Quantum Delta NL

Quantum Technologies and their Global Impact

Discussion Paper

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PREFACE

This discussion paper is the result of a collaboration between UNESCO and the Centre for Quantum and Society (CQS) of Quantum Delta NL, the Dutch programme for developing quantum technologies.

It explores the global impact of quantum technologies and charts the relevant discussions around the human rights, legal, ethical, and social aspects of quantum technologies. Quantum stands for a set of emergent technologies that are growing into a commercial industry. Given its potentially disruptive nature, quantum deserves our full attention. This is emphasized by the proposal for the proclamation by the United Nations of 2025 as the International Year of Quantum Science and Technology. It aims to raise awareness about the significance of quantum science and technology and its potential to revolutionize various fields, including computing, communication, sensing, and simulation. It would provide a platform for showcasing the latest advancements and breakthroughs in quantum research and applications, as well as promoting education and public engagement in quantum-related topics.

This discussion paper invites UNESCO Member States and other stakeholders worldwide to support responsible innovation in the field of quantum technologies – so that they can have a positive, meaningful contribution to our societies.

ABOUT

Centre for Quantum and Society

The Centre for Quantum and Society (CQS) of the Dutch Quantum Delta NL programme for developing quantum technologies, is a knowledge and co-creation center dedicated to maximizing the positive impact of quantum technologies on society. CQS facilitates ground-breaking academic research into ethics, legal frameworks, and effective communication surrounding the impact of quantum technologies and develops tools to assess quantum applications' ethical, legal, and societal aspects and set governance guidelines; supports startups, small businesses, corporate innovation teams, governmental institutions and international organizations in understanding the impact of quantum innovations on their sector, customers, and society and initiates mission-driven innovation in quantum projects.

In collaboration with

UNESCO

UNESCO's Digital Policies and Digital Transformation work in the Communication and Information Sector (CI) supports Member States in navigating human right-based, inclusive digital transformations. Starting from national assessments of digital enabling environments, accompanied by policy advice for inclusive and multistakeholder driven digital development, UNESCO enhances the capacities of Member States to implement digital transformation initiatives across the executive, legislative and the judicial branches of government. UNESCO CI also facilitates digital cooperation through multistakeholder fora to develop capacities, exchange knowledge on good digital policy practices and to enhance strategic foresight.

INTRODUCTION

Quantum technologies are in an early stage of development. Much of the Research & Development (R&D) efforts are driven by public sector investments and efforts by large technology companies, with a growing volume of private capital in the three application areas of quantum computing – and to a lesser extent – communication and sensing related quantum technologies.[1]

These technologies can have major – if not disruptive – effects on a wide range of sectors in the mid-term. The list of potential impact is long, and ranges from securing critical infrastructure to breakthroughs in drug discovery, material science and more. Consequently, quantum computing extends beyond mere advancements within scientific laboratories and the quest for technological milestones. It is increasingly intertwined with national industrial policies and the escalation of competition among countries regarding digital technologies.

Despite the promise, quantum is a long way from commercial use. Many R&D milestones still require year-long research, and talent is scarce. The world's leading quantum clusters have long formed a well-connected network of scholars that collaborate across national borders. While initially, only a handful of countries had a notable presence in quantum technologies, the past 5-10 years have seen an expansion in the number of countries participating in the global quantum community, including from the Global South. This expansion has led to the initiation or scaling up of various national programs worldwide. Nonetheless, the default position of world-wide collaboration is increasingly under pressure.

In view of existing digital divides and today's fragmented innovation landscape, safeguarding international collaboration for quantum science and for developing quantum-based technologies is both essential and difficult. Over the last decades, quantum technologies have evolved as a global scientific endeavor with research groups from all over the world exploring the intricacies of quantum mechanics. More recently, quantum technologies have come to be seen as a potentially disruptive set of technologies. Many uncertainties about the potential applications and the timelines for viable products remain – it is too early to have concrete conversations about how the adoption of quantum technologies will play out exactly. But it is not too early to prepare for the time when quantum will enter the markets.

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[1] In 2023 already 34 billion USD of public funding was reserved for developing quantum technologies, with China in the lead with 15 billion, followed by the European Union (8,4 billion) and the United States (3,7 billion); McKinsey & Company *Quantum Technology Monitor* https://www.mckinsey.com/featured-insights/the-rise-of-quantum-computing

Important questions that will be addressed in the coming years

- What will be the impact of quantum technologies on societies across the globe?
- How can these technologies be developed for good?
- Can we safeguard equal access for non-quantum nations?

These questions on the societal aspects are gradually taken up across the board from academia to policy making. International organizations such as UNESCO have an important role to play in these efforts as they have the mandate to foster an inclusive dialogue and global collaboration around new and emerging technologies.

Various actors have started to address some of these issues at the international stage. On the one hand, there are various initiatives driven by individual countries, such as the Multilateral Dialogue on Quantum Technology[2] and growing number of bilateral agreements to collaborate on quantum technologies. On the other hand, there are various international organizations that have started to engage with the global quantum community: the World Economic Forum's Future Council on Quantum Technology[3] has been active since 2021, the OECD has initiated an expert group on quantum in late 2023. Earlier the same year, the respective quantum member networks in Canada, Europe, United States and Japan joined forces and created an International Council on Quantum Technology to establish a channel for exchanging best practices.[4] There is movement on standards for quantum too: CEN CENELEC, IEEE and ISO all have formally established quantum working groups.[5] And UNESCO is exploring ways in which it can apply lessons learned from its work on ICTs, including AI, for knowledge societies to the quantum field.

This discussion paper provides a starting point to explore the opportunities for international actors like UNESCO to facilitate the pathway to a future quantum societies and economies. It first introduces quantum technologies and their potential impact from a technology perspective; and then turns to a number of key areas that require international collaboration at the intersection of science, business, human rights, ethics, geopolitics, diplomacy and security. The paper concludes with considerations for UNESCO Member States on how to support responsible innovation for quantum technology in the coming years.

[2] https://www.quantumwithoutborders.org/multilateral-dialogue-on-quantum
[3] https://www.weforum.org/communities/gfc-on-quantum-economy/
[4] https://www.euroquic.org/qic-qed-c-q-star-and-quic-form-international-council-to-enable-and-grow-the-global-quantum-industry/
[5] https://untoday.org/how-quantum-computing-will-impact-un-organizations/

1. Quantum Technologies

Quantum stands for a set of technologies in which the quantum mechanical properties of individual objects on the atomic scale are manipulated for practical purposes. These properties are defined by quantum mechanics, which already found its way to technologies such as nuclear, laser and semi-conductor technologies. At the beginning of the Twenty-First Century the technology holds the promise of atomic precision for developing quantum computers, quantum communication systems and quantum sensors. Often cited as a related field, post-quantum cryptography refers to cryptographic algorithms designed to be secure against an attack by a quantum computer. Post-quantum cryptography is not a quantum technology per se since many post-quantum-cryptographic approaches can run on digital (classical) computers.

Quantum Computing

Quantum computers are a new type of computers that can perform calculations that are practically not possible with today's digital (classical) computers. This could potentially enable scientific, commercial and strategic breakthroughs, which makes the creation of quantum computers more than just an academic challenge. Several prototypes with varied hardware approaches exist, but significant technological and financial investments are needed to develop quantum computers that are large and stable enough to perform new types of calculations on a scale that makes them advantageous over digital (classical) computers.

Where today's digital computers perform calculations by manipulating strings of bits, quantum computers work with strings of quantum bits or, in short, 'qubits'.[6] In 1994 it was demonstrated by Peter Shor that by manipulating these qubits a quantum computer can do a calculation that is practically not possible with digital computers[7]. Quantum computers make available new calculations that are significant, including finding prime factors of large integer numbers. This is a central step in breaking regularly used encryption of digital communication and represents therefore potentially also a major risk.

Quantum computation can also be used for searches in databases, relevant for big data analysis. And quantum computing can be employed for modelling the physical behavior of atoms and molecules, opening up new possibilities for analyzing and developing materials and pharmaceutical drugs, and simulating chemical reactions between atoms and molecules.

Quantum computing would achieve what is called 'practical advantage' over digital computing once there are large and stable enough quantum computers that can deliver these new calculations or deliver them faster than digital (super) computers can.

[6] Digital bits have the values of 0 or 1, and the novelty of qubits is that they can have those two values as well as combinations of 0 and 1. In quantum mechanical terms these combinations of 0 and 1 are called 'superpositions.' When a qubit is in a superposition of 0 and 1, this means that when you register its value, you will find a 0 with a certain probability or a 1 with a certain probability.

[7] P. Shor. Algorithms for Quantum Computation: Discrete Logarithms and Factoring. In Proc. 35th Annual Symposium on Foundations of Computer Science. IEEE Press, Nov. 1994.

This point has not yet been reached and it may take another decade or more before it will. At the time of writing, the development of quantum computers is dominated by research institutes in Asia, Europe and North America, and by bigger commercial firms. Even though progress is impressive, the quantum computers currently on offer can best be seen as prototypes to those that will have practical advantages. When considering the number of qubits quantum computers can calculate with, the record in 2023 is held by IBM, the US based technology corporation, with its 1121-qubit Condor system. The estimation is that to have a significant practical advantage this number needs to grow to over 100.000, which is technologically a challenging step. Moreover, there are different competing hardware approaches for creating qubits, and it is not clear which approach will enable quantum computers with such large numbers of qubits. Hence, all of today's prototypes are not likely to deliver practical advantage in the near future.

Quantum Communication

Communication technology represents a second subfield in quantum technology. It includes the exchange of atomic objects, which simplified, enable secure communication that is theoretically immune to eavesdropping if properly implemented. Prototypes of quantum communication systems are already in existence, and some smaller systems are also commercially available. For arriving at full-sized quantum communication systems, often referred to as 'quantum internet,' major R&D milestones still have to be reached.[8]

Technically, in quantum communication the objects that are exchanged are typically light particles (photons) sent through a channel – glass fiber or open air – and carrying a qubit. Such a light particle can be sent from A to B for transferring information from A to B encoded in the 0s and 1s of the qubit. What can also be done is establishing a correlation between A and B by sending from a separate source S one light particle to A and one light particle to B. The qubits carried by the two light particles have correlated properties and transfer this correlation to A and B.[9,10] Practically, the new features that quantum communication brings are twofold.

First, that quantum communication allows for two nodes to detect whether third parties are eavesdropping on the exchanged qubits. Quantum communication is therefore said to be inherently secure, because the communicating parties can abort exchanging information when they detect eavesdropping. This feature of quantum communication is clearly attractive for financial services or governmental communication, etc.

Second, the correlations quantum communication can establish between A and B have properties that are not available through digital communication. They provide the means for

[8] For example, it has proven challenging to develop so-called 'quantum repeaters,' which are nodes that can boost quantum communication signals securely over larger distances.

[9] In quantum mechanical terms the two qubits of the light particles are in a joint 'entangled state,' which relates the 0s and 1s of the qubits in a strong manner.

[10] One can find on the Web further information about quantum mechanics and its key concepts of superposition and entanglement. Learning about these concepts can be recommended. However, the current discussion paper aims at providing a basis for understanding and anticipating the global impact of quantum technologies without a need to also understand the basics of quantum mechanics.

securely exchanging keys for encrypting digital communication.[11] The encryption offered by this scheme cannot be broken by quantum computers. In this way quantum communication holds the promise to provide opportunities to address the problem quantum computers pose to the security of digital communication.

Some first-generation systems are gradually being deployed. For example, China has a 2000-kilometer-long glass fiber network for quantum key distribution that connects multiple cities between Beijing and Shanghai.[12] In the European Union, Member States have stared an effort called EuroQCI of creating prototype national networks which in the coming years will be connected across the Union leading to a prototype quantum internet.[13]

Quantum Sensing

Quantum sensing is the third subfield of quantum technology. It entails measuring physical quantities like time, electric and magnetic fields, temperature and gravity. Using the properties of individual atomic objects, quantum sensors are developed to measure with more sensitivity and precision than existing conventional sensors. Quantum sensors can be seen as the quantum counterparts of existing sensors, for instance of existing MRI scanners that can already scan objects such as the human body with much precision. If quantum sensors can be made substantially smaller than the prototypes currently built in labs, they would offer new functionality to a variety of (industrial) users, such as (deep) underground or medical scanning techniques.

There are multiple types of quantum sensors for sensing various quantities, which all may bring their specific uses.[14] Quantum sensors for measuring time, referred to as atomic clocks, have their uses in the coordination of processes in communication, industry and finance, and may bring more precise and new applications to these domains. The same holds for the use of atomic clocks in navigation, of and by satellites, and of cars, vessels, and planes in both the civilian and military domains. The technology can also be used for more detailed and deeper underground sensing, for geographic research (e.g., volcanos), prospecting for oil, gas and other ores, and for inspecting the underground at building sites. Other promising applications include the use of atomic clocks and gravity sensors for global positioning independent of satellite-based GPS systems. This functionality would allow positioning and navigation at places on earth where GPS is not available. The latter is of particular interest or military use, which is also the case for potential applications in submarine detection, behind-the-corner detection, and quantum radar.

Quantum sensing, when compared to quantum computing and communication, is the most advanced technology of the three, with multiple applications and uses already commercially available.

[11] C. H. Bennett and G. Brassard, in Proceedings of the IEEE International Conference on Computer, Systems, and Signal Processing, Bangalore, India (IEEE, New York, 1984), pp. 175–179.
[12] See Olivier Ezratty (2023) Understanding Quantum Technologies 6th Edition (Version 6.7), pp. 730-731: arXiv:2111.15352 Quant-Ph [Internet]. http://arxiv.org/abs/2111.15352
[13] https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci
[14] Olivier Ezratty (2023) Understanding Quantum Technologies 6th Edition (Version 6.7): arXiv:2111.15352 Quant-Ph [Internet]. http://arxiv.org/abs/2111.15352

Post-Quantum Cryptography

Post-quantum cryptography consists of encryption schemes for digital communication and data that can withstand decryption with quantum computing. As described earlier, one of the calculations a fully functional quantum computer can do is finding prime factors of integer numbers. This factoring can be used for breaking public key encryption schemes that are currently used world-wide in the digital domain. This would substantially undermine the security of communication and data storage in private, public, and governmental domains (such as critical public infrastructure).

And although large and stable quantum computers do not yet exist, the possibility that they may exist and at some day – dubbed Q-day – be used for decryption, is reason enough for governments, institutes and companies to start working on post-quantum encryption. Two considerations support this call to action. The first is that the introduction of new encryption in the digital domain is a logistically complex operation that may take public and private organizations more than a decade. The second is the 'store now decrypt later' option, by which third parties collect conventionally encrypted communication and data before Q-day and decrypt it once large and stable quantum computers are available.

The urgency of post-quantum cryptography was underlined in 2022 by a decision by the United States to make the encryption of its digital spaces quantum safe by 2035.[15] Quantum proof encryption schemes are in development. Quantum key distribution (see above) is such a scheme, as are several encryption algorithms that can be run on digital computers. The United States National Institute of Standards and Technology (NIST) is a driving force behind the international quest for post-quantum encryption schemes and drives the creation of standards.[16]

2. Human Rights, Ethical, Legal and Social Aspects of Quantum Technologies

When looking at the potential societal impact by exploring their human rights, ethical, legal and social aspects (HR-ELSA), we can learn from other emerging technologies such as AI.[17] For example, there are useful tools that were developed for impact assessments and responsible innovation in other fields that can be adapted to HR-ELSA-related work on quantum technologies. It is important to note that this is not a one-on-one comparison. Two factors set HR-ELSA analyses of quantum technologies apart from those of AI and other technologies that have emerged in the past decades. The first is the early phase in which the development of quantum technologies are. By that they are often perceived as incomprehensible and the

[15] https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/04/national-security-memorandum-on-promoting-united-states-leadership-in-quantum-computing-while-mitigating-risks-to-vulnerable-cryptographic-systems/

[16] https://csrc.nist.gov/projects/post-quantum-cryptography

[17] QDNL has published three white papers with lessons from AI for quantum technologies: https://assets.quantum-delta.prod.verveagency.com/assets/lessons-from-ai_white-paper-3_risk-management.pdf

claims about their applications are considered to be uncertain or even hyped. Second, quantum technologies have become subject of global competition even before commercial applications have left the labs. This means that research on the societal impact of quantum technologies has to be done in the context of the current global technological race.

The following paragraphs identify some areas of concern as HR-ELSA work moves ahead within the quantum domain.

Quantum for Good

As the world starts exploring quantum technologies, much depends on how the first applications are developed, and what kind of 'use' they have for our societies. If quantum technology is developed solely based on market considerations, societal acceptance can become a challenge due to the perceived and real risks that come with commercial products and services.[18] Quantum computing and communication initially came with two concrete applications and a series of more generic uses, and the race is on for finding more applications. The first concrete application in quantum computing can potentially break encryption by calculating prime factors of large integers; and for quantum communication the first application is secure digital communication by quantum key distribution.

More generic use cases often focus on big data analysis, modelling atoms and chemical processes, or secure communication and enabling synchronization over large distances (e.g., for the finance sector). Many potential applications have been proposed, from coordination of telescopes in astrophysics, to research on materials for more efficient photovoltaic cells, and real time analysis of sensor data by quantum computing.

The search for commercially viable use cases that can accelerate the adoption of quantum technologies by industry has however not yet led to a set of clear candidates. Quantum sensing is an exception. It has more applications including ones that are attractive for industrial players. And when it brings new functionalities, such as underground scanning, there are clearly interesting applications.

The early phase in the exploration of applications may make the analysis and discussion of the HR-ELSA of these applications somewhat premature; these applications should first become better defined. For some this prematurity is a reason to proactively explore how quantum technologies can be used to realize goals that have a positive impact on society as a whole. The World Economic Forum states in a 2022 report that the governance of quantum computing should direct it to 'the benefit of humanity'.[19] And the Open Quantum Institute by the Geneva Science and Diplomacy Anticipator (GESDA) initiative plans to offer computing time on virtual machines to partners all over the world for realizing the UN Sustainable Development Goals.[20] This "quantum for good" approach is also adopted by Quantum Delta NL and is being developed by its Centre for Quantum and Society.

[18] Think about how the Cambridge Analytica case affected societal acceptance of Big Data and AI.
[19] https://www.weforum.org/publications/quantum-computing-governance-principles/
[20] https://oqi.gesda.global

When doing so, first generation HR-ELSA tools focus less on individual applications, but more on finding these applications by brainstorming, foresight and stakeholder consultation. At the same time, quantum needs technology-specific guidance that reflects the low maturity level of the sector. There are already early-stage tools available for exploring the societal impact of individual applications, such as the Exploratory Quantum Technology Assessment (EQTA) tool.[21]

These emerging guiding principles can play an important role in supporting technology developers to test assumptions, check on potential (unintended) consequences and to eliminate risks that are associated with a specific R&D effort. Some of the risks include:

- the possibility that encryption of digital communication can be broken by quantum computing;
- the prospective energy use of quantum technologies when operated under extremely low temperatures; and
- dual use considerations in the civil-military domain.

Navigating the Global Technology Race

The development of quantum technologies is increasingly shaped by their standing as critical technologies in the global technology race. Nation states care about access to critical technologies, and quantum is no exception: those who develop and control quantum technologies may have an advantage over other nation states. As a result, HR-ELSA analysis must also look at nation states, international (intellectual property) law and national (industrial) policies, in addition to assessing the role of companies, investors, knowledge institutions and industrial end-users.

In fact, economic and strategic motives have long been part of national efforts to developing quantum technologies. For instance, the Quantum Manifesto, written to convince the European Union to invest in quantum technologies, advanced both economic arguments and sovereignty concerns.[22] And after the experiences with the logistic and political hurdles to global supply chains during the COVID-19 pandemic, there has been a steady move towards strategic thinking globally.

For HR-ELSA this means a broadening in the focus in research by gradually including elements of the political domain. In addition to identifying and exploring how applications can affect stakeholders in society, HR-ELSA questions emerge about how to safeguard access to research on quantum technologies, to applications, and to the technologies themselves. The competition around quantum technologies might lead to more national – closed – ecosystems that are disconnected from international partners. States could decide to develop these technologies by themselves instead of together, and with fewer dependencies on others. This runs counter to the default open science approach that marks the global research landscape

[21] https://quantumdelta.nl/news/quantum-delta-nl-launches-exploratory-quantum-technology-assessment-eqta

[22] de Touzalin A, Marcus C, Heijman F, Cirac I, Murray R, Calarco T (2016) Quantum manifesto: A new era of technology. E.g., https://qt.eu/publications

and which UNESCO Member States have endorsed through the Recommendation on Open Science. In the near future, political decisions aimed at guarding high tech R&D may include measures such as export controls, denying visa for foreign researchers, or bans on international ownership of relevant companies. Whereas similar dilemmas have surfaced in the field of AI, proponents of quantum technologies will have to deal with these issues from a much earlier stage. This means that open science and international trade quickly become more conditional – even for fundamental research projects – and may lead to an exclusionary tendency. Some states will have a hard time gaining access to these new technologies, with a quantum divide as a result.

3. Ways Forward for International Collaboration: Possible UNESCO Perspectives

Safeguarding international collaboration for quantum technologies in today's fragmented global landscape is both essential and difficult. Questions that will have to be addressed in the coming years include: What will be the impact of quantum technologies on societies across the globe? How can these technologies be developed for good? Can we safeguard equal access for all? How can we globally enable all to adopt the opportunities quantum might offer, and to protect themselves against possible risks? What governance and regulatory frameworks are needed for responsible use? These questions about the HR-ELSA of quantum are gradually taken up across the board by academia, civil society and policymakers.

UNESCO with its mandate to facilitate international cooperation can take a leadership role: by raising awareness and by connecting the right stakeholders at Member States' level and across the private sector, academia, civil society and the broader public. UNESCO has a unique position to build bridges between nations' outlook on quantum, increase mutual understanding and reduce barriers for collaboration.

There are at least five topics relevant to the global science and technology community.

- Quantum for Good
- Societal Impact
- Equity - Access for All
- State Readiness and Capacity Building
- Regulation and Governance

I. Quantum for Good

Quantum technology potentially poses risks in the field of human rights; examples include privacy breaches through breaking encryption, limiting freedom of expression via enhanced surveillance, and creating unequal access to information (which in turn potentially deepens digital divides). It may also introduce biases and discrimination in decision-making, affect economic and social rights by altering employment, education, and healthcare landscapes, and raise security concerns due to potential military uses, impacting global safety and individual rights.

The contemporary perspective on technological development is not just that it brings economic progress and that possible harmful impacts should be avoided or mitigated by HR-ELSA efforts. Rather, those working on new technologies have the responsibility to create technologies that ignite public trust: they should contribute to addressing societal challenges and play a role in realizing societal goals. Quantum computing notably has already been identified as a technology that could support the realization of the UN Sustainable Development Goals; quantum sensing may have a major impact on monitoring climate change. Beyond these examples, international organizations can facilitate efforts to define what states and communities see as meaningful societal goals to attain with quantum.

UNESCO as a driver for responsible innovation

Consider supporting initiatives aimed at deploying quantum technologies in a human-rights based approach and for good, both by facilitating the discussion of what communities across the globe want to put forward as meaningful for their societies and by creating programmes for developing quantum technologies to realize these goals. In this way UNESCO may contribute to the development of concrete quantum for good initiatives that deliver specific solutions to global challenges.

II. Societal Impact

Quantum technologies have their origin in R&D done in a limited set of states and companies for their economic and strategic advantages. Efforts for understanding the economic and societal impact quantum technologies can have on societies in these states (and in states not yet working on quantum technologies) have been initiated but need more support in the coming years. Additionally, such exploratory efforts should feed back into R&D on quantum technologies for giving communities across the globe a say in shaping the impact of quantum technologies.

UNESCO as a sense maker

Explore how best to facilitate this effort of understanding the societal impact of quantum. This could be done through UNESCO's broad global networks and building on its track record of exploring the impact of other technologies. Capacity building efforts across Member States' governmental entities about the potential technological and economic impact would be a valuable pathway to do so. UNESCO may consider initiatives to let communities across the world explore early-stage quantum use cases with national authorities and companies that can help develop quantum for public applications (for example weather forecasting, secure communications, climate monitoring, etc.).

III. Equity – Access for All

Quantum technologies are increasingly developed under a competitive global technology development landscape, limiting open science, international exchange of researchers, and dissemination of the technologies and of their use. These constraints carry the risk of creating a global quantum divide between states that have the knowledge, usage and the technologies themselves, and states that have not. It also may hamper the development of these technologies in the first place: for example, when the global pool of research and knowledge becomes smaller, and the global market for selling this technology becomes fragmented.

UNESCO as a bridge builder

Explore possibilities to create international collaboration and exchange of knowledge and technology for steering quantum science away from competition to cooperation; safeguard the internationally recognized right to science and drive efforts to reduce barriers to access in those countries that have limited capacity to develop quantum core technology.[23]

IV. State Readiness and Capacity Building

The impact of quantum technologies extends beyond the immediate uses of its applications. Acknowledging the strategic value of quantum, policy-makers should expect that it may affect societies in more invasive and permeating manners. It may address the challenges societies faces such as the UN Sustainable Development Goals; and it may bring threats related to the security of digital communication. If not by mastering the quantum technologies themselves, national authorities should be in the position to build up their knowledge and capabilities of the opportunities and threats quantum can bring. Post-quantum cryptography is a first example of how states have to design policy responses to the potential impact of quantum on the digital infrastructure. Exploration of further positive and negative impact scenario's may reveal that governments need additional capabilities to deal with future consequences.

UNESCO as a catalyst for capacity building

Consider efforts such as offline and online learning platforms aimed at helping Member States to become ready for an era with advanced quantum science-based technologies. It is important that on a global level, the conversation about quantum science can be sustained in a level-playing field: governmental representatives should acquire the capabilities to understand and positively anticipate the emergence of relevant quantum technologies.

[23] For a more detailed assessment of potential impact on global access: AWO *Quantum Computing and the Global South*; Report (forthcoming).

V. Regulation and Governance

As with any other technology, quantum can also bring use cases that have a negative impact. This requires an early start for those looking at the regulation and governance models for quantum as we enter the era of use cases. This includes, for example, the resolution of questions about the dual-use nature that apply to many quantum technologies. It also extends to unintended consequences of quantum technologies that are purely civilian in nature. UNESCO's experience from other emerging technologies can help its Member States to navigate ex-ante assessments of specific quantum applications.

UNESCO as a convener

Develop a mechanism that helps steer the conversation about global governance, and impact assessments, and to instigate international collaboration around the pathways towards possible guidelines and standards that are needed in order to safeguard responsible innovation principles. UNESCO may play a constructive role in bringing together relevant players from public and private actors in the quantum domain.

4. CONCLUSION

It is safe to say that not only quantum technologies themselves still are in an early stage of development. This statement also holds true for the ongoing discussion about how to deal with the to-be-expected societal impact of these technologies. This discussion paper raises an important set of questions, and proposes a number of ways UNESCO can support responsible innovation as this technology matures.

As we move further into the quantum era, this focus should be extended to assessing the impact on the individual realms of persons. Questions about inclusion should be put on the agenda, also in the context of being enabled to participate in the development and usages of applications. In addition, it will be critical to discuss the possible interactions between quantum technologies and other technologies. The impact that quantum computing may have on (undermining) cyber security is already identified, as is the possibility that quantum communication may support that security. UNESCO's past work on AI raises the question of how AI is affected when supported by quantum computing. This also counts for possible combinations of quantum sensing and emerging technology outside the digital realm, for instance, biotechnology.

Tackling these questions all falls within the UNESCO's mandate. UNESCO's role as a trusted partner of national governments, as a laboratory of ideas, standard setter and facilitator of international cooperation provides an opportunity to build bridges where divides may appear, if left unattended. This discussion paper provides a set of preliminary reflections and opportunities, including in view of UNESCO's next mid-term strategy.