at all levels of government and society is also critical as they are key constituents in the quantum economy.**

QETCI: Organization of the ecosystem

QETCI is a private entity established before the Nation Quantum Mission was announced, whose aim is to formulate and engage the community and be the voice for accelerating quantum efforts in India. QETCI is a not-for-profit entity with the mission to enable and accelerate the quantum ecosystem in India, and which is bringing industry, academia, government and partner councils/associations in quantum together. The entity is also enabling international ecosystem connects, making policy recommendations, supporting start-ups, driving awareness programmes for skills development as well as investor awareness, recommending/formulating focus groups and establishing centres for specific projects intended to catalyse the quantum ecosystem.

1.5 Theme 5: Workforce development

Recognizing the escalating demand for quantum expertise, policy-makers should proactively augment the talent pipeline, addressing immediate and long-term needs while upholding principles of diversity, equity and inclusion.

The goal is to build a quantum-literate workforce in key sectors of the economy, encompassing both quantum technologies and the adjacent professional sectors. Recognizing the escalating demand for quantum expertise, policy-makers should proactively augment the talent pipeline, addressing immediate and long-term needs while upholding principles of diversity, equity and inclusion.

The integration of workforce development initiatives with public outreach endeavours is pivotal for fostering awareness across a broader population.

Building block 5.1: Education initiatives

Every nation with a quantum strategy has highlighted the need to increase its talent pipeline at all knowledge levels, spanning researchers, engineers and technicians. This begins with a comprehensive focus on science, technology, engineering and mathematics (STEM) subjects at an early age, from high school programmes to university courses. The education framework should embrace a continuum from fundamental R&D to multi-disciplinary courses in quantum engineering and related disciplines.

> **Promote quantum industry by training human resources and widely disseminating information. Promote quantum industrialization by developing a programme to recruit and train human resources in quantum and related fields; make clear in Japan and internationally that implementation of quantum technology is essential for future society.**
>
> QSTAR Japan

The US National Strategic Overview for Quantum Information Science (2018) stresses the need for a trans-sector and trans-disciplinary approach to quantum information science, and the challenges that this brings within the existing education system. It also emphasizes the benefits of industrial engagement and improving academic-industrial pathways.

> **Growing an American quantum-smart workforce with expertise in a broad range of physical, information and engineering sciences is crucial for assuring sustained progress in QIS. However, America’s current educational system typically focuses on discrete disciplinary tracks, rarely emphasizing cross-disciplinary study that equips graduates for complex modern questions and challenges prominently including QIS. While the responsibility of training students traditionally resides within the academic community, government agencies and industry can partner with academia to meet the nation’s future needs.**
>
> **Fundamental research is the main mechanism for generating a qualified workforce in QIS. Within the context of the need for individuals with a broad mix of skills, support for the trans-sector and trans-disciplinary approach to research is essential. Students trained in such an environment will be exposed to a diverse yet convergent set of disciplines, along with the associated tools and infrastructure.**
>
> “Creating a quantum-smart workforce for tomorrow”, in *National Strategic Overview for Quantum Information Science*, US National Science & Technology Council, 2018.

Building block 5.2: Global, regional and national talent pipeline strategy

The shortage of skilled professionals in STEM subjects is already a challenge in most countries. The gap in the quantum workforce is even more acute. The UK *National Quantum Strategy* acknowledges this challenge: "Demand for quantum skills outstrips supply, despite sustained investment in the UK. Competition for skills is increasing, with recent analysis showing that globally quantum job adverts outstrip qualified talent by as much as three to one, and salaries for top quantum professionals are more than double the UK average in the US".

The strategy also provides explicit quantitative goals, stating, "Since 2014 the UK has funded over 470 postgraduate research students working on quantum technologies or a related discipline. By 2033, we will have funded an additional 1000 postgraduate research students in quantum relevant disciplines".

The growing demand for talent forces countries to look abroad to fill the skills gap. Countries note the need to create a jobs-friendly environment for international talent, including facilitating visas and student and work exchanges.

> **Foreign talent constitutes approximately half of the US graduates in QIST-related fields and flows into the United States from all over the world. As of 2017, approximately 70% of foreign national science, technology, engineering and mathematics (STEM) PhD students who graduated from US institutions of higher education stayed in the United States, where they contribute to the US economy and support the global science and technology enterprise. The development of new QIST expertise is slow, often taking 10 years of post-secondary education and training. Addressing the growing demand for an expert QIST workforce will require both growing the domestic pipeline and promoting the flow of international talent into the United States.**
>
> White House, Office of Science and Technology Policy, *The role of international talent in quantum information science*, 2021.

Countries can increase access to talent through training young scientists, engineers and others in underserved geographies or sectors of the population. For example, the Geneva Science and Diplomacy Anticipator (GESDA) Open Quantum Institute is developing capacity-building tools to train young scientists and developers from quantum-underserved geographies to use quantum devices and explore applications of quantum computing that can help tackle their local challenges.

The global flow of quantum talent can help bridge a short-term talent gap, while educational programmes support the building of a national quantum workforce for the longer term. Countries like India, which have developed a strong workforce skilled in quantum and adjacent technologies, can participate in the global quantum economy. However, these countries also need to build the right incentives to safeguard their local ecosystem and retain talent.

Building block 5.3: Upskilling and cross-skilling strategies

Upskilling and cross-skilling strategies should promote quantum literacy in the existing workforce in adjacent fields across multiple levels. This involves cross fertilization with domain expertise from deep tech PhDs, engineers, manufacturing professionals, technicians, software developers and experts in other fields such as product development, legal, policy and marketing.

This can involve quantum career retraining programmes, upskilling programmes to enhance targeted skill sets in adjacent fields, or cross-skilling within an industry and between departments, with an emphasis on continuing education. Successful strategies include public-private partnership initiatives, such as specialized apprenticeship or internship programmes, the creation of a quantum centre of excellence within an organization or engagement with professional bodies. These approaches can be augmented by the development of tools to enable workers with different levels of expertise to work in the quantum industry.

Building block 5.4: Public-private partnership strategies

Public-private partnerships are key to supporting quantum specialists in hardware dependent fields. Upskilling industry specialists may require access to academic laboratories in universities or quantum centres of excellence.

Conversely, access to QC platforms developed by private industry players is essential for the development of QC-related fields in all industries. Researchers and specialists require access to platform-independent resources and quantum simulation to enable deep learning opportunities and to benefit from the quantum economy.

The paucity of quantum talent can lead to an increase in competition between governments, academia and large industrial players. The UK government notes that, in this context, governments should be aware of the potential risks associated with technology transfer and trade restrictions.

Close relationships between industry, professional bodies, and government will support continuing professional development.

Building block 5.5: Harnessing new job creation potential

The potential for new job creation in the quantum sector is immense, both in unexplored fields as well as in the creation of new skill set requirements in adjacent fields. Quantum technologies create high-value, high-productivity jobs that benefit the broader society in trickle-down effects in the overall value chain. The Australian quantum strategy notes a target of "1.2 million technology jobs by 2030, which will support the quantum industry's requirements" and forecasts that the sector will "generate over 19,400 jobs by 2045, and this number will grow with additional investment". It notes the need to "lift diversity and inclusion in the industry…[to] bring new ideas and insights; reduce bias in the system; ensure we're reflecting the views of Australia's diverse society".

> **We realized as early as 2017 that Africa was behind the curve in understanding the need for quantum technologies, and the potential applications. In 2018, the African Institute for Mathematical Sciences (AIMS) founded Quantum Leap Africa (QLA) to help prepare Africa for the future of quantum technology. This builds upon the proven track record of creating scientific centres of excellence in postgraduate training and research across Africa. With six of such centres established in South Africa, Senegal, Ghana, Cameroon and Rwanda, and with almost 3,000 alumni from our unique postgraduate training programme, many of whom are already making significant contributions to a diverse array of fields, from pure mathematics to epidemiology, computer science, computational finance and AI. Based on a model which gathers academically-gifted African students and brings professors from all over the world to teach them, AIMS has become a magnet for attracting Africa's brightest students.**
>
> **One of the main components of QLA is devoted to quantum training and research, related to and anticipating powerful new QT, including quantum computing, quantum communication and quantum sensors, to develop experts in Africa who are ready to utilize the power of quantum technology for the benefit of Africa and humanity at large.**
>
> **We do not have the financial capacity to develop our own quantum devices, so we rely strongly on partnerships with other entities, both industrial and academic. We also get funding from international donors.**
>
> Prince Koree Osei, Quantum Leap Africa, Rwanda & Centre President, AIMS Ghana

1.6 Theme 6: National and economic security

The aim is to harness quantum technologies in pursuit of national and economic security. Participating in the quantum economy allows countries to access quantum technologies and products which may support longer term national security as well as civil objectives. While not all countries need to own all parts of the supply chain, or independently build their own sovereign quantum computer or other quantum technologies, they do need to ensure adequate long-term access to the necessary components and platforms to ensure their own geoeconomic security.

Building block 6.1: Government defence investment priorities

Many countries specifically target security in their quantum strategy. They typically adopt the model of the government as key first investor, drawing inspiration from examples such as In-Q-Tel from the US and the UK's National Security Strategic Investment Fund (NSSIF).

However, it is not always sufficient for governments to be investors. To ensure the success of QT with longer-term return on investment, governments may need to adopt the role of first customer and take more risk in their procurement of early-stage QT. There are an increasing number of investment funds devoted to developing military and intelligence QT and/or customers to prevent market failure and ensure long-term investment and eventual productization.

Building block 6.2: Geostrategic cooperation strategies

Some governments forge alliances on an international or regional scale to ensure collaboration on R&D, solution development, testing and deployment, as well as to ensure access to key components and software in the supply chain (see theme 2) and to QC platforms.

This includes economic international cooperation as well as defence agreements such as AUKUS, the Quad, NATO and others.

Governments also focus on the need to create a national and international regulatory framework that protects their country's capabilities, as well as national and economic security. There is a risk regarding multi- or dual-use technologies, since societally beneficial applications can be used nefariously as well. This should be regulated and governed as part of the responsible innovation approach of national quantum strategies (see theme 8).

This may include restrictions on export of certain dual-use technologies or components, as well as limiting knowledge transfer at the academic level. However, there is also a risk of a quantum race, which could stymie progress and prevent access to key quantum technologies for certain countries, exacerbating the quantum divide.

Finding a balanced approach is complex. It will require an agile regulatory approach, and collaboration between government and industry in a transparent manner so as to foster technological advancement while at the same time limiting potential risk.

> **From a government perspective, our quantum strategy should incorporate a science-first and innovation-first approach while supporting national security. While the US government continues to examine the appropriate policies related to quantum technologies, our primary goal is to promote, not hinder science, which calls for thoughtful legislation. It is also critical that the United States and our allies retain access to key components in the quantum supply chain, requiring policy-makers to account for the geopolitics surrounding this access. In terms of the Global South and how to support them in the quantum revolution, the applications piece could be the most relevant once the foundational tools emerge.**
>
> Rick Switzer, Director, Strategy and Policy, Office of the Special Envoy for Technology, United States Department of State

1.7 Theme 7: Cybersecurity and privacy

> The goal is to address cybersecurity threats arising from advanced quantum algorithms that will run on future, large, fault-tolerant quantum computers, as well as from potential future unknown quantum attacks.

The goal is to address cybersecurity threats arising from advanced quantum algorithms that will run on future, large, fault-tolerant quantum computers, as well as from potential future unknown quantum attacks. Additionally, countries must mitigate potential data privacy violations arising from a cryptographically relevant QC and through potentially privacy-invasive quantum technologies.

Building block 7.1: Cyber threat and risk analysis

Known QC attacks, such as Shor's factoring algorithm and its variations, as well as future but unknown quantum attacks, pose a clear potential threat. Although these quantum algorithms are awaiting a quantum computer powerful enough to run them (a cryptographically relevant quantum computer or CRQC[17]), the risk already exists due to the "store now decrypt later" attack vector.[18] In this attack, data with long-term criticality is downloaded now by adversaries – typically a nation state – for decryption in the future when a CRQC becomes available. If targeted attacks are performed on a mass scale, then the defence and/or intellectual property data critical to a nation's economic well-being and national security may be accessed and compromised. Citizens' private information – including personal medical and financial data – may be captured and held to ransom.

With this in mind, governments are cooperating to build awareness and put in place regulations to protect critical infrastructures and key industries, with the goal to protect their own economic well-being and ensure protection of their citizens' privacy. Governments need to take into account the requirement to transition to quantum secure cryptographic and trust infrastructures. In Figure 3, the transition to post quantum cryptography is time critical – it should start even before phase 1 (discovery phase) of a quantum strategy, and even if a country does not plan to embark on a holistic quantum strategy.

In its report *Transitioning to the Quantum Secure Economy*,[19] the World Economic Forum outlines the following recommendation for enterprises. Governments should review policy, guidelines and regulations to ensure alignment with these bottom up principles.

BOX 1 The Forum's recommendations for transitioning to a quantum-secure economy

- Build awareness around the quantum threat, by educating senior leaders on the systemic impact. The quantum threat feels far away and largely abstract for many organizations. To combat this, organizations will need to face what is known, but also accept there are implications that are still unknown. Conducting initial quantum readiness assessments will help leaders determine the specific threats their organizations face. Executive buy-in is key to ensuring the quantum transition attracts appropriate investment and prioritization.

- Plan and prepare by adopting a quantum-safe strategy and transition roadmap. Addressing the quantum threat requires organizations to plan and create a timeline that sequences immediate, near-term (3-5 years) and longer-term actions. Organizations should consider adopting a "crypto-agile" posture, enabling them to readily transition cryptographic capability. This will help them prioritize a transition to quantum security as technology advancements and threat knowledge continue to evolve.

- Initiate the transition, using hybrid solutions. Organizations adopting quantum- resistant security will more than likely leverage hybrid solutions that integrate both classical and quantum-ready approaches. This will give organizations some assurance that existing security remains intact, while overlaying that security with relatively new post-quantum cryptography algorithms.

Building block 7.2: Government regulations and directives

To respond to this quantum cryptographic threat, governments are working on an (inter)national framework to assess, manage and align quantum computing-related risks alongside traditional risks, and integrate quantum strategy into cybersecurity strategy. This involves:

- Inventorying current cryptographic artefacts and assets to understand the risk profile and prioritization of critical assets or systems.

- Planning the migration to the next generation of cryptographic algorithms that will be resistant to QC attacks.

- Building in crypto-agility for cyber resilience, where future algorithm or technology upgrades can be as seamless as possible.

The United States National Institute of Standards and Technology (NIST) has led an international programme to solicit, evaluate and standardize quantum-resistant, public-key cryptographic algorithms (also commonly known as post-quantum cryptography or PQC).[20] The first approved algorithms are expected to be standardized in 2024.

The United States National Institute of Standards and Technology (NIST) has led an international programme to solicit, evaluate and standardize quantum-resistant, public-key cryptographic algorithms. The first approved algorithms are expected to be standardized in 2024.

Testing and standardization of the algorithms and their security validations are critical. However, these are not sufficient. There is also a need for clear government directives, regulations and guidelines to bring transparency and certainty to the actual implementation process. These level the playing field and facilitate orderly and timely migration by clarifying the exact requirements, resources and timelines for industries and governments.

The US federal government is leading the way with legislation and budgets allocated to federal agencies for cryptographic inventory, migration to PQC and crypto-agility for future resilience.

Notable memoranda and legislation outlining requirements for federal agencies include:

- *National Security Memorandum 10 (NSM-10) Promoting US in Quantum Computing, Mitigating Risks to Vulnerable Cryptographic Systems*: This directs the federal government to protect quantum technologies and directs NIST to establish standards and set requirements for federal agencies to update cryptographic systems.[21]

- *Quantum Computing Cybersecurity Preparedness Act HR 7535*: This encourages the federal government to adopt technology that is protected from decryption by quantum computing. It mandates federal agencies to prepare an inventory of items for the transition to the new standards and the Office of Management and Budget (OMB) to prepare a budget and a strategy for the transition within a year. Agencies would also be required to update these systems annually, and Congress would receive an annual status briefing.[22]

- *2022: OMB Memorandum Migrating to Post Quantum Cryptography (M-23-02)*: New guidance requiring all agencies to submit cryptographic system inventory in compliance with NSM-10, to assess funding requirements and to test pre-standardized PQC.[23]

The US government has mandated completion of the migration to PQC for federal agencies by 2035, but a 2023 report by the National Quantum Initiative Advisory Committee states "an earlier completion date would be highly preferable and should be achievable through vigorous US government action".

Building block 7.3: Cybersecurity implementation and migration plans

The US government has mandated completion of the migration to PQC for federal agencies by 2035, but a 2023 report by the National Quantum Initiative Advisory Committee states "an earlier completion date would be highly preferable and should be achievable through vigorous US government action."[24]

Other governments are reviewing the requirements but most have not yet passed binding regulations.

To complement this effort, the National Center of Excellence (NCCoE) is engaging with industry and regulated industry sectors and governments to enhance awareness of the issues involved in migrating to PQC. NIST and the NCCoE published a draft document 1800-38A Migration to Post-Quantum Cryptography: Preparation for Considering the Implementation and Adoption of Quantum Safe Cryptography to clarify the relevant guidelines.

Additionally, agencies such as Cybersecurity and Infrastructure Security Agency (CISA) worked with the US National Security Agency (NSA) and NIST to inform organizations, especially those that support critical infrastructure, about the impacts of quantum capabilities. The factsheet *Quantum-Readiness: Migration to Post-Quantum Cryptography (PQC)* includes recommendations for industry – particularly those dealing with critical infrastructure – to establish a quantum-readiness roadmap, steps to prepare a useful cryptographic inventory, considerations for understanding and assessing supply chain, how organizations should engage with their technology vendors to discuss PQC and responsibilities of technology vendors.

CISA is not alone in the efforts to emphasize the advantage of beginning migration now. The Department of Homeland Security published their own *Post-Quantum Cryptography Roadmap* stressing the need to begin laying the groundwork immediately, and the Cloud Security Alliance has set a deadline of April 2030 by which time all enterprises should have implemented post-quantum infrastructure.

BOX 2

CISA, NIST and NSA: establish a quantum-readiness roadmap

While the PQC standards are currently in development, the authoring agencies encourage organizations to create a quantum-readiness roadmap by first establishing a project management team to plan and scope the organization's migration to PQC. Quantum-readiness project teams should initiate proactive cryptographic discovery activities that identify the organization's current reliance on quantum-vulnerable cryptography. Systems and assets with quantum vulnerable cryptography include those involved in creating and validating digital signatures, which also incorporates software and firmware updates. Having an inventory of quantum-vulnerable systems and assets enables an organization to begin the quantum risk assessment processes, demonstrating the prioritization of migration. Lead by an organization's information technology (IT) and operational technology (OT) procurement experts, the inventory should include engagements with supply chain vendors to identify technologies that need to migrate from quantum-vulnerable cryptography to PQC.

Other government agencies, such as the UK's National Cyber Security Centre (NCSC), France's Agence Nationale de la Sécurité des Systèmes d'Information (ANSSI), Germany's Bundesamt für Sicherheit in der Informationstechnik (BSI), and others, are clear about the need to upgrade to PQC and are following suit in providing preliminary recommendations. However, timelines and exact implementation guidelines are generally pending the standardization of algorithms.

From the BSI's point of view, the question of 'if' or 'when' there will be quantum computers is no longer paramount. First, post-quantum algorithms have been selected by NIST for standardization and post-quantum cryptography will be used by default. Therefore, the migration to post-quantum cryptography should be pushed forward."

Federal Office of Information Security, Quantum Technologies and Quantum Safe Cryptography.

Other countries, like Singapore, or regions like the EU, explore a risk-based approach to achieving quantum resistance through combinations of PQC with other quantum technologies, such as quantum key distribution or – in the future – quantum networks.

For example, the National Quantum Safe Network in Singapore,[25] supported by the National Research Foundation, Singapore, is a three-year initiative led by the Quantum Engineering Programme to translate quantum science into solutions for addressing real-world challenges.

> **We provide a platform for technology exploration and develop a vendor-neutral ecosystem for end users and stakeholders to demonstrate the integration of quantum-safe applications.**
>
> **The network will first investigate the deployment of the quantum key distribution technologies, which is a hardware approach to quantum-safe communication involving transmission and detection of quantum signals. Together with the exploration of PQC, which involves upgrading software to deploy quantum-computer resistant cryptographic algorithms, NQSN will serve as a quantum-safe network for potential end users to experience and understand these quantum-safe communication solutions first-hand.**
>
> National Quantum Safe Network, Singapore.

A new programme, NQSN+, was launched in 2023 as part of Singapore's Digital Connectivity Blueprint. The Singapore Infocomm Media Development Authority (IMDA) is working on NQSN+ to enhance the resilience and security of businesses in Singapore's digital economy. "As part of Singapore's efforts to push the next bound of interoperable quantum-safe networks, IMDA together with the NQSN team, are driving international and local standardization of quantum-safe technologies. Singapore will co-lead the first standardization of the QKD protocol framework at the ITU Telecommunication Standardization Sector (ITU-T), together with Japan".[26]

International Organizations like the Forum have also developed toolkits for organizations. The Forum's *Quantum Readiness Toolkit* presents a set of guiding principles for organizations to navigate the quantum computing era securely. The toolkit advocates for a global, cross-border approach to cybersecurity and governing quantum risk.

BOX 3

Quantum Readiness Toolkit

This *Quantum Readiness Toolkit* offers organizations guidelines that they can use to assess, prioritize and act now. To enhance the successful implementation of the principles, organizations should consider to:

- Raise awareness of quantum risk and the need to mitigate it now. Provide decision-makers with a clear and coherent message to build meaningful partnerships and drive action. Despite the deep technical aspects of quantum risk, mitigating it will be a people business and require a workforce that understands and prioritizes the risk.

- Realize there is no silver bullet. No individual quantum security solution, policy or hired expert will make an organization quantum secure overnight. It will require a variety of tools adapted to the environment and use cases focused on people, governance and technology to make an organization resilient to present and future cryptographic risks, of which quantum risk is only one.

- Act now. Nobody knows for sure when a sufficiently powerful quantum computer will arrive, but the timeline is shrinking. Everyone is aware that transitions take time, and nobody wants to be too late. Organizations should start now to give themselves sufficient time to start small, experiment and get acquainted with the challenges and success factors that will allow a quantum-secure transition. Regulators can play an important role in driving timely action across ecosystems, but they should contemplate guardrails that encourage adoption and support organizations in becoming quantum secure.

> Best practices involve an ongoing monitoring and gap analysis between the state and adequacy of privacy regulations versus the potential of new QT and its implementation.

Building block 7.4: Cross-industry collaboration and awareness-building

Since there are industry-specific enterprise risk considerations, best practice involves cross-industry collaboration to investigate, test and solve for systemic risk. Industries leading the charge are financial services, and critical infrastructures such as telecommunications. For example, the GSMA has published a *Post Quantum Telco Network Impact Assessment*, followed by *Guidelines for Quantum Risk Management for Telco*. Telcos have a role to play in protecting the availability of their own infrastructures, as well as the confidentiality and integrity of their customers' data – for both enterprise and individuals.

A key part of the work also involves raising awareness of the threats within that industry. There is also a need for national/international competence centres to test for quantum-resistance in critical infrastructures and enterprises.

Building block 7.5: Privacy impact of other quantum technologies

Much of the privacy debate around quantum focuses on the need to protect long-term data (including personally identifiable information or "PII") from attacks by cryptographically relevant quantum computers.

However, there are other potential privacy issues which need to be addressed in light of new capabilities from QT. For example, many quantum sensors will extend the sensitivity and resolution of existing sensors, and existing privacy protections should be augmented to include their use. Similarly, data from new medical sensing devices, and its use, should be included in any privacy policies and protections. One such example is non-invasive brain imaging.[27]

QT also provides opportunities to enhance privacy:

- Privacy-preserving computer technologies, including private access to shared QC platforms
- Future quantum networks that support data privacy networks to support data privacy.

Many of these threats and opportunities are evolving. Best practices involve an ongoing monitoring and gap analysis between the state and adequacy of privacy regulations versus the potential of new QT and their implementation, an understanding of the need to fast track privacy policy updates specifically to include new challenges arising with QC and QT, scientifically informed analysis of QT co-dependencies with classical infrastructure and the impact on privacy and strategies for enabling the government and key industries to be developers and early adopters of mechanisms to safeguard privacy.

It is advantageous to adopt privacy-preserving principles (privacy by design) at the beginning of product development. In this, lessons can be drawn from cloud and AI. At the beginning of a technology curve, emerging technologies may be concentrated in large companies and not regulated. Once the question of access and other issues such as privacy arises, then the painful process of adopting new policies and regulations starts. Privacy and security by design can help avoid this.

Governments and industries which are implementing potentially privacy-invasive technologies should assess whether current privacy regulations are sufficient to deal with the above threats. Who owns and processes the data? What is the authorized use of the data in personalized or anonymized form?

If there are no privacy-relevant regulations or directives, such as GDPR in Europe, then industries and policy-makers should apply the four primary CARE principles, particularly with respect to interactions with and export of technologies to the global south. The four primary principles are collective benefit, authority to control, responsibility and ethics.[28]

1.8 Theme 8: Governance, responsible innovation and standardization

By adopting responsible innovation and taking an anticipatory approach to understanding the societal impact of technology, potential harms can be mitigated, and equitable societal benefit maximized.

By adopting responsible innovation and taking an anticipatory approach to understanding the societal impact of technology, potential harms can be mitigated, and equitable societal benefit maximized.

The aim here is to establish responsible innovation practices across different soft-to-hard mechanisms. As seen above, in thinking about regional and national strategies for QT, the wheel does not have to be reinvented.

This current stage of development of quantum technologies offers an opportunity to be proactive in thinking about responsible innovation and governance of QT. Doing so requires the introduction of new and existing governance mechanisms that enable responsible technology development and the use and need for interdisciplinary approaches rather than restricting innovation, which can then be adopted for other emerging computing technologies. While some of the challenges related to QT are similar to those for other emerging technologies, e.g. the possibility of dual usage, there are a number of specific ethical challenges that are particularly salient for QT and therefore necessitate specific governance and responsible innovation mechanisms.

These include but are not limited to:

– Questions around epistemic access: QT is often presented as opaque and as requiring domain-specific expertise. This increases the risk of inequity of access to knowledge about QT.

– Application-specific implications: As seen above, there are certain applications which have the potential for multiple use cases. Responsible use strategies can help ensure QT is used for the benefit of society.

– The environmental impact of QT: this is a key topic discussed in theme 9.

Building block 8.1: Definition of core common values

Deciding on the core key values and principles underpinning one's national strategy is key to ensuring a responsible national or regional QT strategy. Not only does this allow for greater buy-in but also for greater transparency with respect to the motivations underpinning national and regional quantum strategies.

Building on the core common values and principles, governance mechanisms can be introduced. These governance mechanisms, underpinned by responsible innovation, can range from more formal structures imposed from the top-down, often termed "hard" governance, such as regulation, to "softer" more informal governance, which can include bottom-up self-governance approaches, such as impact assessments.

The choice of which governance mechanism is appropriate may depend on the context in which it is to be applied, including the maturity of the technology. In the early stages of technology development, a "softer", more agile approach can be pro-innovation while enabling a responsible approach, whereas at a later stage, regulation is less likely to stifle innovation and can be introduced proportionately to risk.

Building block 8.2: Operationalizing responsible innovation

To operationalize values and principles, tools, frameworks and processes can be adopted, including impact assessments, whereby the ethical and other impacts of innovation can be identified and evaluated, and (risk) mitigation strategies can be implemented.

One such tool is the Exploratory Quantum Technology Assessment,[29] developed by Quantum Delta Netherlands, designed for organizations to understand the implications of their work.

FIGURE 12 **The Exploratory Quantum Technology Assessment (EQTA)**

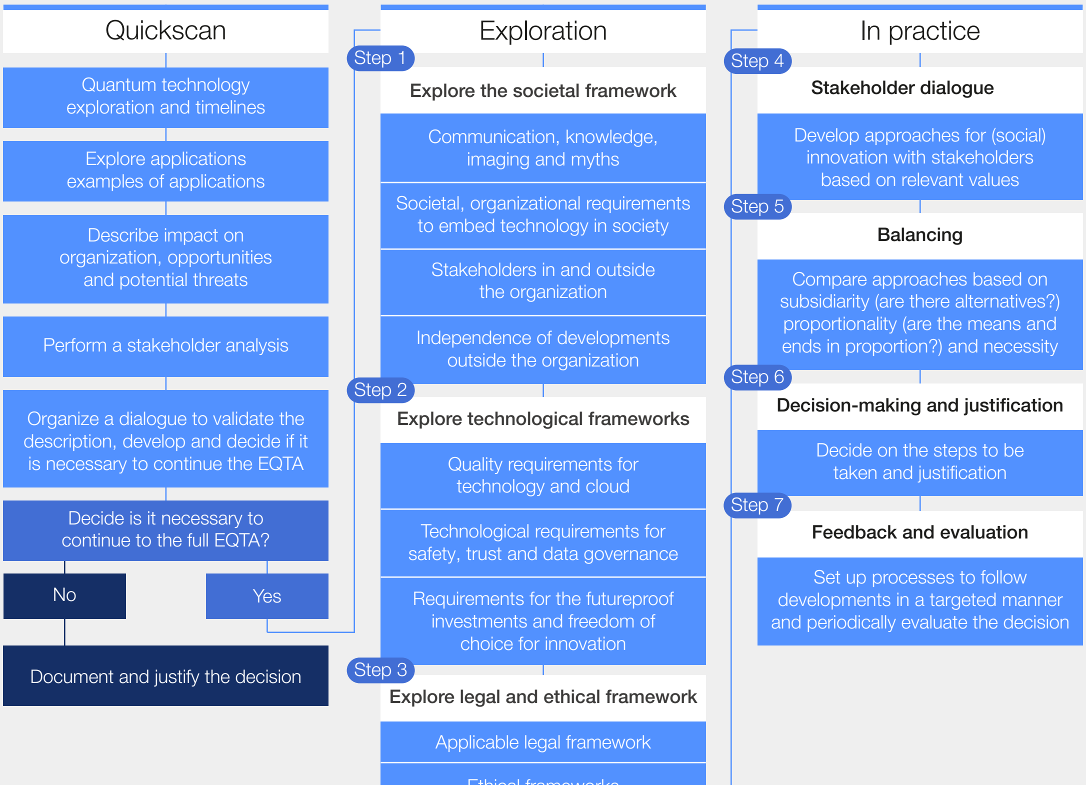
Quickscan and roadmap

The EQTA helps organizations take the steps necessary for responsible application of quantum technology and to manage its impact.

The quickscan provides a quick overview of the points of attention to guide the impact of quantum technology in a timely manner.

If the quickscan shows that responsible embedding of quantum technology requires active guidance, then proceed to step 1 of the roadmap.

If active guidance is not necessary, this decision is also documented.



Source: Quantum Delta Netherlands

A further tool for operationalizing responsible innovation is the use of assurance techniques such as bias auditing of a particular algorithm. For example, the UK's Centre for Data Ethics and Innovation has developed a portfolio of AI Assurance Techniques, which provides freely available case studies of applicable techniques.

The above can be supported by public-private collaboration to identify necessary guardrails and mechanisms for proactive monitoring of ethical implications. A further important element is inclusive engagement, using public dialogues to spot unforeseen consequences, respond to public concerns and mitigate potential downstream negative responses.

The adoption of these tools becomes critical at the point at which applications are being developed and before they are widely utilized, at which point it becomes difficult to influence the trajectory of their use.

Building block 8.3: Technology-enabling regulation

The most formal approach to responsible innovation comes in the form of regulation. Particularly in emerging technologies, it is important to take great care in introducing regulation. As the UK National Strategy emphasizes, regulation should not stifle innovation. In addition, regulation should be introduced in a way that is proportionate to the risk posed and should be appropriate for the relevant technology readiness level. As with other emerging technologies, it is likely that, for the most part, regulation will apply to applications, rather than the technology itself. For export control, noting how regulations handle high-performance computing (HPC) technologies is informative.

BOX 4 | **UK National Quantum Strategy**

Leading quantum regulation

Quantum regulation will need to be:

- Stable, coherent and predictable
- Agile enough to move quickly with technological development
- Simple to understand and inexpensive to implement
- Where possible, co-designed with industry
- Focussed on innovation and industry needs
- Champion the transparent and ethical use of quantum technologies.

Source: UK Department for Science, Innovation & Technology, *National Quantum Strategy*, 2023.

For regulation to be successful, it is critical that policy-makers have sufficient awareness of the capabilities and likely implications of the technology to make informed decisions. Upskilling policy-makers in QT is therefore a key enabler for appropriate regulation. There are initial models aimed at this that show positive results. In addition, industry can support informing regulation through initiatives such as forums, regulatory sandboxes and dialogues. This can benefit both industry and regulators since industry benefits from gaining a forward look into upcoming regulations and an understanding of compliance, and regulators gain a better understanding of the latest developments in technology.

While many QTs are still at an early stage of readiness, there are efforts currently being undertaken to understand their regulatory implications. For example, the UK's Regulatory Horizons Council, an independent expert body which provides advice to the government on the impacts of innovation, was commissioned to carry out a review of QTs to support their safe introduction.

Although at this early stage of maturity, much formal regulation is yet to be introduced, some countries have started to put "hard" governance in place. For example, the UK introduced the National Security and Investment Act 2021,[30] allowing government oversight and intervention into acquisitions involving entities belonging to a number of sensitive areas, including quantum technologies, which might impact national security.

Government regulation related to cybersecurity is covered in theme 7.

Building block 8.4: Standardization strategies

Standards and regulations are intricately entwined, with varying perspectives on their nature. While some perceive standards as a form of regulation, others distinguish them as voluntary commitments to a defined performance threshold. Regardless, standards serve pivotal roles, contributing significantly to various aspects of industries and markets.

National strategies focus on standardization having the following roles: benchmarking for system performance and enablement of collaboration on QT hardware. Standards also serve the role to indicate to application industries what e.g. algorithms to implement. In this vein, NIST has been spearheading a standardisation process for the selection of "quantum-resistant cryptographic algorithms" as outlined in building block 7.2.[31]

Community-led standards can be taken up by industry associations and function as equivalent to standards until those are formalized. For example, in the telecommunications industry, the GSMA has recently announced its task force on recommendations for use of quantum-safe algorithms and a roadmap towards implementation. This work will result in a "community standard". The aim of such work is clear: "to help define policy, regulation and operator business processes for the enhanced protection of telecommunications in a future of advanced quantum computing".[32]

Formalized processes at standardization bodies often include invitation-only working groups with experts from the specific subfield where standards are discussed. Eventually, the suggested standards will be voted on before being adopted by the respective body. There is a risk of bias being introduced based on the selection of experts. This can be countered by open and participatory standardisation processes. Examples of ongoing standardisation processes for more mature QT include, but are not limited to, the Institute of Electrical and Electronics Engineers is working on metrics and benchmarking as well as on a definition of quantum technologies. In a similar manner, the British Standards Institution works on defining QT terminology.[33] The Federal Institute of Metrology in Switzerland is working on quantum metrology and quantum sensing standards.[34]

The Australian *National Quantum Strategy* emphasizes the importance of standards in helping research and development processes and not hindering innovation.

> **The Australian Government will be an active participant in global standards-setting bodies to promote the development of standards that support a thriving, accessible and safe quantum ecosystem; and ensure Australia's regulatory frameworks foster quantum-related research, support investment in quantum companies and support exports while protecting Australia's national interests."**
>
> Australian Government Department of Industry, Science and Resources, *National Quantum Strategy*, 2023.

In essence, the importance of standardization processes lies in their multifaceted contribution to the efficiency, transparency and collaborative potential of industries. Whether viewed as a voluntary commitment or a form of regulation, standards are indispensable tools that shape the contemporary landscape of diverse sectors, fostering innovation and ensuring the reliability and interoperability of systems.

The overall aim for governance, responsible innovation and standardisation is to establish responsible innovation practices across different "soft" to "hard" mechanisms. It is suggested to learn from the past, understand quantum's specific challenges, mitigate undesired implications, and reap and promote socially beneficial applications.

1.9 Theme 9: Sustainability

Strategies for sustainable QT focus research and funding on the development of low-energy-consuming QT that do not require scarce materials.

The goal of this theme is to develop QT sustainably and to incentivize usage aligned with the United Nations' SDGs. There should be a focus on accelerated progress towards the goals of the Paris Agreement[35] and supporting the Intergovernmental Panel on Climate Change.[36]

A general consideration in this theme is to trade off long-term timelines and returns versus short-term returns with the main goal of establishing a sustainable (ecologically, economically and lasting) QT sector.

Building block 9.1: Strategies for sustainable quantum technologies

Strategies for sustainable QT focus research and funding on the development of low-energy-consuming QT that do not require scarce materials. Sustainable supply chains for quantum technologies should be promoted and developed, e.g. with respect to sustainable materials sourcing, as well as by realistic funding and investment, without following undue hype cycles.

> **The United States will focus standards development activities and outreach on these applications, which include […] Critical minerals supply chains, where we will promote standards that support increased sustainable extraction of critical minerals necessary to manufacture renewable energy technologies, semiconductors and electric vehicles.**
>
> The White House, *United States Government National Standards Strategy for Critical and Emerging Technologies*, 2023.

This example of the US government indicates that, in some cases, standards can be used to support sustainable development.

Building block 9.2: Strategies for energy consumption benchmarks

Most of the time, different applications of quantum technologies can be implemented in various ways or with different hardware. In order to make these different approaches comparable to their classical counterparts with regard to their energy usage, benchmarks need to be developed. For example, a quantum sensor is very different from a quantum computer, so different benchmarks must be developed to understand the energy use of each.

For example, the Quantum Energy Initiative advocates for a benchmark for QC.[37] The Quantum Energy Initiative grew out of a paper by Alexia Auffèves called *Quantum Technologies Need a Quantum Energy Initiative*. In the abstract, they state:

> **Quantum technologies are currently the object of high expectations from governments and private companies, as they hold the promise to shape safer and faster ways to extract, exchange and treat information. However, despite its major potential impact for industry and society, the question of their energetic footprint has remained in a blind spot of current deployment strategies.**
>
> Alexia Auffèves, "Quantum Technologies Need a Quantum Energy Initiative", *PRX Quantum*, vol. 2, issue 2, 2022.

In addition, it could also be useful to combine QC strategy with HPC and data centre strategies to reduce infrastructure costs and centralize energy consumption.

With QC, it is anticipated that different hardware platforms will give users a choice of trading off execution time, cost, accuracy and energy use.

> **We argue that interdisciplinary research programmes are required to develop reasonable metrics of the energy consumption of quantum technologies.**
>
> Robert Whitney, CNRS Researcher, Université Grenoble Alpes; Co-Founder, Quantum Energy Initiative

QT has huge potential to positively impact the UN's SDGs, as studies have shown.[38] Guidance in this theme pertains to the use of QT for future enhanced sustainability.

Building block 9.3: Incentivization strategies for sustainability use cases

Identification of use cases where quantum technologies or applications thereof can contribute to global sustainability. Within a quantum strategy or quantum funding assessment, stakeholders may consider prioritizing funding of R&D of technologies and applications that have the aim of tackling problems related to global sustainability or climate change.

Building block 9.4: Focus areas for positive impact on environment

This involves the establishment of detailed research plans for areas in material science, chemistry, environmental monitoring, etc. For example, allowing the development of better and longer lasting batteries, or finding materials to capture CO_2 or for nitrogen fixation. In addition, better and more accurate sensors may drastically reduce emissions, materials consumption and improve environmental monitoring.

For example, QT could help improve fertilizer production through more energy-efficient catalysts. QC and physical simulation can potentially unlock new advanced materials to deliver cleaner and more efficient energy generation and storage. Quantum sensing can help in detecting leakages in gas pipelines, which could in turn help to reduce related emissions.

QT can also help mitigate the impact of climate change. QC could potentially enable more accurate weather modelling and forecasting to help the agriculture sector manage climate change and weather events. Quantum sensors could also be deployed to help detect ground water reserves at a time when the supply of fresh water is increasingly under threat in many places.[40]

> **Countries like Rwanda and Ghana already have some programmes and policies in place. For example, Ghana is focused on drug discovery and healthcare. They have a strong programme for drug development and have done significant work in COVID-19 and malaria. Additionally, Rwanda is focussing on agriculture and environmental monitoring. Here, quantum sensors could be used for high-precision measurements and assessment of soil quality.**
>
> Prince Koree Osei, Director, Quantum Leap Africa; Centre President, AIMS Ghana

BOX 5

The 2023 Australian *National Quantum Strategy* outlines potential sustainable applications of QT

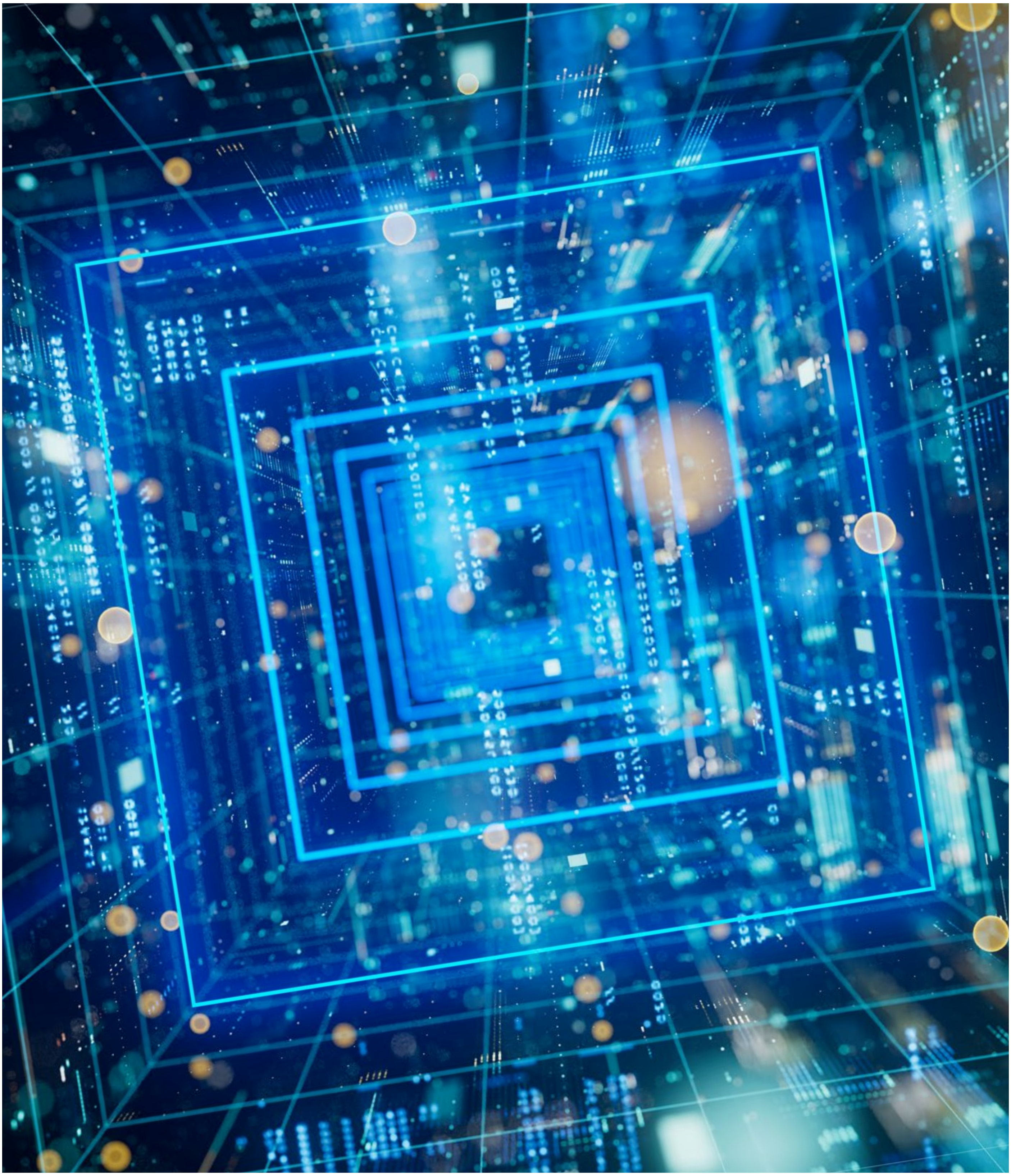
There are already tangible, scalable applications across a range of industries, with more emerging. For example:

- Quantum sensors are being used to detect underground water leaks without digging, which could be used to lower costs and proactively monitor for leaks.
- Quantum sensors are improving the speed and accuracy of measurements in civil engineering.
- Quantum computing can be used to optimize supply chains and public transport, reducing waste and emissions.
- Quantum computing could help increase the energy density of batteries, supporting the transition to renewable energy.

Quantum-based sustainability solutions are now on the agenda of international institutions such as the Forum (Quantum Application Hub initiative) , CERN and GESDA (Open Quantum Institute). There are multiple ways to include sustainability building blocks in regional and national quantum strategies, leveraging insights from these international institutions and developing concrete action and research plans.

2 Blueprint in practice

There are different approaches to the implementation of QT strategies. Each region or country should choose what is best given their current governance approach.



The trigger for quantum strategies may come from influential foundations, industry associations, key industrial players, research institutions or other non-governmental players.

Having analysed the key building blocks of existing national strategies, an additional important factor is how these strategies have been implemented. This section looks at some examples of the processes of establishment and operationalization.

Countries that have implemented, or started to implement, a quantum strategy have taken different approaches. Some have taken a "whole of government" approach, working to create a holistic quantum ecosystem all the way from the R&D lab, through government, defence or venture funding, to supporting accelerator programmes to create and drive quantum applications among industry and end users. Other countries have an industry or academia-led approach, enlisting local industry or multinational tech giants or responding to specific industry initiatives in a given industry vertical.

A country's quantum strategy may be driven holistically and coordinated across multiple ministries and regions by the central government, or responsibility (and funding) may be divided among different government agencies for education, science, defence and/or telecommunication. There may be a geographic distinction, such as regional within the country (e.g. Telangana state in India) or across regions (e.g. as in Europe).

The following are some case studies of different approaches to building and implementing a quantum strategy.

2.1 Responsibility-based – who initiated the strategy?

Strategies can be initiated by different stakeholder groups. Outlined below are two broad approaches: government- intitiated, e.g. the UK National Quantum Strategy and a non-government-initiated approach by Novo Nordisk Foundation.

Non-government-initiated approach

In the case of an industry or academia-led approach, the trigger for quantum strategies may come from influential foundations, industry associations, key industrial players, research institutions or other non-governmental players that push for a harmonized quantum strategy. An example of how this has worked in the past is shared below.

CASE STUDY 3

Novo Nordisk Foundation

In Denmark, the Novo Nordisk Foundation kick-started the quantum strategy, and the Danish government's strategy came after.[41] Focus was on quantum in life sciences. The entire quantum space was mapped, examining strongholds in the Danish ecosystems. Trusted parties were interviewed, and a third-party report was commissioned from RAND Europe for a deep investigation of strongholds for quantum tech in the life sciences.

Based on these reports and feedback, the Novo Nordisk Foundation formulated the strategy. It was recognized that Denmark had an advantage, but it was also acknowledged that swift action was necessary to avoid being overtaken.

From the reports, it was understood that strength would be gained through both international collaborations and public-private partnerships (PPP). This is in the nature of Denmark too. The advantage of PPP is that everyone knows what the others are doing so you can advance with speed. International collaboration includes working with India, start-ups in the UK, and many others.

The positioning of Denmark in the international ecosystem was also reviewed. Denmark and the EU excel in fundamental research but face challenges in creating industry and business downstream. Supply chains with trusted partners are essential for building resilience and avoiding dependencies on countries with potentially unstable political systems. Investing in materials is an example of efforts to build a supply chain within Europe, aiming to maintain a strong position and avoid the setbacks experienced in the semiconductor industry.

Denmark is now home to multiple agencies and centres focusing on quantum, for example, the NATO Centre, which hosts the DIANA accelerator for quantum. This builds up an entire supply chain around it. The Novo Nordisk Foundation also has a biotech innovation hub, which, within a few years, has raised $0.5 billion of venture capital.

This case study shows how the initiative of an industry player can give added impetus to a national process. This approach could work well in cases where there are strong industry players aligned with a national agenda and a high level of enablement power.

Government-initiated approach

The alternative is that a government takes a holistic view of the quantum ecosystem's needs and takes the initiative in developing a quantum strategy. While being advised by national and regional industry, science and academia, the government spearheads the final strategy. This approach could be suitable to contexts that are used to this form of a more centralized operationalization of strategies, as has been observed in other technology sectors.

CASE STUDY 4

Process of the establishment of the UK National Quantum Strategy

In March 2023, the UK government published the National Quantum Strategy, a bold and ambitious £2.5 billion 10-year plan to support the development of quantum technologies in the UK.[42] The strategy seeks to develop the quantum science, technology and innovation ecosystem, developing UK strengths across different technology platforms, and reinforcing capabilities throughout supply chains. The UK is also investing in and strengthening the key ecosystem enablers, such as international partnerships, skills, infrastructure, regulation, procurement and standards.

The UK's journey so far: the development of the UK National Quantum Strategy

In 2014, government, academia, industry and civil society came together to develop a joint action plan towards a mutually beneficial goal. The result was the National Quantum Technologies Programme (NQTP), which has mobilized over £1 billion of public and private investment to develop a thriving quantum ecosystem.

The publication of the strategy is the natural next step and is supported by the strong relationships developed through the NQTP. To develop the strategy, the UK set up bespoke governance structures to involve parties across all parts of the ecosystem and ensure accountability. This was supported by a delivery group responsible for orchestrating activities and drafting the strategy.

New governance fora complemented existing governance structures set up as part of the NQTP. This includes the NQTP Programme Board, which brings together all the NQTP partners to steer the strategic initiatives delivered through the Programme, as well as the Strategic Advisory Board which provides expert advice and independent challenge at a strategic level. These Boards were consulted throughout the development of the Strategy to define objectives, undertake a gap analysis, retest the vision and carry out a road-mapping exercise.

The UK also held workshops with strategic leaders from academia, industry and investors and wider consultation events with stakeholders including iterative feedback sessions and 1:1 conversations as the strategy developed. The government also launched a formal call for evidence through which stakeholders could submit in writing their views on the proposed vision, objectives and activities of the strategy.

What's next: delivering the UK National Quantum Strategy

To drive the delivery of the strategy, the UK set up the Office for Quantum within the new Department for Science, Innovation & Technology (DSIT). The Office for Quantum is responsible for advancing the government's approach towards quantum policy and orchestrating the delivery of the strategy. This includes coordinating work across government departments and arms-length bodies and with international partners.

The Office for Quantum reports to the Quantum Strategy Implementation Board, a cross-government committee which brings together the key departments with policy and resource responsibility over the strategy to steer its delivery. Cross-government coordination is essential for leveraging the full scale of opportunities of quantum technologies and maximizing support for the sector. The board's establishment ensures collective ownership and responsibility of the strategy across government, increasing awareness and ensuring public sector readiness for the opportunities presented by quantum.

To support delivery, the Office for Quantum has developed a delivery plan to break down the strategy's 10-year commitments into a work programme for the coming years. The delivery plan outlines key milestones, a monitoring and evaluation framework with metrics to measure success, and a governance framework.

Innovation has been placed at the heart of the UK government's agenda. Quantum, together with AI, engineering biology, semiconductors and future telecoms, is one of the five priority technologies for the UK under the Science and Technology Framework. At cabinet level, the National Science and Technology Council, chaired by the prime minister, oversees delivery, cementing the UK's commitment to the quantum sector at the highest level. Moreover, the creation of DSIT has allowed for all the UK's priority technologies to come under one roof for the first time, promoting collaboration and harmony while maximizing delivery opportunities across them.

Source: UK Office for Quantum, Department for Science, Innovation and Technology

2.2 Geographic-scope-based: regional vs national vs state

Additionally, strategy approaches can be at a regional, national, or state level. A region can also act for the establishment of strategy and implementation plans, such as in the EU (Quantum Technologies Flagship),[43] where there is very strong regional collaboration. On the state level, Telangana (a state in India) and the Northwest Quantum Nexus[44] (multistate in the US) can be considered as areas for quantum strategies. Industry consortia at the regional level, like the European Quantum Industry Consortium (QuIC),[45] also add impetus to the European strategy, working closely with the governmental QT Flagship.

Regional level strategy approach

CASE STUDY 5

European Quantum Industry Consortium (QuIC)

This is an exciting time in the quantum space, and Europe is one of the global leaders. However, it should be acknowledged that some countries are more developed than others, particularly in industrializing quantum technologies. More quantum maturity in all countries is desired.

There are multiple elements that will lead to an acceleration in the adoption of quantum in different countries, and quantum is not an isolated topic. Conversations are happening in Brussels on how to drive awareness at the policy-maker and industry levels. QuIC aim to help encourage others to advance and are working towards success stories, particularly those with early benefits. Government support is needed to foster global opportunities for quantum businesses, an open market carefully balanced against strategic autonomy needs. As the sector becomes mature and private customer traction becomes established, there will be a natural shift to other parts of Europe that have not developed their own quantum capabilities. There will be an effort to connect with the broader base of talent. Each country will know its own strengths and weaknesses and how it should seek to best capitalize on them.

The guiding star for Europe is that it is an amalgamation of countries, some more strongly tied together. No country should be inert, and tomorrow will be too late.

Work should be done now to develop a homegrown ecosystem that can be competitive on the global scale. This means that it cannot be developed in isolation, even as a regional or EU block. Member countries and companies are required to flourish on global scale.

There are multiple moving parts. For example, the quantum supply chain is global and the international dimension requires consideration. QuIC tries to map out the supply chain reality. Where are the suppliers? What is the level of criticality – are components off the shelf or custom-made? The approach taken has not been top-down; instead, a bottom-up strategy was implemented to understand the interplay. There is a need to de-risk and diversify as part of the global quantum supply chain.

The EU strategy has pivoted from a research-driven effort to a more balanced research and industrialization strategy. This demonstrates the ability of governments to recognize needs, adapt and re-orientate. In Europe, some countries were earlier starting their own industrial ecosystem. Several others followed suit in developing their own plans. There was also discussion on the need for European strategic autonomy and the acknowledgement that Europe should have its quantum industries.

CASE STUDY 6

India – National Quantum Mission

The Union Cabinet of India approved the National Quantum Mission (NQM)[46] on 19 April 2023 at a total cost of INR 6,003.65 crore (Indian rupees) from 2023-24 to 2030-31, aiming to seed, nurture and scale up scientific and industrial R&D and create a vibrant and innovative ecosystem in quantum technology (QT). This will accelerate QT-led economic growth, nurture the ecosystem in the country and make India one of the leading nations in the development of quantum technologies and applications.

Mission implementation includes setting up four thematic hubs (T-hubs) in top academic and national R&D institutes in the domains of quantum computing, quantum communication, quantum sensing and metrology, and quantum materials and devices. The hubs will focus on the generation of new knowledge through basic and applied research as well as promote R&D in areas that are mandated to them.

The mission objectives include developing intermediate-scale quantum computers, satellite-based secure quantum communications, long-distance secure quantum communications with other countries, inter-city quantum key distribution and multi-node quantum networks with quantum memories. There is a focus on developing magnetometers with high sensitivity in atomic systems and atomic clocks for precision timing, communications and navigation. The design and synthesis of quantum materials such as superconductors, novel semiconductor structures and topological materials for the fabrication of quantum devices. Single photon sources/detectors and entangled photon sources will also be developed for quantum communications, sensing and metrological applications.

NQM is intended to elevate the country's technology development ecosystem to a level of global competitiveness.

"India's National Quantum Mission, intricately interwoven into its futuristic vision, signifies a profound leap into the quantum realm. Guided by precision and purpose, we navigate the complex quantum landscape, rewriting the narrative of innovation. Our strategic pursuit spans the nuanced domains of computing, communications, sensing and materials, where the delicate balance of self-reliance and global collaboration is our compass. In the pursuit of breakthroughs, India envisions not just leadership but the orchestration of a transformative narrative, defining our technological legacy in the 21st century."

VK Saraswat, Member, NITI Aayog

India has a federated structure for national and state-level activities. State-level policy and implementation approaches align with national initiatives and also take a look at the ecosystem approach at the state level.

Source: National Quantum Mission (NQM), Department of Science & Technology, https://dst.gov.in/national-quantum-mission-nqm.

CASE STUDY 7

State: Telangana

Telangana's quantum strategy is driven by synergistic collaborations between industry, academia and government with well-structured research initiatives, industry collaborations, start-up support and strategic policies. Telangana is the first state in India to have a Quantum Advisory Committee to shape strategic initiatives to create a conducive policy environment, government incentives, research grants and infrastructure development, creating an environment that competes globally in the dynamic quantum domain.

Research focus and collaborations:
Telangana's quantum research aspirations are led through the Centre of Quantum Science and Technology (CQST) at IIIT Hyderabad. The state government has invested in the centre to support initiatives that drive cutting-edge research focused on quantum computing, quantum communication, quantum technology and equilibrium and control. CQST initiatives are:

- International collaboration: Forging global alliances fosters diverse insights and collaborative breakthroughs, propelling Telangana into the forefront of quantum research.

- Industry engagement: Collaborating with key sectors including banking, financial services and insurance (BFSI), defence/Gov, pharma, tech, and start-ups, CQST implements quantum solutions, driving transformative applications.

- Start-up nurturing: Advising and funding quantum start-ups fuels innovation and entrepreneurship in quantum technology, laying the foundation for a thriving quantum start-up ecosystem.

- Public outreach: Inspiring interest through educational initiatives like short courses, blogs and lectures cultivates awareness, creating a quantum-literate society.

Strategic industry collaborations in key sectors:
Telangana strategically aligns with key industries, formalizing engagements with pharmaceutical giants, BFSI leaders, and technology pioneers focusing on advancing quantum applications, addressing complex industry challenges and nurturing innovation with a global outlook. Telangana is in proactive engagement with major players in the BFSI sector to develop quantum computation and cryptography capabilities in the financial domain. The state actively contributes to quantum simulation algorithms for drug discovery, showcasing its role in advancing computational methodologies for pharmaceutical research. The state actively analyses resource requirements of the tech Industry for implementing practical quantum algorithms in machine learning and optimization.

Fostering quantum start-ups and ecosystem:
Currently Telangana is home to five start-ups, fostering quantum innovation specializing in quantum security, quantum memory, quantum AI, and photonic integrated circuits. Notable players, such as QU Labs and Quantum AI Global, exemplify the state's commitment to diverse quantum solutions focused on photonics for cybersecurity and end-to-end quantum machine learning for portfolio optimization, fraud detection and the supply chain.

Telangana's vibrant start-up ecosystem, anchored by institutions such as T-Hub (incubator located in the largest innovation campus), We-Hub (women-specific start-up incubator), Emerging Technologies Wing, centres of excellence in AI and cybersecurity, and T-Works (India's largest hardware prototyping facility), emerges as a nurturing ground for quantum start-ups. Tailored policies in AI, blockchain, cybersecurity, robotics and space tech fortify the start-up ecosystem, creating an optimal environment for growth in quantum security, quantum memory and quantum AI.

Telangana Academy for Skill and Knowledge is conducting quantum technology awareness programmes and skill development initiatives. These include introductory courses, hands-on training, industry partnership modules and outreach activities to promote quantum knowledge among students across the state.

Quantum Ecosystems and Technology Council of India (QETCI), headquartered in Hyderabad, aims to create an enabling environment with targeted education recommendations, industry consortium projects and collaborations with global counterparts.

Telangana's quantum strategy thrives in an ecosystem where BFSI, pharmaceutical and defence industries are widespread in the region. These established industries provide a solid foundation with their expertise in the quantum field, fostering a dynamic environment that accelerates quantum advancements.

This initiative will help Telangana foster transformative capabilities, promote open innovation and commercialization, address cybersecurity and privacy concerns, and establish responsible innovation governance. The focus areas include leveraging quantum innovation in agriculture, healthcare, transportation, financial services, optimization and fraud detection, and cyber surveillance and secure satellite communication.

"Telangana, the youngest state in India, propels the quantum revolution through strategic industry collaborations, pioneering research, and a thriving start-up ecosystem. Focused on agriculture, BFSI and pharma, the state is fostering transformative quantum innovation. The quantum landscape development is envisaged through a policy framework that leads to a conducive environment."
Duddilla Sridhar Babu, Minister for Information Technology, Electronics & Communications (ITE&C) Department, Industries & Commerce (I&C) Department and Legislative Affairs, Government of Telangana

Conclusion and next steps

It is too early to establish the success of any individual national quantum strategy. However, what can be learned from the different approaches is that there is no one-size-fits-all approach. In choosing an approach, countries and regions should consider closely and objectively their self-assessment. They should map this to their long-term political and industrial goals and review what has or has not worked well in the past. Their approach needs to consider their country's economic and social identity and what their ecosystem is familiar with regarding best practices. While it is not necessary to reinvent the wheel, it is also an opportunity for learning from the past and making improvements.

The Forum, in the next phase of this initiative, will create awareness building of the blueprint with policy-makers and senior industry experts via roundtables, conferences and webinars leveraging its global network of foremost experts across its Quantum Economy Network, Centre for the Fourth Industrial Revolution Network of Centres and Forum Partners.

A call to action is made to policy-makers to join the piloting of the *Quantum Economy Blueprint*. Countries and regions that have not yet embarked on the quantum journey, as well as those with advanced programmes, are encouraged to participate. Their experience will provide valuable insights into their challenges and successes and will feed back into the design of the *Quantum Economy Blueprint* and future building blocks. As such, the pilots are designed to test the usability of the blueprint, gather feedback for further improvement and demonstrate its usefulness with a broad range of geographies. As lessons are learned from the pilots, the blueprint will be updated to capture these insights and maintain its relevance. Updates to this ongoing initiative are anticipated to be shared in future publications of the Forum. Government officials, industry players, civil society representatives and academics are encouraged to join this journey to strengthen the blueprint and ensure its greater impact.

Appendix

The following is a self-assessment template referred to in building block 1.1 of the *Quantum Economy Blueprint*.

National and regional self-assessment

The questions and statements in the section can form the basis for assessing the “quantum readiness” or performing a quantum SWOT analysis of your country or region.

Please respond to each statement about quantum technologies and related issues for your country.

General

Please number the following factors starting with 1 (most important) that you believe will determine your country’s future success in quantum technologies:

– A skilled domestic workforce

– A skilled non-domestic workforce

– University quantum degree programmes

– Domestic intellectual capital

– Gross domestic product (GDP)

– Government investment

– Private investment

– International trade agreements

– Domestic manufacturing capability

– Access to critical foreign supply chain components

For the following, please use this scale:

1. Strongly disagree
2. Disagree
3. Neither agree nor disagree
4. Agree
5. Strongly agree

Workforce and R&D

My country has:

– Colleges or universities that offer undergraduate degree programmes in quantum information theory, quantum computing, applied quantum physics, or quantum hardware engineering

– Colleges or universities that offer master’s degree programmes in quantum information theory, quantum computing, applied quantum physics, or quantum hardware engineering

– Colleges or universities that offer doctoral degree programmes in quantum information theory, quantum computing, applied quantum physics, or quantum hardware engineering

– World-class academic research on software or hardware for quantum technologies

– A skilled software engineering workforce for quantum technologies

– A skilled hardware engineering workforce for quantum technologies

– Domestic companies performing advanced quantum systems research and development

– Academic or commercial institutions working on leading-edge quantum applications for financial services

– Academic or commercial institutions working on leading-edge quantum applications for chemistry or materials science

– Academic or commercial institutions working on leading-edge quantum applications for machine learning

Technology range

My country has domestic companies developing:

– Diamond vacancy quantum computers

– Ion trap quantum computers

– Neutral atom quantum computers

- Photonic quantum computers
- Semiconductor-based quantum computers
- Superconducting quantum computers
- Quantum atomic clocks
- Quantum biomedical sensors
- Quantum gravimeters
- Quantum inertial sensors
- Quantum magnetometers
- Quantum radio frequency receivers

Supply chain

My country:

- Manufactures and delivers components for photonic-based quantum technologies
- Manufactures and delivers components for semiconductors, superconductors or other non-photonic quantum technologies
- Has all necessary commercial access to critical imported or domestic components for photonic-based quantum technologies
- Has all necessary commercial access to critical imported or domestic components for semiconductors, superconductors or other non-photonic quantum technologies

Government investment, partnerships, and policies

My country has:

- A well-funded national quantum initiative for quantum computing.
- A well-funded national quantum initiative for quantum sensing.
- A well-funded national quantum initiative for quantum networking.
- Strong intellectual property protections.
- A progressive procurement policy that supports the investment in and purchase of developing quantum technologies at lower technology readiness levels than traditionally required.
- Strong public-private partnerships to foster the delivery of complete systems incorporating quantum components.
- International agreements with other countries to enhance cooperation in quantum information science and technology
- Strong financial support scaling the manufacturing of quantum devices and systems.
- Well-coordinated government-, department-, ministry-, and agency-wide strategies and execution plans to accelerate investment in and procurement of quantum components and systems, as well as to avoid duplicative efforts.
- Effective government-led programmes for quantum technology transfer from academia to the private sector.

Private investment

My country has:

- Domestic venture capital firms that significantly invest in quantum computing
- Domestic venture capital firms that significantly invest in quantum sensing
- Domestic venture capital firms that significantly in quantum networking
- Significant foreign private investment in quantum computing
- Significant foreign private investment in quantum sensing
- Significant foreign private investment in quantum networking

Potential threats

The success of my country's quantum economic programme may be severely threatened by:

- Geopolitical conflicts
- "Brain drain" to other industries
- Fears of cybersecurity readiness in the face of quantum attacks on encryption
- Trade restrictions and export controls
- Theft of intellectual property
- Ethical concerns about the use of quantum technology

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