Intelligence Report on the multilateral governance of quantum computing for the SDGs.

*Developed during the incubation phase of **the Open Quantum Institute.***

Foreword

Quantum computing has been identified by the Geneva Science and Diplomacy Anticipator (GESDA) community as one key area for anticipatory science diplomacy. By the end of the decade, quantum computers are expected to be mature enough to be deployed for real-world applications, with potentially vast impact on all areas of human security, development, and well-being.

Quantum computing exploits quantum mechanics – the laws of physics that govern the behavior of matter at the microscopic level. This is a complete change of paradigm in the way computation has been practiced by humanity so far. For specific applications, quantum computers might, in principle, solve problems that are today intractable by conventional computers, providing unprecedented accuracy or computational speed-ups, and thus revolutionizing critical sectors for our economies.

GESDA was created to anticipate such future technological breakthroughs. GESDA's aim as an honest broker is to provide a neutral platform to reflect on how future breakthroughs will impact people, society and the planet, so that we can purposefully create the conditions for the use of the technology to best benefit mankind. By using the future to build the present, we enable human agency, and develop the multilateral governance frameworks to be fit for purpose for when the technology reaches effectively society.

Since 2021, GESDA has been curating a diplomatic dialogue on quantum computing with the permanent representations in Geneva, together with inputs from U.N. international organizations, the private sector, and academia. In 2023, this group created the basis for common understandings on the state-of-play of multilateral governance themes most relevant to quantum computing (e.g., standardization, safety and security, the digital divide).

The framing of the exercise was provided by the Sustainable Development Goals and the conviction that science and diplomacy must work together to ensure that scientific and technological breakthroughs benefit all of humanity. The discussion took place as part of the initial incubation phase of the Open Quantum Institute[1], GESDA's most advanced science diplomacy initiative.

The diplomatic representations involved wish to share this initial informal work with peers, so that more countries can be involved in the discussions and contribute to the shaping of innovative approaches for future governance frameworks of quantum computing.

My hope is that the present report, published on the occasion of the 2023 GESDA Summit, will foster such contributions from colleagues and catalyze further dialogue and action by both the quantum computing and science diplomacy communities.

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Swiss State Secretary for Foreign Affairs
Chair of GESDA Diplomatic Forum 2022-2023

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[1] *Cf.* Annex 1., '*From science to solution: an Open Quantum Institute (OQI)*'

Setting the scene for quantum computing

Quantum computers are a complete change of paradigm in the way computation has been practiced so far. The precise manner in which the technology works can seem rather abstract,[2] but key takeaways can be summarized as:

- Quantum computing, like other quantum technologies (e.g., quantum sensing, quantum communication), leverages quantum phenomena, such as superposition, where a quantum entity's physical properties remain undefined until they are measured, creating an entirely novel mechanism for encoding information, and entanglement superposition, and entanglement, where quantum entities have intertwined properties that mean action on one entity instantly affects the outcome of future actions on its entangled twin, even when they are physically separated. Quantum information is stored and processed in "qubits" that operate in a different capacity than their classical equivalent, "bits", and hold the promise for unprecedent performance improvements with specific computational problems.[3]

- The exact nature of these problems is not yet well understood. However, there is a consensus in the quantum community that quantum computing holds an advantage over classical computing for problems related to material science or chemistry (which requires simulating the quantum behavior of matter on quantum computers). 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 (R&D) must be pursued in the building of larger-scale and more 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, and multiple hardware modalities are being tested. Many large companies are developing superconducting qubits, while others pursue other promising modalities of qubits based on trapped ions, cold atoms, photonics, silicon, and diamonds. Each of these hardware modalities has pros and cons; it is too early to identify which approach will lead to the best overall performance.

- While advancements in a pre-fault-tolerant era have been recently reported[4], quantum computers are still small scale and unreliable. Further technological development is needed to reach the goal of a quantum advantage: outperforming conventional computing in terms of execution, speed, accuracy, or energy efficiency when handling real-world relevant problems.

- The aim is to find reliable ways to create more, and more 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 and various error-correction protocols are being investigated to ensure that quantum processors become more resilient and stable over a long period of time.

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[2] Cf. Annex 1., '*From science to solution: an Open Quantum Institute (OQI)*'
[3] Cf. Annex 3., '*How quantum computing works*', based on GESDA (2022), *Quantum Computing, Impact Story*, https://gesda.global/wp-content/uploads/2022/09/GESDA-Quantum-Computing-Impact-Story-Apr2022-1.pdf (accessed 29 August 2023)
[4] 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 14 September 2023)

- 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 continue to exist 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 to classical computers, traditional algorithms are not directly transferable to quantum computing. As a result, a range of quantum algorithms are being developed to perform computational tasks, such as quantum simulation[5] and factorization, as well as quantum-inspired optimization[6], and machine learning.

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 development of quantum computing requires significant investment. The timeline to bring quantum computing to full maturity is relatively long (decades) compared to other technology development cycles, so sustained, long-term investment is required.

- Governments are the main drivers behind quantum R&D and their nascent national industries, investing an estimated $25-30 billion in quantum technologies (including quantum computing, sensing, communication) in 2022, mostly in North America, the Asia-Pacific region and Europe[7].

- In addition to public funding, private investment continues to rise and to support the growing number of quantum computing start-ups across the globe (also mostly in North America, the Asia-Pacific region and Europe). For instance, investment in quantum computing software companies increased to $764 million (2020-2021), up from $440 million (2010-2019)[8].

- Quantum computing is estimated to create $450 billion to $850 billion in value over the next 15-30 years[9]. The latest forecasts project customer spend for quantum computing to grow from $1.1 billion in 2022 to $7.6 billion in 2027[10]. Among the first end-users to test quantum computing are the financial, pharmaceutical, energy and automotive industries[11].

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[5] Many chemical and biological processes play out 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.

[6] 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.

[7] The Quantum Insider, (2023), *Technology Investment Update,* https://thequantuminsider.com/wp-content/uploads/2023/02/Quantum-Technology-Investor-Update_vFF.pdf (accessed 3 September 2023)
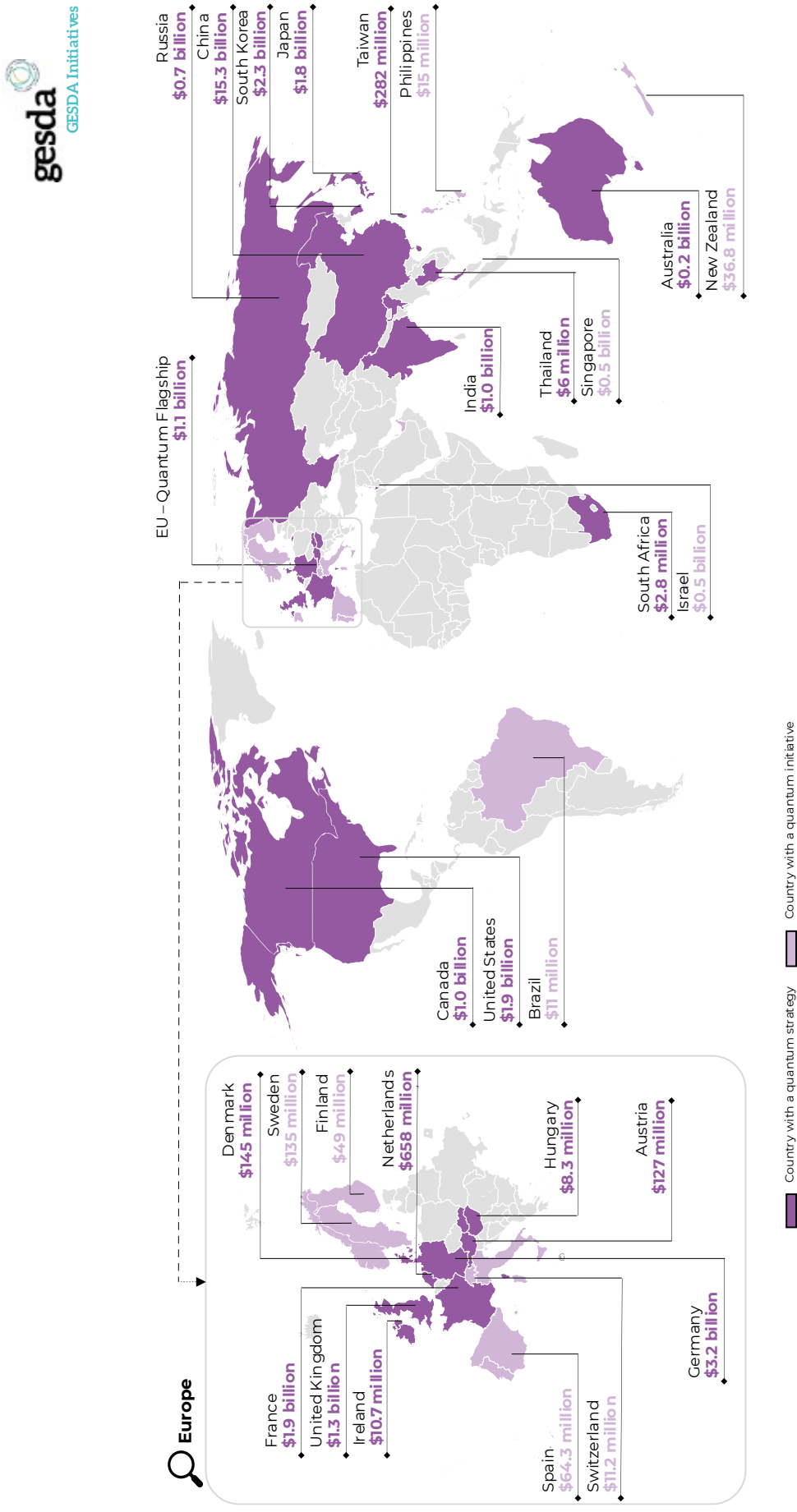
[8] WEF Insight Report, (2022), *State of Quantum Computing: Building a Quantum Economy*, https://www3.weforum.org/docs/WEF_State_of_Quantum_Computing_2022.pdf (accessed 5 September 2023)

[9] Boston Consulting Groups (2021)*, What Happens When 'If' Turns to 'When' in Quantum Computing?* https://www.bcg.com/publications/2021/building-quantum-advantage (accessed 3 September 2023)

[10] International Data Corporation (IDC), (2023), *IDC Forecasts Worldwide Quantum Computing Market to Grow to $7.6 Billion in 2027*, https://www.idc.com/getdoc.jsp?containerId=prUS51160823 (accessed 26 September 2023)

[11] McKinsey & Company, (2023) *Quantum Technology Monitor*, https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20technology%20sees%20record%20investments%20progress%20on%20talent%20gap/quantum-technology-monitor-april-2023.pdf, (accessed 1 September 2023)

Map of global public investment in quantum technologies

gesda
GESDA Initiatives

Russia
$0.7 billion

China
$15.3 billion

South Korea
$2.3 billion

Japan
$1.8 billion

Taiwan
$282 million

Philippines
$15 million

Australia
$0.2 billion

New Zealand
$36.8 million

EU – Quantum Flagship
$1.1 billion

India
$1.0 billion

Thailand
$6 million

Singapore
$0.5 billion

South Africa
$2.8 million

Israel
$0.5 billion

Canada
$1.0 billion

United States
$1.9 billion

Brazil
$11 million

Europe

Denmark
$145 million

Sweden
$135 million

Finland
$49 million

Netherlands
$658 million

Hungary
$8.3 million

Austria
$127 million

France
$1.9 billion

United Kingdom
$1.3 billion

Ireland
$10.7 million

Germany
$3.2 billion

Spain
$64.3 million

Switzerland
$11.2 million

Country with a quantum strategy

Country with a quantum initiative

Country with a quantum strategy

Note: Not exhaustive; timelines for investment of funding vary by country; Cf. Annex 5 - *Overview of national quantum strategies/initiatives*, where data sources for funding is also provided (data compiled as of 13 September 2023)

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

▪ As of August 2023, at least 32 countries had some form of quantum national initiative or strategy[12]. The United Kingdom enacted the first one in 2014 and renewed it for ten years in 2023. The United States followed and adopted 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 as well as with regards to standardization initiatives that support national interests)[13].

▪ Where they differ usually has to do with 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 tech strategies); main drivers (research, industry or government); and the modality of their implementation (top-down or bottom-up approaches) and stage of development.

▪ Most national strategies support the establishment of national industry consortia to foster ecosystem coordination, fast-track technology transfers and accelerate the industrialization of sovereign quantum technologies. Such quantum industry consortia are, for instance, QED-C in the U.S.[14], QIC in Canada[15], QuIC in Europe[16], and Q-STAR in Japan[17].

▪ International cooperation on R&D efforts remain mostly at the bilateral level[18]. Some examples of bilateral agreements can be found among the U.S.[19], Switzerland[20], the Netherlands[21], India[22], South Korea[23], and Japan[24].

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[12] 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 1 September 2023) and GESDA data

[13] 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 1 September 2023)

[14] QED-C, *QED-C website*, https://quantumconsortium.org/ (accessed 5 September 2023)

[15] QIC, *QIC website*, https://www.quantumindustrycanada.ca/ (accessed 13 September 2023)

[16] QuIC, *QuIC website*, https://www.euroquic.org/ (accessed 5 September 2023)

[17] Q-STAR, *Q-STAR website*, https://qstar.jp/en (accessed 5 September 2023)

[18] Kearny Report (2023), *The rise of national quantum strategies*, https://www.kearney.com/industry/aerospace-defense/article/-/insights/the-rise-of-national-quantum-strategies (accessed 6 September 2023)

[19] United States Government, website, *Enhancing competitiveness*, https://www.quantum.gov/competitiveness/#INTERNATIONAL-COOPERATION (accessed 6 September 2023)

[20] 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/media-releases.msg-id-90775.html, (accessed 6 September 2023); 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-with-switzerland (accessed 6 September 2023)

[21] Government of the Netherlands, (2023), *Joint declaration – Government Consultations Netherlands – France.*, https://www.government.nl/documents/diplomatic-statements/2023/04/12/joint-declaration---government-consultations-netherlands---france-12-april-2023 (accessed 6 September 2023)

[22] Government of India, (2023), *India and the United States today jointly launched a call for proposals on Critical and Emerging Technology: Quantum Technologies and Artificial Intelligence for Transforming Lives*, https://dst.gov.in/india-and-united-states-today-jointly-launched-call-proposals-critical-and-emerging-technology (accessed 6 September 2023)

[23] United States Government, (2023), *Joint Statement of the United States of America and Republic of Korea on Cooperation in Quantum Information Science and Technologies.*, https://www.state.gov/joint-statement-of-the-united-states-of-america-and-republic-of-korea-on-cooperation-in-quantum-information-science-and-technologies/ (accessed 6 September 2023)

[24] United Kingdom Government, (2023), *Joint Statement between DSIT and METI of Japan on Semiconductors Partnership.*, https://www.gov.uk/government/publications/uk-japan-semiconductors-partnership-joint-statement/joint-statement-between-department-for-science-innovation-and-technology-and-ministry-of-economy-trade-and-industry-of-japan-on-semiconductors-partn (accessed 6 September 2023)

- At the multilateral level, initiatives have been nascent. Closed groups involving like-minded countries that align their roadmaps and discuss internal cooperation have been recently emerging. For instance, in May 2022, representatives of 12 countries attended a roundtable meeting on 'Pursuing Quantum Information Together' in Washington, D.C. This was followed by another meeting in November 2022 on 'Progressing Multilateral Dialogue on Quantum.' 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)[25].

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

ACCESS – 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[26]. These inequalities exist between countries, regions, and specific populations according to age, gender, and socioeconomic factors. At the multilateral level, the U.N. Secretary-General's call to develop a Global Digital Compact[27] 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[28]. 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 put to use in conjunction with conventional computing without further adjustments, it could very likely amplify these existing unbalances. 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

[25] Entanglement Exchange, https://entanglementexchange.org/ (accessed 5 September 2023)

[26] 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-inclusive-society/ (accessed 1 September 2023); 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-the-power-of-ai-for-good/ (accessed 1 September 2023); 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-responsible-adoption (accessed 1 September 2023); 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 1 September 2023); UNESCO Report (2021), *Recommendations on the Ethics of Artificial Intelligence*, https://unesdoc.unesco.org/ark:/48223/pf0000381137

[27] 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/our-common-agenda-policy-brief-gobal-digi-compact-en.pdf (accessed 29 August 2023)

[28] Cf. Previous chapter, '*Setting the scene for quantum computing.*'

constituents. Some industry associations offer some level of information[29] but policymakers may need more help in being able to distinguish 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[30].

- Some quantum computing companies are setting up measures allowing selected users to use their devices for training purposes (e.g., Microsoft's first $500 in free credits[31]) or to conduct research projects (e.g., IBM's Researchers program[32]; OQC is also working on such a plan[33]). Public stakeholders are considering similar mechanisms for enabling access to the devices they fund. The European Union, for instance, is examining the possibility of providing access to some of its future quantum devices to a broader scope of users[34].

- All of the above measures have limitations and may not be sufficient. Broader geopolitical considerations and concerns over the dual-use nature of the technology (c.f. page 10 below) have prevented making these schemes available to certain geographies. Other barriers include a lack of information and limited duration for these measures, limitations in the volume of quantum computational power, and the practical difficulties in operating the 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. This 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 to accelerate their research[35] but these are mostly located in developed countries and the costs are prohibitive for some students.

- The proposal to name 2025 the International Year of Quantum Science and Technology will be taken up by at UNESCO this coming November and could accelerate efforts to accelerate more inclusive efforts through awareness-building, education, and outreach activities worldwide.

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[29] 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-quantum-industry-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 6 September 2023)

[30] UNICEF and ITU, Giga., *Giga website*, https://giga.global/map/ (accessed 29 August 2023); Facebook initiative, Internet.org., *Internet.org website*, https://www.internet.org/ (accessed 29 August 2023)

[31] Microsoft, (2023), *Azure Quantum Pricing*, https://learn.microsoft.com/en-us/azure/quantum/pricing?tabs=tabid-AQcredits%2Ctabid-AQcreditsQ%2Ctabid-AQcreditsRigetti%2Ctabid-learndevelop (accessed 6 September 2023)

[32] IBM, Access Awards, https://quantum-computing.ibm.com/programs/researchers (accessed 6 September 2023)

[33] The Quantum Insider, (2023), *OQC and CogniFrame Partner to Let Experts and Non-Experts Test Drive Quantum*, https://thequantuminsider.com/2023/07/31/oqc-and-cogniframe-partner-to-let-experts-and-non-experts-test-drive-quantum/ (accessed 6 September 2023)

[34] EuroHPC, (2023), *One step closer to European quantum computing: The EuroHPC JU signs hosting agreements for six quantum computers*, https://eurohpc-ju.europa.eu/one-step-closer-european-quantum-computing-eurohpc-ju-signs-hosting-agreements-six-quantum-computers-2023-06-27_en (accessed 1 September 2023)

[35] 50+ master's programs at the time of writing.

How the Open Quantum Institute (OQI) addresses this challenge

A core mission of the OQI is to provide future users with inclusive access to quantum machines so that no one is left behind in the quantum revolution.

Industry providers, and soon national institutions, are partnering with the OQI to donate time on quantum computers and simulators/emulators, which the OQI can grant to its target audiences.

In this way, the OQI provides access to a pool of quantum computers through the cloud that represents all the available technology modalities, profiles of providers (start-ups/ corporates) and geographies.

This offering is complemented by education and capacity-building that broadens inclusivity.

SDG APPLICATIONS – exploring real-world impact

- The SDGs, adopted by consensus among all 193 UN member nations at the UN Sustainable Development Summit in 2015, provide 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 can tackle[36] 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 conducive to the attainment of SDG 6 include developing efficient new membranes for water purification, or catalysts that break down toxic contaminants. New materials for direct air capture of CO_2 that are designed faster, using quantum computing, would help us progress towards SDG 7. Quantum computers could support SDG 2 by enabling the design of protein-based pesticides and herbicides that only target specific species, reducing use of toxic alternatives and making it harder for pests to develop immunity.

- Significant applied R&D, however, is still needed to better comprehend where quantum computing will 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 is 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 expertise in a range of topics along with a clear understanding of the conventional computation range of applicability and limitations. Only then will we be in a position to develop quantum computing applications that can deliver clear quantum advantages once they are implemented on future quantum computers[37]. Overall, this is not a straightforward exercise. Too often, it is done on a superficial level, which, as a consequence, only feeds the hype.

- Few people have the needed expertise to develop quantum computing applications. Most of their efforts naturally focus on applications with an immediately apparent geostrategic advantage or promise of commercial interest for organizations with the resources to bet a long-term return on investment. This does not bode well for applications that can support the SDGs; these could be deprioritized.

- To date, there has been no coordinated multilateral effort to accelerate potential uses of quantum computing for the SDGs similar to what's been done for artificial intelligence (AI) with the International Telecommunication Union's AI for Good movement, or within broader

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[36] GESDA (2022), *Quantum Computing, Impact Story*, https://gesda.global/wp-content/uploads/2022/09/GESDA-Quantum-Computing-Impact-Story-Apr2022-1.pdf (accessed 29 August 2023)
[37] 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.

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 to express their interests and priorities toward the challenges that can be taken on with quantum computing.

▪ Individual companies or philanthropic foundations support sector-specific initiatives, mostly by launching domain-specific competitions[38]. Other multi-stakeholder, practice-led initiatives include references to the SDGs or provide guidelines as to how to best integrate these global goals in 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[39]), presents a guidance approach for companies, governments, or any organization to explore quantum technology's ethical, legal, and societal implications. The World Economic Forum (WEF) Quantum Computing Governance Principles[40] also emphasize the importance of ensuring that the development and use of quantum computing is aligned with the SDGs.

How the OQI addresses this challenge

A key objective of the OQI is to accelerate the applications of quantum computing to support the attainment of the SDGs (and the succeeding post-2030 framework).

The role of the OQI is to become the missing link between the SDGs practitioners who are tackling challenges in the field – those at UN organizations and large NGOs[41], for instance – and the quantum experts who are conducting the crucial step of determining and streamlining where quantum computing can provide an advantage over classical methods. The OQI will also help those in quantum R&D comprehend and maximize the impact of the SDG applications they explore.

A core value of the OQI is inclusivity. Participants from all countries – regardless of whether they have any quantum capability of their own – should be able to share their governance needs and to submit proposals for applications that address their own specific challenges.

The OQI use case activities will be focused on the applications of quantum computing. This is where the barrier to entry is the lowest and the OQI can more readily contribute to a greater diversity among those in quantum R&D who are contributing to the effort.

SECURITY – maintaining the potential for innovation while managing risks inherent to the dual-use nature of the technology

▪ The projected computational power of quantum computing is unprecedented and has raised concerns as to what could happen should the technology fall into the wrong hands.

▪ The most immediate concerns relate to data security and privacy. The ability of quantum computers to carry out high-speed factorization could crack today's most widely used encryption schemes. This needs to be addressed today. Though practical quantum

[38] 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-case-competition/ (accessed 29 August 2023); Pasqal (2023), *The Blaise Pascal [Re]generative Quantum Challenge*, https://pasqal-quantum-challenge.bemyapp.com/ (accessed 29 August 2023); QunaSys, (2023), *QunaSys begins effort to utilize quantum technology to contribute to society*, https://qunasys.com/news/posts/230714jp/ (accessed 5 September 2023)
[39] 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-for-quantum-society-releases-its-exploratory-quantum-technology-assessment-tool (accessed 29 August 2023)
[40] WEF Insight Report, (2022), *Quantum Computing Governance Principles*, https://www3.weforum.org/docs/WEF_Quantum_Computing_2022.pdf (accessed 29 August 2023)
[41] UN organizations and NGOs that have been contributing to the development of use cases led by the OQI include: Food and Agriculture Organization (FAO), Global Alliance for Improved Nutrition (GAIN), The Global Antibiotic Research & Development Partnership (GARD-P), International Committee of the Red Cross (ICRC), Periodic Table of Food Initiative, SDG Lab, United Nations Human Settlements Programme (UN-Habitat), United Nations Framework Convention on Climate Change (UNFCCC), World Food Program (WFP), World Health Organization (WHO), and World Intellectual Property Organization (WIPO).

computers remain a distant prospect, today's hackers could still try to steal mass amounts of encrypted data and bide their time until a quantum computer is ready to decrypt it.

- Solutions exist to protect data from future decryption by quantum computers. New so-called "post-quantum algorithms" are being developed and approved. The US National Institute for Standards and Technology (NIST) has published standards and started approving algorithms that effectively protect any encrypted data that is either in transit or at rest from quantum attacks. These are not international standards, but many stakeholders around the world will likely follow the NIST's recommendations. Another type of quantum-safe solution being developed[42] is a QKD (quantum key distribution[43]) that enables keys to be shared securely over optical links via the transfer of quantum states[44]. Widespread deployment of QKD would involve implementing the solution in every applicable device; this would not be without challenges.

- The incidence of some nations or regional blocs championing a particular post-quantum approach, as part of their defense of interests, could lead to technological polarization and fragmentation, with the development of competing standards and an erosion of IT interoperability, which could in turn cause significant economic disruption.

- Migrating from current cryptography schemes to future ones that are safe for quantum use will be no small endeavor. Many critical infrastructures depend on legacy systems that are complicated to upgrade. Governments are working towards raising awareness on this security threat, encouraging owners of sensitive data to identify which datasets will be sensitive until quantum computers mature then start the migration as early as possible.

- 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 application domains. 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 material science, 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.

- 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. The most recent of such measures took force on September 1st, 2023[45], as the Netherlands reinforced the existing export measures for advanced semiconductor manufacturing equipment, particularly those used in the quantum field. Because of the potential role these chips might play in contributing to advanced military applications, the Netherlands holds the view that unrestricted chip exports could present risks to national security[46]. Strengthening export control measures thus accentuates the race for quantum primacy, notably between the United States and China.

- Researchers and developers, both from academia and industry, emphasize that export control measures could slow down or prevent achievement of the promises that quantum

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[42] National Security Agency/Central Security Service, *Quantum Key Distribution (QKD) and Quantum Cryptography (QC)*, https://www.nsa.gov/Cybersecurity/Quantum-Key-Distribution-QKD-and-Quantum-Cryptography-QC/ (accessed 14 September 2023)

[43] ETSI, Quantum *Key Distribution (QKD)*, https://www.etsi.org/technologies/quantum-key-distribution (accessed 6 September 2023)

[44] ETSI, (2022) *ISG QKD Activity Report*, https://www.etsi.org/committee-activity/activity-report-qkd (accessed 5 September 2023)

[45] Government of the Netherlands (2023), *Government publishes additional export measures for advanced semiconductor manufacturing equipment*, https://www.government.nl/latest/news/2023/06/30/government-publishes-additional-export-measures-for-advanced-semiconductor-manufacturing-equipment#:~:text=On%201%20September%202023%20additional,to%20a%20national%20authorisation%20requirement. (accessed 30 August 2023)

[46] *Ibid*.

technologies hold by limiting the exchange of scientific ideas and blocking scientists from accessing promising research and early-stage prototypes. 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 are attempting to sketch alternative responses. Responsible computing frameworks – like those proposed by Quantum Delta NL and WEF[47] – serve as examples. Other reflections are focused on technology responses, i.e., how to make quantum computers safer by design. For example, regulators, industry partners, vendors, legal experts and research teams could be brought together to address gaps and prioritize crucial areas for safe quantum ecosystems[48]. The anti-money laundering compliance measure known in financial circles as "Know Your Customer" (KYC) also could serve as a goalpost for future, albeit softer, control processes.

▪ From a multilateral governance perspective, existing normative frameworks of the application domains apply to future quantum computing breakthroughs. For example, existing norms and principles of the Chemical Weapons Convention (1997) and the Biological Weapons Convention (1975), may be applied to outputs of quantum computing.

▪ As quantum technology matures, innovative frameworks and best practices will be needed to ring-fence the beneficial applications and mitigate potential risks. Longstanding multilateral organizations like CERN and IAEA that are involved in nuclear physics also could provide guidance as to how this could be done practically.

> **How the OQI addresses this challenge**
>
> Cryptography is not one of the OQI's core priorities. However, the OQI works with the most recognized experts from industry, government, and academia to ensure its activities are deployed safely.
>
> The OQI's mission is to promote SDGs-related quantum applications by ensuring that applied R&D creates positive impacts. To ensure this is the case, oversight mechanisms and compliance processes will be embedded within the OQI governance.

ENVIRONMENTAL IMPACT – balancing the environmental gains enabled by quantum computing with the cost of running the machines at scale

▪ Digital tools accounted for an estimated 4-6% of the electricity used worldwide in 2020[49], 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 energy-intensive classical supercomputers[50].

▪ 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 carbon-capture materials, 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. There are fewer concerns about the raw materials, which for most of them are relatively common. As the novel new

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[47] Cf. Previous chapter, '*SDG APPLICATIONS – exploring real-world impact*'

[48] 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)

[49] IEA Report, (2017), *Digitalization and Energy*, https://www.iea.org/reports/digitalisation-and-energy (accessed 1 September 2023)

[50] Auffèves, A., Hao Chai J., Khoon Ng H., et al., (2022), *Optimizing resource efficiencies for scalable full-stack quantum computers*, https://arxiv.org/pdf/2209.05469.pdf / https://doi.org/10.48550/arXiv.2209.05469 (accessed 6 September 2023)

components and other enabling technologies (e.g., control systems, cabling, cryogenics, software and algorithms) are being developed to create mature quantum computers, the environmental costs of their larger-scale manufacturing will have to be taken into account. That will require a holistic, transversal approach that considers the overall value chain and life cycle of quantum systems.

▪ Co-located in France and Singapore, the Quantum Energy Initiative[51] (QEI) was launched in August 2022. Its aim is "to foster a worldwide community of experts caring about the physical resource cost of emerging quantum technologies, willing to develop scientific approaches to estimate and minimize these costs"[52]. At present, 350 scientists and industry leaders from 43 countries are part of the QEI community, reflecting a growing desire to collectively reduce the environmental footprint that the manufacture and broad usage of quantum computers could entail. QEI will propose optimization methodologies, frameworks, and benchmarks for quantum technologies, enabling technologies and software engineering. QEI also initiated a standardization working group within IEEE[53] with the goal of developing a new standard for the measurement of the environmental impact of quantum computing.

▪ Similar approaches to those used by the QEI could augment other multilateral initiatives looking to reduce the ecological footprint of products like the UNEP Life Cycle Initiative[54], the Council of Engineers for the Energy Transition[55], or the UNFCCC Global Innovation Hub[56].

How the OQI addresses this challenge

The OQI seeks to accelerate applications of quantum computing with positive environmental impacts, notably those conducive to the achievement of SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 12 (Responsible Consumption and Production). UN-affiliated organizations leading the efforts related to SDGs, notably UNFCCC, are actively contributing to shaping use cases with the OQI.

The OQI will showcase the progress made by the QEI and disseminate its outcomes to support their consideration at a multilateral level.

STANDARDIZATION INITIATIVES – nascent international initiatives, slightly ahead of phase?

▪ International standardization is a global effort that relies on participation by experts from around the world and requires nations' general consent on standards' projects. 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 the standard readiness is reached. For this to happen, there is a need for 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 performance. It fosters the promotion of industry and the support of economic growth, social development, and regulations. It also improves market access

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[51] QEI, (2023), *Manifesto archive*, https://quantum-energy-initiative.org/manifesto-archive/ (accessed 1 September 2023)

[52] QEI (2023), *QEI 2023*, https://quantum-energy-initiative.org/qei2023/ (accessed 29 August 2023)

[53] 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%20its%20energy%20consumption (accessed 1 September 2023)

[54] Life Cycle Initiative, UNDP, *Life Cycle website*, https://www.lifecycleinitiative.org/ (accessed 1 September 2023)

[55] CEET, UNIDO and SDSN, *CEET website*, https://www.unsdsn.org/ceet (accessed 1 September 2023)

[56] UNFCCC Global Innovation Hub, UN, *UNFCCC website*, https://unfccc.int/topics/un-climate-change-global-innovation-hub (accessed 1 September 2023)

management, quality and safety, and support for sustainable strategies. It also leads to benefits in deploying innovation, access to markets, and support for economic performance. Standards can stall innovation, however, if they are imposed too early in the process.

- The development of international standards may become a geostrategic and geopolitical process as countries may seek benefits for their own constituents or national competitiveness.

- Only countries with local expertise can truly influence what will eventually become an international standard. In this context, large corporations can dedicate resources to participate in the standardization effort and take leadership over smaller companies or academic institutions with less means. Thus far, rich countries are in the lead on the development of what will eventually become internationally adopted quantum standards.

- While quantum computing technology is still under development, standardization initiatives are starting to take place. The first steps in quantum standardization 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/JTC 1/WG 14, (under the large Joint Technical Committee of "Information Technology") covers quantum information[57]. Their report, "Terminology and Vocabulary of Quantum Computing", is the most advanced report on quantum computing and the first step in establishing a common language before developing future quantum standards. IEC is also delivering a standardization roadmap and recommendations through its Standardization Evaluation Group (SEG 14)[58]. Other initiatives have been launched at the European level within CEN/CLC/JTC 22, with its Working Group 3 on Quantum Computing and Simulation[59], and within IEEE-SA, which has created six working groups related to Quantum Computing[60].

> **How the OQI addresses this challenge**
>
> For the OQI, it is crucial to keep a global watch on standards and keep track of the various initiatives occurring in different places. The objective is to assess whether the outcomes from these standardization initiatives will support or hinder inclusivity and promote more applications of quantum computing for the SDGs.
>
> A next step of engagement for the OQI would be to actively contribute to the standardization initiatives by participating in working groups and commenting on draft proposals. The OQI also may consider publishing informative articles, accessible to everyone, clarifying the role and influence that standards have in the inclusive development of quantum technologies.

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[57] ISO, IEC, (2022), *ISO/IEC JTC 1/WG 14 Quantum Information Technology*, https://jtc1info.org/sd-2-history/jtc1-working-groups/wg-14/ (accessed 30 August 2023)
[58] IEC, *SEG 14*, https://www.iec.ch/ords/f?p=103:186:102233874606062::::FSP_ORG_ID,FSP_LANG_ID:28910 (accessed 30 August 2023)
[59] CEN-CENELEC, *Quantum Technologies*, https://www.cencenelec.eu/areas-of-work/cen-cenelec-topics/quantum-technologies/ (accessed 30 August 2023)
[60] IEEE SA, *Quantum Standards & Activities*, https://standards.ieee.org/practices/foundational/quantum-standards-activities/ (accessed 30 August 2023)

Conclusion

The present report outlines key findings on the themes addressed by the diplomatic group curated by GESDA during 2023. It represents a first attempt to provide an overview of the state-of-play of the multilateral governance initiatives relevant for quantum computing and is not meant to be exhaustive. Some additional topics that have been touched upon deserve deeper analysis, such as the resilience of value chains and challenges around workforce development and capacity building.

The ambition of this report is to foster a broader and anticipatory discussion on how to create an effective and inclusive governance architecture for quantum computing. GESDA and its multi-stakeholder community welcome complementary contributions and engagement from more interested parties willing to participate in these reflections.

As a novel science diplomacy instrument set to be launched in 2024, the Open Quantum Institute will provide a global and inclusive science-based forum that helps shape the future multilateral governance of quantum computing in service of global goals like the SDGs.

Annexes

Annex 1 – From science to solution: an Open Quantum Institute (OQI)

From the 42 emerging scientific topics covered by GESDA[61], Quantum Technologies is the most advanced in the Anticipatory Situation Room (ASR)[62] pipeline. 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 phase to create the conditions for their use in the best interest of humanity. By acting in the present, we enable human agency, and prepare for the future multilateral governance to be ready when the technology is effectively deployed.

Located in Geneva, the OQI is intended as a novel multilateral and multistakeholder anticipatory science diplomacy instrument, with the following objectives:

- **Accelerating the exploration of use cases** of quantum computing geared towards the achievement of the UN's Sustainable Development Goals (SDGs) and other beneficial applications for humanity, linking industry and academic researchers and developers to SDGs experts and UN organizations

- **Widening the circle of beneficiaries and users** of quantum technologies by providing global, inclusive and equitable access to a pool of public and private computers and simulators available via the cloud

- **Levelling the playing field** by **developing the capacity building instruments** for all bright minds across the world to contribute to the development of the technology, notably those in currently underserved geographies

- **Providing a neutral forum for diplomatic discussions** to frame the future quantum computing multilateral governance enabling the technology to be leveraged for the SDGs

Once at full speed, the OQI with its partners ambition to deliver a pipeline of disruptive innovations enabled by quantum computing. For instance, UN organizations and quantum scientists identified potentialities to develop new carbon capture materials, filters to remove micropollutant compounds from wastewater, or novel ways to produce fertilizers.

In addition, the OQI will also devise targeted educational programs at the nexus of quantum computing and the SDGs, and it will initiate diplomatic processes to hand over in due course to relevant multilateral organizations.

The incubation conducted by GESDA in 2023 provides a strong basis for the next phase of the implementation of the OQI: the gradual handover to a partner for a pilot implementation phase of 3 years (2024-2025-2026). During this phase GESDA will remain involved to guarantee the continuity of the project as co-chair of the future OQI Advisory Committee. It will also play a coordination role with the funding partner of the OQI. Finally, GESDA will contribute to the diplomatic workstream as part of its anticipatory science diplomacy roadmap.

GESDA actively engaged more than 130 international experts for the development of the OQI. We would like to thank them for their contribution to this initiative, for their willingness to step out of their comfort zone, their openness to share their experiences and their enthusiasm for anticipatory science diplomacy.

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[61] GESDA, *Science Breakthrough Radar,* https://radar.gesda.global/ (accessed 26 September 2023)
[62] GESDA developed its own methodology, the Anticipatory Situation Room: GESDA, GESDA Solutions, https://gesda.global/solutions/ (accessed 26 September 2023)

Annex 2 – Participants in the informal discussions of Quantum Computing multilateral governance for the SDGs

Diplomatic community:

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

Other:

The following experts have contributed their expertise: **Andrew Dryden** (Technical Team Leader, International Standard Organisation (ISO)); **Brad Lackey** (Sr. Principal Quantum Architect, Microsoft); **Deborah Nas** (Professor Strategic Design for Technology-based Innovation, TU Delft - Faculty of Industrial Design Engineering), **Jérôme Duberry** (Managing Director, Tech Hub, The Graduate Institute); **Joris Van Hoboken** (Scientific Researcher, Quantum Delta NL); **Jovan Kurbalija** (Director, DiploFoundation and Head, Geneva Internet Platform); **Julien Pitton** (Responsible Data Lab, Ecosystem, Stractic Advisors); **Michael Kende** (Internet Policy Expert, Senior Advisor, Analysys Mason, and Professor, The Graduate Institute); **Mira Wolf-Bauwens** (Responsible Quantum Computing Lead, Responsible & Inclusive Technologies Research, IBM); **Nicolas Fleury** (Co-Founder and Managing Partner, Stractic Advisors); **Olivier Ezratty** (Co-Founder, Quantum Energy Initiative); **Ulrike Till** (Director of the Division of Artificial Intelligence (AI) Policy, World Intellectual Property Organization (WIPO)).

Annex 3 – 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 the flicking on and off of 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. That allows them to store and process much more information simultaneously.

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

- **Superposition** – While in a classical computer, bits exists as either 0 or 1, qubits, the fundamental information processing units in a quantum computer, can exist as a complex combination of the two, in which 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. Bits are like a flipped coin that is either heads or tails, while a qubit in superposition is like a coin spinning on its side. *

- **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 of 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 all 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 each other 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 you need lots of qubits to encode bigger problems into the machine, but also to deal with the fact that the fragility of quantum systems makes qubits error-prone. To get round this quantum computers require **error-correcting schemes** to ensure that mistakes don't pile up too quickly and de-rail whatever computation the machine is trying to do. But to do this you need a lot more qubits to run the error-correction code – somewhere between 1,000 and 10,000 times as many.

Sources used to develop the explanations in this box (accessed 6 September 2023)
*) 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/how-does-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/en-us/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)

Annex 4 – Applications of quantum computing conducive to the SDGs

In 2023, the OQI focused its exploration of possible future applications of quantum computing on SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy) and SDG 13 (climate action).

Below are examples of use cases that the OQI's partners are currently examining on:

- **Food production**: Quantum computing optimization solution to produce more nutritious food locally using less land, taking into account key components in food and environmental parameters (SDG 2)

  Team: École polytechnique fédérale de Lausanne (EPFL), National Institute for Theoretical and Computational Sciences (NITheCS), The Global Alliance for Improved Nutrition (GAIN)

- **Antimicrobial resistance**: Quantum computing solution to improve current AI models and predict quicker and more accurately patterns of antimicrobial resistance and identify new chemical compounds with low resistance on more targeted bacteria. (SDG 3)

  Team: University of Copenhagen, Alphanosos, The Global Antibiotic Research & Development Partnership (GARD-P)

- **Medical imaging**: Quantum machine learning solution to improve accuracy of imaging and early diagnosis of diseases (SDG 3)

  Team: Raman Research Institute (RRI), European Organization for Nuclear Research (CERN), Cleveland Clinic

- **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 (SDG 2)

  Team: Ernst & Young (EY), ForeQuast, Oxford University (tbc), Food and Agriculture Organization (FAO) (tbc)

- **Renewable resources**: Quantum computing simulation to design new catalyst to break down lignin with the aim of valorizing waste products into fuel alternatives (SDG 7)

  Team: Microsoft, Swiss Federal Institute of Technology in Zurich (ETH Zurich), United Nations Human Settlements Programme (UN-Habitat)

- **Carbon reduction**: Quantum computing simulation to improve the catalysis process responsible for the fixation of carbon on the surface of materials, thus reducing CO_2 in the atmosphere (SDG 13)

  Team: ETH Zurich, EPFL, United Nations Framework Convention on Climate Change (UNFCCC)

- **Biodiversity**: Quantum computing simulation to predict the impact of climate change on biodiversity, improve current models, and process more complex biological and environmental data (SDG 13)

  Team: University of Sherbrooke, World Wildlife Fund (WWF) (tbc)

Other topics in discussion include tackling antibiotics in wastewater; eco-friendly fertilizer production: optimization of vaccine distribution, genomics, novel batteries, photocatalysis, and agritech. Some of these are presented in GESDA (2022), *SDG use cases*, https://gesda.global/wp-content/uploads/2022/10/GESDA_Quantum-for-SDG-Use-Cases_10102022_Final.pdf (accessed 5 September 2023).

Annex 5 – Overview of national quantum strategies/initiatives

Disclaimer: 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.

Country	Strategy/ Initiative	Further details (URL accessed on 6 September 2023)	Public investment in quantum computing	Data Source(s) on public investment
Asia-Pacific	Strategy	https://swissnex.org/news/swissnex-report-on-quantum-in-the-asia-pacific	n/a	n/a
Australia	Strategy	National Quantum Strategy | Department of Industry, Science and Resources, https://www.industry.gov.au/publications/national-quantum-strategy	0.2 $ billion	McKinsey & Company 2022: Betting big on quantum, https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-of-the-day/betting-big-on-quantum
Austria	Strategy	Quantum Austria https://www.ffg.at/en/quantum-austria	127 $ million, 107 million Euro	Research Promotion Agency FFG 2021: https://www.fwf.ac.at/de/news-presse/news/nachricht/nid/20210621-2666
Brazil	Initiative	https://thequantuminsider.com/2023/05/16/4-countries-that-began-funding-quantum-initiatives-in-2022/ https://thequantuminsider.com/2023/05/16/4-countries-that-began-funding-quantum-initiatives-in-2022/#:~:text=The%20Brazilian%20government%20announced%20its,in%20Quantum%20Technologies%20in%20Brazil	11 $ million	New Funding For Quantum Computing Accelerates Worldwide (forbes.com)
Canada	Strategy	https://ised-isde.canada.ca/site/national-quantum-strategy/en	1.0 $ billion	McKinsey & Company 2022: Betting big on quantum, https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-of-the-day/betting-big-on-quantum
China	Strategy	https://thequantuminsider.com/2023/04/13/chinese-quantum-companies-and-national-strategy-2023/ (not official doc)	15.3 $ billion	McKinsey & Company 2022: Betting big on quantum, https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-of-the-day/betting-big-on-quantum and https://thequantuminsider.com/2023/04/13/chinese-quantum-companies-and-national-strategy-2023/
Denmark	Strategy	Explainer: Denmark's national quantum strategy (part 1) (dqc.dk), https://dqc.dk/news/explainer-	1 billion DKK = $ 145 million	https://ufm.dk/en/newsroom/press-releases/2023/the-danish-government-is-ready-with-a-dedicated-

		denmarks-national-quantum-strategy-part-1/		investment-of-one-billion-dkk-as-first-part-of-a-new-quantum-strategy
European Union	Strategy	https://digital-strategy.ec.europa.eu/en/policies/quantum-technologies-flagship	1.1 $ billion	https://digital-strategy.ec.europa.eu/en/policies/quantum-technologies-flagship
Finland	Initiative	Quantum Technology Finland, The National Centre of Excellence, https://qtf.fi/	45 million € = $ 48.8 million	https://www.helsinki.fi/en/news/quantum-technology/finnish-quantum-agenda-details-road-ahead-and-stresses-need-national-quantum-strategy https://instituteq.fi/wp-content/uploads/2023/02/FQA-February-2023.pdf
France	Strategy	Technologies quantiques | Gouvernement.fr https://www.gouvernement.fr/technologies-quantiques, and https://thequantuminsider.com/2023/08/31/french-national-quantum-update-august-2023/	1.8 € billion = $ 1.9 billion	https://www.gouvernement.fr/france-2030-strategie-quantique-lancement-d-une-plateforme-nationale-de-calcul-quantique
Germany	Strategy	https://qbn.world/wp-content/uploads/2023/04/Action-Plan-Quantum-Technologies-by-German-Government-2023-2026.pdf, and https://thequantuminsider.com/2023/05/03/germany-announces-3-billion-euro-action-plan-for-a-universal-quantum-computer/	3 billion € = $3.2 billion	https://www.quantumcomputinglab.cineca.it/en/2023/05/09/germanys-action-plan-for-quantum-technologies/#:~:text=The%20goal%20is%20for%20the,for%20example%2C%20IBM's%20in%202022.
Hungary	Strategy	Main page | HunQuTech (wigner.hu), https://wigner.hu/quantumtechnology/en/node/1	HUF 3 billion = $ 8.3 million	https://www.elte.hu/en/content/complex-quantum-information-development-launched-with-the-contribution-of-elte.t.2682
India	Strategy	https://thequantuminsider.com/2023/05/03/a-brief-overview-of-quantum-computing-in-india/	1.0 $ billion	McKinsey & Company 2022: Betting big on quantum, https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-of-the-day/betting-big-on-quantum
Ireland	Initiative	'Impact 2030', Ireland's Research and Innovation Strategy 2022, mentions the National Strategic Action Plan for Quantum Computing, https://www.gov.ie/pdf/?file=https://assets.gov.ie/224616/5f34f71e-e13e-404b-8685-4113428b3390.pdf#page=null	10 million € = $ 10.7 million	https://www.gov.ie/en/press-release/075e0-ireland-and-the-eu-invest-10-million-in-a-national-quantum-communications-infrastructure-network/#:~:text=The%20Irish%20Government%20and%20the,two%20years%20by%20the%20IrelandQCI.
Israel	Strategy	The Government of Israel has formed the Israel National Quantum Initiative (INQI), a joint venture between the Council for Higher Education, Israel Innovation Authority, Ministry of Science, Ministry of Defense and Ministry of Finance.	0.5 $ billion	McKinsey & Company 2022: Betting big on quantum, https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-of-the-day/betting-big-on-quantum

Italy	Initiative	A quantum trapped ion computer in Padua, https://www.quantumcomputinglab.cineca.it/en/2022/03/18/the-first-quantum-computer-in-italy-is-coming/	<320 million €	In 2022, Italy is among the governments that have decided to invest in this type of technology, with funding of 320 million euros over 3 years for a recently established National Center on HPC, big data and quantum computing. https://forbes.it/2022/12/09/quantum-computing-fondi-pnrr-sviluppo/
Japan	Strategy	https://www8.cao.go.jp/cstp/english/strategy_r08.pdf	1.8 $ billion	McKinsey & Company 2022: Betting big on quantum, https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-of-the-day/betting-big-on-quantum
Mexico	Initiative	https://www.dicu.com.mx/imtc	n/a	https://conahcyt.mx/
Netherlands	Strategy	https://quantumdelta.nl/	0.76 billion € = $ 658.8 million	https://www.tudelft.nl/over-tu-delft/strategie/vision-teams/quantum-computing/impact/the-netherlands-and-quantum#:~:text=The%20Dutch%20government%20is%20including,may%20use%20quantum%20computing%20itself.
New Zealand	Initiative	https://www.stuff.co.nz/science/300358358/aotearoa-leaps-into-the-second-quantum-revolution	$ 36.8 million	https://www.stuff.co.nz/science/300358358/aotearoa-leaps-into-the-second-quantum-revolution
Norway	Initiative	https://www.quantumcomputing.no/ Norway has no official quantum strategy or agenda, nor any dedicated investments. https://www.simula.no/news/researchers-call-norwegian-quantum-computing-strategy	n/a	The aim of the Norwegian Quantum Computing Centre is not to build its own quantum computer, but to develop software that will put Norway in a position to apply the technology when the machines are fully developed. https://www.sintef.no/en/latest-news/2021/quantum-technology-offers-norway-a-data-revolution/
Philippines	Initiative	The Philippines government has announced their quantum technology roadmap, https://ovcre.uplb.edu.ph/press/memos/item/647-dost-s-harmonized-national-research-and-development-agenda-2022-2028	P 860 million = $ 15 million	https://ovcre.uplb.edu.ph/press/memos/item/647-dost-s-harmonized-national-research-and-development-agenda-2022-2028
Portugal	Initiative	Portuguese Quantum Institute : https://pqi.pt/	n/a	No public investment data found
Russia	Strategy	https://thequantuminsider.com/2023/07/25/russian-company-presents-16-qubit-quantum-computer/#:~:text=Among%20other%20programs%2C%20the%20Russian,leader%20in%20the%20global%20economy	0.7 $ billion	McKinsey & Company 2022: Betting big on quantum, https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-

				of-the-day/betting-big-on-quantum
Singapore	Strategy	Quantum Engineering Program - Asia Tech x Singapore, https://asiatechxsg.com/sponsors/5ef3b42c-e00b-4a7c-ab4b-39e922950683/	0.5 $ billion	McKinsey & Company 2022: Betting big on quantum, https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-of-the-day/betting-big-on-quantum
Slovakia	Strategy	Slovak National Center for Quantum Technologies, http://qute.sk/	n/a	No public investment data found
South Africa	Strategy	https://thequantuminsider.com/2023/05/16/4-countries-that-began-funding-quantum-initiatives-in-2022/	R 54 million = $2.8 million	https://www.wits.ac.za/news/latest-news/research-news/2022/2022-10/wits-to-kick-start-a-national-quantum-technologies-initiative-with-r54-million-funding.html
South Korea	Strategy	https://quantuminkorea.org/#1678074692395-6cac4700-6335 ; also good analysis: https://thequantuminsider.com/2023/06/29/south-korea-to-invest-2-33-billion-in-quantum-by-2035/#:~:text=South%20Korea%20plans%20to%20invest,computer%20and%20advanced%20quantum%20sensors)	W3 billion =$ 2.3 billion	https://thequantuminsider.com/2023/06/29/south-korea-to-invest-2-33-billion-in-quantum-by-2035/ https://www.korea.net/Government/Briefing-Room/Press-Releases/view?articleId=6930&insttCode=A110439&type=O
Spain	Initiative	Quantum Spain, https://portalayudas.mineco.gob.es/Quantum%20Spain/Paginas/Index.aspx	60 million € = $ 64.3 million	https://www.tas-consultoria.com/blog-en/quantum-spain-and-the-first-quantum-computer-in-spain/
Sweden	Initiative	A Swedish quantum agenda | Vinnova, https://www.vinnova.se/en/publikationer/a-swedish-quantum-agenda/	SEK 1.5 billion = $ 135 million	https://www.iva.se/en/published/iva-focuses-on-why-a-swedish-quantum-agenda/ https://www.vinnova.se/globalassets/bilder/publikationer/the-swedish-quantum-agenda.pdf?cb=20230328130156
Switzerland	Initiative	Swiss Quantum Initiative (SQI) (admin.ch), https://www.sbfi.admin.ch/sbfi/en/home/research-and-innovation/research-and-innovation-in-switzerland/sqi.html	10 million CHF = $ 11.2 million	https://www.sbfi.admin.ch/sbfi/en/home/research-and-innovation/research-and-innovation-in-switzerland/sqi.html
Taiwan	Initiative	https://www.taiwannews.com.tw/en/news/4071610	NT$ 8 million = $ 282 million	https://thequantuminsider.com/2020/12/08/taiwan-invests-282-million-us-to-compete-in-rapidly-expanding-global-quantum-technology-industry/
Thailand	Strategy	Thai quantum information, consortium (quantum-thai.org)	200 million baht = $ 6 million	https://www.bangkokpost.com/thailand/general/1740175/cabinet-backs-37bn-baht-science-innovation-scheme
United Arab Emirates	Initiative	https://thequantuminsider.com/2022/12/19/quantum-tech-in-the-middle-east-2022/	n/a	No public investment data found

United Kingdom	Strategy	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1142942/national_quantum_strategy.pdf, UK Quantum Strategy Published (techuk.org)	$1.3 billion	McKinsey & Company 2022: Betting big on quantum, https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-of-the-day/betting-big-on-quantum
United States	Strategy	https://www.quantum.gov/strategy/	$1.9 billion	McKinsey & Company 2022: Betting big on quantum, https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/chart-of-the-day/betting-big-on-quantum and https://www.quantum.gov/strategy/ and https://www.quantum.gov/wp-content/uploads/2023/01/NOI-Annual-Report-FY2023.pdf