Saudi Arabia
Centre for the
Fourth Industrial
Revolution

Quantum Economy Landscape in Saudi Arabia

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Foreword

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The Kingdom of Saudi Arabia stands at the dawn of the quantum revolution—a transformative force that will reshape computation, communications, and sensing across every industry. As the inaugural report of the Centre for the Fourth Industrial Revolution Saudi Arabia (C4IR Saudi Arabia) demonstrates, “the Kingdom is strategically positioned to become a global quantum technology hub.”

This report marks a significant milestone in our journey towards embracing and integrating quantum technologies into our national fabric. The quantum revolution promises unprecedented capabilities in computational power, encryption for cybersecurity, and ultra-precise sensors for various applications.

Saudi Arabia aims to harness this technological revolution’s potential to foster economic growth, enhance national security, and improve citizens’ quality of life.

Our vision aligns with the bold goals of Vision 2030, positioning the Kingdom as a global key player in technological innovation and economic diversification.

This report analyzes the Kingdom’s current capabilities and reflects our dedication to understanding and leveraging quantum technologies.

We extend our gratitude and appreciation to all stakeholders who contributed to this report, as together, we are laying the groundwork for a thriving quantum economy.

We invite all partners and collaborators to continue this journey with us, exploring quantum technology’s vast possibilities and ensuring Saudi Arabia remains at the forefront of this exciting field. Let us move forward to realize the full potential of a quantum-enabled future.

Executive Summary

Saudi Arabia is poised to harness quantum technology's transformative power to revolutionize its economy, strengthen national security, and advance society. This report maps the Kingdom's quantum landscape and charts a path to leadership in this critical domain. It analyzes the Kingdom's current capabilities, and identifies key stakeholders and innovative initiatives in the quantum technology domain. The report also explores the potential impact of this technology across various sectors, including healthcare, energy, and finance, while examining its potential societal impacts, as well as economic, educational, and geopolitical dimensions.

Saudi Arabia is actively embracing the exciting field of quantum technology. While the Kingdom is still building its quantum expertise, it has already shown a strong commitment to its development. Moreover, there is a commitment to nurturing and attracting a new generation of scientists and engineers through education initiatives and global collaborations.

Various stakeholders play a crucial role in overcoming these challenges and advancing quantum technology in Saudi Arabia. For instance, an increasing number of universities have established research centers and designed undergraduate and graduate curricula focused on quantum technology. They also contribute through specialized programs, professional training courses, and collaborations with industry and government entities. Additionally, companies such as Aramco are collaborating with global players to deploy quantum computers and create innovation hubs in Saudi Arabia. These collaborations bring expertise, technology, and resources to the Kingdom, accelerating the development and commercialization of quantum technologies.

This report marks a pivotal step towards charting a course for a national quantum roadmap harnessing quantum advancements, fostering innovation, and bolstering productivity across diverse industries, potentially revolutionizing the country's technological and economic landscape. By analyzing the current quantum landscape, the report identifies essential stakeholders and innovative initiatives, setting the stage for substantial technological and economic growth.

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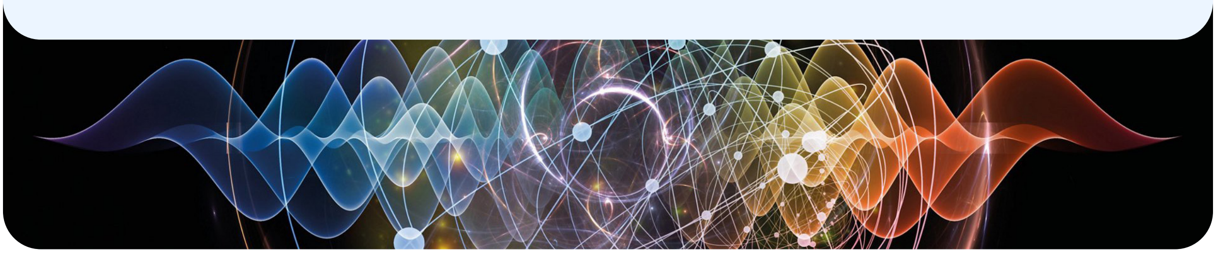
Introduction



Quantum technology is grounded in the principles of quantum mechanics, which govern the behavior of matter and energy at the atomic and subatomic level. Pioneered by renowned physicists such as Bohr, Heisenberg, Planck, and Schrödinger in the early 20th century, these principles have been fundamental to shaping our modern world, quietly driving technological advancements from nuclear energy to the minuscule transistors powering our digital devices.

Quantum technology represents a paradigm shift with the potential to revolutionize industries. By harnessing the principles of quantum mechanics, this emerging field offers time- and energy-efficient computational power, secure communication, and precise sensing capabilities. The quantum economy, a nascent ecosystem, is poised to generate immense value through the application of quantum technologies across various sectors. From accelerating drug discovery to optimizing financial models, quantum computing can tackle complex problems beyond the reach of classical computers. In the realm of communication, quantum cryptography ensures impenetrable security for sensitive data, while quantum sensors promise breakthroughs in fields like medicine and materials science. However, the rapid development of quantum technology might lead to a "quantum divide," as identified by the World Economic Forum (WEF), between nations with quantum capabilities and those without. This divide could worsen global inequalities and spark new geopolitical challenges.

Saudi Arabia acknowledges the revolutionary impact of quantum technology and is strategically positioning itself to become a global leader in this domain. This comprehensive report represents a crucial step towards developing a national quantum roadmap, aimed at seamlessly incorporating and maximizing the benefits of quantum technologies across vital economic sectors. Through a thorough examination of the existing quantum ecosystem, the report pinpoints key players and groundbreaking projects, laying the groundwork for significant advancements in both technology and the economy.

In a pioneering move, Saudi Arabia has become the first nation to pilot the World Economic Forum's Quantum Economy Blueprint. The Quantum Economy Initiative, spearheaded by the Centre for the Fourth Industrial Revolution Saudi Arabia (C4IR Saudi Arabia) in partnership with the WEF, aims to harness the blueprint's themes to develop a national roadmap that will inform a comprehensive national quantum strategy. This initiative seeks to build a robust quantum ecosystem by integrating efforts from government bodies, academic institutions, and industry.

The initiative aims to catapult key industries like cybersecurity, energy, healthcare, and manufacturing into the quantum era, positioning Saudi Arabia at the forefront of global technological progress. By promoting collaborative efforts and harmonizing with international quantum benchmarks and national goals, it strives to transform the Kingdom into a hub for quantum innovation, research, and commercial applications. This strategic approach is designed to support Saudi Arabia's economic diversification efforts and drive sustainable growth, aligning with the country's vision for a technologically advanced and economically robust future.

This report, serving as the foundational document of this initiative, begins with a landscape analysis and progresses through detailed discussion of the quantum technology fundamentals (Section 1), its potential impacts on technology and society (Section 2), and the status of quantum technology both nationally and globally (Sections 3 and 4). Finally, it outlines strategic recommendations for moving forward (Section 5).

01 Quantum Technology Fundamentals

Quantum Technologies, referring to technologies in “quantum 2.0” (as the evolution of “quantum 1.0”), represents a transformative set of protocols and methods that utilize quantum mechanical principles and resources based on peculiar properties of quantum mechanics such as superposition, entanglement, and quantum measurement and ultimate properties such as noncloning theorem, indistinguishability, and coherence. To complete the depth of the knowledge, Table 1 illustrates the main quantum mechanic’s principles.

Keyword	Definition
Superposition	Enables a quantum system to be in multiple states simultaneously, allowing quantum computers to process numerous possibilities at once.
Entanglement	A unique property where interacting particles remain interconnected regardless of distance, with their quantum states entangled, exhibiting correlations that cannot be explained classically.
Quantum measurement	Observing a quantum system can significantly alter its state, showcasing the probabilistic and superpositional nature of quantum mechanics.
Noncloning theorem	It's impossible to create an exact copy of an unknown quantum state, impacting quantum cryptography and computing.
Indistinguish-ability	A core concept in quantum mechanics where particles exist in multiple states or locations at once.
Coherence	The loss of quantum coherence in a system due to environmental interactions, posing a challenge for quantum computing and technologies.

Table 1: Main principles of quantum mechanics.

The interdisciplinary field of quantum information processing and communication is a new and rapidly developing part of Information and Communication Technology (ICT). It connects classical information theory with quantum technology to achieve tasks that are impossible with classical information and communication methods. This fusion yields new concepts, such as the qubit, quantum network, quantum gates, and algorithms. Table 2 identifies the main principles of quantum information.

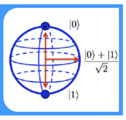
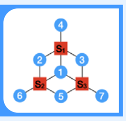
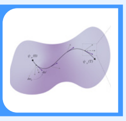
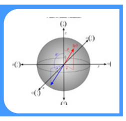
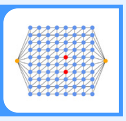
Keyword	Definition
Qubit 	The fundamental unit of quantum information that can exist in a superposition state, for example, 0 and 1 states, unlike classical bits which exist in either 0 or 1.
Quantum Repeaters 	Devices that enhance quantum communication range by entanglement swapping and quantum memories, enabling long-distance transmission of quantum information.
Quantum Internet 	A network connecting quantum devices like computers, sensors, and nodes via quantum channels, facilitating secure communication and distributed quantum computing.
Quantum Algorithms 	Utilize quantum mechanics principles like superposition and entanglement to solve certain problems more efficiently than classical algorithms, such as Shor's for factoring integers and Grover's for speeding up database searches.
Quantum Gates 	Operation that changes the state of the qubits over time, including single-qubit (e.g., Pauli, Hadamard) and two-qubit (e.g., controlled not (CNOT)) gates, manipulating quantum states using quantum mechanics.
Quantum Error Correction 	Techniques that use quantum mechanical principles, such as entanglement, to protect quantum information by detecting and correcting emerging errors caused by qubit decoherence and noise.

Table 2: Main principles of quantum information.

The integration of classical information theory with quantum technology leads to novel applications like quantum communication and quantum computing, enabling us to tackle challenges beyond the reach of classical technologies. Key technologies include quantum cryptography, communication, sensing, simulation and computing, as shown in Table 3 below.

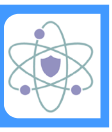
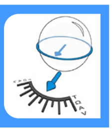
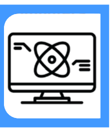
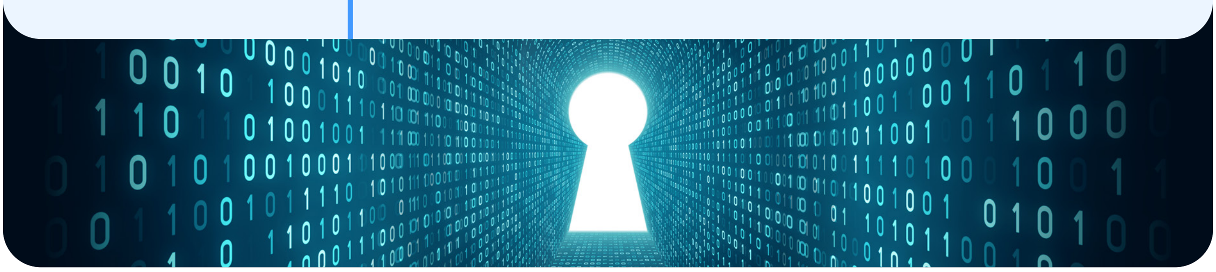
Keyword	Definition
Quantum Cryptography 	Utilizes quantum mechanics for unmatched security, detecting eavesdropping instantly through key properties like the violation of Bell inequalities. Challenges include range limitations and noise susceptibility, with research focused on enhancing practicality for secure communications.
Quantum Communication 	Leverages quantum mechanics to transmit information securely via superposition, entanglement, and quantum measurement, enabling advancements like quantum teleportation and secure networks.
Quantum Sensing 	Employs quantum systems to measure physical quantities precisely, enhancing applications from GPS systems in atomic clocks to medical imaging with quantum magnetometers.
Quantum Simulation 	Mimic quantum systems to study phenomena unmanageable by classical computers. Types include analog simulators using physical systems and digital ones employing quantum algorithms for tasks like Quantum Chemistry Simulations.
Quantum Computing 	Proposed by Richard Feynman as a potential solution to simulate complex quantum problems, it has evolved into various models including gate-based and adiabatic quantum computing. Solid-state platforms build qubits using nanotechnologies, aiming for industrial scalability despite challenges like ultra-low temperature requirements.

Table 3: Main categories of quantum technology.

02 Potential Impacts and Societal Aspects of Quantum Technology



2.1 Technology Potential Impact Use Cases

Quantum technology can drive innovation across multiple sectors, creating new industries and economic growth. It could lead to the development of new products and markets. As quantum technology advances, there will be a growing demand for skilled workers in quantum computing, chemistry, materials science, and related fields, creating new job opportunities. Figures 1 to 4 present some applications of quantum technology.

Quantum Communication

Quantum Key Distribution (QKD)	Next-Generation Encryption	Securing Sensitive Data	Quantum Internet
QKD allows two parties to share encryption keys securely. The laws of quantum mechanics guarantee the security of QKD.	Quantum-secure communication networks that can protect against classical and quantum based cyberattacks.	Organizations handling sensitive information could use quantum communication to protect data transmission and storage, reducing the risk of espionage, data breaches, and cyberattacks.	Quantum information is transmitted across vast distances to enable secure global communications, distributed quantum computing, and new forms of networking that leverage quantum entanglement.

Figure 1: Quantum communication potential impact.

Quantum Sensing

Healthcare	Environmental Monitoring	Security and Defense	Industry and Manufacturing
Quantum sensors could revolutionize medical sectors, leading to more accurate and less invasive diagnostic tools. For example, in neurology, quantum magnetometers could enhance brain imaging, leading to better understanding and treatment of neurological disorders.	Providing more precise measurements that can be exploited in better monitoring of climate changes and civil engineering applications.	Developing more sensitive detection systems for use in surveillance and other military applications.	Very high precision in material characterization leads to the development of new materials and improves quality control in manufacturing processes.

Figure 2: Quantum sensing potential impact.

Quantum Imaging

Healthcare and Life Sciences	Enhanced Detection	Nanotechnology	Environmental Monitoring & Remote Sensing
Improved diagnostics by enhancing medical imaging techniques, such as MRI, OCT, and microscopy, leading to earlier and more accurate diagnosis and the minimization of invasive procedures, for example, by requiring lower light levels.	Improving surveillance systems enables sensitive detection in low-light or obscured environments.	Fabrication and inspection of nanoscale devices, driving advancements in electronics and photonics.	Enhancing the ability to monitor environmental changes, such as deforestation, pollution, and climate change, with greater accuracy.

Figure3: Quantum imaging potential impact.

Quantum Computing and Simulation

Cryptography and Cybersecurity

Breaking Classical Encryption

Quantum computers pose a significant threat to current encryption methods, such as RSA, which rely on the difficulty of factoring large numbers or solving discrete logarithms.

Cryptography protocols

Developing new cryptographic protocols resistant to quantum computer attacks will ensure digital communications security in the quantum era. Modeling potential quantum attacks on existing cryptographic systems will aid in developing defenses against such threats.

Drug Discovery and Healthcare

Enzyme and Protein Folding

Modeling the behavior of complex biological molecules like proteins and enzymes is critical for drug discovery and understanding diseases.

Enzyme and Protein Folding

Modeling complex biological processes would lead to new insights in biology and enabling personalized medicine, tailoring treatments to individual patients based on their unique biological makeup.

Material Science

New Materials

Discovering and designing new materials with specific properties, such as superconductors, could revolutionize energy transmission and storage.

Nanotechnology

Designing and understanding the properties of nanomaterials at the atomic level, enabling advancements in nanotechnology.

Molecular Simulations

Modeling the behavior of molecules and chemical reactions with high accuracy, leading to more efficient methods for designing new drugs, catalysts, and industrial chemicals.

Optimization models

Machine Learning

Enhancing machine learning algorithms, particularly in areas requiring the optimization of large datasets and complex models.

Optimization Problems

Novel methods for solving optimization problems more efficiently than classical approaches, such as logistics, supply chain management, and financial modeling.

Financial Services

Risk Management

Improving the accuracy and speed of risk analysis would enable better prediction and management of financial risks. This could transform areas like portfolio optimization, fraud detection, and pricing of complex financial instruments.

High-Frequency Trading

Developing faster and more sophisticated trading strategies potentially gives firms that adopt quantum technology a competitive edge.

Figure 4: Quantum computing and simulation potential impact.

Quantum Computing and Simulation

Climate Modeling and Environmental Science

Accurate Climate Models

Simulating complex environmental systems with greater accuracy leads to better climate models and more effective strategies for mitigating climate change.

Optimizing Resource Use

Optimizing natural resources, utilizing quantum sensors for measuring environmental parameters, leads to more sustainable agriculture, manufacturing, and urban planning practices.

Logistics and Transportation

Route optimization

Improving route optimization for logistics companies could reduce fuel consumption, delivery times, and costs.

Traffic Management

Optimizing city traffic flow, reducing congestion and emissions, and improving traffic monitoring in urban transportation systems.

National Security and Defense

Military Applications

Developing new materials for military applications, such as more robust, lighter armor or efficient energy sources. Model and predict the behavior of complex systems, aiding in strategic planning and defense. Enhanced surveillance, recognition, and situational awareness using quantum sensors.

Cyber Defense

Developing secure communication protocols and cryptographic systems resistant to quantum attacks is crucial for maintaining national security in the quantum era.

Energy

Improving Energy Efficiency

Optimizing the design and operation of energy systems, such as power grids and renewable energy sources, leads to more efficient energy use and reduced carbon emissions. Understanding and improving catalytic processes, such as energy storage and conversion.

Green Chemistry

Simulating chemical reactions with high precision, leading to the development of more efficient and environmentally friendly chemical processes, reducing waste and energy consumption.

Figure 4: Quantum computing and simulation potential impact.

2.2
Societal Potential Impacts

The societal aspects of quantum technologies are vast and multifaceted, encompassing ethical, legal, economic, educational, and cultural dimensions. As these technologies advance, they will bring about profound changes in how societies operate, how economies function, and how individuals interact with technology and each other. Addressing the societal impacts of quantum technologies will require thoughtful consideration, inclusive policies, and proactive efforts to ensure that the benefits of quantum advancements are widely shared and that potential harms are mitigated. As the world stands on the brink of the quantum era, how society navigates these challenges will shape the future trajectory of technology and its role in our lives. Figure 5 summarizes the potential impact on society.

	Job Creation and Displacement	Economic Inequality	Innovation and Competition
Economic Impacts	Quantum technologies are set to revolutionize the job market, creating new career opportunities in fields like quantum computing and cryptography. However, this shift may also lead to job losses in sectors dependent on traditional computing and encryption methods. As quantum solutions become more prevalent, roles in classical data processing and certain areas of software development may become obsolete. This technological transition will likely require significant workforce adaptation, emphasizing the need for continuous learning and skill development to remain competitive in the evolving job landscape.	Nations and companies with substantial financial resources investing heavily in quantum technologies may gain significant advantages. This quantum leap could potentially widen the technological and economic divide, as less affluent regions might struggle to keep pace with these rapid advancements. The disparity in quantum capabilities could lead to an imbalance in technological prowess, economic opportunities, and strategic advantages on the global stage, potentially exacerbating existing inequalities between developed and developing areas. The issue is being addressed by WEF.	The emergence of quantum technologies is poised to catalyze innovation across multiple sectors, including pharmaceuticals and logistics. This quantum revolution is expected to intensify competition on both corporate and national levels, as entities compete to pioneer and implement quantum-based solutions. The race to harness quantum capabilities could reshape industry dynamics, potentially altering market leadership and creating new competitive advantages. As quantum technologies mature, early adopters may gain significant edge in their respective fields, driving a global push for quantum supremacy in various industrial and economic domains.

Figure 5: Societal potential impacts of quantum technology.

	Curriculum Development	Upskilling and Reskilling	Access to Education
Education and Human Capital Development	As quantum technologies gain prominence, educational systems must evolve to meet new demands. This transformation requires integrating quantum concepts across all educational levels from primary to advanced research programs, as well as lifelong learning. This comprehensive approach aims to build a workforce ready for the quantum era, ensuring a pipeline of skilled individuals from early education through to advanced research and industry applications.	The emergence of quantum technologies necessitates a workforce proficient in these advanced fields. Continuous upskilling and reskilling programs will be essential to meet this demand. This proactive approach to workforce development aims to bridge the skills gap, ensuring a smooth transition into the quantum era and maintaining economic competitiveness in a changing job market.	To prevent widening socioeconomic gaps in the quantum era, it's crucial to democratize access to quantum education. This includes targeted scholarship programs, online courses, forging partnerships between industry and educational institutes, establishing outreach programs for underserved communities, creating mentorship opportunities, and ensuring that quantum education resources are available in multiple languages. These strategies aim to broaden participation in quantum fields, fostering a diverse and inclusive quantum workforce. By making quantum education widely accessible, we can mitigate potential socioeconomic disparities and ensure that the benefits of quantum technologies are shared across society.

Figure 5: Societal potential impacts of quantum technology.

Global Power Dynamics

Technological Leadership

The emergence of quantum technologies is set to reshape global geopolitics. Nations that achieve quantum supremacy are likely to gain substantial strategic advantages, potentially altering existing power dynamics on the world stage. This shift could catalyze the formation of new alliances between countries with complementary quantum capabilities, while also sparking rivalries based on disparities in quantum technological prowess.

Quantum Sovereignty

The advent of quantum communication technologies is driving nations towards digital sovereignty. Countries are increasingly recognizing the strategic importance of controlling their own quantum infrastructure to ensure secure and independent communication networks. This push for autonomy in quantum technologies aims to reduce reliance on foreign-developed systems, which could pose potential security risks or create unwanted dependencies.

Environmental & Sustainability

Energy Consumption

Quantum computing offers potential environmental benefits through improved energy efficiency for certain computational tasks, potentially reducing the carbon footprint of data centers and computing infrastructure. This advantage could lead to significant energy savings in large-scale computing operations. However, it's important to note that the development, production, and maintenance of quantum systems may still have considerable environmental impacts.

Sustainable Technologies

Quantum technologies hold significant potential to advance sustainability efforts through groundbreaking developments in key areas such as materials science, energy storage and optimization, and resource management. By leveraging these quantum-enabled advancements, industries can develop more sustainable solutions, potentially leading to significant reductions in carbon emissions and more efficient use of resources across multiple sectors.

Communication & Information Sharing

Secure Communication

Quantum communication technology offers the potential for unbreakable encryption, poised to transform information security and data privacy. This advancement could provide unprecedented protection for sensitive data, benefiting both individuals and organizations. However, this level of security also presents significant challenges for law enforcement and national security agencies.

Quantum Internet

The advent of quantum communication and quantum network protocols is poised to revolutionize existing communication infrastructures, ushering in a new era of enhanced security and resilience. This quantum transformation is expected to have far-reaching implications, reshaping the fundamental architecture of the Internet and altering global information flows.

Figure 5: Societal potential impacts of quantum technology.

03 Current Global Quantum Technology Context

Global efforts in quantum technology are focused on advancing a range of cutting-edge applications, from quantum computing and communication to quantum sensing and cryptography. Countries around the world are investing heavily in research, development, and commercialization of quantum technologies due to their potential to revolutionize various industries and institutions. National efforts are executed through a quantum technology national agenda, initiatives, and strategy. Building a quantum national ecosystem involves large national education and research institutions and major companies, as well as setting up quantum technology hubs. As the quantum race intensifies, countries are also focusing on international collaboration and partnerships to leverage global expertise and resources. This collaborative approach, combined with significant public and private sector investments, is shaping the future of quantum technologies and their applications across various industries and sectors.

Updated analyses are subject to wide margins, but predict that the market size by 2035 for quantum computing will reach $28 billion to $72 billion; for quantum communication, $11 billion to $15 billion; and for quantum sensing, $0.5 billion to $2.7 billion. Private and corporate funding for start-ups has slowed since 2010, while a strong flow of public funding totalling ~$42 billion was announced by several governments. The ecosystem continues to progress towards unlocking estimated economic value of ~$2 trillion by 2035. Public investments continue to be strong: Germany, the United Kingdom, South Korea, and India announced significant new funding for quantum technology development. The current global efforts by key nations are summarized in Table 4.

Country	Efforts in quantum technology
United States	Passed the National Quantum Initiative Act, committing over $1.2 billion to quantum research. Key players include the DOE, NSF, and NIST, with private companies including IBM and Google leading in hardware and software. Notable hubs include the Boston Area Quantum Network and Chicago Quantum Exchange. Post-quantum cryptography is gaining traction, with initiatives such as Apple's PQ3 and US CISA's PQC Initiative.
China	Invests heavily in quantum communication and encryption, with public investments totaling $15.3 billion and private investments of $359 million. Major projects include the QUESS for quantum communication technologies.
European Union	The EU Quantum Flagship initiative, with over €1 billion funding, focuses on establishing a secure quantum communication backbone across Europe through the EuroQCI.
Denmark	Quantum investment for 2023-2029 totals €827 million, driven by the Novo Nordisk foundation and subsequent governmental strategies.
Sweden	Plans a €140 million quantum investment by 2030, initiated by the Knut and Alice Wallenberg Foundation.
Germany	Committed $2.25 billion over three years to develop a 100-qubit quantum computer and other technologies, with hubs like Munich Quantum Valley.
France	Supports quantum technology with $1.3 billion over five years, focusing on hubs like the Paris Centre for Quantum Technologies and photonic quantum computer development.
United Kingdom	Invests heavily in quantum technologies with public and private investments totaling $5.8 billion, emphasizing quantum hubs for computing and communications.
Canada	Known for its strong research in quantum computing, with contributions from institutions like the Institute for Quantum Computing and companies such as D-Wave.
Japan	Focuses on quantum encryption and communication, with public and private investments totaling $1.8 billion, aiming for a fault-tolerant quantum computer by 2050.
India	Recently launched a national quantum strategy with a $1.75 billion public investment, planning to establish 21 quantum hubs and 4 research parks.
Global Collaboration	EU-US Quantum Cooperation: In 2021, the EU and the USA signed an agreement to collaborate on quantum research, with a focus on standards, ethics, and the commercialization of quantum technologies. Countries are working together to establish global quantum communication standards and best practices, with entities like the WEF advocating for a coordinated approach to quantum policy.

Table 4: Summary of the current global effort in Quantum Technology.

04 Current State of Quantum Technology in Saudi Arabia

Saudi Arabia is intensifying its commitment to advancing quantum technologies, recognizing their transformative potential across various economic sectors. The Kingdom's government has initiated collaborative efforts with key industry players and academic institutions to establish itself as a significant player in the quantum field. These comprehensive initiatives encompass education, research, and development, with a strategic focus on integrating quantum technologies into the national economy.

Currently, Saudi Arabia's national efforts in quantum technologies are dispersed across different institutions and sectors. This report serves two primary purposes: firstly, to act as a catalyst for consolidating these scattered efforts, and secondly, to gather and analyze data reflecting Saudi Arabia's current position in quantum technology.

To effectively position Saudi Arabia among global leaders in quantum technology and its value chain, a thorough assessment of the nation's internal strengths and weaknesses, as well as external opportunities and threats, is essential. This evaluation aims to identify critical factors that influence the development and growth of the quantum sector within the Kingdom.

Saudi Arabia is well-positioned to advance in the field of quantum technology, leveraging several key strengths. The nation's forward-looking Vision 2030 strategy prioritizes technological innovation, fostering an environment conducive to quantum research and development. This commitment is further bolstered by robust government support for the research, development, and innovation (RDI) sector, enabling strategic investments in quantum infrastructure, talent acquisition, and cutting-edge research initiatives. Saudi Arabia's advantageous geopolitical position facilitates international collaborations, providing access to a diverse pool of expertise and knowledge in quantum technologies. Furthermore, the Kingdom is cultivating a supportive ecosystem that can significantly accelerate quantum advancements through carefully crafted policies, substantial financial backing, and a regulatory framework designed to encourage innovation. These combined strengths position Saudi Arabia to potentially emerge as a significant player in the global quantum technology landscape, aligning with its broader goals of economic diversification and technological leadership.

Despite the promising outlook for quantum technology in Saudi Arabia, the Kingdom faces several significant challenges in this domain. The country currently has a limited number of quantum scientists and engineers compared to global leaders, creating a substantial obstacle to rapid advancement. This talent shortage is compounded by a scarcity of specialized quantum laboratories, hindering crucial research and development efforts. The quantum industry in Saudi Arabia is still in its infancy, with few commercial applications, making it difficult to attract investment and create a thriving ecosystem. Moreover, the global competition for skilled quantum professionals presents a formidable challenge in retaining top talent within the Kingdom. These hurdles collectively underscore the need for strategic investments in education, infrastructure, and talent development to bolster Saudi Arabia's position in the evolving global quantum landscape.

The emergence of quantum technologies presents a monumental opportunity to leapfrog existing limitations and unlock transformative advancements across various sectors. By seizing these opportunities, Saudi Arabia can capture the economic and strategic benefits of quantum technology.

> Saudi Arabia has significant opportunities to establish itself as a key player in the quantum technology race. By pursuing quantum sovereignty, the Kingdom can safeguard its technological independence and enhance national security. Saudi Arabia is well-positioned to become a regional quantum hub, drawing talent, investment, and fostering collaboration. Furthermore, the nation can leverage quantum technologies to address crucial domestic challenges, such as improving hydrocarbon reservoir simulation. These strategic advantages present Saudi Arabia with a unique chance to advance its technological capabilities and strengthen its position in the global quantum landscape.

The global quantum technology field is fiercely competitive, presenting Saudi Arabia with several external challenges. The Kingdom faces competition from nations with well-established quantum programs, which could impede its progress. The highly competitive nature of the global talent market makes it challenging to attract top quantum experts. Additionally, the evolving geopolitical landscape poses difficulties in terms of technology access and the potential division of technology platforms. Lastly, quantum technology itself is still in its early stages of development, with substantial technical obstacles yet to be overcome. These factors collectively shape the external environment in which Saudi Arabia must navigate its quantum ambitions. A SWOT analysis is summarized in figure 6.

Figure 6: SWOT Analysis of Saudi Arabia's Quantum Technology Landscape (source: team analysis.)

In the following pages, an assessment of the efforts and activities of quantum technologies undertaken in Saudi Arabia, is presented.

4.1
Human Capital and Talent Development

Quantum technology is a rapidly evolving field demanding highly specialized skills. Developing a robust quantum workforce is essential for advancing both research and commercial applications. The complexity and interdisciplinary nature of quantum physics make it challenging to find individuals with the necessary expertise. Moreover, a quantum economy requires more than just postgraduate degrees in physics; it also needs professionals with backgrounds in information technology, software development, and engineering.

To address this challenge, it is helpful to conceptualize quantum talent development as a three-phase pipeline as shown in figure 7.

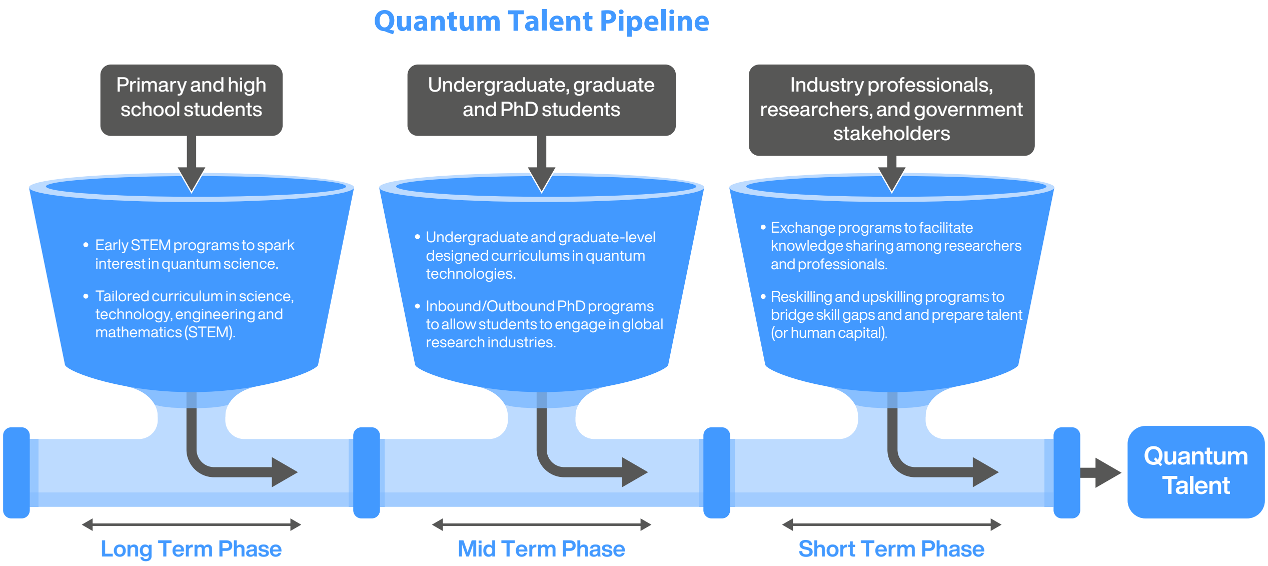


Figure 7: The Quantum talent pipeline: from early education to advanced specialization.

1. Long-Term Phase (Primary and high school students)

Early engagement programs spark interest and fundamental understanding in quantum science and related STEM fields. Initiatives may include enrichment programs, exchange opportunities, and high-school-level introductions to quantum principles. By exposing young learners to the possibilities of quantum technology, these efforts create a foundation for more advanced studies later on.

2. Medium-Term Phase (Undergraduate, graduate and PhD students)

At the university level, rigorous quantum-focused curricula and dedicated research initiatives help students acquire the in-depth technical and theoretical competencies needed for advanced work. Undergraduate and graduate programs introduce students to areas like quantum computing, quantum communication, and quantum sensing, while PhD-level research focuses on cutting-edge topics and global research collaborations. Saudi Arabia's universities and research institutions are currently strengthening their quantum offerings—creating new courses, establishing research centers, and launching specialized training programs—as they position themselves in this crucial mid-stage of the pipeline.

3. Short-Term Phase (Industry professionals, researchers, and government stakeholders)

For current professionals—researchers, engineers, and industry specialists—continuous upskilling and hands-on training programs are essential. Internships, specialized workshops, industry-academia collaborations, and government-supported initiatives help these professionals transition into quantum-focused roles. Such efforts ensure the immediate availability of skilled practitioners who can drive R&D activities and translate theoretical advances into commercial solutions.

Saudi Arabia's ongoing efforts to develop a quantum-savvy talent pipeline currently span over only short- and medium-term phases. At present, there are no clearly defined, large-scale national efforts focused on nurturing quantum interest and skills from the early education to high school. While some individual educators and smaller groups may be introducing basic concepts informally, a coordinated strategy to build this foundational layer of the quantum pipeline has yet to emerge.

Academic institutions are creating undergraduate and graduate-level quantum curricula, while research centers support advanced studies and innovation. Although these efforts are underway, the rapidly evolving quantum landscape demands continual expansion and diversification of skill development pathways.

The efforts of Saudi universities and research institutions are in the second development phase (mid-term) by establishing research centers and designing undergraduate and graduate curricula focused on quantum technology. However, while these efforts are crucial, they are insufficient to meet the rapidly growing demand in this field.

In addition, universities are playing an active role in addressing the talent gap through specialized programs and professional training courses aimed at developing a skilled quantum workforce. Table 5 identifies some of the programs offered by Saudi universities.

University	Program offered
King Fahd University for Petroleum and Minerals	• Undergraduate concentration program (minor) in quantum computing. • Master's degree in Quantum Computing.
King Abdullah University for Science and Technology	• Quantum Computing Reading Group launched in 2024. • One research group in Quantum Photonics as a thesis option for Masters and PhD students in the Applied Physics and Materials Science and Engineering Programs.
Imam Abdulrahman Bin Faisal University	• Elective course: "Quantum Computation and Quantum Security."
Prince Sultan University	• Several programs quantum computing and communication.
TUWAIQ Academy	• Special Programs "Information Science and Quantum Computing."
King Saud University	• A Quantum Technologies track is included within the Physics Masters of Science program.
Jazan University	• Master's program in theoretical Quantum Optics.

Table 5: Current Quantum-related courses and programs at Saudi Universities (source: team analysis and survey)

Government and industry collaborations significantly enhance these short-term educational initiatives aimed at rapidly building and strengthening the quantum talent pool. Prominent organizations such as National Information Technology Academy (NITA), King Abdulaziz City for Science and Technology (KACST), and the Saudi Federation for Cyber Security and Programming through TUWAIQ Academy actively contribute to workforce development through internships, specialized training, and skill transition programs. Furthermore, quantum hackathons, such as the IBM Quantum Challenge, provide hands-on experience, which is crucial for nurturing practical skills in quantum technologies.

In addition, King Fahd University for Petroleum and Minerals (KFUPM), in collaboration with Aramco, has established a Quantum Chair Professor program to foster research, education, and innovation in quantum technologies. This joint initiative serves as a hub for academic and industrial collaboration, focusing on areas such as quantum computing, quantum communication, and quantum sensing. Moreover, there are ambitious programs aimed at attracting talent to the quantum field, with the availability of Arabic-language resources particularly advantageous for engaging the younger generation.

KFUPM also demonstrates active engagement in quantum education and research. The university's Physics students' club organizes an annual Quantum Week event. In 2022, KFUPM hosted a Quantum Information and Computing Workshop. Looking ahead, the university is preparing to hold a symposium on Quantum Computing and Technologies in 2025.

KAUST conducts regular quantum seminars as part of its graduate seminar series. Additionally, the university hosts a quantum computing self-study group that convenes on a monthly basis.

KACST hosts seminars focused on quantum technology. These events gather prominent experts to explore recent developments, discuss challenges, and examine potential applications in quantum optics and quantum information.

The advancement of quantum technology, particularly in the complex and resource-intensive realm of hardware development, necessitates a concerted effort to enhance workforce capabilities. This effort is crucial to align human capital with the growing demands of quantum research and development.

A collaborative approach involving universities, research institutions, industry leaders, and government bodies is essential to cultivate a highly skilled quantum workforce, which will be vital to realizing the Kingdom's ambitions in this rapidly advancing field.

4.2
Research and Development

Research and development (R&D) in quantum technologies is crucial for advancing our understanding of quantum mechanics and harnessing its potential for applications such as quantum computing, quantum communication, and quantum sensing. C4IR Saudi Arabia has reached out to research universities and centers to survey their interests and areas of focus in quantum technologies. The findings, highlighting the research priorities of selected ecosystem partners, are presented in Table 6.

Entity	Communication	Sensing	Computing
King Abdulaziz City for Science and Technology	X	X	X
Saudi Aramco	X	X	X
King Abdullah University for Science and Technology	X	X	
King Fahd University for Petroleum and Minerals	X	X	X
King Saud University	X	X	
Imam Abdulrahman Bin Faisal University	X		
Prince Sultan University	X	X	X
Jazan University	X	X	

Table 6: Research interests of some universities and research institutes in quantum technologies in the Kingdom (source: survey.)

When evaluating how well a country is performing in quantum technology research, the H-index provides valuable insights. This metric aims to capture both the quantity and influence of a researcher's publications, giving an overall picture of research strength. The analysis depends on research papers published between 2019 and 2023 and calculates the H-index for quantum communication as shown in Figure 8.

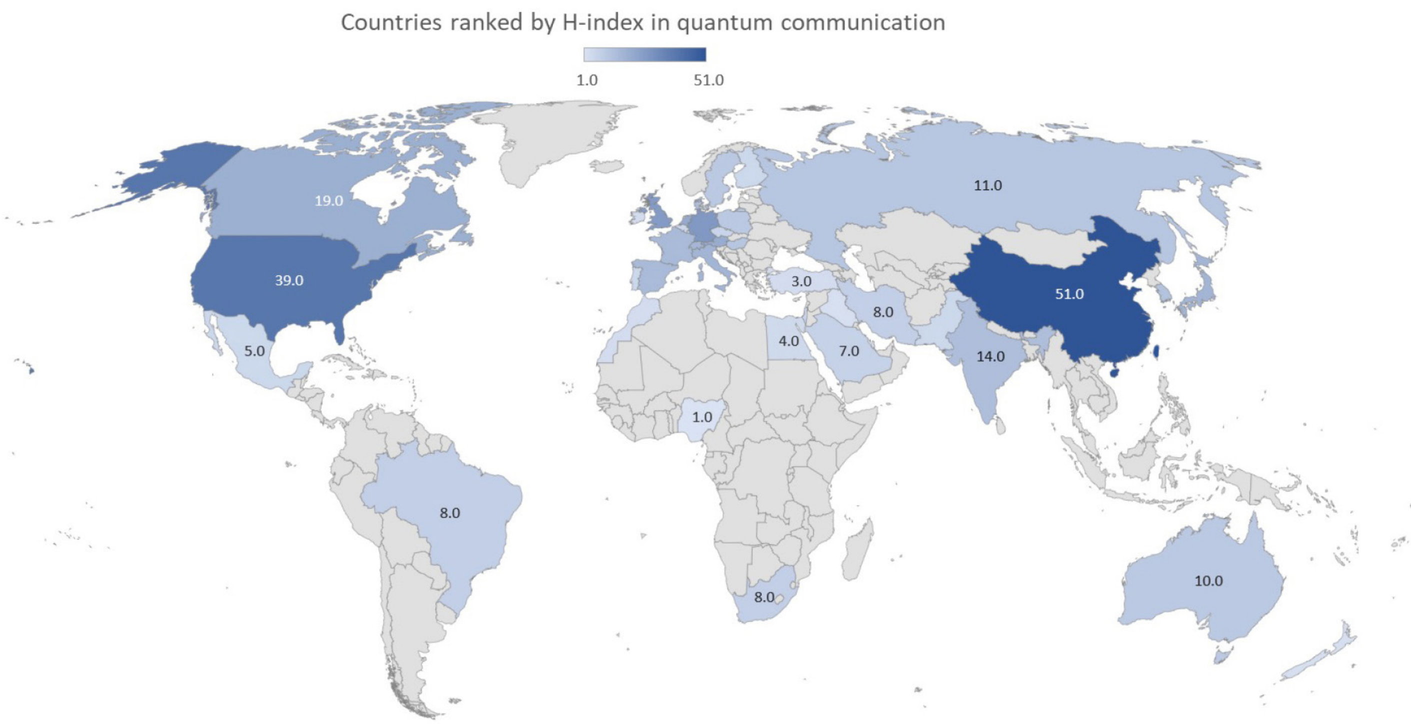


Figure 8: H-index by country (source: Critical Technology Tracker, 2024)

The H-index of Saudi Arabia is relatively low, compared to leading countries, which suggests an opportunity to prioritize this field through a dedicated national strategy and funding initiatives. However, looking at the data collected, there is a large number of current and upcoming research projects at different entities that involve quantum technology locally.

C4IR Saudi Arabia conducted an analysis on the research focused on quantum technology, encompassing areas like quantum computing, sensing, cryptography, and communication locally. This analysis includes papers, conference presentations, and journal articles published between 2010 and the present. The research is primarily affiliated with Saudi universities or research institutes and is indexed in databases such as IEEE Conferences, IEEE Transactions, Physical Review A, Physics Reports, Nature Physics, ACM, and Springer. Key terms associated with this research include quantum technology, quantum computing, quantum sensing, quantum cryptography, and quantum communication. The analysis highlights that the number of publications (shown in Figure 9) exhibit an upward trend.

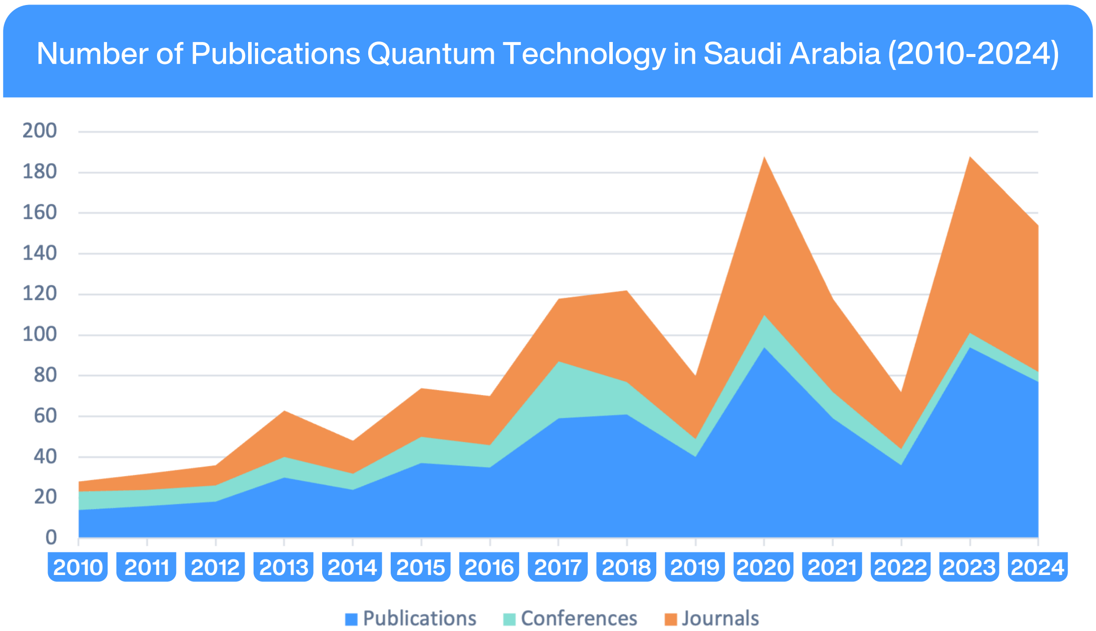


Figure 9: Number of publications, conferences and journals by Saudi Universities and research institutes in quantum-related technologies for the period of 2010 - 2024.

This indicates a gradual increase in the interest of this technology in the region; hence, the demand for strategic investment in research and development is crucial for addressing the technical hurdles, fostering innovation, and securing a prominent position in the global quantum technology landscape. To foster effective quantum technology development, prioritizing strategic research areas will ensure that resources are allocated efficiently and aligned with national goals.

To highlight some recent research development efforts in quantum technology, in May 2024, the Research, Development and Innovation Authority (RDIA) and stc Group announced a public–private partnership R&D initiative on open radio access networks and quantum computing.

Furthermore, on the academic front, KFUPM has a high-performance and quantum computing lab and an optics lab. Additionally, KFUPM's Intelligent Secure Systems Center has plans for a superconducting quantum circuit, quantum emulation and quantum communication Labs.

KSU has established the Center of Excellence in Information Assurance, which focuses on information security and post-quantum cryptography. Furthermore, laboratories primarily focusing on classical technologies, can potentially be leveraged for quantum research and development. For example, KSU houses the RFTONICS laboratory, equipped with state-of-the-art equipment for fiber-optic communication and sensing applications. The university also operates the only Attosecond Optical laboratory in the MENA region.

4.3
Hardware Innovation

To build a strong infrastructure for quantum technologies on a national level, a Quantum Foundry (QF), as a part of the desired national strategy, needs to be established to support academic and industry activities in quantum technology in the Kingdom.

A QF is a foundry capable of developing on-chip quantum technologies. Moreover, QF is an important strategic extension of the current semiconductor efforts because the field is rapidly developing and leverages the same facilities and infrastructure. Furthermore, the semiconductor workforce can potentially be upskilled to lead in quantum technology development.

The QF functions as a collaborative center for researchers, engineers, and industry partners to jointly develop and commercialize quantum technologies. Its primary focus is on creating high-quality, high-performance on-chip devices, including photonic, superconducting, and semiconducting components. By leveraging on-chip quantum technologies, the QF can harness the advancements and capabilities of semiconductor foundries to scale up quantum technologies efficiently. This approach enables the integration of quantum systems with existing semiconductor infrastructure, potentially accelerating the development and deployment of practical quantum applications.

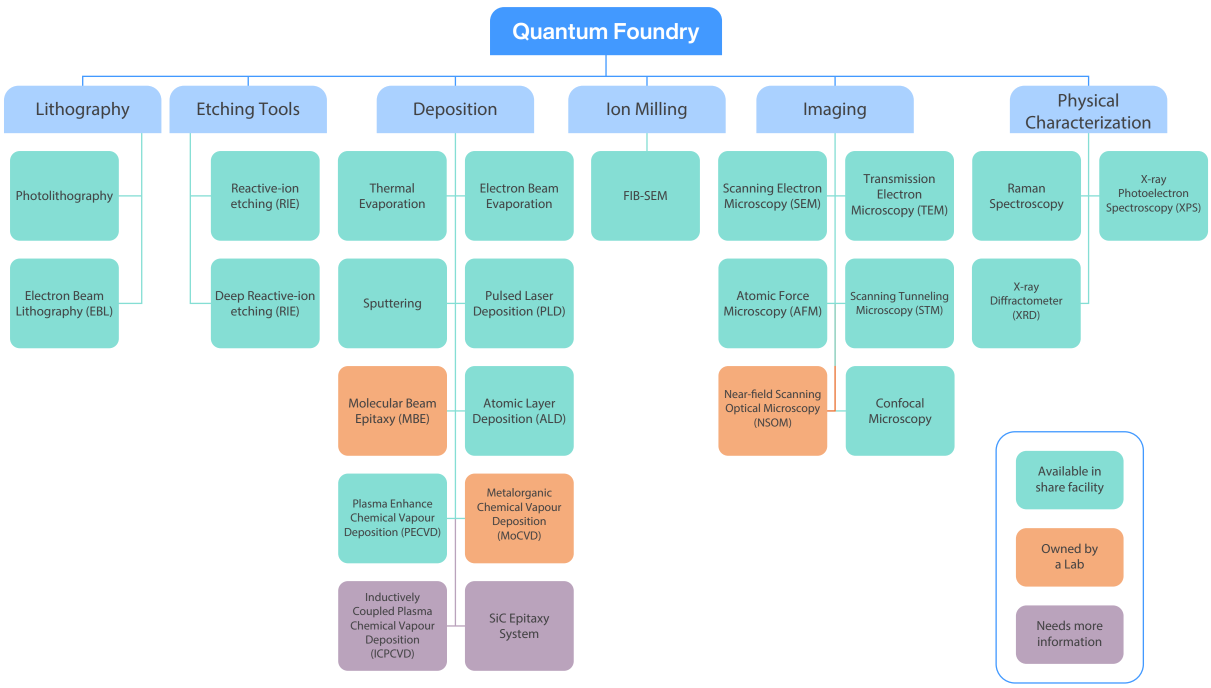


Figure 10: Quantum foundry main components and status of availability in Saudi Arabia. (source: experts input & team analysis.)

Figure 10 lists the tools needed to establish a Quantum Foundry (QF) and their status in two clean rooms in KACST and KAUST. These tools can be used to develop wide range of quantum technology platforms like photonics, optics or superconducting circuits.

For on-chip quantum technologies, patterning, deposition and etching technology are needed to manufacture quantum devices from substrates like silicon wafers:

- **Patterning**: both photolithography (for features larger than 200 nm) and electron beam lithography (for features down to a few nanometers) are needed. Quantum devices have components ranging from thousands of nanometers to few nanometers.

- **Deposition**: A wide range of deposition techniques are required to make quantum devices because the capability to deposit a wide range of high-quality materials like metals (elemental and alloys), oxides and nitrides is needed. Furthermore, the QF must be flexible to allow the integration of emerging materials systems like 2D materials into the processes, so it does not become obsolete when new materials are introduced. Therefore, a wide range of deposition techniques are required for a QF.
- **Etching**: To transfer the pattern from the lithography and deposition steps, etching must be performed to remove excess materials and release the devices; current QFs depend on directional dry etching like reactive ion etch (RIE) and deep reactive ion etch (DRIE).
- **Quality assurance and process optimization**: Finally, the devices must be inspected using a variety of imaging and physics characterization techniques, both to develop and optimize the fabrication processes, and as quality assurance.

Figure 10 illustrates that, driven by the synergy between advancements in semiconductor manufacturing—providing cutting-edge microfabrication facilities—and the economic and technological potential of quantum technologies, Saudi Arabia is well-positioned to advance the development of on-chip quantum technologies.

As the infrastructure and ecosystem for quantum hardware continue to develop, access to quantum computers via the cloud and supercomputer clusters capable of emulating quantum hardware will serve as a crucial catalyst for training and research in quantum algorithms. For example, in May 2024, Aramco and Pasqal signed a groundbreaking agreement to import and deploy the first quantum computer in Saudi Arabia. Pasqal will install, maintain, and operate a 200-qubit quantum computer, scheduled for deployment in the second half of 2025.

4.4 Partnerships and Quantum Technology Commercialization

Strategic partnerships between the public and private sectors, as well as academia, play a pivotal role in accelerating the development, deployment, and commercialization of quantum technologies in Saudi Arabia. By forging alliances with international tech leaders, research institutions, and platforms that facilitate innovation, the Kingdom is positioning itself at the forefront of the quantum revolution.

NEOM and Arqit have joined forces to develop and test a quantum security system. The system will be designed to protect cognitive cities, such as NEOM, from advanced cyberattacks.

Saudi Aramco has also engaged in multiple endeavors to secure its position in the global quantum ecosystem. In partnership with IBM, it is establishing an innovation hub in the Kingdom, fostering a fertile environment for quantum research and integration into various industrial applications. Complementing this effort, Aramco's European arm has expanded agreements with D-Wave to explore the potential of quantum computing for optimizing energy operations and enhancing efficiency. These initiatives underscore Aramco's commitment to remaining at the cutting edge of technology and influencing the future of the energy sector through quantum innovation.

In addition to industry-driven collaborations, C4IR Saudi Arabia has partnered with the World Economic Forum's UpLink platform—a digital, crowd-engagement initiative dedicated to accelerating solutions aligned with the United Nations' Sustainable Development Goals (SDGs). Through this collaboration, the 'Quantum for Society Challenge' calls on global innovators to leverage quantum technologies to address critical societal and environmental issues spanning climate resilience, sustainable materials and manufacturing, healthcare advancements, agricultural improvements, and freshwater systems management. Submissions have been received from a diverse array of participants worldwide, illustrating the far-reaching potential of quantum technologies in tackling pressing global challenges.

The winning solutions are slated for announcement at a World Quantum Day event in 2025, highlighting Saudi Arabia's commitment to leveraging quantum innovation for global impact. By connecting entrepreneurs, researchers, and investors, the challange fosters a collaborative ecosystem where promising innovations can gain visibility, resources, and support.

4.5 Raising Awareness

Raising awareness about quantum technologies is essential for guiding their responsible development and addressing the ethical, social, legal, and economic challenges they present. As these technologies advance, fostering early dialogue and collaboration among stakeholders is essential to maximize benefits, mitigate risks, and align progress with national priorities. Efforts in Saudi Arabia to elevate awareness and promote collaboration include various events and publication, demonstrating the Kingdom's growing commitment to advancing quantum technologies while building a robust ecosystem for national and international collaboration, preparing Saudi Arabia to lead in the global quantum landscape.

As part of efforts to raise public awareness and promote collaboration around quantum technologies, C4IR Saudi Arabia joined the Quantum Economy Network, a community initiated and led by the World Economic Forum. This network fosters global collaboration and understanding by bringing together governments, businesses, and academia to explore the potential of quantum technologies, shape their development, and prepare for their integration into the economy.

In alignment with the goals of the Quantum Economy Network and to elevate awareness, particularly in education, C4IR Saudi Arabia, in collaboration with KACST and King Salman Science Oasis (KSSO), organized a week-long celebration of World Quantum Day 2024, which is observed annually on April 14. The celebration took place from April 17 to 25, 2024 (main event shown in figure 11). This event was designed to increase public understanding of quantum technologies and stimulate both national and international collaboration in this rapidly evolving field. The event featured a variety of activities designed to engage diverse audiences, ranging from policymakers and industry leaders to students and the general public. Exhibitions showcased advancements in quantum computing, communication, and cryptography, while panel discussions explored the role of quantum science in driving economic growth. These discussions highlighted the importance of collaboration between government, academia, and industry to harness the potential of quantum technologies and integrate them into Saudi Arabia's economy.

Particular emphasis was placed on education and talent development during the event, recognizing the need to prepare future generations for a quantum-driven world. Student-focused activities at KSSO were designed to spark interest and foster a foundational understanding of quantum physics and computing among younger audiences, helping to build the future talent pipeline.

Figure 11: Celebration of the World Quantum Day 2024.

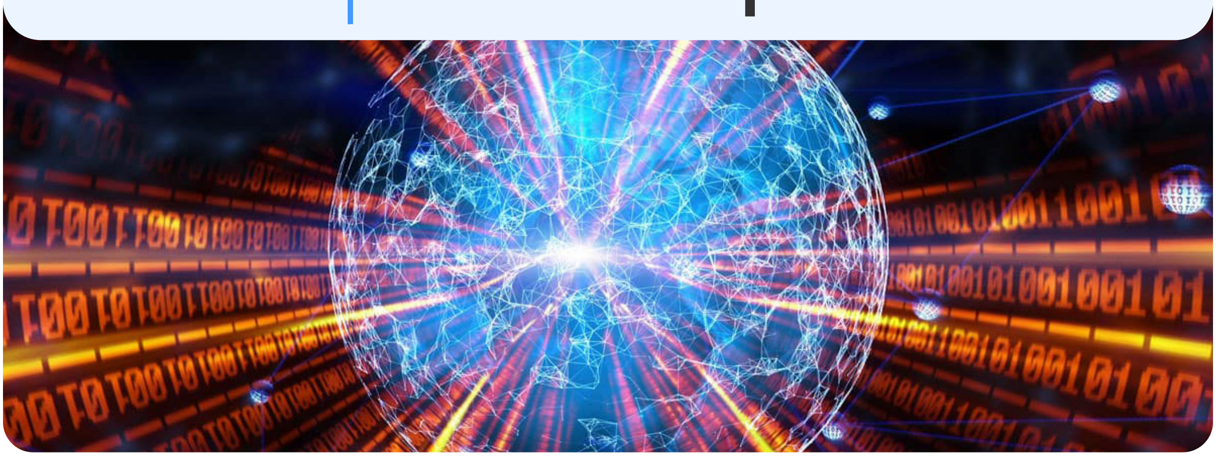
The success of World Quantum Day 2024 has set the stage for even greater initiatives in the future. Plans are already underway for the 2025 celebration, which coincides with the United Nations' designation of the International Year of Quantum Science and Technology. This upcoming event aims to further strengthen collaboration across government, private, and public sectors, creating a nationwide celebration that will elevate awareness and engagement with quantum technologies throughout Saudi Arabia. These ongoing efforts reflect a broader commitment to embedding quantum science into the national conversation, preparing the Kingdom to play a leading role in the global quantum landscape.

The Ministry of Communications and Information Technology (MCIT) in Saudi Arabia is taking a proactive role in advancing the discourse on quantum technologies. Through a variety of initiatives, MCIT is working to educate policymakers, industry leaders, and the public about the transformative potential of quantum technologies. One key example is the Digital Technology Forum held on October 9, 2024, and organized by the Communications, Space & Technology Commission (CST). This event featured a dedicated panel discussion on "The Making of a Saudi Quantum Technology Landscape," highlighting the growing importance of quantum technologies in the Kingdom's tech ecosystem. MCIT has also taken steps to promote broader understanding of quantum technologies. It commissioned a technology foresight report on quantum computing, providing valuable insights into the potential impacts and opportunities of this emerging field. Additionally, MCIT has encouraged the publication of articles on quantum technologies, contributing to a growing body of knowledge accessible to stakeholders and the general public

The Digital Government Authority (DGA) released an in-depth report exploring quantum computing applications in the public sector. This comprehensive study highlights the advantages of quantum technologies, including accelerated processing capabilities, advanced problem-solving, and enhanced decision-making processes. The report serves as a valuable resource for government entities, guiding them in leveraging quantum solutions to deliver more efficient and citizen-focused services.

Quantum technology awareness has made significant strides, yet comprehensive understanding across all segments of society remains an ongoing challenge. A significant challenge remains in effectively engaging non-technical audiences and incorporating quantum subjects into general educational programs. Moving forward, it is crucial to focus on reaching underserved communities through targeted initiatives, enhancing partnerships with media organizations to simplify and disseminate quantum concepts, and creating user-friendly resources that make quantum technologies more understandable to the general public. These efforts are essential to bridge the existing knowledge gap and foster a more quantum-literate society across all demographics.

05 Moving Forward: Quantum Economy Roadmap



Quantum technologies have wide-ranging applications across sectors like healthcare, energy, finance, and logistics, spurring the creation of new products, markets, and jobs. Quantum communication enables highly secure networks to protect sensitive information from cyberattacks. Quantum imaging could enhance medical diagnostics, improve low-light detection, and advance nanotechnology.

However, quantum computers may also pose security risks to existing classical infrastructure.

To maximize benefits and minimize risks of quantum technologies, a comprehensive national program is crucial. This should be led by a governance consortium of key stakeholders from government, industry, and academia. The program should be nationally mandated to prepare a National Quantum Agenda with these objectives:

- Identify promising areas of quantum technology development for Saudi Arabia.
- Develop strategic plans for research, development, and commercialization.
- Address potential societal impacts, including economic, educational, and geopolitical aspects.
- Focus on workforce development through education, training, and talent retention.
- Promote investment in research infrastructure, including specialized quantum labs.
- Enable commercialization and market development of quantum technologies.
- Raise public awareness and understanding of quantum technologies.

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