gesda
GESDA Diplomatic Forum
Quantum for All Initiative
Geneva Science and Diplomacy Anticipator

OQI
Open Quantum Institute

Intelligence Report
on Quantum Diplomacy for the Sustainable Development Goals (SDGs)

Second Edition · Geneva · October · 2024

Foreword

This has truly been a landmark year for quantum technology. We've witnessed rapid advancements and groundbreaking innovations that have brought quantum technology closer to real-world use cases. The potential to revolutionize industries and redefine our technological landscape has never been more tangible. The significance of these developments has been so profound that the United Nations declared 2025 as the International Year of Quantum Science and Technology. The main emphasis has been on responsible quantum computing, ensuring the technology progresses for the benefit of all humanity. Key conversations focus on how to prevent a new quantum divide, strengthen security measures, and manage global supply chains.

GESDA has been at the forefront of these efforts, playing a crucial role in making these anticipated advancements accessible and fostering global collaboration and cooperation. A standout achievement this year was the launch of the Open Quantum Institute (OQI) on March 5th, which is now fully operational in its pilot phase within CERN. GESDA also proudly hosted the 2024 Quantum Diplomacy Symposium: this event brought together over 70 participants from diverse communities, including high-level diplomats, academics, the private sector, and civil society, for a rich multi-stakeholder dialogue. The symposium offered a unique platform for interdisciplinary debate that deepened our understanding of quantum technology's potential, and the multilateral efforts that will be required to harness it responsibly and inclusively.

Based on the warm reception for our collective work and the ever-expanding interest of the diplomatic community, we are encouraged to continue raising awareness and understanding about quantum computing. We must prepare for the large-scale availability of this technology by developing an anticipatory approach that is accompanied by action-oriented engagement. Practitioners should gather evidence-based information and foster futures-literacy. That will facilitate shared understanding and encourage widespread discourse. In this way, we can make sense of the quantum revolution and be ready to benefit from its potential when that becomes possible.

GESDA, as an honest broker, is dedicated to building global partnerships that democratize access to quantum technology, ensuring its benefits are shared widely and equitably across the globe.

Alexandre Fasel
State Secretary,
Federal Department of
Foreign Affairs
Switzerland

Enrico Letta
Chair of GESDA's
Diplomatic Forum

Contents

A point of departure for quantum computing

Quantum computers represent a complete change of paradigm in the way that computation is practiced. Some key takeaways about how the technology works:[1]

- Quantum computing, like other quantum technologies (e.g., quantum sensing, quantum communication), leverages quantum phenomena, such as superposition and entanglement, creating an entirely novel mechanism for encoding information. **Quantum information is stored and processed in "qubits" that operate in a different capacity than "bits," their classical equivalent. That holds the promise for unprecedent performance improvements with specific computational problems**.[2]
- The exact nature of these computational problems is not yet well identified. However, there is a consensus in the scientific community that **quantum computing would hold an advantage over classical computing to accelerate discoveries in material science and chemistry**, since this involves the simulation of quantum behavior of matter. With steady, rapid progress, quantum computers may outperform classical computers in real-world applications by the end of this decade. To reach this critical milestone, **significant research and development is needed to produce larger-scale, reliable quantum computing devices**.

Technology maturity

Quantum computing is a multifaceted reality, with the potential to be ready at scale within the next decade

- **Quantum computing technology is still under development** as hardware modalities are tested. Many large companies are developing superconducting qubits, while others pursue alternative promising modalities of qubits based on trapped ions, cold atoms, photonics, silicon, and diamonds. Each of these hardware modalities has pros and cons and it is too early to tell which approach will perform the best.
- While advancements in a pre-fault-tolerant era have been recently reported,[3] **quantum computers are still performing on a small scale and unreliable**. Further technological development is needed to reach quantum advantage: outperforming conventional computing in terms of execution, speed, accuracy, or energy efficiency when handling real-world relevant problems.
- **The aim is to create an adequate number of reliable qubits**. Researchers expect that it will require thousands, if not millions, of qubits to solve useful tasks. Quantum properties are highly sensitive to environmental disturbances. Error-correction protocols are being investigated to ensure that quantum processors become more resilient and stable over a long period of time.
- While hardware is essential, **the implementation of quantum algorithms within the hardware is what will unlock the full potential of quantum systems**. As part of the development and testing phase, quantum algorithms today can be implemented on simulators and emulators, which reproduce the quantum properties of quantum computers on classical devices at relatively small-scale. These allow the performance of small-scale, proof-of-concept simulations for practical applications, accelerating the exploration of valid use cases. **Simulators and emulators may play an important role in bridging the gap that will remain until quantum hardware becomes available at scale, a milestone that may take another decade to achieve**.
- Because quantum computers operate in a fundamentally different manner than classical computers, traditional algorithms are not directly transferable to quantum computing. As a result, quantum algorithms are being developed to perform computational tasks, such as quantum simulation[i] and factorization, as well as quantum-inspired optimization,[ii] and machine learning.

How quantum and AI will work together

Artificial intelligence (AI) has so far enabled disruptive applications. From efficient analysis and predictive tasks on large datasets to "recommendation" systems and chatbots, AI's rapid adoption across a spectrum of industries is broadening.[4] Combining classical machine learning (ML)[5] - which is a subset of AI - with quantum computing is, unsurprisingly, a field of growing expectations and hype. The intersection of AI and quantum[6] is still a nascent field, and the effort is at the research and development level. Quantum machine learning, for example, accounts for less than 1% of total machine learning research publications.[7]

The interplay of machine learning and quantum computing can be summarized in three categories:

— **Using classical machine learning to develop quantum computers**: Already in use today, classical machine learning can help to improve experimental control of quantum computers and reduce hardware errors,[8] construct quantum circuits,[9] and simulate the result of quantum computations.[10]

— **Quantum-inspired machine learning**: Research on quantum computing has inspired the exploration of new techniques and theoretical insights benefiting classical machine learning.[11]

— **Quantum machine learning**:[12] Industry and academic researchers are exploring ways of using classical machine learning techniques on quantum computers. Currently, much of their research focuses on using existing small-scale quantum computers jointly with classical computers (so called "hybrid computing") to identify potential benefits.[13] Quantum computers also offer some benefits[14] for learning from quantum data (data that itself originates from quantum sensors for instance). **One major challenge is the efficient input and output of classical data to and from quantum data**. It is still too early today to predict if this hybrid approach could realize a quantum advantage for practical applications (i.e. outperforming classical computing),[15] even with future fault-tolerant quantum computing.[16]

In sum, **quantum machine learning will not replace classical machine learning**. One could potentially augment the other by **working in tandem**. Classical machine learning[17] already benefits the development of quantum computers. Despite the early stage of this research field, the intersection of AI and quantum offers exciting avenues that can benefit from more direct collaboration between experts in different disciplines.[18] As the field matures, a transdisciplinary approach should learn from recent AI governance principles and adapted them to this emerging field at the cross-section of AI and quantum computing.

i Many chemical and biological processes play at the nanoscale of matter, where quantum effects are prominent. Classical computers struggle with the complexity of simulating these interactions and so have to rely on approximations that produce imprecise results in all but the smallest systems. Quantum computers, on the other hand, are a natural fit for simulating quantum behavior like this and should be able to produce accurate results for large systems.

ii One of quantum computers' "superpowers" is the ability to escape from being trapped in one state of calculation, by using a property called "quantum tunneling": this is useful for optimization problems that involve finding the best solution to a problem that has a very large number of options. Surprisingly, quantum tunneling can be efficiently emulated on classical computers and quantum optimization using these quantum-inspired optimization algorithms is available today on classical hardware.

Economic maturity

Quantum computing already carries significant economic weight, and is being leveraged as an innovation accelerator in many sectors critical to the world's major economies

— **The timeline to bring quantum computing to full maturity is relatively long** compared to other technology development cycles, so its development requires sustained, significant long-term investment.

— **Governments are key drivers behind quantum R&D**. Nations have committed **$40 billion** to quantum computing, sensing, and communication as of mid 2024, with most of the pledged spending concentrated in North America, the Asia-Pacific region and Europe.[19]

— Private investment into quantum technology companies (including quantum computing, sensing, and communication) slowed in 2023 ($1.7bn in 2023, down from $2.3bn in 2022 and $2.33bn in 2021), accompanied by a shift towards more established companies that were founded at least five years earlier.[20, 21]

— The quantum computing market (revenue earned by quantum hardware and software vendors) is estimated at $870 million in 2024. Forecasts estimate this market could reach $5 billion by 2030.[22]

— Among the first end-users to test quantum computing are the financial, pharmaceutical, energy and automotive industries. Their expectation from quantum computing is that they will gain the ability to generate new revenue, profits, or cost savings. Estimates of the added economic value are complex, but some experts' forecasts put the amount at $180 billion by 2030.

Policy responses and current investments

A growing number of countries are adopting quantum strategies to affirm their sovereignty and competitiveness, while multilateral governance remains nascent

— **As of August 2024, at least 29 countries had some form of quantum national initiative** or **strategy** with public funding.[23] The United Kingdom enacted the first one in 2014 and renewed it for ten years in 2023. The United States followed with its adoption of a national approach in 2018.

— Key common themes include more support for R&D (foundational and applied research); development of a quantum workforce (education and upskilling programs); preparing future users in the likely fields of application; resilience of the value chain (securing the supply of enabling components and technologies); national security considerations; and international cooperation (in connection with all the above themes, and with standardization that supports national interests).[24]

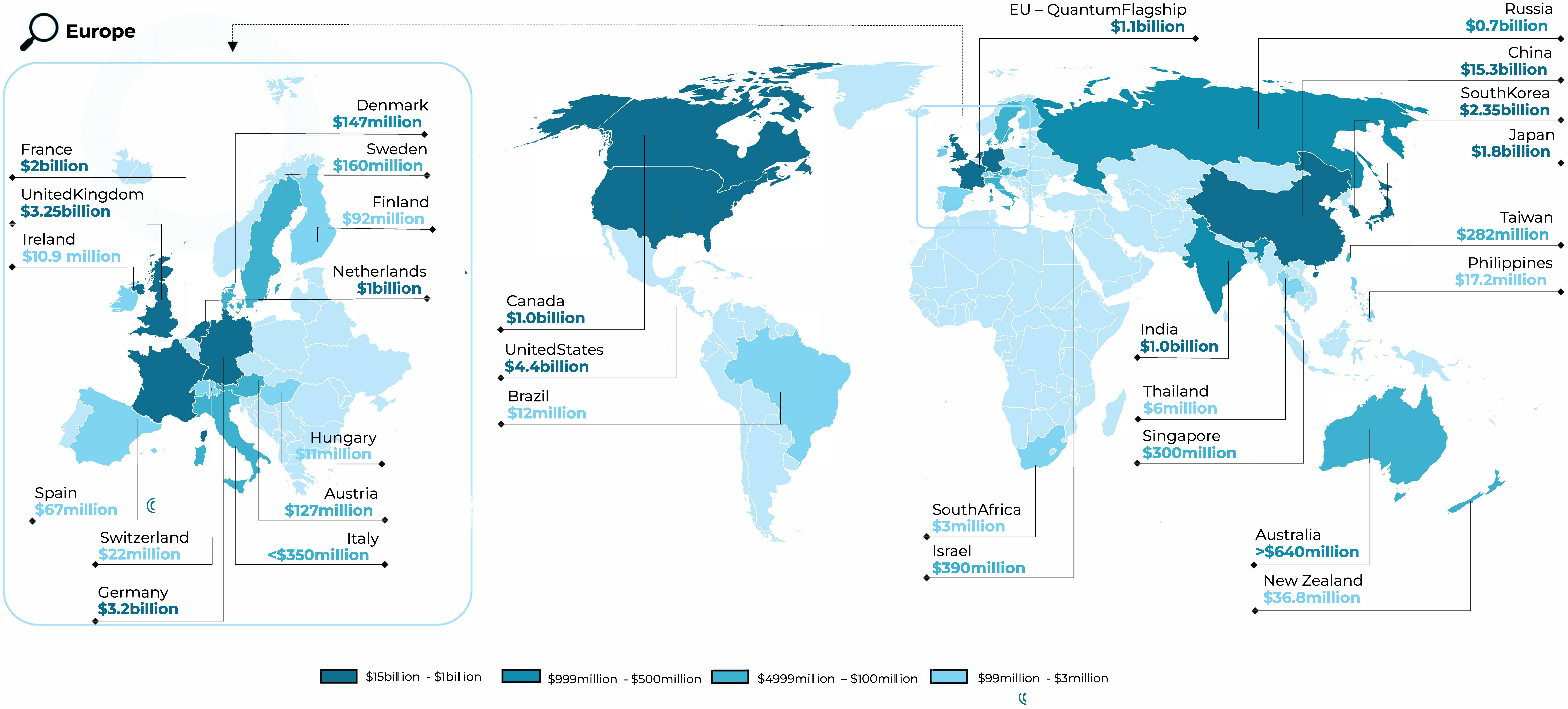
— Where they differ usually involves the level of financial support and funding mechanism. **A key differentiator is whether a country aims to develop a sovereign infrastructure or competitively rely on the private sector**. The focus can also differ as to priorities among quantum technologies (computing, communication, or sensing) depending on the local expertise; their scope (quantum specific, or quantum as part of deep technology strategies); main drivers (research, industry or government); and the modality of their implementation (top-down or bottom-up approaches) and the stage of development.

— **Most national strategies support the establishment of national industry consortia to foster ecosystem coordination**, fast-track technology transfers, and an acceleration in the industrialization of sovereign quantum technologies. Quantum industry consortia include QED-C in the U.S.,[25] QIC in Canada,[26] QuIC in Europe,[27] and Q-STAR in Japan.[28, 29]

— International cooperation on R&D efforts remain mostly at the bilateral level.[30] Some examples of **bilateral agreements** can be found among the United States,[31] Switzerland,[32] Australia, United Kingdom, and Germany.[33]

— **Multilateral initiatives are nascent at the international level**. Closed groups are emerging among like-minded countries that align their roadmaps and discuss internal cooperation. For instance, in May 2022, representatives of 12 countries attended a roundtable meeting on 'Pursuing Quantum Information Together' in Washington, D.C. One outcome was the creation of the Entanglement Exchange, a portal for highlighting international exchange opportunities for students, postdocs, and researchers in quantum information science (QIS).[34] This first roundtable was followed by additional meetings, including in September 2024 on 'Multilateral Dialogue on Quantum'. The working group is now composed of 13 countries.[35]

Public funding for quantum computing



Note: This illustration is not meant to be comprehensive but to represent major public investment by country; Cf. Annex 5 - Overview of national quantum strategies/initiatives, where data sources for funding is also provided (data compiled as of 27 August 2024)

State-of-play in the governance of quantum computing for all

Digital and economic inclusivity: mitigating the risk of a new digital divide

- Initially coined to highlight gaps in internet connectivity, the term **'digital divide'** is increasingly used more broadly to encompass the world's unequal access to digital technologies.[36] These inequalities exist between countries, regions, and specific populations according to age, gender, and socioeconomic factors.[37] At the multilateral level, the U.N. Secretary-General's call to develop a Global Digital Compact[38] and the U.N. General Assembly's decision to appoint co-facilitators in support of this effort reflect, among other things, **global concerns about the digital divide and the need for multi-stakeholder action to foster an inclusive and sustainable digital future for all.**
- **Quantum computing has been recognized as a technology that could exacerbate the digital divide.** Investment in quantum computing is polarized.[39] The fastest-moving countries are adopting national quantum strategies to coordinate efforts between academia and industry, repatriate enabling technologies, and educate a quantum-ready workforce.
- **Quantum researchers report that international collaboration, which once was the norm, is no longer encouraged**, and that setting up diverse talent teams is increasingly difficult. For them, the digital divide means that the most diverse human intelligence available to solve some of humanity's biggest common challenges cannot be mobilized, putting at risk the great promise that quantum computing holds.
- More generally, the consequences of the traditional digital divide are well-known: increased disparities in economic competitiveness and development, more pronounced social and societal disbalances, biased algorithms and other enabling technologies. If quantum computing is used with conventional computing but without further adjustments, it could very likely amplify these existing imbalances. With increasing polarization and fragmentation, more people could be left behind. Those economies that will likely depend on sectors enhanced by quantum computing – chemistry, for example – could be strongly affected. **Policymakers will need concise, trusted, and actionable information to understand and anticipate the impact of quantum computing on their constituents. Some industry associations offer some level of information**[40] but policymakers may need more help in distinguishing scientific and economic facts from hype as the sector seeks to attract investors.
- For the immediate future, a first level of action may entail engaging those who are sufficiently trained to use quantum computers but do not have the financial resources to do so. **Providing more inclusive access can be facilitated by the availability of more quantum computers via the cloud**.[41]
- **The United Nations proclaimed 2025 as the International Year of Quantum Science and Technology (IYQ)**.[42] It recognizes the transformative potential of quantum science and technology in addressing pressing global challenges. The IYQ is a chance to promote global access to knowledge, build capacities – particularly for young people – and develop sustainable quantum solutions in energy, education, communications, and human health. A steering committee composed of leading scientific and industrial organizations has developed activities for the yearlong event and the Open Quantum Institute is also taking part, promoting more opportunities to build capacity and broaden inclusivity around the world.
- Some quantum computing companies are setting up measures allowing selected users to use their services for training purposes or to conduct research projects (e.g. Microsoft's first $500 in free Azure Quantum Credits,[43] IBM's program for researchers,[44] and NVIDIA's open-source platform for hybrid quantum-classical computing[45]). Public stakeholders are considering similar mechanisms to enable access to the devices they fund. For instance, the European Union,[46] the U.K.,[47], Japan,[48] Israel,[49] and other countries are integrating quantum computers in their national supercomputing infrastructure. Their aim is to promote greater national access to cutting-edge facilities, develop applications that will have significant social and economic impact, and create a national quantum computing ecosystem around these advanced facilities.
- All the above measures have limitations, however, and may not be sufficient to meet the demand. Broader geopolitical considerations and concerns over the dual-use nature of the technology have prevented making some of these initiatives available in some places. Other barriers include a lack of information, too brief of a duration for some of these measures, limited volume of quantum computational power, and practical difficulties in operating these computers without preliminary guidance (access modalities differ greatly from one quantum computer to another).

— **A second level of action involves the training of experts in quantum computing**. Training is spreading among institutions, such as Italy's Abdu Salam International Center for Theoretical Physics (ICTP), one of nine institutes and centers that are an integral part of UNESCO's program and budget. Increasingly, academic institutions are creating curriculums to train specialists in future applications of quantum computing that can accelerate their research[iii] but these are mostly located in developed countries and the costs are prohibitive for some students.

Technology for the SDGs: accelerating the exploration of relevant use cases

— **The SDGs**, adopted by consensus among all 193 U.N. member nations at the U.N. Sustainable Development Summit in 2015, **provide a blueprint for all humanity and the planet and a framework for multilateral governance**. In his September 2021 report "Our Common Agenda", U.N. Secretary-General António Guterres called for science and technology to be used to help turbocharge efforts to fulfill the SDGs. Quantum computing could contribute to this effort through disruptive innovations and new business models.

— Problems that quantum computing researchers and developers can tackle[50] could be solved mostly by using **four types of computational methods: chemical and material simulation, factorization, quantum machine learning, and optimization**. Such computational methods can potentially be applied to problems related to most, if not all, of the SDGs. For instance, use cases[51] could help in the achievement of SDG 2 (No Hunger) by enabling the production of nutritious and affordable food locally, while minimizing the environmental impact. Quantum computers could support SDG 3 (Good Health and Well-being) by accelerating research on antibiotic resistance and discovering new, more targeted drugs. Efficient detection and mitigation of water leaks in water distribution systems assisted by a quantum computing solution could contribute to SDG 6 (Clean Water and Sanitization) by ensuring people have daily access to clean water in urban areas around the globe. New designs for catalytic processes to accelerate decarbonization in the atmosphere could be explored more accurately using quantum computing and helping speed progress towards SDG 13 (Climate Action).

— A significant amount of applied R&D, however, is still needed to better comprehend where quantum computing could deliver a clear advantage over conventional computing. **Exploring these future applications is possible using devices that simulate or emulate the quantum computers that will be available in the future**. Beyond the technological challenge of developing the hardware, there is a need to better understand the specific range of applicability for quantum algorithms – i.e. the conditions and parameters in which quantum methods are valid and can lead to a quantum advantage. There is also the need to ensure that applications are developed for their potential to tackle real-world problems. For that to happen, it is critical to bring together deep subject matter expertise along with a clear understanding of the conventional computation range of applicability and limitations. Only then will we be able to develop quantum computing applications that can deliver clear quantum advantages when implemented on large-scale quantum.

— **Few people around the world have the proper expertise to develop quantum computing applications**. Most experts' efforts tend to focus on applications that bring an apparent short-term geostrategic advantage or the promise of a profitable commercial interest for organizations with the resources to bet on a long-term return on investment. This does not bode well for applications that can support the SDGs, and these potential impactful applications are less prioritized.

— To date, **there has been no coordinated multilateral effort to accelerate potential uses of quantum computing for the SDGs, like what's been done for artificial intelligence (AI) with the International Telecommunication Union's AI for Good movement**, or within broader processes like the WSIS forum, for example. In the spirit of anticipatory action, there is an opportunity to support the creation of a neutral multi-stakeholder platform for countries to gather trusted information and express their interests and priorities for challenges that quantum computing might solve.

— Individual companies or philanthropic foundations support sector-specific initiatives, mostly by launching subject-specific competitions.[52] Other **multi-stakeholder, practice-led initiatives include references to the SDGs or provide guidelines for integrating these global goals into the development of quantum computing applications**. Among the most advanced is Quantum Delta NL, a Dutch technology ecosystem released in 2023. Its tool, called the Exploratory Quantum Technology Assessment (EQTA[53]), offers guidance for companies, governments, and organizations on how to explore and navigate quantum technology's ethical, legal, and societal implications. The World Economic Forum (WEF) Quantum Computing Governance Principles[54] also emphasize the importance of ensuring that the development and use of quantum computing is aligned with the SDGs.

iii 50+ master's programs at the time of writing. computers iv. All too often such efforts have remained on a superficial level, which only serves to feed the hype.

Global Security: preparing for quantum safe cryptography and anticipating dual use

- The projected computational power of quantum computing is unprecedented and raises concerns about misuse of the technology. **The most immediate concerns relate to data security and privacy**. Future large-scale quantum computers may pose a significant threat to current cryptographic systems, with the potential of breaking many of the public key or asymmetric cryptosystems in use today. That would seriously compromise the confidentiality and integrity of digital communications. As a result, significant **global efforts are underway to develop cryptographic systems that can withstand quantum computers. This new field is called Post-Quantum Cryptography (PQC)**. It is hard to predict when such large-scale quantum computers will be available. Governments are urgently developing strategies for creating quantum-resistant information security systems.
- Nations or regional blocs that pursue their own quantum interests or defense could give rise to competing standards that erode IT interoperability, causing significant economic disruption.
- **Migrating to future cryptography schemes that are safe for quantum use will be no small task**. Many critical infrastructures depend on legacy systems that are difficult to upgrade. Governments are trying to raise awareness about this security threat by encouraging owners of sensitive data to start the migration as soon as possible. Examples of selected national strategies for transitioning to PQC solutions are detailed below:
    - In the **United States**, the government has a clear timeline to address the quantum threat. In 2021, the National Institute of Standards and Technology (NIST) initiated the process of standardizing PQC algorithms, with final standards expected during 2024. Federal agencies must begin transitioning to PQC between 2024 and 2030, aiming for cryptographically relevant quantum computers by 2030.[55]
    - The **European Commission** advocates for a coordinated implementation roadmap for transitioning to PQC. This recommendation aims to orchestrate a synchronized shift to PQC to safeguard digital infrastructures and services across public administrations and critical sectors in the EU. Governments are urged to promptly establish expert groups on PQC and devise comprehensive roadmaps within two years of the recommendation's issuance. These roadmaps are expected to delineate clear objectives, milestones, and timelines for the integration of PQC solutions into existing systems, thereby fortifying cybersecurity and mitigating emerging threats.[56]
    - The Monetary Authority of **Singapore** (MAS) asks financial institutions to keep abreast of quantum developments, maintain an inventory of cryptographic assets, and develop strategies to address quantum cybersecurity risks. However, it does not provide specific dates for a roadmap. It focuses on preparation and ongoing efforts, urging financial institutions to monitor developments, upgrade infrastructure, and conduct proof-ofconcept trials for quantum security solutions.[57]
    - The **Australian** Signals Directorate (ASD) monitors PQC standardization efforts – in particular, those led by NIST in the U.S., with the goal of updating ASD-Approved Cryptographic Algorithms (AACA)[58] and ASD-Approved Cryptographic Protocols (AACP). Australia also monitors alternate methods of securing communications in the presence of Cryptographically Relevant Quantum Computers, such as quantum key distribution (QKD). ASD encourages research, testing and practical trials of PQC algorithms. Australia also monitors alternate methods of securing communications in the presence of Cryptographically Relevant Quantum Computers, such as quantum key distribution (QKD). ASD encourages research, testing and practical trials of PQC algorithms.[59]
- **Beyond cryptography applications, quantum computers, like any tool, can be used for beneficial or malevolent purposes**. They are dual use items by nature (goods, software and technology that can have both civilian and military uses), as are many of their applications. In chemistry, quantum computing could make it easier to discover new drugs to treat neglected diseases, but these methods also could result in the production of more toxic chemicals (chemical weapons, for instance). In materials science and engineering, the discovery of stronger and lighter materials will help build safer civilian vehicles but also enhance military apparatus. In nuclear physics, modeling forces in the atomic nucleus will lead to more advanced scientific knowledge (i.e., clean and efficient nuclear energy) and the potential for developing more effective strategic weapons.

iv Note: Quantum advantage means outperforming conventional computing in terms of accuracy, speed, or energy efficiency. Today, this is done as a theoretical projection of future performance of quantum devices that are still under development.

- **The current response to such threats is through export control**. These governmental regulations are designed to control the transfer of sensitive goods, software, and technology to protect national security and economic interests. In practice, suppliers are prohibited from selling their products and services in certain countries. One recent example is the measure that took force on 31 May 2024, as Global Affairs Canada, the department that manages diplomatic and consular relations, issued a notice on the Export Control List (ECL) of a new regulation specifically targeting quantum computing and advanced semiconductor technologies. Because of the threats that these new technologies represent, the regulation was made to safeguard national and international security.[60] Strengthening export control measures thus accentuates the race for quantum primacy, notably between the United States and China.
- Nations or regional blocs that pursue their own quantum interests or defense could give rise to competing standards that erode IT interoperability, causing significant economic disruption.
- Researchers and developers, both from academia and industry, emphasize that export control measures could slow down or prevent achievement of the potential that quantum technologies hold by limiting the exchange of scientific ideas and blocking scientists from accessing promising research and early-stage prototypes.[61] Some stress the economic or market disadvantages that companies would face in countries enacting these kinds of export controls while the broader quantum field is engaged in a global race. Some argue that export controls are intrinsically limited, since malevolent actors could still operate from within countries where the technology is available.
- **Practice-led initiatives can lead to alternative responses. Responsible computing frameworks** – like those proposed by Quantum Delta NL, WEF,[62] IBM,[63] the U.K.'s RQIF,[64] and Action 5.1 and 5.2 in the Australian National Quantum Strategy[65] - serve as examples. Some focus on how to make quantum computers safer by design. For example, regulators, businesses, legal experts and researchers could jointly design.[66] The anti-money laundering compliance measure, "Know Your Customer" (KYC), also could inspire future control processes.
- Pre-existing multilateral governance frameworks could be used for future quantum computing breakthroughs. For example, some of the norms and principles of the Chemical Weapons Convention (1997) and Biological Weapons Convention (1975), may apply to outputs of quantum computing.
- **As quantum technology matures, innovative frameworks and best practices will be needed to safeguard the beneficial applications and mitigate potential risks**. Longstanding multilateral organizations like CERN and IAEA that are involved in nuclear physics can provide practical guidance.

Interoperability: emerging standardization initiatives

- **International standardization is a global effort that relies on participation by experts from around the world and requires nations' general consent**. Standards can be incorporated as recommendations, technical reports, requirements, specifications, or characteristics to consistently ensure that materials, products, processes, and services are fit for purpose.
- The development of standards can only occur when nations are ready for them. For this to happen, **certain conditions must be met in terms of technology readiness, market maturity, and an existing community** (i.e., users and vendors).
- **Establishing standards in a field holds several benefits**. It enables interoperability, quality, safety and health, operational excellence, customer satisfaction, trust, access to markets, and economic growth. It fosters the promotion of industry, social development, and regulations. It also improves market access management, quality and safety, support for sustainable strategies and innovation. Standards can stall innovation, however, if they are imposed too early in the process.
- The development of international standards may take on geopolitical considerations as national interests emerge.
- **Only countries with local expertise can truly influence the development of an international standard**. In this context, large corporations with extensive resources, experience and leadership have an advantage over smaller companies or academic institutions with lesser means. Thus far, rich countries lead the development of quantum standards.
- While quantum computing technology is still under development, **standardization initiatives are starting to take place**. The first steps are to define common languages and technology roadmaps. The next phase will be technical reports on functional description and requirements, characterization, and performance benchmarks, with the goal of defining interoperability standards.

— For instance, ISO/IEC created a new Joint Technical Committee (JTC 3) entirely devoted to quantum technologies[67] and kicked off its activities in May 2024. Until then, standardization activities at ISO/IEC were conducted under the Information Technology JTC 1 umbrella. The Working Group WG 14[68] created a report on "Terminology and Vocabulary of Quantum Computing," a first major step in establishing a common language. European initiatives were launched in 2023 within CEN/CLC/JTC 22, with its Working Group 3 on Quantum Computing and Simulation,[69] and within IEEE-SA, which created six working groups for Quantum Computing,[70] including a standardization roadmap on quantum applications.[71]

Trade: addressing current and future choke points in the global supply chains

— As the field of quantum computing matures, **nations are examining their industrial supply chains[72] and sourcing enabling technologies[v], components[vi] and critical raw materials (CRMs) that are essential to build quantum computers.**

— In the U.S.[73] and Europe[74, 75] frameworks have been developed to examine vulnerabilities in supply chains and deal with critical chokepoints now and in the future.

— Quantum Computing **supply chains are highly global, fragmented and complex**. The situation is further complicated by significant variance in supply chains depending on the type of quantum computer that is involved and its distinct physical architecture.

— The following chart presents an **overview of the critical parts of the supply chains** for six of the most common types of quantum computers.

	Superconducting (e.g. IBM, Google, Rigetti, IQM, OQC, Alice & Bob)	Trapped Ions (e.g. Quantinuum, IonQ, AQT)	Neutral Atoms (e.g Pasqal, QuEra, Infleqtion, Atom Computing,Planqe)	Semiconductor spin (e.g. Intel)	NV Diamond color centers (e.g. Quantum Brilliance)	Photonics (e.g PsiQuantum, Xanadu, Quandela)
Enabling technologies	**Cryogenics** **Packaging and Nanofabrication technology**	**Laser Technology and Optics** **Nanofabrication technology**	**Laser Technology and Optics** **Nanofabrication technology**	**Cryogenics** **Packaging and Nanofabrication technology**	**Laser Technology and Optics** **Cryogenics** **Nanofabrication technology**	**Laser Technology and Optics** **Cryogenics** **Packaging and Nanofabrication technology**
Components	**Superconducting chip, customized PCBs, cables/connectors, dilution refrigerators** Microwave electronics, magnetic shields, control systems	**Ion sources, MOT, optical components, optical fiber, laser(NLO crystals)** Interconnects and fiber, optical table, microwave electronics, control systems, Imaging optics (EMCCD camera/APD), ultra- high vacuum chamber, magnets and magnetic shielding	**Atom sources, optical components and optical fibers, lasers (NLO crystals)** Optical table, microwave electronics, control systems, Imaging optics (EMCCD camera/APD), ultra- High Vacuum chamber, magnets and magnetic shielding	**Semiconductor chip, specialized PCBs, cables and connectors, dilution refrigerators** Spin qubit, microwave electronics, magnets and magnetic shielding, control systems	**Synthetic diamonds, laser. and other optical components** Microwave electronics, control systems, magnets and magnetic shielding, interconnects and fiber, optical table, cryostat	**Erbium doper fiber (EDFA), NbN, super conducting nano-wire single photon detector (SNSPD)** Photonic chip, optical components, interconnects, control system and fiber/ integrated photonic circuits, control systems, PCBs, magnets, Cryostat
Raw Materials	**Mo, Ta, Nb, He-3(for dilution refrigerators), Pt (for super conducting chip and dilution refrigerators), v, graphene, Cu, Ni (for PCB),Eus** W, Sapphire (for superconducting chip) Au (for superconducting chip, PCB, cables and connectors), si (for superconducting chip, PCB, microwave electronics) Nb-Ti (for cables and connectors), Al (for superconducting chip, magnetic shield), NiFe mu-metal (for magnetic shield)	**Be, Yb,Er (for ion, laser), PbMo, 04, Y, Sr, Ga (for ion source), Te02 (for AOD),Ba** Ca, Al, Mg, Hg, Cd, SiN, GaN (for ion source), Er (for ion, laser), NiFe mu-metal (for magnetic shielding), Cu, Au (for MOT), titanium (for vacuum chamber)	**Te02 (for AOD), Ge, Sr, Yb** Ca Ba, Be, Al, Mg, Hg, Cd, SiN, GaN (for ion source), PbMo, Er (for ion, laser), NiFe mu-metal (for magnetic sheilding), Cu, Au (for MOT), titanium (for vacuum chamber)	**Ge, As, In, Sb, Ga, He-3 (for dilution refrigerator), Cd, Te, Bi (for spin qubit and semiconductor chip)** Graphene, Sapphire, Er (for spin qubit and semiconductor chip), Au (for PCB, cables and connectors), Si (for semiconductor qubit, PCB, microwave electronics), Nb-Ti (for cables and connectors), Cu-Ni (for PCB)Hg, P, Al (for magnetic shielding, microwave electronics)	**Ir, Ga** C, Si, N, Ir, He-3 (for cryostat), Ne, Nd (for magnet), Au (for cryostat, synthetic diamond)	**In, LiNbO3, Nb, P, Er, LINbO3 crystal, KTIOPO4 (PPKTP) crystal, PPLN crystal** LiNbO3,Si3N4, Ga, Al, As, P- lasers

Figure 1. This chart is based on 10+ interviews by OQI with academic and industry providers. A full list of sources is available upon request. Current and emerging choke points in the supply chains are highlighted in bold.[76, 77] Owing to the nascency of the technology, this overview will continue to evolve.

— **Vulnerabilities can emerge from different factors**: intrinsic scarcity of the raw material; concentration of the supply in a limited number of countries; exclusivity of the technical or manufacturing know-how among a few suppliers; lack of viable alternatives to produce materials and components; and trade disruptions arising from geopolitical tensions or conflicts.[78]

— Current strategies to mitigate such vulnerabilities primarily focus on the supply chains of the more prominent **types of quantum computers** – notably the superconducting developed by global corporations like Google or IBM – **or those where supply chains overlap**.

— One example of a chokepoint can be found with **optics and laser technologies**, which are both needed for ion traps and neutral atom quantum computers. Another example can be found with **dilution refrigerators and cryogenics** that are required both for semiconductor spin qubits and superconducting qubits. These dilution refrigerators are produced almost exclusively in Finland and the United Kingdom,[79] while most of the helium isotope He3 that is needed for cryogenics is exported from the United States and Russia. The global shortage of He3 is affected by geopolitics.

— **Some bottlenecks are exacerbated by competition with other technologies that depend on the same pool of finite resources** (sustainable energy, defense and aerospace technologies or other quantum technologies). Specifically, supply chains for color centers and ion trap-based quantum computers overlap with those for quantum sensing and quantum communication. Policymakers may have to make tough decisions about how best to allocate an already scarce pool of resources.

— Nations are monitoring the timelines for how long it takes quantum computing to mature. For now, the timelines are mainly driven by research; production volumes are small. The quantities of raw materials needed for quantum computing are insignificant compared to global yearly mining volumes.[80] However, the **supply chain landscape could soon change significantly as more commercial devices are produced**.

— In the meantime, efforts remain focused on developing **alternatives to existing chokepoints**. Regional industry groups like QED-C[81] and QUIC[82] are starting to create strategies for finding substitutions that plug the gaps in device components and instrumentation. For instance, research is being conducted to find alternatives to superconductivity by using new cryogenic systems (magnetocaloric cooling) that are superior to the traditional, bulky dilution refrigerators used today. Breakthroughs in materials science could also enable the use of different critical raw materials.

— **Controlling the value chains can not only ensure technological sovereignty but also create barriers to entry for new players**. To anticipate such scenarios, some nations have set up **bilateral and multilateral mechanisms, including export control measures**.[83] Several governments such as France,[84] Canada,[85] the United Kingdom[86] and the United States[87, vi] recently imposed similar export controls on quantum computers. The United States and Switzerland issued joint statements on Quantum Information Science and Technology (QIST) to promote cooperation, research integrity, inclusive scientific communities, and secure markets and supply chains.[88] Other initiatives to promote resilient cross-border supply chains include the Indo-Pacific Economic Framework for Prosperity[89] and EU Quantum Declaration.[90]

— The competition for critical raw materials stands out as an area of cross-cutting importance in the future of quantum computing. Improved multilateral governance efforts would help to address the potential for supply chain vulnerabilities and benefit multiple sectors, not only quantum computing.[91, 92]

v Enabling technologies: A non-quantum technology that has a separate supply chain and ecosystem, but assists and enables the development of quantum computing hardware

vi Components: built from raw materials and combined with other components to perform a specific function within equipment

Environment: addressing environmental impacts of technological developments

- **Digital tools accounted for an estimated 6% to 12% of the electricity used worldwide in 2024**,[93] but our understanding of how much energy it will take to power quantum computers at scale remains limited.
- Some indications show that quantum computing may need less power than energyintensive classical supercomputers.[94]
- Several of the projected quantum computing applications would also have a positive impact on the environment. **Some of the most cited examples are those dealing with carboncapture materials, optimization of energy grids, and more efficient ways of producing fertilizers.**
- Building quantum computers at industrial scale, however, requires new components and solutions – and the environmental costs of those are uncertain. As novel new components and other enabling technologies (e.g., control systems, cabling, cryogenics, software and algorithms) are developed to create mature quantum computers, the environmental costs of their larger-scale manufacturing must be considered.
- **Global initiatives are emerging to foster worldwide communities willing to use and develop quantum computing for positive impact on the environment**. Such initiatives include Quantum for Climate, founded in 2021,[95] as well as the Quantum Energy Initiative (QEI),[96] launched in August 2022. QEI aims at reducing the environmental footprint of quantum computers and proposes optimization methodologies, frameworks, and even the development of a new IEEE standard[97] to measure the environmental impacts of quantum computing.
- Similar approaches could augment other multilateral initiatives such as the UNEP Life Cycle Initiative,[98] Council of Engineers for the Energy Transition,[99] or the UNFCCC Global Innovation Hub.[100]

Talent: training at scale at the right time

- Helping people gain the educational background needed to develop quantum technology is key to realizing its potential. Until now, the need for quantum computing talent has mainly resided with companies looking to recruit experts in quantum theory, hardware and software developers and quantum applications developers. Among the most sought-after positions are quantum machine learning scientists, quantum software engineers, qubit researchers, and quantum control researchers. The skills needed for such roles are specific to quantum computing: understanding of quantum physics and how to map problems to the quantum space, programming languages, architectures, workflows and software.[101]
- Such talent is in short supply. In 2022, half of the open jobs could not be filled due to lack of suitable skills. This hinders development and innovation, particularly for start-ups that are struggling to compete with larger players and to equip themselves with experienced specialists such as staff or advisors.
- The gap, however, is partly being addressed. Universities are introducing new master's degree programs in quantum technologies. In 2023, 195 universities offered quantum technology research programs and 50 offered master's degrees in quantum computing vs. 180 and 48 in 2022.[102]
- The geographic distribution of the quantum talent remains highly concentrated. An estimated 90% of quantum technology graduates are trained in the European Union, United States, China and India.[103] Programs like the Quantum Africa series, Quantum Leap Africa led by the African Institute for Mathematical Sciences (AIMS) or Quantum Latino are geared towards nurturing a talent pool in developing countries.
- In parallel, as the technology edges closer to commercialization, the demand for quantum talent is shifting from hardware to software.[104] End-users that want to be quantum-ready will seek experts who can provide quantum applications for their businesses. Brief training programs for computer scientists and applications engineers could address this need. To date, such courses are rare.
- Given the uncertainty around the time it will take for quantum computing to mature, a key policy challenge is to define how much specialized knowledge is needed for different tasks. Those tasks include making decisions about investments, new technology uses, and ways of heading off undesired consequences.
- Education and training systems must remain agile and relevant, due to the uncertainties around quantum computing, and enable people to transfer their applicable expertise gained from other fields.
- The International Labor Organization's efforts to better comprehend how new technologies will impact the future of work are pertinent for quantum computing. Some of the key findings of its work recently conducted on AI may also be relevant for quantum computing, in particular regarding the need for proactive policies that focus on job quality, ensure fair transitions, and are based on dialogue and adequate regulation.[105]

Human Agency

- As distinct from human capital, **human agency** is the innate capacity to exert control over the nature and quality of one's life. It is the freedom that individuals have to pursue goals and values they consider important, and, more significantly, to take action towards realizing them. Agency is not just a state or a capacity, but a process that drives action, whether in technology, societal change, or personal decision-making. In other words, agency translates intentions into real-world outcomes.
- Human agency could be divided into **three fundamental components**: intrinsic value, related to personal satisfaction and self-expression; instrumental value, describing how agents achieve outcomes affecting personal and communal well-being; and constructive value, showing how agency fosters the exchange of ideas through collective and democratic action, leading to socially valuable outcomes106. It is a temporal phenomenon that affects all phases of human existence: it is influenced by past experiences; it dictates present actions; and it shapes future ambitions. This capacity to act is a driving force within humanity, allowing us to approach the future with optimism and vitality, as it drives our ability to feel alive and proactive in our endeavors.[107]
- Human agency is deeply manifest at the individual level, but also in institutional contexts: individuals with strong agency, so-called "institutional entrepreneurs," are those who initiate and drive change, challenging and reforming existing institutions to better serve societal well-being. This perspective helps us to view institutions not as static monoliths, but as dynamic entities, driven to change by the innate force of human actors.[108]
- As we look towards future possibilities, human agency also directs our approach to unresolved challenges. For instance, while current computers cannot solve complex problems such as analyzing matter at the subatomic level, the anticipated advent of quantum computing promises to address critical issues such as resolving water scarcity and world hunger. Thus, **quantum computing may enhance human agency, serving as a tool to help humans express their true intention and purpose in the face of rapid technological developments and potential constraints**. In addition, quantum mechanics may intersect with concepts of free will, decision-making, and consciousness, particularly due to the subjective and indeterministic nature of both consciousness and the quantum phenomenon — contrary to the deterministic nature of classical physics. Some researchers argue that quantum indeterminacy could provide a basis for free will, suggesting that not all events are predetermined and that human decisions might be influenced by quantum processes in the brain.[109, 110] This emphasizes further how technology might serve as a catalyst for human action.
- Technology permeates every aspect of our lives it shapes how we work our work, access and use healthcare and medical solutions, communicate and get information, and engage with educational systems, social media; and economic activities, and even peace and security. Human agency manifests as the ability to navigate and utilize these technologies with different social roles but at the same time-space frame. It involves continuous adaptation, negotiation, and setting of boundaries, as well as the creative and strategic use of technology to achieve both personal and professional goals effectively. Everyday technology is now filled with the growing presence of artificial intelligence (AI), raising questions about our **ability to retain control** over our own actions. Some members of the scientific community argue that AI will limit human freedom of action, as humans will be dependent on something they cannot fully understand and that operates without transparency. Conversely, other experts believe AI can be developed in a way that could preserve and even enhance human agency by enabling more **efficient decision-making.**
- Experts are divided over AI. Some scientists argue that AI will limit human freedom as we become dependent on something we cannot fully understand that operates without transparency. Others believe that AI can be developed to preserve and even enhance human agency by enabling **more efficient decision-making**. Ultimately, the **governance** and regulation of AI and other emerging technologies, notably quantum computing, will be critical to ensuring human agency remains the vital force it has always been. For example, governments and institutions, such as the European Union, have begun regulating AI through frameworks like the General Data Protection Regulation (GDPR), to ensure transparency and uphold human oversight in AI systems. This proactive governance reflects the ongoing exercise of agency at the institutional level, helping to safeguard individual autonomy in an increasingly automated world. Neurotechnology also presents opportunities and threats related to human agency. By acting directly on the brain, the seat of agency, microdevices can enhance human capacity by removing physical limitations and amplifying one's ability to express one's true self. Yet, they also pose risks. Users of neural devices have reported symptoms such as increased impulsivity and emotional changes, which can undermine their sense of control and authenticity.[111]

- This dichotomy highlights the need to develop "relational agency competencies." These competencies are essential for individuals to manage their agency in relation to the influences of external agents such as microdevices. They focus on preserving **autonomy** and maintaining **identity integrity**. Implementing relational agency competencies involves several steps: providing education and training, creating robust support systems, establishing clear health policies, and ensuring continuous feedback from users to adapt and refine interventions. These actions are crucial for ensuring that human agency remains robust, particularly as new technologies continue to transform how we live and work.
- The United Nations has increasingly recognized the importance of "human agency" in development contexts, defining it as the "capability of people's ability to hold values, set goals and make commitments that may, or may not, advance their well-being." This capability is threatened by escalating insecurities in **developing regions**, where the U.N. has highlighted the presence of "**agency gaps**," i.e., disparities in individuals' ability to exercise agency, linked to economic, social, and political inequalities.
- To address these issues, the United Nations is focusing on building and strengthening human capital in developing economies to reduce these gaps and to empower citizens to take meaningful action and exercise their agency effectively. This approach underscores once more the essential role that inclusive institutions serve in bridging these agency gaps. But **human agency** itself can be a **driver** and **enabler of development** in such regions. That is the case with reforestation, as highlighted in the 2021-2022 UNDP report.[112]
- In emerging economies, governments, non-governmental institutions, and people are making efforts to preserve biodiversity by converting and rehabilitating land into forests.
- As part of hiss Global Digital Compact (GDC) initiative, U.N. Secretary-General António Guterres' Envoy on Technology, Amandeep Singh Gill, has asserted that **privacy** is a fundamental aspect of human agency, in terms of how we deal with challenges without the prejudice or coercion of others. In this sense, human agency is profoundly linked to our right to life and liberty.

Concluding remarks: OQI as an example of responsible computing in practice.

As the operationalization of the Open Quantum Institute progresses, principles of responsible computing are important. Questions of governance and responsible innovation in practice become more central.

The Need for Responsible Quantum Computing

- The impact of quantum computing applications will be paradigm-shifting. However, as the exact scale remains unknown, responsible computing and governance frameworks are needed to avoid misuse.
- Existing mechanisms for the promotion of responsible computing can be adapted where applicable, but quantum computing's distinct opportunities and challenges require specific responsible innovation frameworks.[113]
- It is a unique moment in time that allows being pro-active. Multistakeholder discussions after the fact can be avoided and frameworks developed and implemented now.[114]

Key Considerations of Responsible Quantum Computing in Practice

- The impacts and multitude of quantum computing applications are hard to predict. Principled approaches are the most suitable. They can help orient us and later serve as the basis for governance frameworks. Other border-spanning technologies inform us that these efforts must be multilateral.[115] While approaches vary, they mostly rest on common values, anticipatory technology assessment, stakeholder impact mapping and broad participation.[116]
- While multilateral governance efforts remain nascent, responsible innovation principles are included in several recently published national strategies.[117] Technology providers also are promoting their own versions of responsible quantum computing frameworks and approaches. Some multi-stakeholder efforts have been initiated, such as the Responsible Quantum Industry Forum (RQIF) in the U.K. and the GESDA's Quantum Diplomacy Symposium.[118] Although their focus varies, some of these approaches share common themes such as an emphasis on anticipation and mitigation; inclusion and diversity; developing and using quantum computing for good; broad access to computing resources and education; and sustainability.[viii]

OQI and Responsible Quantum Computing

- Against this backdrop, the OQI is contributing to responsible quantum computing efforts on different levels. With its mission to advance applications for the SDGs, the OQI has the 'quantum for good' principle at its core. Science diplomacy is at the core of the foundation, which is seen in the Quantum Diplomacy Symposium. Diplomatic discussions provide a basis for multilateral quantum governance, especially by including technology and academic experts in the process from the beginning. Furthermore, the OQI is uniquely positioned to strengthen participants' ties to the SDGs.

viii As also reflected during OQI's first Quantum Diplomacy Symposium (July 2024).

Annexes

Annex 1
The Open Quantum Institute, hosted at CERN, born at GESDA, supported by UBS

From the 40 emerging scientific topics covered by GESDA,[119] Quantum Technologies is the most advanced in the Anticipatory Situation Room (ASR) pipeline.[120] Quantum computing is identified as a technology with great transformative capability requiring a science and diplomacy mobilization to ensure global access and benefits. The related solution idea – the Open Quantum Institute (OQI) – reached the incubation phase in 2023.

In line with GESDA's core mission, the OQI is an anticipatory instrument. We are anticipating the moment when quantum computers will be ready at scale by reflecting now on their future impact on people, society and the planet, and by acting ahead of time to create the conditions for using them in the best interests of humanity. By acting now, we enable human agency and prepare the future multilateral governance so it will be ready when the technology can be effectively deployed.

Located in Geneva, the OQI is a multilateral governance initiative, born at GESDA, hosted at CERN, and supported by UBS for its pilot phase (2024-2026). The OQI promotes global and inclusive access to quantum computing and the development of applications for the benefit of all humanity. As a novel science diplomacy instrument, it brings together stakeholders in research, diplomacy, the private sector and philanthropy.

The OQI's mission is divided into four pillars:

A1
Accelerating applications for humanity

We want to achieve the broadest possible societal impacts from the full potential of quantum computing. To accomplish that, we're working to accelerate the development of use cases geared towards achieving the United Nations' Sustainable Development Goals (SDGs) and its succeeding post-2030 framework. We're confident we can fulfill our vision thanks to the combined forces of researchers, developers and entrepreneurs from academia and private sector, as well as from the United Nations, and some prominent NGOs.

A2
Access for all

We want to provide global, inclusive and equitable access to a pool of public and private quantum computers and simulators via the cloud.

A3
Advancing capacity building

We are developing educational tools to enable everyone around the world to contribute to the development of quantum computing and to make the most of the technology.

A4
Activating multilateral governance for the SDGs

We are providing a neutral forum to help shape the multilateral governance of quantum computing for the SDGs

Annex 2
How Quantum computing works

Quantum computers exploit quantum mechanics: the laws of physics that govern the behavior of matter at the tiniest of scales. Quantum mechanics defy all our intuitions about how the physical world operates. It is a world of probabilities rather than clear cause and effect, and it upends our understanding of time and space.

At the most basic level, all information in a classical computer is encoded as sequences of bits – 1s and 0s that represent flicking on and off tiny electrical switches known as 'transistors.' Qubits are the quantum equivalent of bits, but because they represent quantum systems rather than simple switches, they have unusual properties that classical bits don't share. That allows them to store and process much more information simultaneously.

The unusual properties of quantum computers stem from three main quantum effects:

Superposition

In a classical computer, bits exist as either 0s or 1s. They are like flipped coins that are either heads or tails. In a quantum computer, qubits, which are the fundamental information processing units, can exist as a complex combination of the two outcomes. Each outcome has a certain probability of being true. This state, known as superposition, can be maintained until the qubit is measured, at which point it will settle on one of the two values. Q Qubits in superposition are like coins spinning on their sides.*

Entanglement

When two quantum systems are entangled, changing the state of one instantaneously changes the state of the other, no matter the distance between them. This is what Einstein called "spooky action at a distance." Entanglement makes it possible to connect multiple qubits together so that all their fates are intertwined. The result is a single superposition of all the possible outcomes encoded in each individual qubit. Reading one of these qubits provides information about the states of the others, which means a quantum computer can process information exponentially faster than a classical one.

Interference

How qubits are linked up matters. The probabilities that govern the outcome of each qubit can interfere with those of its neighbors, amplifying or canceling the other one out. To go from all possible outcomes to the one that is the solution to a problem, a quantum algorithm is needed that carefully choreographs a pattern of interference that leads to the correct solution. There are several options for how to arrange the qubits. The most popular model involves organizing them into circuits, like in classical computers. These circuits are built from a sequence of operations on smaller subsets of qubits that together help to solve whatever problem the quantum computer has been set to take on.

While this approach is common to most quantum computers under development today, the physical systems used to implement qubits can vary considerably. The leading modalities are:**

Superconductors	qubits encoded in electrical properties of a loop of superconducting wire
Ion traps	qubits encoded in quantum states of an ion trapped by lasers
Cold atoms	qubits encoded in quantum states of an atom trapped by lasers
Silicon	qubits encoded in quantum states of electrons in a silicon chip
Photonics	qubits encoded in quantum states of photons moving along circuits in silicon chips

Researchers expect we will need thousands if not millions of qubits to build practical quantum computers that can solve a wide variety of useful tasks. That's partly because of the large number of qubits needed to encode bigger problems into the machine and to deal with the fragility of quantum systems, which makes qubits error prone. To get around this, quantum computers require **error-correcting schemes** to ensure that mistakes don't pile up too quickly and derail a computation. But to do this, up to 10,000 times as many qubits may be needed to run the error-correction code.

Sources used to develop the explanations in this box (accessed 6 August 2024)

***) Quantum computing and quantum supremacy, explained | WIRED UK**,
https://www.wired.co.uk/article/quantum-computing-explained

****) What Happens When 'If' Turns to 'When' in Quantum Computing**
The Path to Building Quantum Advantage | BCG,
https://www.bcg.com/publications/2021/building-quantum-advantage

GESDA (2022), Quantum Computing, Impact Story,
https://gesda.global/wp-content/uploads/2022/09/GESDA-Quantum-Computing-Impact-Story-Apr2022-1.pdf

Explainer: What is a quantum computer? (MIT Technology Review),
https://www.technologyreview.com/2019/01/29/66141/what-is-quantum-computing/

How does a quantum computer work? (Scientific American),
https://www.scientificamerican.com/video/howdoes-a-quantum-computer-work/

What makes quantum computing so hard to explain? (Quanta Magazine),
https://www.quantamagazine.org/why-is-quantum-computing-so-hard-to-explain-20210608/

Understanding quantum computing (Cosmos Magazine),
https://learn.microsoft.com/enus/azure/quantum/overview-understanding-quantum-computing

Quantum computing for the qubit curious (Cosmos Magazine),
https://cosmosmagazine.com/science/quantum-computing-for-the-qubit-curious/

Quantum computing in a nutshell (Qiskit),
https://docs.quantum.ibm.com/guides/hello-world

Annex 3
Diplomatic community engagement: key findings of the Quantum Diplomacy Symposium

Diplomatic community core group:

Australia | Austria | Brazil | Chile | Czech Republic | Egypt | Finland | France | India | Israel | Italy | Japan | Kenya | Malta | Mexico | Morocco | Netherlands | Pakistan | Singapore | South Africa | Slovenia | Switzerland | The United Kingdom | The United States

The symposium fostered dialogue among key international stakeholders, including diplomats who serve in their nations' missions as permanent representatives to the United Nations and other international organizations in Geneva. The aim of the discussions was to anticipate future multilateral governance for quantum computing that can accelerate the achievement of the SDGs and its post-2030 successor. The collected inputs were incorporated into this report for release at the 2024 GESDA Summit in October. GESDA was delighted to invite all the missions in Geneva for an inclusive dialogue.

These were the highlights:

Encryption and Security

Quantum computers are set to break current encryption methods, compromising the security of sensitive data. standards. Solutions like post-quantum cryptography (PQC) and quantum key distribution (QKD) exist, but the transitions will be time-consuming. National policies recommend expedited deployment. Technological polarization could lead to competing standards, harming interoperability. Future scalable quantum computers will enhance dual-use applications, such as chemistry simulations, requiring new safety designs and applying existing normative frameworks.

Access and Education

Quantum computing could deepen inequalities over access to digital technologies. The U.N.'s Global Digital Compass and Pact of the Future advocate for an inclusive and sustainable digital future. Policymakers need concise and trusted information to understand quantum computing's impacts. Cloud access enables the use of small-scale quantum computers for education and exploring novel use cases. Education and capacity building are essential, focusing on upskilling both computer scientists and experts in quantum computing applications.

Human Capital

The quantum talent gap is narrowing, yet a third of all job openings went unfilled in 2022 as the demand shifted from hardware to software and companies prepared to be quantum ready. Educational programs in quantum technologies grew to 195 in 2023, with 55 universities offering master's degrees, mostly in Europe and the United States. Short, applied programs for building quantum applications remain rare. The uncertain timeline for the maturity of quantum technology makes it difficult for managers to decide when to intensify training efforts, highlighting the importance of adaptability and transferable skills.

Human Agency

Human agency, a multidisciplinary concept integrating psychology, physics, and social sciences, enables us to drive our actions and influence institutional change. Quantum computing poses risks to both, potentially impinging on our ability to control our own actions and reducing opportunities to develop beneficial applications. Significant gaps in human agency exist globally due to unequal participation in decision-making. Stronger multilateral governance is key to promoting evidence-based knowledge, futures literacy, and SDG-aligned initiatives.

Annex 4
Overview of national quantum strategies and initiatives

Country	Public investment in quantum computing (all currency conversions are approximate)	Data Source(s) on public investment
Australia	At least $640 million	Australian Government 2023 - Department of Industry, Science and Resources (page 7) Australian Government - national quantum strategy
Austria	107 million euros ($127 million)	Austrian Science Fund - Quantum Austria
Brazil	BRL 60 million ($12 million)	Empresa Brasileira de Pesquisa e Inovação Industrial Forbes
Canada	CAD 1.41 billion (1 $billion)	Government of Canada - Canada's National Quantum Strategy Government of Canada- news release
China	$15.3 billion	IOP Science McKinsey Digital – Quantum Technology Monitor 2024 McKinsey Digital
Denmark	1 billion DKK ($147 million)	Danish Ministry of higher education and science Danish Quantum Community
European Union	1 billion euros ($1.1 billion)	European Commission - Quantum Technologies Flagship Quantum Flagship
Finland	84 million euros ($92 million)	State of Quantum 2024 - IQM report(page 47) University of Helsinki - Finnish Quantum Agenda Quantum Technology Finland HPC wire - Finland's 2nd Quantum computer with 20 Qubits University of Helsinki - latest investment in quantum
France	1.8 billion euros ($2 billion)	French Government The Quantum Insider - French National Quantum Update 2024 French Government - Quantum Technologies
Germany	3 billion euros ($3.2 billion)	Quantum Business Work German Federal Government Action Plan for quantum technologies The Quantum Insider
Hungary	3.5 billion HUF ($11 million)	National Research, Development and Innovation Office HunQuTech
India	80 billion INR ($1billion)	Government of India Ministry of Science and Technology Government of India - National Quantum Mission The Quantum Insider

Annex 4
Overview of national quantum strategies and initiatives

Country	Public investment in quantum computing (all currency conversions are approximate)	Data Source(s) on public investment
Ireland	10 million euros ($10.9 million)	Government of Ireland Government of Ireland - Impact 2030 Report - Ireland research and innovation strategy Government of Ireland - Quantum 2030
Israel	NIS 1.2 billion ($390 million)	The Times of Israel
Italy	320 million euros ($350 million)	Forbes Quantum Computing Lab HPC Wire
Japan	266 billion yen ($1.8 billion)	McKinsey Digital - Quantum Technology Monitor 2024 Secretariat of Science, Technology - Strategy of Quantum Future Industry Development Summary
Netherlands	965 million euros ($1 billion)	TU Delft -The Netherlands and Quantum QuTech Quantum Delta
New Zealand	NZD$ 36.8 million ($22.7 million)	Stuff New Zealand
Philippines	860 million pesos ($ 17.2 million)	McKinsey Digital - Quantum Technology Monitor 2024 Government of the Philippines - Quantum Technology Roadmap
Russia	72 billion rubles ($0.7 billion)	The Quantum Insider The Quantum Insider
Singapore	SGD 400 million ($300 million)	National Quantum Office - Singapore
South Africa	54 million rands ($3 million)	University of Witwatersrand, Johannesburg South African Quantum Technology Initiative The Quantum Insider The Quantum Insider
South Korea	3.02 trillion won ($2.35 billion)	Quantum In Korea The Quantum Insider Korea.net
Spain	60 million euros ($67 million)	Quantum Spain European Commission Government of Spain TechUnwrapped
Sweden	SEK 1.6 billion ($160 million)	Royal Swedish Academy of Engineering Sciences (IVA) Swedish Quantum Agenda

Annex 4
Overview of national quantum strategies and initiatives

Country	Public investment in quantum computing (all currency conversions are approximate)	Data Source(s) on public investment
Switzerland	CHF 20 million ($22 million)	Swiss Quantum Initiative Swiss Confederation - State Secretariat for Education, Research and Innovation
Thailand	200 million baht ($6 million)	Bangkok Post
United Kingdom	£2.5 billion ($3.25 billion)	TechUK Department for Science, Innovation and Technology - National Quantum Strategy The Quantum Insider
United States	$4.4 billion	National Quantum Coordination Office Covington [ix]

[ix] This list is meant to illustrate quantum strategies across the globe rather than serve as authoritative overview or exhaustive list of formal national and regional references.The data sources used to track public global investments that OQI has consulted as well as the ones listed above are: World Economic Forum, IBM, & SandboxAQ. (2024b). January 2024 In collaboration with IBM and SandboxAQ. https://www3.weforum.org/docs/WEF_Quantum_Economy_Blueprint_2024.pdf (accessed 15 July 2024) IQM . (2024, January).

State of Quantum 2024 - Understanding the 2023 trends and outlook for 2024. https://uploads-ssl.webflow.com/6523f13a748909d3e1bbb657/65e6d35be62d08db2e7b3b71_State-of-Quantum2024-report.pdf (accessed 15 July 2024)

McKinsey Digital. (2024a). Quantum Technology Monitor 2024 https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/steady%20progress%20in%20approaching%20the%20quantum%20advantage/quantum-technology-monitor-april-2024.pdf?shouldIndex=false (accessed date 15 July 2024)

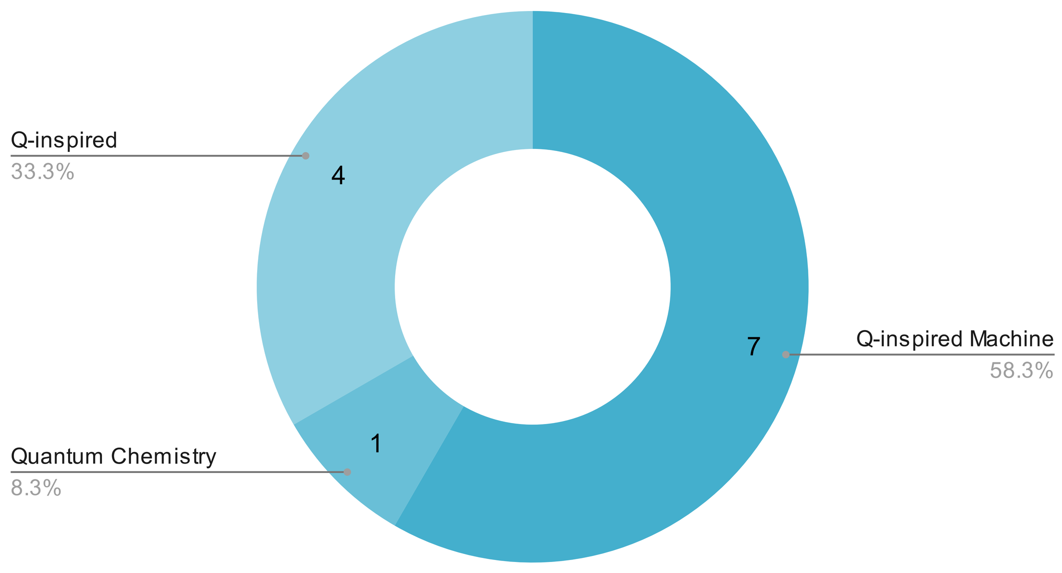
Swissnex Network in Asia and Australia. (2022). The state of quantum technologies in the APAC region Regional Report 2022 Swissnex Network in Asia and Australia. https://swissnex.org/app/uploads/2023/05/Report_Epdf_290323_Final-Publish.pdf (accessed 15 July 2024)

Annex 5
Examples of quantum computing applications conducive to the SDGs

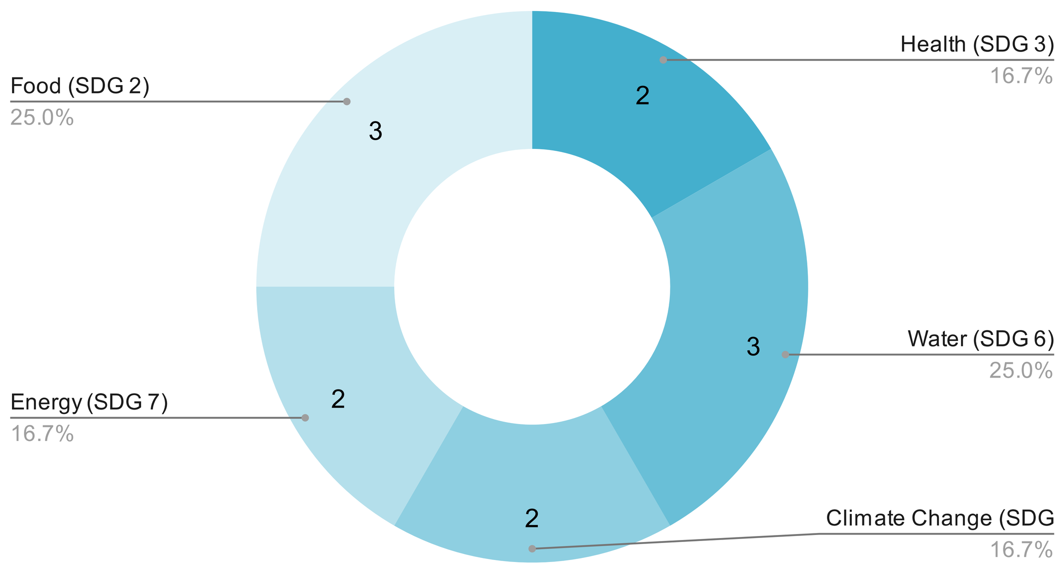
Since 2023, the Open Quantum Institute has focused its exploration of possible future applications of quantum computing on SDG 2 (zero hunger), SDG 3 (good health and wellbeing), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy) and SDG 13 (climate action).

Quantum and subject experts of the OQI community have been collaborating with U.N. agencies to explore the potential of quantum computing in these domains, with the support of OQI. So far, the OQI has supported 12 projects that leverage the expertise of participants from 18 countries.

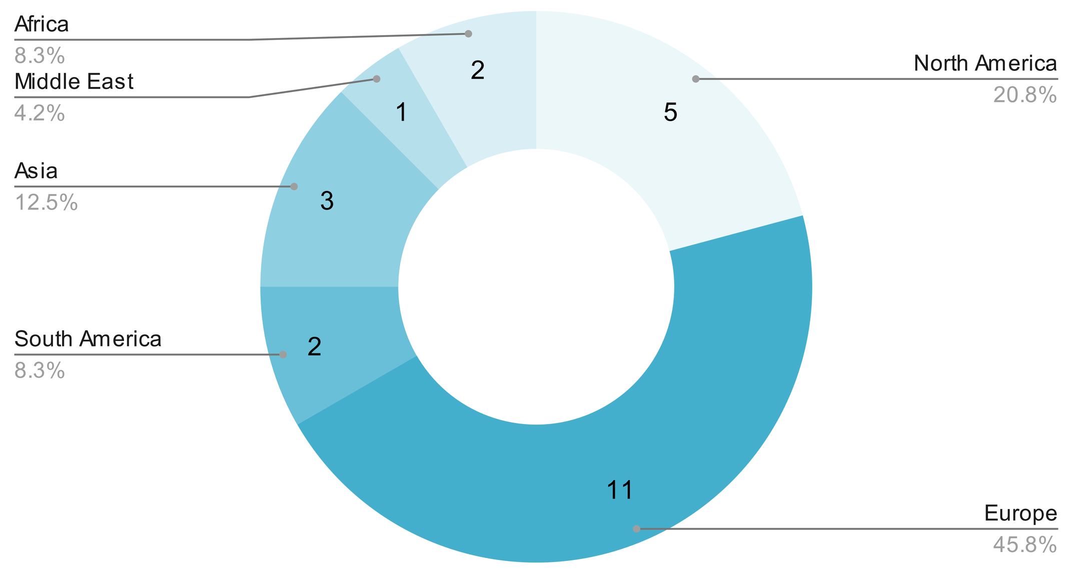
Quantum Approaches to SDG applications



SDG relevance of quantum computing applications



Global participation to the OQI use case development



The two most advanced of these 12 use cases are being are being tested on quantum simulators by October 2024:

Water Leak Detection

This quantum machine learning solution could improve the placement of sensors that detect water leaks in urban water systems, helping prevent severe water crises. Rapid urban growth and aging infrastructure pose a challenge for many cities facing water shortages.

Mexico City's water shortages, for example, are exacerbated by the need to pump water uphill over long distances from sources outside the city. About 40% of that water is lost to leaks. Finding the leaks often is challenging due to the vastness and complexity of the city's water pipe systems. This network can be represented as a graph problem; classical computational approaches to the problem exist, but they struggle to cope with the complexity. Quantum algorithms could help find a better way to place sensors within a water distribution system to efficiently detect leaks. Accomplishing that would mark a turning point in the maintenance and repair of essential urban infrastructure.
Team: Quindata, SigmaReply, UN Habitat, Pasqal

Sustainable Food Production

This quantum optimization solution could produce more nutritious food locally on less land, accelerating improvements in the consumption of safe and nutritious food that is produced sustainably.

A nutritional value score for the application would take into account nutrient density and dietary factors related to non-communicable diseases. But societal, environmental, and economic factors would also need to be mapped. This class of optimization problems is known as mixed-integer linear programming. Classical algorithms to find approximate solutions (heuristics) for this class of problems exist but are computationally difficult. As a result, finding ways to optimize large-scale scenarios for crops, farmers, consumers and other factors is challenging with classical computers and algorithms and take too to reach a solution. Quantum algorithms hold the potential to solve these optimization problems.

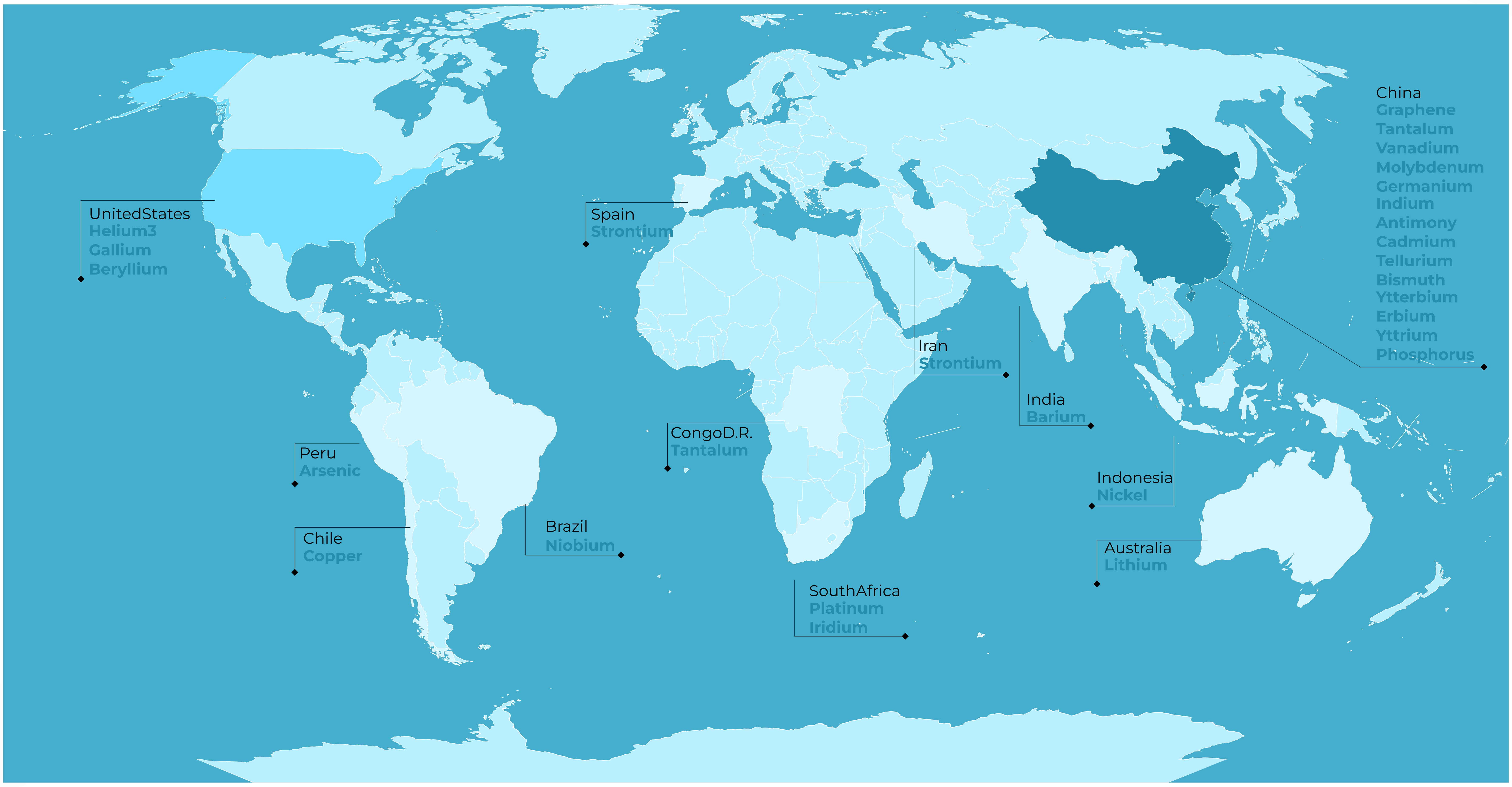
Team: École Polytechnique Fédérale de Lausanne (EPFL), Global Alliance for Improved Nutrition (GAIN), National Institute for Theoretical and Computational Sciences (NITheCS).

The table below illustrates all the projects under development at the OQI. More details can be found in the OQI Use Case Whitepapers 2022,[121] 2023,[122] and 2024.[123]

SDG (main)	Topics	Short description (Quantum approach; Phase of development; Experts; Countries)
2 ZERO HUNGER	**Nutritious Food production**	Quantum computing optimization solution to produce more nutritious food locally using less land, taking into account key food and environmental parameters. Combinatorial optimization (quantum inspired) Phase 2 – from the OQI incubation phase École Polytechnique Fédérale de Lausanne (Switzerland), National Institute for Theoretical and Computational Sciences & Stellenbosch University (South Africa), The Global Alliance for Improved Nutrition (U.K., Switzerland)
	Food security	Quantum computing optimization of the food supply chain, in particular in the route planning of food delivery in underserved regions impacted by climate change or other crises. Combinatorial optimization (quantum inspired) Phase 1 – reactivated from the OQI incubation phase QWorld (Poland), QAI Fondation (Poland), Hassan II University of Casablanca (Morocco), Yale University (U.S.)
	Plant Genomics	Quantum computing solution to improve wheat, corn and soy yield by targeted Genomics gene editing. Machine learning (quantum inspired) Phase 1 – reactivated from the OQI incubation phase QuEra (U.S.), Inari (U.S.), Eversoles Associates (U.S.), Venturus (Brazil)
3 GOOD HEALTH AND WELL-BEING	**Accelerating Novel Antibacterial Discovery**	Quantum simulation and quantum machine learning solution to accelerate the antibacterial discovery and lower resistance. Simulation (chemistry), Machine learning (quantum inspired) Phase 1 – reactivated from the OQI incubation phase GARDP (UK), McMaster University (Canada), Universita degli Studi di Cagliari (Italy), qBraid (U.S.)
	Molecular docking to clean up pollution	Quantum simulation and quantum machine learning solution to accurately model the chemical process of molecular docking involved in removing organic pollutants in water/air. Simulation (chemistry), Machine learning (quantum inspired) Phase 1 – from the call for submission Quandela (France), QunaSys (Japan)
	Predicting Gastrointestinal Cancer	Quantum machine learning solution to improve accuracy of gastrointestinal cancer diagnosis and speed up medical treatment and prevention. Machine learning (quantum inspired) Phase 1 – from the call for submission University of Coimbra (Portugal)

SDG (main)	Topics	Short description (Quantum approach; Phase of development; Experts; Countries)
6 CLEAN WATER AND SANITATION	**Water Leak**	Quantum machine learning solution to optimally position sensors and detect water leaks in urban water systems. Quantum Machine Learning (quantum-inspired) Phase 2 – from the OQI incubation phase Quindata (Belgium), Reply (France), UNHabitat (Switzerland)
	Eliminating forever chemicals from water sources	Quantum simulation of the decomposition of "forever chemicals" (Poly-fluoroalkyl substances or PFAS) for more efficient removal in water, limiting physiological and environmental harm. Quantum Simulation Phase 1 – from the call for submission SandboxAQ (Switzerland), Quantum South (Uruguay)
7 AFFORDABLE AND CLEAN ENERGY	**Layout of turbines in a windfarm**	Quantum optimization solution to efficiently layout turbines in a wind farm and maximize the amount of power produced. Combinatorial optimization (quantum inspired) Phase 1 – from the call for submission University of Plymouth (U.K.)
	Smart grid management	Quantum optimization solution to improve the management of large energy grids and efficiently distribute energy. Combinatorial optimization (quantum inspired) Phase 1 – from the call for submission Classiq (Israel, U.S.), Wolfram (U.S.)
13 CLIMATE ACTION	**Carbon Capture**	Quantum machine learning solution to improve efficiency of catalysts involved in the chemical process of carbon capture. Machine learning (quantum inspired), Quantum simulation Phase 1 – reactivated from the OQI incubation phase Centroid (Spain, Finland)
	Flood risk assessment	Quantum machine learning solution to provide better accuracy in flood predictions and improve prevention mechanisms in regions at risk, particularly Malaysia. Quantum Machine learning (quantum inspired) Phase 1 – from the call for submission Universiti Teknologi Petronas (Malaysia)

Annex 6
Map: international supply of critical raw materials for quantum computing



The above map presents a view of several critical raw materials (CRMs)[124,125] that are vulnerable to supply bottlenecks, such as Ge, Si, Mo, in table 1. The materials are essential to semiconductor and superconducting qubits. Most are sourced from China, Russia, the United States and South Africa.

Annex 7
Acknowledgements

OQI would like to thank all the experts whose valuable contributions informed the report and reviewed it:

// Alabaster, Graham (Chief Geneva Office, UN-Habitat) **// Caroff, Philippe** (Executive Director EPFL Center for Quantum Science and Engineering (QSE)) **// Challans, Alex** (CEO, Resonance Holdings / Quantum Insider) **// Dryden, Andrew** (Technical Team Leader, International Standard Organization) **// Duberry, Jérôme** (Managing Director, Tech Hub, The Graduate Institute) **// Ezratty, Olivier** (Co-Founder, Quantum Energy Initiative) **// Espinosa, Fernando** (Ambassador, DPR Mexico) **// Fan, Rebecca C.** (Social Scientist, Fellow, Research Institute for Democracy, Society, and Emerging Technologies of the National Science and Technology Council (NSTC-DSET)) **// Fleury, Nicolas** (Co-Founder and Managing Partner, Stractic Strategic Advisors) **// Jakimavicius, Tomas** (Director, European Government Affairs Corporate, External and Legal Affairs) **// Kende, Michael** (Internet Policy Expert, Senior Advisor, Analysys Mason, and Professor, The Graduate Institute) **// Kasry, Amal** (Chief of Section for Basic Science, Research, Innovation and Engineering, UNESCO) **// Kurbalija, Jovan** (Director, DiploFoundation and Head, Geneva Internet Platform) **// Kyoseva, Elica** (Director of Quantum Algorithm Engineering at NVIDIA, OQI Advisory Committee Member) **// Lackey, Brad** (Sr. Principal Quantum Architect, Microsoft) **// Lee, Min-ha** (Fellow at Stanford Center for Responsible Quantum Technology at Stanford University and Korea Institute of Industrial Technology) **// Makamara, Gillian** (Project Officer, ITU) **// Maloor, Pretaam** (Head of Emerging Technologies Division, ITU) **// Mans, Ulrich** (Lead Strategic Partnerships, Quantum Delta NL) **// Nas, Deborah** (Professor Strategic Design for Technology- based Innovation, TU Delft - Faculty of Industrial Design Engineering) **// Odeh, Sana** (Professor of Computer Science, NYU) **// Omar, Yasser** (Professor, IST, University of Lisbon & PQI, Founder, European Quantum Software Institute, and World Quantum Day) **// Parker, Edward** (Ph.D. Physical Scientist RAND) **// Pitton, Julien** (Responsible Data Lab, Ecosystem, Stractic Strategic Advisors) **// Persi Paoli, Giacomo** (Head of Program, Security, UN Institute for Disarmament Research) **// Richdale, Kelly** (Executive Fellow, World Economic Forum) **// Robinson, Douglas** (Policy Advisor, OECD) **// Rodriguez, Andrea G.** (Leading ImpaQT UA) **// Sanders, Barry** (Scientific Director of Quantum City, University of Calgary, OQI Advisory Committee Member) **// Savona, Vincenzo** (Director, EPFL Center for Quantum Science and Engineering) **// Shawn, David** (Chief Analyst, Global Quantum Intelligence, LLC) **// Till, Ulrike** (Director of the Division of Artificial Intelligence (AI) Policy, World Intellectual Property Organization (WIPO)) **// Van Hoboken, Joris** (Scientific Researcher, Quantum Delta NL) **// Violi Benjamin, Emily** (Program Manager, Microsoft)

Authors of the report:

// Bargellini, Filippo (Stakeholder engagement support, GESDA) **// Huber, Elias X.** (Student at Yenching Scholar | Prev. Quantum Research NUS, ETHZ | ETH Junior) **// Hood, Marieke** (Executive Director Impact Translator, GESDA) **// Lefebvre, Catherine** (Senior Advisor for the Open Quantum Institute) **// Melillo, Brigida** (OQI Program Management Support, GESDA) **// Mohan, Padmapriya** (MSc Quantum Information Science and Technology, TU Delft; Member Steering Committee, QIndia) **// Muñoz, Maricela** (Director of Strategic Partnerships, GESDA) **// Schörling, Marianne** (Senior Program Manager, GESDA) **// Wolf-Bauwens, Mira** (Responsible Quantum Computing Lead, IBM Research Europe).

1 Cf. Annex 2., 'How quantum computing works', based on GESDA (2022), Quantum Computing, Impact Story, https://gesda.global/wp-content/uploads/2022/09/GESDA-Quantum-ComputingImpact-Story-Apr2022-1.pdf (accessed 07 August 2024)

2 Ibid.

3 Kim, Y., Eddins, A., Anand, S. et al. (2023) Evidence for the utility of quantum computing before fault tolerance. Nature 618, 500–505, https://doi.org/10.1038/s41586-023-06096-3 (accessed 07 August 2024)

4 McKinsey. (2024). The state of AI in early 2024: Gen AI adoption spikes and starts to generate value | McKinsey. www.mckinsey.com. https://www.mckinsey.com/capabilities/quantumblack/ourinsights/the-state-of-ai (accessed 29 August 2024)

5 Google. (n.d.). AI vs. Machine Learning: How Do They Differ? Google Cloud. https://cloud.google.com/learn/artificial-intelligence-vs-machine-learning?hl=en (accessed 16 August 2024)

6 Castelvecchi, D. (2024). The AI–quantum computing mash-up: will it revolutionize science? Nature. https://doi.org/10.1038/d41586-023-04007-0 (accessed 16 August 2024)

7 Zeng, W. (2024, July 9). The AI Boom is good for Quantum Tech, Quantonation, https://www.quantonation.com/2024/07/09/the-ai-boom-is-good-for-quantum-tech/ (accessed 16 August 2024)

8 Liao, H., Wang, D., Iskandar Sitdikov, Salcedo, C., Seif, A., & Zlatko Minev. (2024, March 3). Machine Learning for Practical Quantum Error Mitigation. IBM Research https://research.ibm.com/publications/machine-learning-for-practical-quantum-error-mitigation (accessed 16 August 2024)

Q-CTRL. (2024, August 2). Making sense of quantum noise with machine learning. Q-Ctrl.com; Q-CTRL. https://q-ctrl.com/case-study/making-sense-of-quantum-noise-with-machine-learning (accessed 16 August 2024);

Zeng, Y., Zhou, Z., Rinaldi, E., Gneiting, C., & Nori, F. (2023). Approximate Autonomous Quantum Error Correction with Reinforcement Learning. Physical Review Letters, 131(5) https://doi.org/10.1103/physrevlett.131.050601 (accessed 16 August 2024)

9 IBM Quantum Documentation. (2024). AI transpiler passes | IBM Quantum Documentation. IBM Quantum Documentation. https://docs.quantum.ibm.com/guides/ai-transpiler-passes (accessed 16 August 2024)

10 Lange, H., Van De Walle, A., Abedinnia, A., & Bohrdt, A. (2024). From Architectures to Applications: A Review of Neural Quantum States. https://arxiv.org/pdf/2402.09402 (accessed 16 August 2024)

11 Multiverse Computing. (2024). CompactifAI: Extreme Compression of Large Language Models using Quantum-Inspired Tensor Networks. https://multiversecomputing.com/papers/compactifaiextreme-compression-of-large-language-models-using-quantum-inspired-tensor-networks (accessed 16 August 2024)

12 Schuld, M., & Petruccione, F. (2021). Machine Learning with Quantum Computers. In Quantum science and technology. Springer. https://doi.org/10.1007/978-3-030-83098-4 (accessed 29 August 2024)

13 Abbas, A., Sutter, D., Zoufal, C., Lucchi, A., Figalli, A., & Woerner, S. (2021). The power of quantum neural networks. Nature Computational Science, 1(6), 403–409 https://doi.org/10.1038/s43588-02100084-1 (accessed 16 August 2024); Caro, M. C., Huang, H.-Y., Cerezo, M., Sharma, K., Sornborger, A., Cincio, L., & Coles, P. J. (2022). Generalization in quantum machine learning from few training data. Nature Communications, 13(1). https://doi.org/10.1038/s41467-022-32550-3 (accessed 16 August 2024)

14 Huang, H.-Y., Broughton, M., Cotler, J., Chen, S., Li, J., Mohseni, M., Neven, H., Babbush, R., Kueng, R., Preskill, J., & McClean, J. R. (2022). Quantum advantage in learning from experiments. Science, 376(6598), 1182–1186. https://doi.org/10.1126/science.abn7293 (accessed 16 August 2024)

15 Cerezo, M., Verdon, G., Huang, H.-Y., Cincio, L., & Coles, P. J. (2022). Challenges and opportunities in quantum machine learning. Nature Computational Science, 2(9), 567–576. https://doi.org/10.1038/s43588-022-00311-3 (accessed 16 August 2024)

16 Tang, E. (2022). Dequantizing algorithms to understand quantum advantage in machine learning. Nature Reviews Physics, 4(11), 692–693. https://doi.org/10.1038/s42254-022-00511-w (accessed 16 August 2024); Aaronson, S. (n.d.). Quantum Machine Learning Algorithms: Read the Fine Print. https://www.scottaaronson.com/papers/qml.pdf (accessed 16 August)

17 Nvidia Developer. (2024, May 12). Enabling Quantum Computing with AI. NVIDIA Technical Blog. https://developer.nvidia.com/blog/enabling-quantum-computing-with-ai/ (accessed 16 August 2024)

18 Vanoli, C. (2024, July 17). Key findings on the state of global AI Governance - ITU. https://www.itu.int/hub/2024/07/key-findings-on-the-state-of-global-ai-governance/ (accessed 21 August 2024)

19 McKinsey Digital, Bogobowicz, M., Dutta, K., Gschwendtner, M., Heid, A., Issler, M., Mohrg, N., Soller, H., Zemmel, R., & Zhang, A. (2024). Steady progress in approaching the quantum advantage. https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20in sights/steady%20progress%20in%20approaching%20the%20quantum%20advantage/steadyprogress-in-approaching-the-quantum-advantage.pdf (page 4)(accessed 27 July 2024);

World Economic Forum, IBM, & SandBoxAQ. (2024). Quantum Economy Footprint. (page 8) https://www3.weforum.org/docs/WEF_Quantum_Economy_Blueprint_2024.pdf (accessed 27 July 2024)

20 McKinsey Digital. (2024a). Quantum Technology Monitor. https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20in sights/steady%20progress%20in%20approaching%20the%20quantum%20advantage/quantumtechnology-monitor-april-2024.pdf?shouldIndex=false (page 4)(accessed 27 July 2024)

21 McKinsey Digital . (2024, April 24). Steady progress in approaching quantum advantage | McKinsey. www.mckinsey.com. https://www.mckinsey.com/capabilities/mckinsey-digital/ourinsights/steady-progress-in-approaching-the-quantum-advantage (accessed 06 September 2024)

22 Resonance. (2024, September 13). The Quantum Insider Projects $1 Trillion in Economic Impact From Quantum Computing by 2035. The Quantum Insider. https://thequantuminsider.com/2024/09/13/the-quantum-insider-projects-1-trillion-in-economicimpact-from-quantum-computing-by-2035/ (accessed 16 September 2024)

23 CIFAR, (2021), A Quantum Revolution: Report on Global Policies for Quantum Technology, https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf (accessed 26 July 2024); complemented by GESDA data

24 Ibid.

25 QED-C, QED-C website, https://quantumconsortium.org/ (accessed 26 July 2024)

26 QIC, QIC website, https://www.quantumindustrycanada.ca/ (accessed 25 July 2024)

27 QuIC, QuIC website, https://www.euroquic.org/ (accessed 25 July 2024)

28 Q-STAR, Q-STAR website, https://qstar.jp/en (accessed 25 July 2024)

29 Tomasetti, A. (2023, January 31). Quantum consortia QIC, QED-C, Q-STAR and QuIC form international council to enable and grow the global quantum industry | QED-C. https://quantumconsortium.org/quantum-consortia-qic-qed-c-q-star-and-quic-form-internationalcouncil-to-enable-and-grow-the-global-quantum-industry/ (accessed 01 August 2024)

30 Kearny Report (2023), The rise of national quantum strategies, https://www.kearney.com/industry/aerospace-defense/article/-/insights/the-rise-of-nationalquantum-strategies (accessed 02 August 2024)

31 United States Government, website, Enhancing competitiveness, https://www.quantum.gov/competitiveness/#INTERNATIONAL-COOPERATION (accessed 02 August 2024); Parker, Edward, Promoting Strong International Collaboration in Quantum Technology Research and Development, RAND Corporation (PE-A1874-1), 2023 (accessed 16 August 2024)

32 The Swiss Federal Council (2022), The United States and Switzerland Sign Joint Statement to Strengthen Collaboration on Quantum, https://www.admin.ch/gov/en/start/documentation/mediareleases.msg-id-90775.html, (accessed 02 August 2024); United Kingdom Government (2022), UK signs major science co-operation agreement with Switzerland, https://www.gov.uk/government/news/uk-signs-major-science-co-operation-agreement-withswitzerland (accessed 02 August 2024)

33 Swayne, M. (2024, March 25). UK, Germany Say Agreement Will Boost Scientific Partnerships in Quantum, AI. The Quantum Insider. https://thequantuminsider.com/2024/03/25/uk-germany-sayagreement-will-boost-scientific-partnerships-in-quantum-ai/ (accessed 16 August 2024)

34 Entanglement Exchange, https://entanglementexchange.org/ (accessed 02 August 2024)

35 Ibid.

36 Stewart, U., AI can help to bridge the digital divide and create and inclusive society, ITU, https://aiforgood.itu.int/ai-can-help-to-bridge-the-digital-divide-and-create-an-inclusivesociety/(accessed 02 August 2024); Vecchione, M., (2020) Using 'reverse innovation' to harness the power of AI for Good, ITU, https://www.itu.int/hub/2020/04/using-reverse-innovation-to-harness-thepower-of-ai-for-good/ (accessed 02 August 2024); Hamdar, Y., Ngodup Massally, K., Peiris, G., (2023) Are countries ready for AI? How they can ensure ethical and responsible adoption, UNDP, https://www.undp.org/blog/are-countries-ready-ai-how-they-can-ensure-ethical-and-responsibleadoption(accessed 02 August 2024); OECD (2022), Harnessing the power of AI and emerging technologies: Background paper for the CDEP Ministerial meeting, OECD Digital Economy Papers, No. 340, OECD Publishing, Paris, https://doi.org/10.1787/f94df8ec-en (accessed 02 August 2024); UNESCO Report (2021), Recommendations on the Ethics of Artificial Intelligence, https://unesdoc.unesco.org/ark:/48223/pf0000381137 (accessed 02 August 2024)

37 Kop, M., Aboy, M., De Jong, E., Gasser, U., Minssen, T., Cohen, I. G., Brongersma, M., Quintel, T., Floridi, L., & Laflamme, R. (2023). 10 Principles for Responsible Quantum Innovation. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4475556 (accessed 06 August 2024)

38 UN Secretary-General, António Guterres, A Global Digital Compact, an Open, Free and Secure Digital Future for All – Policy Brief, United Nations, https://www.un.org/sites/un2.un.org/files/ourcommon-agenda-policy-brief-gobal-digi-compact-en.pdf (accessed 02 August 2024)

39 Cf. chapter, 'A point of departure for quantum computing.'

40 These industry associations include the international level, e.g., the International Council of Quantum Industry Associations, https://qt.eu/news/2023/2023-02-02_international-quantumindustry-councils-formally-joining-forces-for-the-development-of-quantum-technologies, the regional level, e.g., European Quantum Industry Consortium https://www.euroquic.org/, the national level, e.g., QED-C | The Quantum Economic Development Consortium, https://quantumconsortium.org/, or the Quantum Ecosystems and Technology Council of India, https://qetci.org/ (accessed 04 August 2024)

41 UNICEF and ITU, Giga., Giga website, https://giga.global/map/ (accessed 29 August 2023); Facebook initiative, Internet.org., Internet.org website, https://about.meta.com/ (accessed 29 July 2024)

42 UNESCO. (2024, June 7). International Year of Quantum Science and Technology. Quantum2025.org. https://quantum2025.org/en/ (accessed 16 August 2024)

43 Microsoft, (2023), Azure Quantum Pricing, https://learn.microsoft.com/enus/azure/quantum/pricing?tabs=tabid-AQcredits%2Ctabid-AQcreditsQ%2CtabidAQcreditsRigetti%2Ctabid-learndevelop (accessed 05 August 2024)

44 IBM, Access Awards, https://quantum-computing.ibm.com/programs/researchers (accessed 06 August 2024)

45 Nvidia Developer. (2024a). CUDA-Q. NVIDIA Developer. https://developer.nvidia.com/cuda-q (accessed 16 August 2024)

46 The European High Performance Computing Joint Undertaking (EuroHPC JU). (n.d.). Leading the Way in European Supercomputing. Eurohpc-Ju.europa.eu. https://eurohpc-ju.europa.eu/index_en (accessed 16 August 2024)

47 UK National Quantum Computing Centre. (n.d.). National Quantum Computing Centre. https://www.nqcc.ac.uk/ (accessed 16 August 2024)

48 AIST, & G-QuAT. (2024). Global Research and Development Center for Business by Quantum-AI technology (G-QuAT). https://unit.aist.go.jp/g-quat/index_en.html (accessed 16 August 2024) 49 Israeli Quantum Computing Center by Quantum Machines. (2024, June 26). Home - IQCC. IQCC. https://i-qcc.com/ (accessed 16 August 2024)

50 GESDA (2022), Quantum Computing, Impact Story, https://gesda.global/wp-content/uploads/2022/09/GESDA-Quantum-Computing-Impact-Story-Apr2022-1.pdf (accessed 19 August 2024)

51 GESDA Solutions GESDA Solution Idea . (2022). Open Quantum Institute - SDG Use Cases. https://open-quantum-institute.web.cern.ch/wp-content/uploads/2023/10/GESDA_OQI_UseCases_WhitePaper2022.pdf (accessed 16 August 2024); Solution GESDA, GESDA Idea. (2023). Open Quantum Institute - SDG Use Cases White Paper 2023. https://oqi.gesda.global/wp-content/uploads/2023/10/GESDA_OQI_WP1-WhitePaper2023_final_versionPDF.pdf (accessed 16 August 2024)
Open Quantum Institute. (2022). Applications https://open-quantum-institute.cern/applications/ (accessed 29 August 2024)

52 Xprize. (n.d.). Quantum Applications XPRIZE. XPRIZE. https://www.xprize.org/prizes/qc-apps (accessed 16 August 2024); Wellmann, B., & Deloitte. (2024, March 7). Deloitte's Quantum Climate Challenge. Deloitte Deutschland. https://www2.deloitte.com/de/de/pages/innovation/contents/deloitte-quantum-climatechallenge.html (accessed 16 August 2024); GenQ Quantum Computing Hackathon — QAI Ventures. (2024, October 4). QAI Ventures. QAI Ventures. https://qai-ventures.com/events-agenda/2406genqhackathon (accessed 16 August 2024); Wellcome Leap (2023), Quantum for Bio, https://wellcomeleap.org/q4bio/ (accessed 29 August 2023); University of Calgary (2023), Energy Case Transition Competition, https://innovatecalgary.com/events/energy-transition-casecompetition/ (accessed 05 August 2024); Pasqal (2023), The Blaise Pascal [Re]generative Quantum Challenge, https://pasqal-quantum-challenge.bemyapp.com/ (accessed 05 August 2024); QunaSys. (2023), QunaSys begins effort to utilize quantum technology to contribute to society, https://qunasys.com/news/posts/230714jp/ (accessed 05 August 2024)

53 De la Rie, J., (2023), The Centre for Quantum & Society releases its Exploratory Quantum Technology Assessment Tool, Quantum Delta NL, https://quantumdelta.nl/news/the-centre-forquantum-society-releases-its-exploratory-quantum-technology-assessment-tool (accessed 06 August 2024)

54 WEF Insight Report, (2022), Quantum Computing Governance Principles, https://www3.weforum.org/docs/WEF_Quantum_Computing_2022.pdf (accessed 06 August 2024)

55 US Department of Homeland Security, & CISA - Cybersecurity, Infrastructure Security Agency. (2021, October) Preparing for Post-Quantum Cryptography Prioritization of Systems for Replacement. https://www.dhs.gov/sites/default/files/publications/post-quantum_cryptography_infographic_october_2021_508.pdf (accessed 15 April 2024)

56 European Committee for Standardization. (n.d.). CEN-CENELEC https://www.cencenelec.eu/aboutcen/ (accessed 05 June 2024); ENISA. (2021, May). Post Quantum Cryptography. Current state and quantum mitigation. CEN-CENELEC.(accessed 06 June 2024); European Commission. (2024, April 11). Recommendation on a Coordinated Implementation Roadmap for the transition to Post-Quantum Cryptography | Shaping Europe's digital future. https://digital-strategy.ec.europa.eu/en/library/recommendation-coordinated-implementation-roadmaptransition-post-quantum-cryptography

57 Monetary Authority of Singapore. (2024, February 20). Advisory on addressing the cybersecurity risks associated with quantum https://www.mas.gov.sg/-/media/mas-media-library/regulation/circulars/trpd/mas-quantum-advisory/mas-quantum-advisory.pdf (accessed 14 May 2024)

58 Australian Signals Directorate. (2023). Information Security Manual (ISM) | Cyber.gov.au. Cyber.gov.au. https://www.cyber.gov.au/resources-business-and-government/essential-cybersecurity/ism (accessed 07 May 2024)

59 Australian Government - Australian Signal Directorate. (2023, August 25). Planning for PostQuantum Cryptography | Cyber.gov.au. Cyber.gov.au. https://www.cyber.gov.au/resources-businessand-government/governance-and-user-education/governance/planning-post-quantumcryptography(accessed 07 May 2024)

60 Canada, G. A. (2024, June 19). Notice to exporters No. 1129 – Amendment to the Export Control List: Quantum computing and advanced semiconductors. GAC. https://www.international.gc.ca/tradecommerce/controls-controles/notices-avis/1129.aspx?lang=eng (accessed 07 August 2024)

61 Elias X. Huber. (2024). Technology Controls to Contain China's Quantum Ambitions Are Here. Lawfare. https://www.lawfaremedia.org/article/technology-controls-to-contain-china-s-quantumambitions-are-here (accessed 06 September 2024)

62 World Economic Forum. (2022, January 19). Quantum Computing Governance Principles. World Economic Forum. https://www.weforum.org/publications/quantum-computing-governanceprinciples/ (accessed 03 September 2024)

63 Roukos, M. (2023, August 16). IBM's dedication to responsible computing. IBM Blog; Security Intelligence. https://www.ibm.com/blog/ibms-dedication-to-responsible-computing/ (accessed 03 September 2024)

64 Government of the U.K. - Department of Science, Innovation and Technology. (n.d.). National Quantum Strategy. GOV.UK. https://www.gov.uk/government/publications/national-quantumstrategy/national-quantum-strategy-accessible-webpage (accessed 03 September 2024)

65 Australian Government. A trusted, ethical and inclusive quantum ecosystem. https://www.industry.gov.au/publications/national-quantum-strategy/themes-national-quantum-strategy/theme-5-trusted-ethical-and-inclusive-quantum-ecosystem (accessed 03 September 2024)

66 Microsoft Blog (2023), Building a quantum-safe future, https://blogs.microsoft.com/blog/2023/05/31/building-a-quantum-safe-future/ (accessed 6 September 2023)https://about.meta.com/

67 International Electrotechnical Commission. (2024). IEC. https://www.iec.ch/dyn/www/f?p=103:7:::::FSP_ORG_ID:49854 (accessed 16 August 2024)

68 ISO, IEC, (2022), ISO/IEC JTC 1/WG 14 Quantum Information Technology, https://jtc1info.org/sd-2-history/jtc1-working-groups/wg-14/ (accessed 11 August 2024)

69 CEN-CENELEC, Quantum Technologies, https://www.cencenelec.eu/areas-of-work/cen-cenelectopics/quantum-technologies/ (accessed 30 August 2024)

70 IEEE SA, Quantum Standards & Activities, https://standards.ieee.org/practices/foundational/quantum-standards-activities/ (accessed 15 August 2024)

71 Standards Association. (2024, June 18). Standardization Roadmap on Quantum Applications. IEEE Standards Association. https://standards.ieee.org/industry-connections/activities/standardizationroadmap-on-quantum-applications/ (accessed 16 August 2024)

72 Parker, E., Gonzales, D., Kochhar, A. K., Litterer, S., O'Connor, K., Schmid, J., Scholl, K., Silberglitt, R., Chang, J., Eusebi, C. A., & Harold, S. W. (2022, February 2). An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology https://www.rand.org/pubs/research_reports/RRA8691.html (accessed 16 August 2024)

73 Lee, M.-H. (2023). GTG Policy White Paper A Framework for Assessing Vulnerabilities in the Quantum Computing Materials Supply Chain October 2023. https://fsi9-prod.s3.us-west-1.amazonaws.com/s3fs-public/2023-11/2023-10-27_-_minha_lee_-_quantum_computing_mapping_supply_chain_vulns_final.pdf (accessed 28 March 2024)

74 Mans, U., Rabbie, J., & Hopman, B. (2023). Critical raw materials for quantum technologies. Towards European technology sovereignty in an emerging industry. https://assets.quantum-delta.prod.verveagency.com/assets/white-paper-crms-for-qt-1709556206.pdf (accessed 08 April 2024)

75 Ibid.

76 European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Grohol, M., Veeh, C.,Study on the critical raw materials for the EU 2023 – Final report, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2873/725585 (accessed 08 April 2024)

77 Das, S., Ghosh, S., & Chatterjee, A. (2023). A First Order Survey of Quantum Supply Dynamics and Threat Landscapes. https://arxiv.org/pdf/2308.09772 (accessed 08 April 2024)

78 Lee, M.-H. (2023). GTG Policy White Paper A Framework for Assessing Vulnerabilities in the Quantum Computing Materials Supply Chain October 2023. https://fsi9-prod.s3.us-west1.amazonaws.com/s3fs-public/2023-11/2023-10-27_-_minha_lee_-_quantum_computing_mapping_supply_chain_vulns_final.pdf (accessed 08 April 2024)

79 Mans, U., Rabbie, J., & Hopman, B. (2023). Critical raw materials for quantum technologies. Towards European technology sovereignty in an emerging industry. https://assets.quantum-delta.prod.verveagency.com/assets/white-paper-crms-for-qt-1709556206.pdf (accessed 08 April 2024)

80 Ibid.

81 QEDC. (2023, September). Tracking the global supply chain https://quantumconsortium.org/framework23/ (accessed 15 July 2024)

82 QUIC - European Quantum Industry Consortium. (2024). Strategic Industry Roadmap (SIR). https://www.euroquic.org/wp-content/uploads/2024/02/PUBLIC-version-Strategic-Industry-Roadmap-2024.pdf (accessed 15 July 2024)

83 Matthew Sparkes. (2024, July 3). Multiple nations enact mysterious export controls on quantum computers. New Scientist. https://www.newscientist.com/article/2436023-multiple-nations-enactmysterious-export-controls-on-quantum-computers/?fbclid=IwY2xjawD_GEdleHRuA2FlbQIxMQABHUH9jQV_tYy6XJsK0_cwAhdhilpYvPHOdVsxyc9bjT36FsQMm-mM7jEdQ_aem_OMTDd2Z448SQ5YoRGcNmrw&sfnsn=scwspmo (accessed 15 July 2024)

84 Swayne, M. (2024, February 26). France Advances Quantum Technology Export Controls under New EU Regulation Framework. The Quantum Insider.(access date: July 2024) https://thequantuminsider.com/2024/02/26/france-advances-quantum-technology-export-controlsunder-new-eu-regulation-framework/ (accessed 15 July 2024)

85 Canada, G. A. (2024). Notice to exporters No. 1129 – Amendment to the Export Control List: Quantum computing and advanced semiconductors. GAC. https://www.international.gc.ca/tradecommerce/controls-controles/notices-avis/1129.aspx?lang=eng (accessed 15 July 2024)

86 Baker, B. (2024, March 14). UK Cracks Down on Quantum Computer Exports. Enter Quantum; IOT World today. https://www.iotworldtoday.com/quantum/uk-cracks-down-on-quantum-computerexports (accessed 15 July 2024)

87 Bureau of Industry & Security, U.S. Department of Commerce. (2024, May 9). Commerce Adds 37 PRC Entities to Entity List for Enabling PRC Quantum and Aerospace Programs, Aiding Russian Aggression in Ukraine | Bureau of Industry and Security. Bis.gov. https://www.bis.gov/pressrelease/commerce-adds-37-prc-entities-entity-list-enabling-prc-quantum-and-aerospace-programs (accessed 16 August 2024)

88 State Secretariat for Education, Research and Innovation. (2022). The United States and Switzerland Sign Joint Statement to Strengthen Collaboration on Quantum. www.admin.ch. https://www.admin.ch/gov/en/start/documentation/media-releases.msg-id-90775.html (accessed 15 July 2024)

89 U.S. Department of Commerce. (2022, May). Indo-Pacific Economic Framework. U.S. Department of Commerce https://www.commerce.gov/ipef (accessed 22 August 2024)

90 European Commission. (2023, December 6). European Declaration on Quantum Technologies | Shaping Europe's digital future. Digital-Strategy.ec.europa.eu. https://digital-strategy.ec.europa.eu/en/library/european-declaration-quantum-technologies (accessed 22 August 2024)

91 Lee, M.-H. (2023). GTG Policy White Paper A Framework for Assessing Vulnerabilities in the Quantum Computing Materials Supply Chain October 2023. https://fsi9-prod.s3.us-west-1.amazonaws.com/s3fs-public/2023-11/2023-10-27_-_minha_lee_-_quantum_computing_mapping_supply_chain_vulns_final.pdf (accessed 15 July 2024)

92 European Commission. (2024, March 21). Raw materials diplomacy - European Commission. Single-Market-Economy.ec.europa.eu. https://single-market-economy.ec.europa.eu/sectors/rawmaterials/areas-specific-interest/raw-materials-diplomacy_en (accessed 15 July 2024)

93 UN Trade & Development. (2024, July 10). Digital Economy Report 2024. UNCTAD. https://unctad.org/publication/digital-economy-report-2024 (accessed 07 August 2024)

94 Fellous-Asiani, M., Chai, J. H., Thonnart, Y., Ng, H. K., Whitney, R. S., & Auffèves, A. (2022). Optimizing resource efficiencies for scalable full-stack quantum computers. ArXiv (Cornell University). https://doi.org/10.48550/arXiv.2209.05469 (accessed 6 August 2024); Meier, F., & Yamasaki, H. (2023). Energy-Consumption Advantage of Quantum Computation. https://arxiv.org/pdf/2305.11212 (accessed 07 August 2024)

95 Q4Climate. (n.d.). Q4Climate - The union of quantum and climate research. Q4climate.github.io. https://q4climate.github.io/ (accessed 16 August 2024)

96 QEI, (2023), Manifesto archive, https://quantum-energy-initiative.org/manifesto-archive/ (accessed 5 August 2024)

97 IEEE SA, IEEE P3329 Quantum Energy Initiative (QEI) Working Group, https://sagroups.ieee.org/qei/#:~:text=IEEE%20P3329%20Quantum%20Energy%20Initiative%20Working%20Group&text=Scope%3A%20This%20standard%20defines%20energy,computation%20to%20it s%20energy%20consumption (accessed 5 August 2024)

98 Life Cycle Initiative, UNDP, Life Cycle website, https://www.lifecycleinitiative.org/ (accessed 5 August 2024)

99 CEET, UNIDO and SDSN, CEET website, https://www.unsdsn.org/ceet (accessed 5 August 2024)

100 UNFCCC Global Innovation Hub, UN, UNFCCC website https://unfccc.int/topics/un-climatechange-global-innovation-hub (accessed 5 August 2024)

101 Leprince-Ringuet, D. (2021, August 2). Quantum computing's next big challenge: A quantum skills shortage. ZDNet. https://www.zdnet.com/article/quantum-computings-next-challenge-findingquantum-developers-and-fast/ (accessed 06 September 2024)

102 McKinsey Digital. (2024). Quantum Technology Monitor. https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20in sights/steady%20progress%20in%20approaching%20the%20quantum%20advantage/quantumtechnology-monitor-april-2024.pdf?shouldIndex=false (accessed 06 Spetember 2024)

103 Ibid.

104 McKinsey Digital. (2022, December 1). Closing the quantum workforce gap: Lessons from AI | McKinsey. Www.mckinsey.com. https://www.mckinsey.com/capabilities/mckinsey-digital/ourinsights/five-lessons-from-ai-on-closing-quantums-talent-gap-before-its-too-late (accessed 06 September 2024)

105 International Labour Organization. (2023, October 11). Generative AI and Jobs: Policies to Manage the Transition | International Labour Organization. Www.ilo.org. https://www.ilo.org/publications/generative-ai-and-jobs-policies-manage-transition (accessed 06 September 2024)

106 Alkire, S. (2005). Subjective quantitative studies of human agency. Social Indicators Research, 74(2), 217-260. https://doi.org/10.1007/s11205-005-6525-0 (accessed 22 August 2024)

107 Cousins, K. C., & Robey, D. (2005). Human agency in a wireless world: Patterns of technology use in nomadic computing environments. Information and Organization, 15(2), 151-180. https://doi.org/10.1016/j.infoandorg.2005.02.008(accessed 22 August 2024)

108 Colomy, P. (1998). Neofunctionalism and neoinstitutionalism: Human agency and interest in institutional change.Sociological Forum, 13(2), 265-300. http://www.jstor.org/stable/684885

109 Atmanspacher, H. (2024). Quantum approaches to consciousness. In E. N. Zalta & U. Nodelman(Eds.), The Stanford Encyclopedia of Philosophy (Summer 2024 Edition) https://plato.stanford.edu/archives/sum2024/entries/qt-consciousness/(accessed 22 August 2024)

110 Zhi, G., & Xiu, R. (2023). Quantum theory of consciousness. Journal of Applied Mathematics and Physics, 11(9), 2652-2670 https://doi.org/10.4236/jamp.2023.119174 (accessed 22 August 2024)

111 Goering, S., Brown, T., & Klein, E. (2021). Neurotechnology ethics and relational agency. Philosophy Compass, 16(4), e12734. https://doi.org/10.1111/phc3.12734 (accessed 22 August 2024)

112 United Nations Development Programme. (2023-2024). Human development report 2023-24. pp. 5-7. https://hdr.undp.org/system/files/documents/global-report-document/hdr2023-24reporten.pdf(accessed 22 August 2024)

113 Ten Holter, C., Inglesant, P., & Jirotka, M. (2021). Reading the road: challenges and opportunities on the path to responsible innovation in quantum computing. Technology Analysis & Strategic Management, 35(7), 844–856. https://doi.org/10.1080/09537325.2021.1988070 (accessed 06 September 2024).

114 Mandelbaum & Wolf-Bauwens (2024). The era of quantum utility must also be the era or responsible quantum computing. IBM Research blog. Available at: https://www.ibm.com/quantum/blog/responsible-quantum (accessed 06 September 2024). Troyer (2024) Responsible computing and accelerating scientific discovery across HPC, AI, and Quantum. Azure Quantum blog. Available at at: https://azure.microsoft.com/enus/blog/quantum/2024/03/05/responsible-computing-and-accelerating-scientific-discovery-acrosshpc-ai-and-quantum/ (accessed 06 September 2024)

115 OECD (2023). "Emerging technology governance: Towards an anticipatory framework", in OECD Science, Technology and Innovation Outlook 2023: Enabling Transitions in Times of Disruption, OECD Publishing, Paris, https://doi.org/10.1787/d67d5380-en. (accessed 06 September 2024)

116 One of these participatory approaches is currently under way in the Canda, called Stimules Quantum Dialogues, PI: Isabelle Lacroix (Universite de Sherbrooke).

117 Ref 63 & Ref 62

118 National Quantum Computing Center. (2024, January 4). Responsible Quantum Industry Forum 2024 - NQCC. NQCC. https://www.nqcc.ac.uk/events/responsible-quantum-industry-forum-2024/ (accessed 06 September 2024)

119 GESDA, Science Breakthrough Radar, https://radar.gesda.global/ (accessed 23 August 2024)

120 GESDA developed its own methodology, the Anticipatory Situation Room: GESDA, GESDA Solutions, https://gesda.global/solutions/ (accessed 26 September 2023)

121 OQI 2022 Use Case White Paper, https://open-quantum-institute.web.cern.ch/wpcontent/uploads/2023/10/GESDA_OQI_Use-Cases_WhitePaper2022.pdf (accessed 15 August 2024)

122 OQI 2023 Use Case White Paper, https://open-quantum-institute.web.cern.ch/wpcontent/uploads/2023/10/GESDA_OQI_WP1-WhitePaper2023_final_versionPDF.pdf (accessed 15 August 2024)

123 OQI 2024 Use Case White Paper, https://open-quantum-institute.cern/applications/ (accessed 31 August 2024)

124 European Commission. (2023). CRITICAL INFRASTRUCTURE PROTECTION & RESILIENCE - Study on the Critical Raw Materials for the EU 2023. Europa.eu. pg.9,10 https://ec.europa.eu/newsroom/cipr/items/787007/en (accessed 28 August 2024) 125U.S. Department of the Interior - U.S. Geological Survey. (2024). MINERAL COMMODITY SUMMARIES 2024. https://pubs.usgs.gov/periodicals/mcs2024/mcs2024.pdf (accessed 28 August 2024)