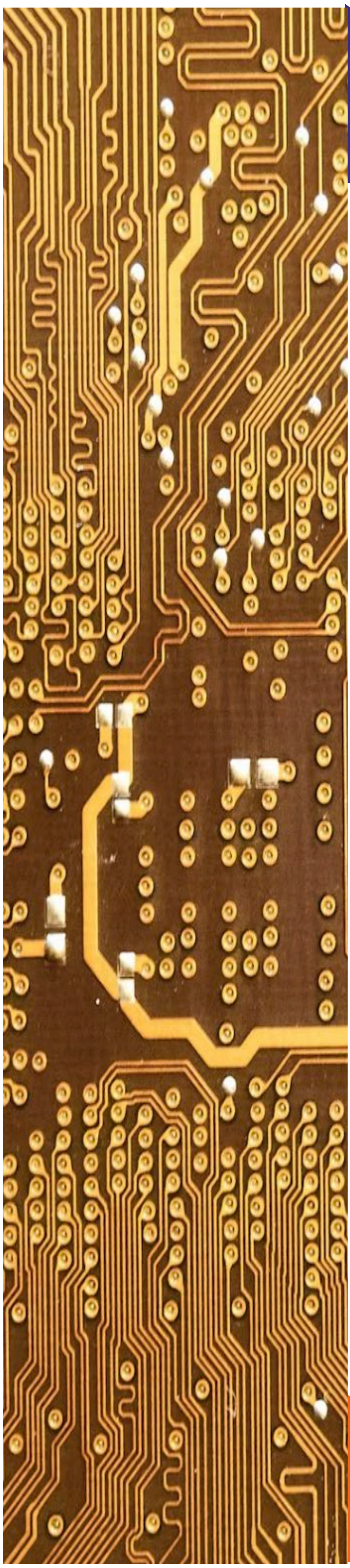

Strategic Industry Roadmap (SIR)

January 2024

QuIC
European Quantum Industry Consortium

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Glossary

Term	Definition
5G	Fifth generation of cellular network technology
A	
ACES	Atomic Clock Ensemble in Space
ADC	Analogue to Digital Converter
ADR	Adiabatic Demagnetisation Refrigeration
AES	Advanced Encryption Standard
AI	Artificial Intelligence
APD	Avalanche PhotoDiode
API	Application Programming Interface
AQC	Adiabatic Quantum Computation
ASIC	Application-Specific Integrated Circuit
B	
BB84	Bennett and Brassard 1984 QKD protocol
C	
CMOS	Complementary Metal Oxide Semiconductor
CSA	Coordination and Support Action
CSEM	Swiss Center for Electronics and Microtechnology
CV QKD	Continuous Variable QKD
CW	Continuous Wave
D	
DAC	Digital-to-Analogue Converter
DCI	Data Centre Interconnect
DigiQ	Digitally Enhanced Quantum Technology Master
DIGITAL	Digital Europe Programme
DLOG	Discrete Logarithm
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DV QKD	Discrete Variable QKD
E	
EB QKD	Entanglement-Based QKD
EC	European Commission
EPFL	École Polytechnique Fédérale de Lausanne
EPO	European Patent Office
ESA	European Space Agency
ESG	Environmental, Social, and Governance
EU	European Union
EuroHPC	European High-Performance Computing Joint Undertaking
EuroQCI	European Quantum Communication Infrastructure
F	

FET	Field-Effect Transistor
FinFET	Fin FET
FPGA	Field Programmable Gate Array
FTQC	Fault-Tolerant Quantum Computing
G	
GKP	Gottesman–Kitaev–Preskill (code)
GM	Gifford–McMahon
GNSS	Global Navigation Satellite System
GPU	Graphical Processing Unit
H	
HCPCF	Hollow-Core Photonic Crystal Fibre
HPC	High-Performance Computing
I	
IC	Integrated Circuit
ICT	Information Communication Technology
INRIA	Institut National de Recherche en Informatique et en Automatique
IP	Intellectual Property
IPR	Intellectual Property Rights
IR	Intermediate Representation
ISL	Inter-Satellite Link
ISO	International Organization for Standardization
IT	Information Technology
ITS	Information-Theoretically Secure / Information-Theoretic Security
J	
K	
KPI	Key Performance Indicator
KMS	Key Management System
L	
LEO	Low Earth Orbit
LiDAR	Light-based Detection And Ranging
LMIC	Low- or Middle-Income Country
LNE	Laboratoire National de métrologie et d’Essais
M	
MDI	Measurement-Device-Independent
ML	Machine Learning
MRI	Magnetic Resonance Imaging
N	
NDT	NonDestructive Testing
NISQ	Noisy Intermediate-Scale Quantum system
NIST	(American) National Institute of Standards and Technology
NMR	Nuclear Magnetic Resonance
NV	Nitrogen Vacancy

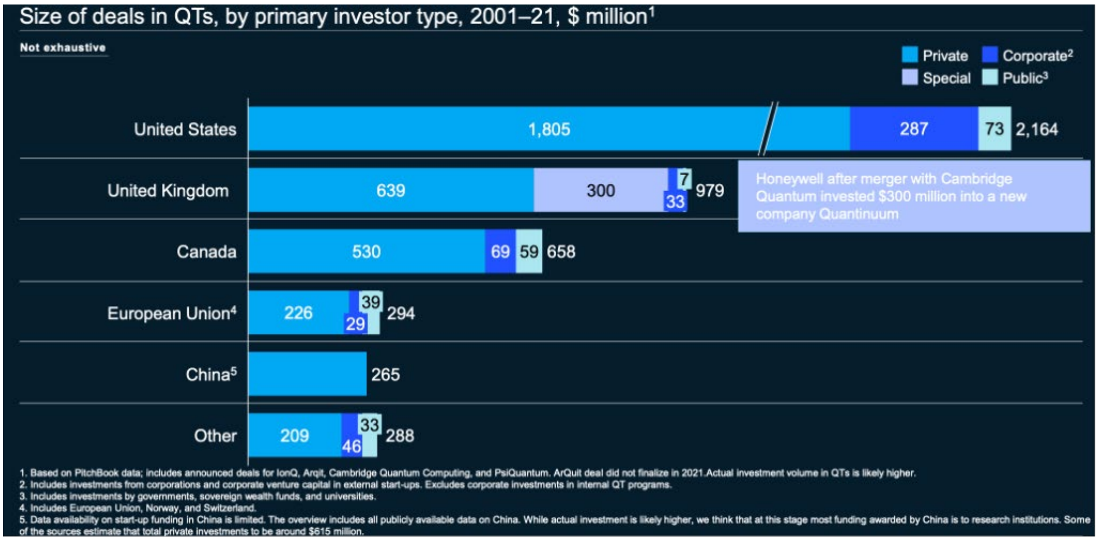
O	
OIDA	Optoelectronics Industry Development Association
OGS	Optical Ground Station
OPM	Optically Pumped Magnetometer
OS	Operating System
OSI	Open System Interconnection model
OTP	One-Time Pad
P	
PIC	Photonic Integrated Circuit
PM	Prepare-and-Measure
PQC	Post-Quantum Cryptography
PRNG	Pseudo-Random Number Generation/Generator
PISQ	Perfect Intermediate-Scale Quantum computing
PT	Pulse Tube
Q	
QuA	Quantum Annealing
QC	Quantum Computing
QCI	Quantum Communication Infrastructure
QComm	Quantum Communication(s)
QEC	Quantum Error Correction
QED-C	Quantum Economic Development Consortium
QFlag	Quantum Flagship of the European Commission
QHE	Quantum Hall Effect
QKD	Quantum Key Distribution
QPU	Quantum Processing Unit
QRAM	Quantum Random-Access Memory
QRNG	Quantum Random Number Generation/Generator
QT	Quantum Technology
QTEdu	CSA for Quantum Technology Education – European Commission
QTIndu	Quantum Technologies courses for Industry
QUBO	Quadratic Unconstrained Binary Optimisation
QuIC	European Quantum Industry Consortium
R	
R&D	Research and Development
REST	Representational State Transfer
RF	Radiofrequency
RNG	Random Number Generation/Generator
RSA	Rivest–Shamir–Adleman cryptosystem
RTO	Research and Technology Organisation
S	
SAGA	Satellite Advanced Global Architecture
SDK	Software Development Kit

SDO	Standards Developing Organisation
SEP	Standard Essential Patent
SHB	Spectral Hole Burning
SI	International System of units
SIR	Strategic Industry Roadmap
SKR	Secure Key Rate
SME	Small or Medium-sized Enterprise
SNR	Signal-to-Noise Ratio
SNSPD	Superconducting Nanowire Single-Photon Detector
SPAD	Single-Photon Avalanche Diode
SPD	Single-Photon Detector
SQIF	Superconducting Quantum Interference Filter
SQUID	Superconducting QUantum Interference Device
STEM	Science, Technology, Engineering, and Mathematics
SWaP-C	Size, Weight, and Power Cost
T	
TF QKD	Twin-Field QKD
TN	Trusted Node
TRL	Technology Readiness Level
TRNG	True Random Number Generation/Generator
U	
UV	Ultraviolet
V	
VC	Venture Capital
VQE	Variational Quantum Eigensolver
W	
WG	Working Group
WG IPT	WG – Intellectual Property & Trade
X	
Y	
Z	

Introduction

Quantum technologies represent a promising and rapidly growing sector with the potential to develop and shape new global industry value chains. Across the world, an increasing number of companies are developing solutions that leverage the fundamental properties of quantum mechanics. Based on these technologies, many products and services are now being developed that will be capable of addressing existing and future challenges that are impossible, or very difficult, to solve using traditional means. It is foreseen that QTs will have a wide social impact by reshaping how information is processed and communicated, and even how we interact with our environment both here on Earth and in deep space. Growth in the sector is being fuelled both by governments and investors, with many tens of billions of euros in funding and investments.

The second quantum revolution is currently unfolding. As this revolution gains traction, so does the associated quantum race. According to a recent QC report released by McKinsey in June 2022[1], North America leads the QT market, with nearly 40% of players and over 60% of all startup funding. Ten out of the twelve biggest hardware players are based in North America, while China has the broadest commercial implementation of QComm. The McKinsey analysis (see Figure 1-1) shows that the majority of investments are still in US companies, driven primarily by private investors.



1. Based on PitchBook data; includes announced deals for IonQ, Arqit, Cambridge Quantum Computing, and PsiQuantum. ArQuit deal did not finalize in 2021.Actual investment volume in QTs is likely higher.
2. Includes investments from corporations and corporate venture capital in external start-ups. Excludes corporate investments in internal QT programs.
3. Includes investments by governments, sovereign wealth funds, and universities.
4. Includes European Union, Norway, and Switzerland.
5. Data availability on start-up funding in China is limited. The overview includes all publicly available data on China. While actual investment is likely higher, we think that at this stage most funding awarded by China is to research institutions. Some of the sources estimate that total private investments to be around $615 million.

Figure 1-1: Total investments in QTs by investor type[2]

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[1] *McKinsey & Co., "Quantum Technology Monitor," June 2022, https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20computing%20funding%20remains%20strong%20but%20talent%20gap%20raises%20concern/quantum-technology-monitor.pdf.*

[2] *McKinsey & Co.*

Regarding public funding, QURECA reports that China leads the announced public funding with US$ 15 billion, followed by the European continent (EU and its Member States, the UK, Switzerland, and Israel) with a combined total of approximately US$ 13 billion. Figure 1-2 shows the totals for the promised public funding.

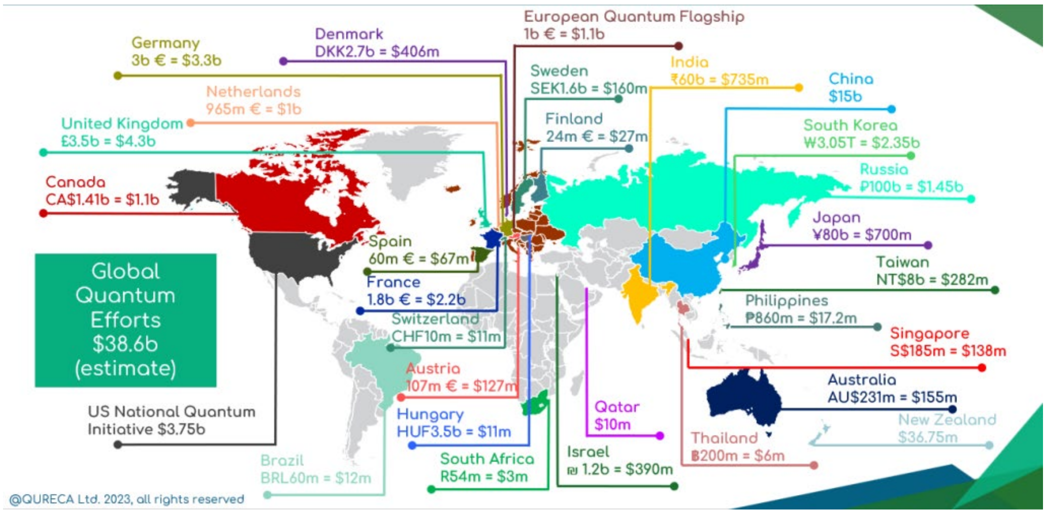

Figure 1-2: Total public funding announced (committed and pledged) up to 2023[3]

These figures give us a snapshot of the present state of the quantum race around the world. In light of the strategic implications of QTs, decisive action is crucial.

Success in developing commercial quantum solutions goes beyond the QTs themselves, or the skills, know-how, and business capabilities of individual companies. The long-term success of the quantum sector will depend on creation of a fertile ecosystem with sustained demand for quantum solutions. This demand will emerge from the capacity of QTs to deliver tangible value to businesses, not only in the long term, but also – indeed, crucially – in the short term. Although there are still significant challenges to be solved, existing QC tools are already, despite their limitations, beginning to offer promising results in specific applications, such as optimisation, simulation and ML/AI. QComm is another fertile area, and quantum key exchange demonstrations have been successful in different locations worldwide, through terrestrial and space segments. It is anticipated that there will be increasing focus on interoperability and the development of larger-scale demonstrations within the next few years. In the field of quantum sensing, there are already some commercially available products to address niche applications, and a wide variety of new sensors are being developed and should hit the market over the coming years.

Looking beyond pure quantum solutions, we are already seeing a broad spectrum of industries benefiting tangibly from quantum-inspired solutions that can be executed on traditional HPC infrastructure – in particular, current GPUs. Ultimately, sustained

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[3] *Maninder, "Overview of Quantum Initiatives Worldwide 2023," Qureca (blog), July 19, 2023, https://qureca.com/overview-of-quantum-initiatives-worldwide-2023/.*

demand for QC solutions will come from the tangible value that they are able to create, and quantum software and applications are the key components in creating this value.

Quantum hardware is of course also fundamental, but to fully realise its potential, hardware development needs to be integrated with quantum software development, including the software layers for operation of the quantum computer (e.g., OS, compilers) and quantum algorithms for different applications. In other words, it is always the quantum software and quantum applications that will drive value for QTs.

The extensive potential of QComm for quantum-secure information exchange and, in future, for building the quantum internet, is well recognised. High-performance quantum devices, in conjunction with the imminent development of quantum repeaters, will enable efficient and secure communication based on QT. Governments are already supporting the design and deployment of small and medium-size demonstrators in the terrestrial and space segments, thereby following the example of various academic and industrial consortia. However, the market for these systems is currently small and for the technology to grow into its full potential at industrial scale and become widely adopted, it will be essential to build support from the industrial sector. At present, this sector has already begun to channel some investments towards demonstrators. Another important element in developing the potential of QTs will be standardisation and certification, and work in this area needs to be expanded and solidified.

Successful deployment of QT will also rely on the right framework conditions: a large and skilled labour pool; a reliable supply chain of components, devices and services; industry-wide standards and accreditation procedures; and a favourable environment for international trade. Ultimately, the broader social and economic impact of QT will be realised mainly by integrating the new technology into existing industries and ecosystems. The involvement of a broad set of actors from the various sectors will be crucial to the success of this programme.

QuIC was established in 2021 to bring together companies, investors, RTOs, and other stakeholders from different sectors with the aim of maximising the commercial success of the pan-European quantum industry. QuIC is Europe’s largest and most influential nonprofit association dedicated to establishing a thriving commercial quantum ecosystem. QuIC has grown rapidly from its 14 founding members, and now has more than 175 members from across the EU, as well as Israel, Norway, Switzerland, Turkey, and the UK. Its members collectively span the broad landscape of quantum solutions – computing, communication, sensing and metrology, and enabling technologies – and have a combined public and private worth in the trillions of euros.

QuIC’s activities are centred around WGs on topics of common interest. These include economically relevant use cases, best practices in IP protection, standardisation requirements, education and training for a quantum-aware workforce, funding for SMEs, monitoring progress in QT, and the creation of an interconnected European ecosystem.

This document presents the collective vision of QuIC's members for the European quantum industry over the coming decade. Chapters 2, 3, 4, 5, and 6 provide an overview and roadmap for the development of, respectively, QC, quantum simulation, QComm, quantum sensing and metrology, and their enabling technologies. Chapters 7, 8, 9, and 10 outline industry needs with respect to core aspects that underpin the growth of all QTs: education and training, standardisation, IP, and funding in Europe. Chapter 11 identifies key elements necessary to the achievement of the quantum industry's governance principles. Finally, the main conclusions are presented in Chapter 12.

This document is intended to help policy- and decision-makers across Europe, in businesses as well as at regional, national, and European government levels, to understand the quantum industry's ambitions and to highlight areas of targeted support for accelerated growth.

Quantum Computing

General Overview

Definition of Terminology

When talking about quantum computers and simulators, misunderstandings often arise about terminology and capabilities. For clarification, this section gives a short definition of each concept before developing the general overview.

When differentiating between QC and simulation, there are two dimensions to consider: the application (software) dimension (QC and quantum simulation) and the device (hardware) dimension (quantum computers and quantum simulators).

Application dimension

QC is a computational paradigm that exploits quantum effects such as superposition, interference, and entanglement to solve problems by applying a quantum algorithm. There are different variants of this paradigm. The most common is digital gate-based QC, in which quantum algorithms are represented as quantum circuits – i.e., a sequence of quantum gates applied to qubits. Digital QC is universal; in principle, a digital quantum computer can solve any quantum algorithm, although the currently available devices are still quite limited. An alternative paradigm is AQC, in which the problem is encoded in the ground state of the system's Hamiltonian, and the system evolves towards this solution through continuous modulation of its tuneable parameters. This variant of analogue QC is typically executed on devices similar to those used for quantum simulation. The equivalence between the digital and AQC models has been formally proven.

Quantum simulation is a process that determines the physical properties of quantum systems such as molecules or crystals by calculation methods or by studying a different quantum system with similar properties (as opposed to a direct measurement on the system of interest).

Device dimension

Quantum computers are quantum systems that are designed to execute quantum algorithms. The most common variant of quantum computers follows the gate-based model.

Quantum simulators are special-purpose quantum systems that are designed to simulate other quantum systems. They have similar properties to the systems of interest but can be more easily controlled. They usually work in an analogue fashion and are usually not universal.

Quantum annealers are quantum systems that are designed to determine the ground state of a Hamiltonian in an analogue fashion, most commonly by employing the adiabatic principle. They are currently not universal and can only be used to solve certain types of problems such as QUBO or Ising problems. Quantum annealers can be viewed as a specific type of quantum computer or quantum simulator, depending on the issue they tackle.

Classical quantum simulators and classical quantum emulators are classical computers used to simulate/emulate quantum computers or quantum simulators. They can be software packages running on standard classical hardware or computer appliances (integrated software/hardware solutions). Typically, they will simulate/emulate gate-based quantum computers; however, some simulate/emulate analogue quantum computers, annealers, or quantum simulators. They can either use arbitrary classical methods to obtain the same result as a quantum computer (simulator – e.g., linear algebra simulator of a gate-based quantum computer) or replicate the inner workings of a quantum computer (emulator – e.g., pulse-level emulation of quantum gate sequences).

As there is often some confusion about whether the term “quantum simulator” refers to an actual quantum device used for quantum simulation or to a classical computer simulating a quantum computer, it has been suggested that classical simulators be referred to as “quantum emulators”. However, this naming convention does not consider the differences between simulation and emulation. Therefore, we suggest explicitly using the terms “classical quantum simulators” and “classical quantum emulators” when referring to these classical devices.

Brief Overview

Computing technologies form the bedrock of today’s modern societies: products of all types are designed and fabricated using computer programs, and services are optimised and powered by computers. The classical processing units found in smartphones, laptops, desktop computers, and many high-performance computers are rooted in the dawn of the microprocessor in the 1970s. The evolution of these technologies was exponential for many decades, as captured by Moore’s Law: processing power doubles roughly every two years. However, this rapid development trend has slowed since the start of this millennium. The ever more compact processors and systems-on-chips are manufactured at nanometre scale, and manufacturing processes must battle against the fundamental laws of physics that limit the degree of improvement for every new generation of technology. This has led to the emergence of new flavours of information processing systems, such as FPGAs, GPUs, and ASICs. Each system has its own characteristics regarding flexibility, acceleration, and customisation.

The ability to cluster several general-purpose processors together with purpose-made devices (also known as co-processors) to process data and perform complex calculations at high speed has been rapidly developed in recent years. Such HPC platforms form the basis of exascale computing (exascale computing refers to computing systems capable of calculating at least “10^{18} IEEE 754 Double Precision (64-bit) operations (multiplications and/or additions) per second – exaFLOPS”)[4]. Nevertheless, all these processors rely on “classical” information processing, and the resulting power-hungry platforms now consume between 1.5% and 3% of total energy production.

In contrast, QC represents a fundamental paradigm shift in the approach to HPC, by exploiting the properties of quantum physics. A quantum computer working with data encoded as qubits is, in principle, able to perform specific tasks many orders of magnitude faster than today’s most powerful supercomputers, solving problems that are impossible to solve using classical computing architectures[5,6]. However, attaining this performance requires overcoming several engineering challenges, such as the degradation of information (“decoherence”).

Quantum computers can also be used as accelerators in combination with classical computers to run hybrid quantum/classical algorithms in which specific parts of the calculation are run on the quantum computer and the other parts on the classical computer. This method combines the advantages of classical and quantum computers. It also lowers the technical requirements on the quantum hardware, thus making it possible to reap the benefits of QC earlier. However, developing suitable integration between classical and quantum computers is still in its infancy.

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[4] *Peter Kogge, ed., “ExaScale Computing Study: Technology Challenges in Achieving Exascale Systems” (Defense Advanced Research Projects Agency Information Processing Techniques Office (DARPA IPTO), September 2008), https://sites.astro.caltech.edu/~george/aybi199/ExascaleReport.pdf.*

[5] *Frank Arute et al., “Quantum Supremacy Using a Programmable Superconducting Processor,” Nature 574, no. 7779 (October 24, 2019): 505–10, https://doi.org/10.1038/s41586-019-1666-5.*

[6] *Ming Gong et al., “Quantum Walks on a Programmable Two-Dimensional 62-Qubit Superconducting Processor,” Science 372, no. 6545 (May 28, 2021): 948–52, https://doi.org/10.1126/science.abg7812.*

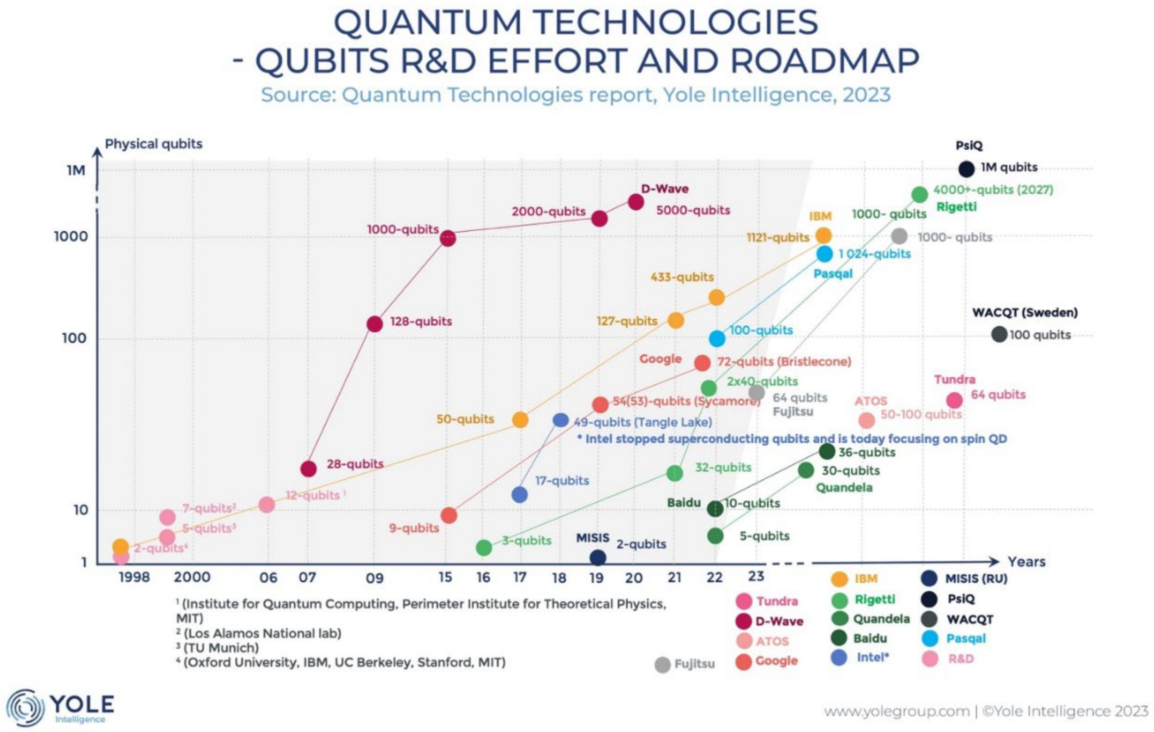

Figure 2-1: Number of qubits attributed to a selection of hardware developers[7]. Note, however, that the quality of a quantum computer's qubits is decisive for scalability (not shown in this graph)

Advances in the QC field are staggering (see Figure 2-1). The rapid progress has led to recent demonstrations of quantum advantage[8,9,10]. Quantum advantage is achieved when a programmable quantum device can solve a problem faster than the fastest known classical computer solution. In 2019, Google's Sycamore, a quantum computer based on superconducting qubits, took 200 seconds[11] to perform a calculation that it had been thought would take 10,000 years on Summit, the world's most powerful supercomputer at that time (although this estimate was later revised to 2.5 days, or

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[7] *Source: Yole Intelligence, "Quantum Technologies 2021," Yole Group - Follow the latest trend news in the Semiconductor Industry, accessed January 5, 2023, https://www.yolegroup.com/product/report/quantum-technologies-2021/.*

[8] *Arute et al., "Quantum Supremacy Using a Programmable Superconducting Processor."*

[9] *Gong et al., "Quantum Walks on a Programmable Two-Dimensional 62-Qubit Superconducting Processor."*

[10] *Qingling Zhu et al., "Quantum Computational Advantage via 60-Qubit 24-Cycle Random Circuit Sampling," Science Bulletin 67, no. 3 (February 2022): 240–45, https://doi.org/10.1016/j.scib.2021.10.017.*

[11] *Kogge, "ExaScale Computing Study: Technology Challenges in Achieving Exascale Systems."*

200,000 seconds[12]). Two years later, the Chinese light-based quantum computer Jiuzhang 2.0[13], and the superconducting quantum computer Zuchongzhi 2.1[14], solved specific problems respectively 100 trillion and 10 million times faster than the most powerful supercomputer available today. In June 2022, Xanadu, a Canadian company specialising in photonic QC, also demonstrated quantum computational advantage with an experiment run on their cloud-accessible machine Borealis[15]. The most recent experiment (taking measurements that correspond to drawing a sample from a distribution) took Borealis 36 μs per sample, whereas the estimated time for the world's fastest supercomputer to model the same experiment using the best algorithms currently known would have been 9000 years. All four demonstrations were based on curated problems specifically designed to showcase quantum advantage. In June 2023, IBM claimed "quantum utility" when it solved an Ising problem with applications in physics and engineering on its 127-qubit Eagle processor[16]. In this case, the advantage over classical systems is in the memory requirements. While IBM's claim has been disputed and efficient quantum-inspired classical solutions using tensor networks have been found[17,18], it is still an important step forward regarding the ability of QC to solve real problems. On 4 December 2023, IBM revealed a 1121 qubit processor (Condor) based on its existing technology and a new higher quality qubit processor codenamed Heron (with 133 qubits)[19]. Demonstrating quantum advantage in practical applications remains a primary objective for global QC projects.

Despite these impressive technological breakthroughs, today's quantum computers need to improve their performance before they can create tangible value for businesses across a broad range of sectors. The main bottlenecks to achieving the necessary performance are in the manufacturability and manipulation of large numbers of physical qubits, combined with their significant rates of error: errors are generated throughout the whole computing cycle, including qubit preparation,

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[12] *"On 'Quantum Supremacy,'" IBM Research Blog, October 21, 2019, https://www.ibm.com/blogs/research/2019/10/on-quantum-supremacy/.*

[13] *Arute et al., "Quantum Supremacy Using a Programmable Superconducting Processor."*

[14] *Gong et al., "Quantum Walks on a Programmable Two-Dimensional 62-Qubit Superconducting Processor."*

[15] *Lars S. Madsen et al., "Quantum Computational Advantage with a Programmable Photonic Processor," Nature 606, no. 7912 (June 2022): 75–81, https://doi.org/10.1038/s41586-022-04725-x.*

[16] *Youngseok Kim et al., "Evidence for the Utility of Quantum Computing before Fault Tolerance," Nature 618, no. 7965 (June 2023): 500–505, https://doi.org/10.1038/s41586-023-06096-3.*

[17] *Joseph Tindall et al., "Efficient Tensor Network Simulation of IBM's Eagle Kicked Ising Experiment" (arXiv, August 16, 2023), https://doi.org/10.48550/arXiv.2306.14887.*

[18] *Siddhartha Patra et al., "Efficient Tensor Network Simulation of IBM's Largest Quantum Processors" (arXiv, October 16, 2023), https://doi.org/10.48550/arXiv.2309.15642.*

[19] *"IBM Quantum Computing | Summit 2023," accessed December 29, 2023, https://www.ibm.com/quantum/summit-2023.*

quantum gates and qubit readout. They result mostly from quantum decoherence, generated by the interactions between the qubits and their environment, as well as from defects from control electronics signals.

In this context, error correction becomes a crucial challenge. Solving this issue is a very active field of research for quantum hardware builders and many different methods exist for each specific technology. Regardless of method, the objective remains the same: create an artificial fault-tolerant qubit called a logical qubit. Conceptually, a logical qubit sits between a physical qubit (with a short lifetime and prone to significant error rates) and a mathematically perfect qubit (with infinite computing time and zero error rate). It has a longer lifetime than a physical qubit and should have an error rate comparable to that of a classical computer.

The number of physical qubits that must be assembled to create a logical qubit depends on the fidelities of the underlying physical qubits and their connectivity (which differs between qubit technologies), and the QEC code used. Current estimates range between 100 and 10,000 physical qubits to create a logical qubit, depending on the above-mentioned factors. This corresponds to the plans published by IBM[20], Google[21] and PsiQuantum[22] with 100 logical qubits created out of one million physical qubits. On the physical architecture side, topological qubits are an analogue version of surface codes that should make it possible to reduce this ratio of logical to physical qubits. The cat qubits of Alice & Bob, which take a similar approach, are forecast to require fewer than 100 physical qubits to create one logical qubit[23]. In December 2023, Harvard University, QuEra, MIT and NIST/UMD presented the results of running quantum algorithms with 48 logical qubits and several hundred entangling operations on a neutral-atom-based quantum computer with 280 physical qubits[24]. While this setup still has its limitations[25], it is nevertheless a huge leap towards FTQC.

Achievement of logical qubits is the first milestone toward FTQC. Beyond having a logical qubit with good quality, FTQC introduces other principles related to implementing a practically useful QEC scheme with logical qubits: fault-tolerant state

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[20] *"IBM Quantum Computing | Summit 2023."*

[21] *"Google Is Building a 1 Million Qubit Quantum Computer | Information Age | ACS," accessed December 29, 2023, https://ia.acs.org.au/article/2021/google-is-building-a-1-million-qubit-quantum-computer.html.*

[22] *"Silicon Photonic Quantum Computing towards Large-Scale Systems | Quantum Australia | Jeremy O'Brien - YouTube," accessed December 29, 2023, https://www.youtube.com/watch?v=81_JNyeBagk.*

[23] *Charles Choi, "How Tiny Schrödinger's Cats Could Upend Quantum Again - IEEE Spectrum," September 2023, https://spectrum.ieee.org/schrodingers-cat-qubit.*

[24] *Dolev Bluvstein et al., "Logical Quantum Processor Based on Reconfigurable Atom Arrays," Nature, December 6, 2023, 1–3, https://doi.org/10.1038/s41586-023-06927-3.*

[25] *Scott Aaronson, "Staggering toward Quantum Fault-Tolerance,"* Shtetl-Optimized *(blog), December 7, 2023, https://scottaaronson.blog/?p=7651.*

preparation, fault-tolerant quantum gates, fault-tolerant measurement, and fault-tolerant error correction. FTQC theoretically allows the execution of algorithms of arbitrary length, whereas without it, algorithms are limited to a few series of gates.

Looking forward, we anticipate that ongoing advances in quantum hardware, middleware, and software will lead to a general-purpose quantum advantage machine becoming available around 2030–2035. This machine will be capable of delivering beyond-classical performance for large instances of textbook quantum algorithms, and solving classically intractable relevant problems for industry and research applications. Moreover, greater access to QC through cloud services and consortia will stimulate an ever-growing base of algorithm designers and end users, fostering the identification of new application areas for QC. Developments in pure quantum and hybrid quantum/classical algorithms will either expedite the realisation of practical quantum advantages or yield more significant quantum advantages from given quantum systems. Finally, co-design, the intricate interplay between algorithm development and the design choices for quantum hardware, is a likely vector for successful demonstrations of end-user-relevant quantum advantage. One concept that is relevant in this context is the PISQ-methodology[26]. It allows researchers, in combination with universities, to focus on the functional correctness of quantum circuits, independent of what qubit technology they will be executed on. This approach allows researchers from, for instance, chemical or biomedical fields to develop quantum circuits for their core problems.

The value of QC to industry and society is estimated to be between US$ 450 billion and US$ 850 billion[27] over the next few decades. The financial stakes for companies are thus enormous. Finance, manufacturing, aerospace, automotive, defence, and cybersecurity are some of the strategic sectors already harnessing the power of QTs and, specifically, QC. European companies already working on this from the consumer side include Airbus, BASF, BBVA, Bosch, Crédit Agricole, EDF, MBDA, Thales, and Repsol.

To further accelerate the adoption of QC, the EuroHPC Joint Undertaking recently selected six sites across the EU to host and operate the first EuroHPC quantum computers: in the Czech Republic, Germany, Spain, France, Italy, and Poland. This first group will be extended to include further centres over the next five years. The availability of these resources will serve as an important accelerator for training QC specialists, developing new QC algorithms, and support of emerging European QC companies.

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[26] *Koen Bertels et al., "Quantum Computing -- from NISQ to PISQ" (arXiv, July 8, 2022), http://arxiv.org/abs/2106.11840.*

[27] *Bobier, Jean-François et al., "What Happens When 'If' Turns to 'When' in Quantum Computing?," Leading in the New Reality | Digital Transformation (Boston Consulting Group, July 2021), https://web-assets.bcg.com/89/00/d2d074424a6ca820b1238e24ccc0/bcg-what-happens-when-if-turns-to-when-in-quantum-computing-jul-2021-r.pdf.*

Quantum Computing Stack: Organisation

The development of QC solutions encompasses a wide range of technologies, from hardware systems to software tools. Furthermore, the entry into service of these solutions requires a quantum-literate user community that can map use cases onto quantum machines.

These QC landscape dimensions are represented by layers of abstraction like those used to describe traditional computing systems (see Figure 2-2: QC stack). Several European SDOs are working together to achieve alignment in terminology and definitions surrounding QC[28]. As this activity matures, QuIC members are likely to adopt these standards. In the remaining sections of this chapter, we provide details on the state of development of products and services and present the industry's ambitions for each stack layer on the road to 2035.

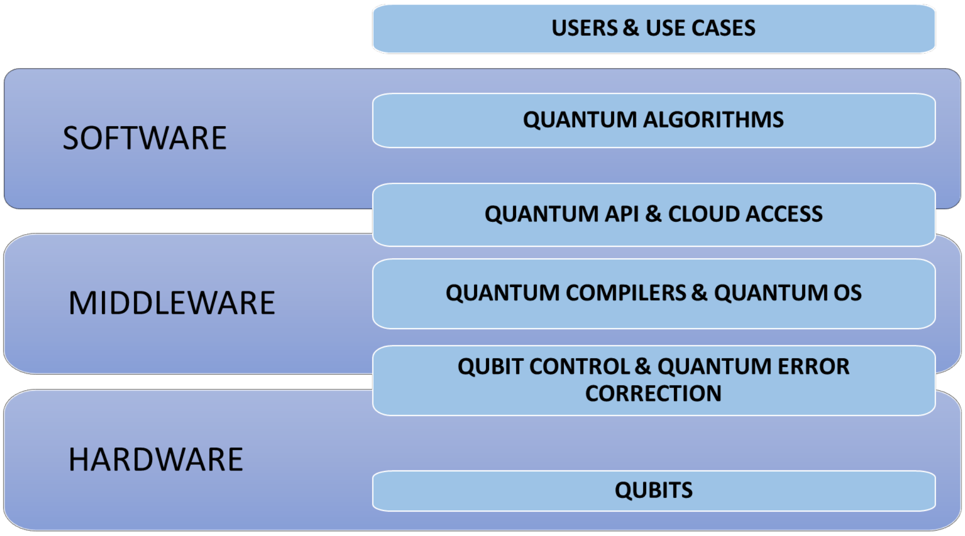

Figure 2-2: QC stack

Developing QC products and services requires a complete, robust, and future-proof supply chain with suppliers that can cater to each layer of the entire stack of the QC ecosystem. As entities in the US and Asia currently dominate today's supply chain, the growth of European suppliers is of prime importance. They will mostly fit into the existing HPC, semiconductor, and ICT supply chains. However, large-scale quantum computer manufacturing is likely to require additional industry segments. Having several sizeable quantum system integrators within Europe will also be important.

Although a robust supply chain is necessary to develop quantum products and services, it is not sufficient. The needs of enterprises, and the capability of QTs to address those needs, will drive the growth of quantum products and services. In other

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[28] *Oskar van Deventer et al., "Towards European Standards for Quantum Technologies," EPJ Quantum Technology 9, no. 1 (December 2022): 33, https://doi.org/10.1140/epjqt/s40507-022-00150-1.*

words, practical applications of QTs will drive the development of quantum products and services. In this context, we include users and use cases as an integral element of the QC stack.

Quantum Computing Hardware

QC hardware can be characterised by the types of qubits supported and the kind of computations the hardware can run. Table 2-1 provides an overview of key European QC hardware integrators who are QuIC members, classified according to this characterisation. Most integrators focus on general-purpose QC applications (gate-based systems). QuA systems generally have a narrow operational mode; however, many computing and simulation problems can be restructured to run on these systems.

	Quantum Computers (gate based systems)	**Quantum Simulation** (annealers, adiabatic systems)
Superconducting	IQM QILIMANJARO QUANTUM TECH QUANTWARE	QILIMANJARO QUANTUM TECH
Semiconductor	QUANTUM MOTION TNO QuTech equal1 SemiQon	
Trapped Ion	AQT eleQtron	eleQtron
Neutral Atoms	PASQAL	PASQAL
Photons	QUIX QUANTUM QUANDELA	
NV Centres in Diamonds	SaxonQ	

Table 2-1: Leading QC hardware (qubits) integrators in Europe who are members of QuIC

Superconducting

Overview

Superconducting quantum circuits are now one of the most prevalent forms of QC technology in current global QC R&D, including work by large international companies such as IBM, Google, and Intel. They are based on an electrical (LC (inductor/capacitor) or resonant) circuit forming a loop that can be described as a harmonic oscillator. Such a circuit is generally built using aluminium, which allows the frictionless flow of electricity at low temperatures. A Josephson junction has a nonlinear inductance, leading to an anharmonic spectrum of the superconducting circuit that resembles a two-level atom spectrum (artificial atom). This system allows macroscopic quantum effects to be designed and measured by tuning the classical electrical elements of the circuit.

There are different types of superconducting qubits (see Figure 2-3: Classifying superconducting qubits). Depending on the degrees of freedom in the encoding, we may encounter charge, flux, and phase qubits. In flux qubits, the two quantum states of the qubit are a magnetic flux pointing up and down and are represented by a double-well potential. Phase qubits use the change of phase in the oscillation amplitudes of the conductance wave function (which is a superconducting order parameter) across a Josephson junction. A charge qubit encodes the state as an integer number of Cooper pairs in a superconducting island. The transmon qubit (or Xmon) falls within this last group and is currently the dominant superconducting qubit implementation.

Research in superconducting qubit architecture remains a very active field. Indeed, while achieving good results, transmon architecture remains extremely sensitive to errors, which is problematic for scaling up the technology. As a result, bosonic codes and their abilities to self-correct appear to be a promising family of qubits. Importantly, the reduction in error drastically reduces the number of qubits dedicated to error correction, which in turn hugely reduces hardware overhead. For example, Alice & Bob's cat qubit approach is estimated to require 60 times fewer physical qubits to run Shor's prime factorisation algorithm (350,000 cat qubits vs several millions of qubits with Google's technology)[29].

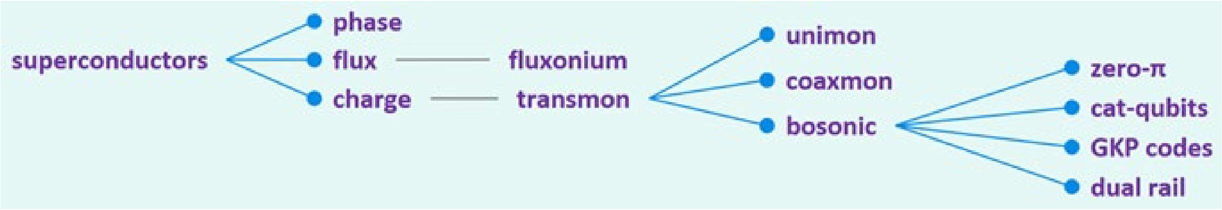

Figure 2-3: Classifying superconducting qubits[30]

Indeed, cat qubits are among the most well-known of the bosonic code family, and work by encoding a qubit in a harmonic oscillator which has an infinite-dimensional Hilbert space and can therefore replace a register of multiple physical qubits, thus reducing the hardware overhead required for QEC. GKP codes, also popular, consist of a superposition of position eigenstates to form grid states of a single oscillator. Other types of protected qubit include zero-π, dual-rail, bifluxon, cos(2θ), Kerr-cat, etc.

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[29] *Gouzien, Élie, et al. "Performance Analysis of a Repetition Cat Code Architecture: Computing 256-bit Elliptic Curve Logarithm in 9 Hours with 126 133 Cat Qubits." Physical Review Letters 131.4 (2023): 040602*

[30] *Source: Olivier Ezratty, "Understanding Quantum Technologies 2023" (arXiv, November 12, 2023), https://doi.org/10.48550/arXiv.2111.15352.*

Alice & Bob and Quantum Circuits were the first companies to try the cat qubit approach, followed soon after by AWS. Nord Quantique focuses on GKP codes.

Each of these implementations is best suited to a certain type of quantum computation. We recall that there are two main models or paradigms of QC: the gate-based and the analogue models. Transmon qubits are the preferred implementation for the gate-based model, with qubit architectures that have been around since 2008 with steadily improving lifetime or coherence times (Figure 2-4). Flux qubits are a suitable hardware implementation for analogue systems, due to their natural mapping to spin Hamiltonians in which analogue algorithms are formulated. Furthermore, flux qubits allow smooth control of the spin Hamiltonian parameters, high anharmonicity of the spectrum, and extended coherence times of tens of microseconds[31].

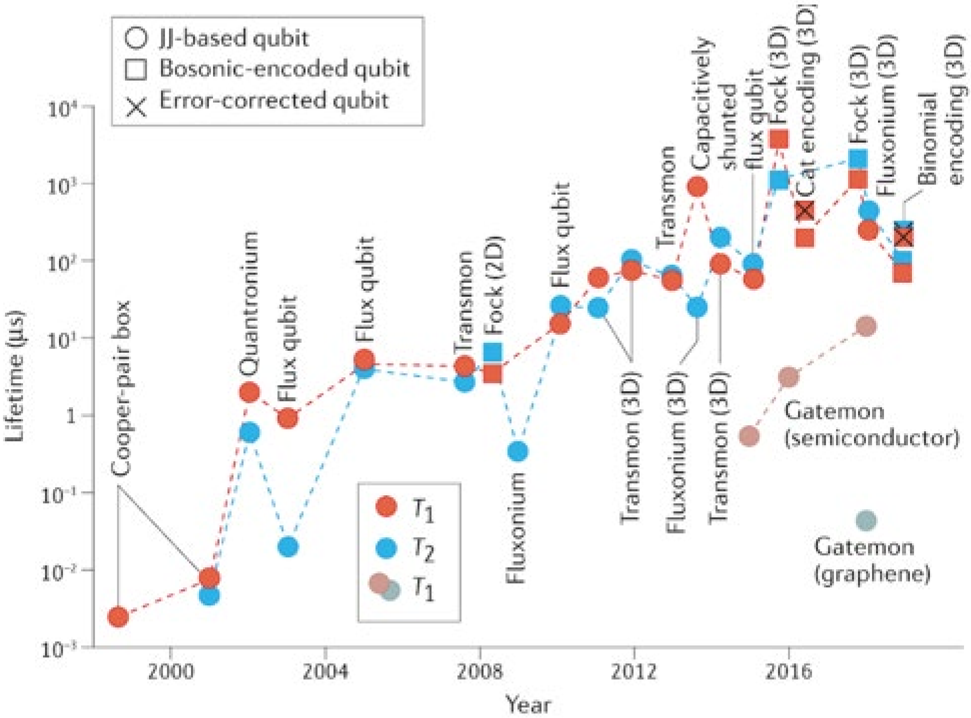

Figure 2-4: Evolution of superconducting qubit operational lifetimes (T_1)[32]

Access to European superconducting QC hardware has largely been limited to academic institutions producing qubit devices and laboratory equipment for their own research. More recently, supply chain companies have emerged in Europe, broadening access to this hardware. For instance, four companies were recently

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[31] *Fei Yan et al., "The Flux Qubit Revisited to Enhance Coherence and Reproducibility," Nature Communications 7, no. 1 (November 3, 2016): 12964, https://doi.org/10.1038/ncomms12964.*

[32] *Irfan Siddiqi, "Engineering High-Coherence Superconducting Qubits," Nature Reviews Materials 6, no. 10 (September 23, 2021): 875–91, https://doi.org/10.1038/s41578-021-00370-4.*

founded in the Netherlands, each one addressing a different part of the superconducting QC stack: QuantWare (QPUs), Qblox (electronics), Orange Quantum Systems (testing systems), and Delft Circuits (cabling). Together, they represent a substantial part of the stack. Note that Qblox, Orange Quantum Systems and Delft Circuits support not just superconducting qubits but also other modalities. Outside the Netherlands, the two main superconducting qubit technologies, transmons and flux qubits, are provided by IQM and Qilimanjaro respectively. The potential customers for early-generation NISQ superconducting hardware are primarily RTOs, quantum systems integrators, and HPC centres wishing to integrate quantum computers into their existing architectures. An affordable and resilient supply chain for components will be essential for made-in-Europe superconducting qubits to enjoy long-term success.

Road to 2035

Two of the main drawbacks of superconducting qubits are the errors in the manufacturing process for the device and the low temperatures required for operation. These issues are hurdles for the scaling-up process for this architecture. Nevertheless, superconducting qubit technology is one of the most advanced QC technologies, and several solutions to tackle both limitations are gaining traction; e.g., more efficient cryogenic units are starting to be commercialised (see Chapter 6 – Enabling Technologies).

The quality and scale of superconducting qubit technology, including enabling technologies, must be developed to facilitate progress towards universal FTQC. The pathway to progress includes the achievement of logical qubits, demonstration of FTQC and universal FTQC through the realisation of the minimal set of quantum gates required to achieve it.

The usefulness of QC depends upon the achievable fidelities and the number of qubits in the QPU. Scaling up quality and numbers of qubits will require advanced 3D architectures and assembly techniques, as well as the exploration of novel superconducting qubit designs to yield better coherence times or interconnection of separated processors via photonic links.

An important aspect of scaling QC hardware is the development of industrial-scale fabrication facilities with the capacity to miniaturise, assemble and integrate large QPUs. The semiconductor industry offers a good comparison: its existing facilities offer integration orders of magnitude beyond what is currently possible in QC. The QC facilities will also need to provide high-quality qubits and ICs. This will require additional research into materials, fabrication techniques, and processing methods. The enabling hardware that connects to the QPUs, such as cryogenic coolers, electronic systems, and cabling, must also be matured (see Chapter 6 – Enabling Technologies).

Spin Qubits

Overview

The semiconductor quantum industry focuses on developing spin qubits, and spin qubits have somewhat limited operating times (coherence times). Nonetheless, advocates believe that leveraging the decades-long investment and success of the semiconductor industry offers the optimum development path towards the million-qubit target – estimated as necessary to solve some of the more challenging use cases. Spin qubit researchers recently met in Japan for SiQEW 2023, following the Fifth Conference on Spin-Based Quantum Information Processing in late 2022 (Switzerland), and the proceedings of these conferences capture the current status of this set of technologies.

Several members of QuIC presented some of their recent results at these events. QuTech, a collaboration between TU Delft and TNO, is working closely with Intel, CEA/Leti, and others to design and manufacture Si and SiGe QPUs and full-stack systems. In 2022, QuTech published a report on the design, fabrication, and operation of a 6-qubit processor with universal control on SiGe/^{28}Si/SiGe material[33]. A similar device, also fabricated at QuTech, is currently being incorporated in Quantum Inspire (QuTech's full quantum computer demonstrator), which will be accessible online in 2024. In a parallel project, also in 2022, QuTech demonstrated two-qubit gate fidelity surpassing the 99% barrier for surface code error correction. In the same year, VTT published a paper[34] showing spin qubits fabricated using their internal custom process. This was followed by the VTT spinoff SemiQon being established in February 2023. SemiQon builds monolithically integrated Si quantum dots and cryogenic CMOS platforms on a pilot scale, operating at the Micronova Center, a part of Finland's national infrastructure OtaNano. Equal1 has developed several generations of integrated CMOS quantum test chips operating at 1–4 K, using a commercial European CMOS silicon foundry. The next generation of Equal1's integrated QPU includes spin qubits, control electronics, and error correction logic. These devices aim to generate sufficient error-corrected qubits to enable a small set of quantum algorithms to outperform classical computers.

It should also be noted that Australia has a vibrant community working on spin qubits (e.g., Silicon Quantum Computing, Diraq, the University of New South Wales, and the University of Sydney). Silicon Quantum Computing takes an interesting approach using a custom manufacturing process to build electron traps for single electrons on a chip. Similar technology is also under development at several universities in Europe

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[33] *QuTech, "Full Control of a Six-Qubit Quantum Processor in Silicon," QuTech, September 28, 2022, https://qutech.nl/2022/09/28/full-control-of-a-six-qubit-quantum-processor-in-silicon/.*

[34] *Heorhii Bohuslavskyi et al., "Scalable On-Chip Multiplexing of Low-Noise Silicon Electron and Hole Quantum Dots," August 2022, https://arxiv.org/abs/2208.12131.*

(e.g., RWTH Aachen with funding from the QuantERA ERA-NET Cofund in Quantum Technologies programme).

Road to 2035

Spin qubits are a promising QT with many active European research teams and companies. In addition to ongoing research to improve the quality of the qubits, several research activities focus on the overall system-level challenges, many of which are common to other qubit technologies.

Spin qubit research focuses on developing improved materials (^{28}Si, SiGe, Ge and C), novel architectures, process reproducibility, single-qubit and multi-qubit readout fidelity, and several other aspects. The latest results indicate that commercial semiconductor foundries must support additional features to accommodate the semiconductor spin qubits.

System-level aspects include selection of the optimum operating temperature (10 mK to 4 K), qubit physical architectures (2D/3D), qubit addressability, novel error correction codes, connectivity to classical electronics, cryoelectronics design, and low-power-consumption ADC and RF circuits.

It will be necessary, if a semiconductor spin qubit QPU is to be built, to channel investments into developing a multi-project wafer processing service with the flexibility to modify design rules to support spin qubits, and into advanced cryoelectronics development.

Despite these limitations, several enterprises are on track to develop products targeting the more valuable use cases. These early spin-based quantum devices will probably take a pragmatic approach, combining gate-level and analogue QPU features.

Near term (2025–2029)

Although no fundamental roadblocks are foreseen, several significant engineering obstacles must be overcome[35]; therefore, continued research is essential regarding the ingredients needed to achieve a semiconductor spin-based quantum computer (e.g., spin qubit performance, cryogenic silicon technology operating at 1 K, 3D silicon design and packaging, low-power electronic design, error-correcting algorithms, and software compilers that accommodate the architecture). We can compare this with the example of advanced CMOS technology: hardware devices (transistors) were improved by process optimisation (small steps) and technology boosters (larger steps). Examples of technology boosters for advanced CMOS include: successfully introducing high-K dielectrics, strain engineering, and redesigning the device

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[35] *M. F. Gonzalez-Zalba et al., “Scaling Silicon-Based Quantum Computing Using CMOS Technology: State-of-the-Art, Challenges and Perspectives,” Nature Electronics 4, no. 12 (December 20, 2021): 872–84, https://doi.org/10.1038/s41928-021-00681-y.*

architecture from planar CMOS to FinFETs to nanosheet-FETs. Similar technology boosters will be sought to achieve improved silicon qubits, improved device architecture design and the incorporation of process modules (new materials, new semiconductor processes). The use of silicon foundries will not suffice: these novel concepts require engagement with research institutes and academic institutions where access and contamination protocols are more relaxed, offering adequate scope for blazing new trails.

Long term (2030–2035)

Improvements discovered between now and 2030 will be incorporated into silicon foundry processes to accommodate spin qubits. Smaller-dimension lithographic nodes will result in higher performance qubits and mitigate the wiring density challenge inherent to the current technology.

Trapped Ions

Overview

Trapped-ion QC leverages an advanced technology base stemming from atomic, molecular and optical physics and the development of atomic clocks and mass spectrometers. Trapped-ion qubits have demonstrated some of the best quantum gate fidelities and the largest quantum volumes worldwide. Generating trapped-ion qubits requires the orchestration of several devices, including the ion source and trap, dedicated lasers, various optical components and sensors, vacuum and cooling mechanisms, and realtime control and measurement electronics (see Chapter 6 – Enabling Technologies). These components are readily available from European companies as early-stage products for research environments and first quantum computers.

There are two main approaches to implementing ion-based qubits, which differ in the way qubit control is implemented: optical and microwave control. Both tackle specific technical challenges regarding the scaling of ion-trap-based QC.

The optical control approach (pursued by, e.g., Alpine Quantum Technologies and NeQxt) combines laser-cooled trapped ions with qubit control using ultra-narrow-band lasers. Compact realisations of several digital quantum computers installed in standardised 19-inch rack mounts in regular office environments have been demonstrated. These systems routinely operate with about 10–30 qubits but can be pushed up to 50 qubits with reduced levels of control. The devices hold fully connected quantum registers, which facilitate the implementation of quantum algorithms. The initialisation, manipulation, and readout errors are typically below 1% and thus close to a fault-tolerant regime (in terms of gate-fidelity threshold). Alpine Quantum

Technologies recently demonstrated a universal gate-set for logical qubits realised on a 19-inch rack-mounted QC device[36].

The devices are already accessible to selected partners via the cloud and support major quantum SDKs – in particular, Qiskit, Cirq, and Pennylane. Consequently, various quantum software developers can and do access these devices in a hardware-agnostic fashion.

The other approach uses microwaves for qubit control, as pursued by eleQtron, QUDORA, and others. Microwave control has already been miniaturised in the context of consumer electronics (in computers, telecommunications, etc.), and may provide a more straightforward medium-term route to integration with chip-based ion trapping. Other interesting features are high-fidelity (> 99.99%) single-qubit gates and low crosstalk (the unintentional modification of spectator qubits) on a ppm level, as the combination of these features is advantageous for error correction and reduces the need to physically transport ions.

Several recent demonstrators have been set up with specifications (in terms of qubit numbers) comparable to laser-controlled ions. A laboratory setting with climate control and other advanced features can be considered temporarily acceptable to offer early access to machines of this sort via the cloud. In the long run, these machines will be improved and operate in typical industrial settings.

Road to 2035

The main focus will be increasing the number of qubits while lowering error rates for quantum gates, initialisation, readout, and manipulation. The number of qubits for a single QPU will increase to > 1000 qubits. Building such processors will require integrating optical elements and electronics near the ion trap, potentially embedded in a cryogenic ultra-high-vacuum environment. Additional challenges to be addressed include higher gate speeds, better connectivity across the entire processor, cryo-compatible highly integrated control systems and superior processor architectures, including photonic links.

These systems will be used as demonstrators for advantage in QEC and drive towards operation with increased circuit sizes. Given the overhead of encoding a logical qubit into physical qubits, it is possible that QEC will not be used routinely in the near future. It is likely that efforts focused on error suppression and mitigation will dominate the field for the next few years.

It will also be necessary to prepare for interconnection between QPUs. Ions levitated in an evacuated chamber can be easily moved using electromagnetic fields or entangled using individual photons; this suggests potential approaches for

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[36] *Alpine Quantum Technologies, "AQT | Access 20 Fully-Connected Qubits Using a 19'' Rack," accessed December 29, 2023, https://www.aqt.eu/pine-system-20-qubit-control/.*

interconnection. Ion transport (between processing zones on the same ion-trap chip and between different ion-trap chips) and photonic coupling of subprocessors are under investigation. Several groups in Europe have already succeeded in establishing an optical connection between two remote ion traps, but substantial improvements in coupling speed and fidelity are needed. An objective for the next few years should be to map the resource management knowledge from the classical distributed computer setting to distributed ion-trap quantum computers, thus paving the way for future QC clusters.

Near term (2025–2029)

The near-term challenges involve fully supporting up to a few hundred qubits in new, better integrated, scalable trap architectures and introducing faster, better integrated and scalable qubit control solutions in the electronics and optical domains. The first error correction implementations with large numbers of qubits are expected. Comprehensive automation is being developed, e.g., including self-calibration and automated resource management, with an objective of 24/7 operation. Reliable integration with HPC resources will be established.

Long term (2030–2035)

The long-term perspective includes realising a fully integrated scalable quantum device encompassing interconnected (or segmented) traps, control electronics, and optics in a reliable, industrially feasible, and scalable manufacturing process. Such devices should be able to support up to a few thousand qubits with the promise of scalability to tens of thousands of qubits. In parallel, the hardware necessary for distributed QC should be matured.

Neutral Atoms

Overview

Recent academic progress has demonstrated high-fidelity (> 99.5%) entangling gates in neutral-atom QPUs working in digital mode[37]. Moreover, these gates can be applied in parallel. One of the leading European companies exploiting this technology is Pasqal. Exploration of digital QC is currently underway using Pasqal's R&D prototype. Although digital QC is less mature than analogue QC on these platforms, developments are now taking place in various directions in this field. In addition to the

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[37] *Ivaylo S. Madjarov et al., "High-Fidelity Entanglement and Detection of Alkaline-Earth Rydberg Atoms," Nature Physics 16, no. 8 (August 2020): 857–61, https://doi.org/10.1038/s41567-020-0903-z.*

progress in 2-qubit gate fidelities, 3-qubit Toffoli gates have also been implemented[38], as well as the toric code[39].

Neutral-atom QC seems more suited, at least at present, to use in quantum simulations – constructing experimental situations that represent specific Hamiltonians of interest and to which the atom cloud is exposed. Ultimately, the scaling challenge will involve developing a new sophisticated optical tweezer technology offering the flexibility to address individual sites or qubits in the generated optical lattice with multiple optical or radio frequencies.

Generating neutral-atom qubits also requires orchestrating several devices, including the neutral-atom source and trap, dedicated lasers, various optical components and sensors, vacuum and cooling mechanisms, and control and measurement electronics (see Chapter 6 – Enabling Technologies). These components are readily available from European companies, at least as early-stage products for research environments and at small scales. Reliability and SWaP-C work on the QC support environment has started but is difficult to drive forward given the small volumes needed today.

Future work will focus on improving gate qualities and full parallelisation of operations. Efforts should also be devoted to developing specific compilers for neutral-atom devices in terms of gate sets and parallelisation capabilities.

Road to 2035

The main objectives for the rest of the decade are:

- Digital QPU available;
- High level of parallelisation of gates;
- Exploration of fault-tolerant architectures and development of QRAM designs.

Photons

Overview

Photonic QC, conceptually different from the matter-based QC platforms mentioned above, leverages both a solid theoretical framework and mature industries (telecommunications and semiconductor). Two different approaches for large-scale

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[38] *Harry Levine et al., "Parallel Implementation of High-Fidelity Multiqubit Gates with Neutral Atoms," Physical Review Letters 123, no. 17 (October 22, 2019): 170503, https://doi.org/10.1103/PhysRevLett.123.170503.*

[39] *Dolev Bluvstein et al., "A Quantum Processor Based on Coherent Transport of Entangled Atom Arrays," Nature 604, no. 7906 (April 21, 2022): 451–56, https://doi.org/10.1038/s41586-022-04592-6.*

FTQC with single photons and entangled photons, i.e., cluster states[40, 41], were proposed in the early 2000s, making photon-based platforms one of the earliest paradigms with a viable path to fault tolerance. The two recent demonstrations of QC advantage[42,43] using optical quantum information processors reflect the high level of maturity of photonic QC systems in terms of technology implementation.

Another example of technological maturity comes from Quandela, who recently delivered[44] a full-stack QC system to a European private datacentre (OVHcloud). This is the first time that a private company has integrated a quantum computer from a European QC provider. Quandela itself has also been hosting a cloud service[45] since January 2023 (the first commercial proposition in the EU, second in Europe to UK-based OQC), providing access to photon-based QPUs and a simulator.

Optical quantum computers integrate commercially available hardware technologies: optical circuits (e.g., 20 x 20 devices from QuiX Quantum), photon (qubit) generators (from Quandela), and superconducting nanowire detectors (from Single Quantum). These companies have already sold several hundred units to research laboratories (academic and private) worldwide. New opportunities for industry are also being explored.

Work is also underway at the academic level to integrate all three technology building blocks via a Europe-funded project: PHOQUSING (PHOtonic QUantum SamplING machine), funded by the Future and Emerging Technologies programme, aims to interconnect qubit generators (sources provided by Quandela as an external supplier), ICs (produced by QuiX Quantum), and detector systems to develop two large optical QC platforms: one being assembled at the University La Sapienza in Rome and one in Enschede (at QuiX Quantum).

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[40] *E. Knill, R. Laflamme, and G. Milburn, "Efficient Linear Optics Quantum Computation" (arXiv, June 20, 2000), https://doi.org/10.48550/arXiv.quant-ph/0006088.*

[41] *R. Raussendorf, D. E. Browne, and H. J. Briegel, "Measurement-Based Quantum Computation with Cluster States," Physical Review A 68, no. 2 (August 25, 2003): 022312, https://doi.org/10.1103/PhysRevA.68.022312.*

[42] *Han-Sen Zhong et al., "Quantum Computational Advantage Using Photons," Science 370, no. 6523 (December 18, 2020): 1460–63, https://doi.org/10.1126/science.abe8770.*

[43] *Madsen et al., "Quantum Computational Advantage with a Programmable Photonic Processor."*

[44] *"Quandela Delivers First Quantum Computer, MosaiQ, To OVHcloud, Pioneering European Quantum Computing — Quantum Zeitgeist," November 6, 2023, https://quantumzeitgeist.com/quandela-delivers-first-quantum-computer-mosaiq-to-ovhcloud-pioneering-european-quantum-computing/.*

[45] *"Welcome to Quandela Cloud," accessed January 5, 2023, https://cloud.quandela.com/.*

Road to 2035

Scaling up optical quantum computers via error correction will ultimately occur by means of manipulating large systems of entangled photons[46]: devices generating these cluster states of entangled photons on demand have already[47] been demonstrated. Despite these technological advances, scalability is bounded by photon loss through the component chain and photon quantum purity (multi-photon component and indistinguishability). Unlike the matter-based qubits used in other forms of QC, photons do not suffer from decoherence, so photon purity and losses represent the primary sources of errors and are thus the key challenges to tackle.

In other words, quantum light sources must generate single photons (and entangled photons) more efficiently, ICs must reduce losses while integrating dozens of waveguides and thousands of components, and detectors must provide near-unity efficiency while integrated into the circuits. Another important difference of photonic QC compared to other platforms resides in the native interconnectivity of these systems, which allows computing power to be scaled by connecting separate QPUs with no need for matter-to-photon qubit transduction (currently very inefficient). Such long-range connectivity will also make it possible to explore error correction codes with much more favourable logical-to-physical qubit ratios. These codes (low-density parity-check[48]) are currently under intensive study as they could bring fault tolerance much closer to practical implementations by considerably reducing the number of required physical qubits.

Short term (2025–2027)

- Assemble optical QC platforms of up to 50 digital qubits, in fully reconfigurable IC platforms. Deliver reconfigurable optical circuits of up to 200 modes for use in specialised algorithms;
- Increase the performance of deterministic single-photon sources from the current efficiency of 50% to > 70% (increase in generation speed in one optical mode);
- Increase single-photon purity (indistinguishability) from 95% to 98%;
- Increase the fidelity of three-photon cluster states to > 95%;
- Further develop photonic routers (active time-space demultiplexers) both in terms of switching speed (up to MHz speeds) and number of outputs (> 10 spatial outputs);
- Develop and deliver up to 200 reconfigurable circuits in on-chip mode with ~1 dB optical loss;

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[46] *Raussendorf, Browne, and Briegel, "Measurement-Based Quantum Computation with Cluster States."*

[47] *N. Coste et al., "High-Rate Entanglement between a Semiconductor Spin and Indistinguishable Photons" (arXiv, July 20, 2022), https://doi.org/10.48550/arXiv.2207.09881.*

[48] *Nikolas P. Breuckmann and Jens Niklas Eberhardt, "Quantum Low-Density Parity-Check Codes," PRX Quantum 2, no. 4 (October 11, 2021): 040101, https://doi.org/10.1103/PRXQuantum.2.040101.*

- Develop ICs and sources at mutually compatible wavelengths, including telecommunications (C-band) and 935 nm (practical for solid-state sources);
- Develop and integrate fast, low-loss switches.

Medium term (2028–2029)

- Increase the number of qubits in optical QC platforms to 1000;
- Further improve the performance of deterministic single-photon sources, to > 80% efficiency (increase in the generation rate in an optical mode) and single-photon purity (indistinguishability) close to 100%;
- Increase the size of cluster states generated from one device up to 10 photons, with fidelity > 95%;
- Improve the semiconductor technology (reproducibility and large-scale production of single-photon semiconductor emitters) so that several dozen identical emitters can be fabricated;
- Have multiple identical single-photon emitters and routers to distribute up to 1000 single photons in ICs with hundreds of modes each;
- Develop and deploy modular ICs with up to 1000 modes;
- Implement feed-forward control across the modules via fast electronics;
- Deploy error correction on a small number of logical qubits using up to 1000 physical optical modes to demonstrate universal QC prototypes;
- Fully integrate sources, circuits, and detectors on-chip.

Long term (2030–2035)

- Interconnect several optical QPUs with hundreds of thousands of qubits in total via optical links and entanglement distribution. The platform will operate under a measurement-based model, including feed-forward protocols and error correction codes;
- Demonstrate efficient generation of large (> 10,000) entangled photon clusters via external modules, and direct generation from deterministic sources;
- Develop feed-forward control from detection to qubit generation;
- Deploy non-local error correction codes with a highly favourable logical-to-physical qubit ratio;
- Demonstrate arbitrary scaling of a universal quantum computer via interconnectable modules.

Nitrogen Vacancy Centres in Diamond

Overview

NV centres are point defect complexes consisting of a substitutional N atom next to a vacancy in a diamond carbon lattice. This technology is thus sometimes called diamond QC. The physical properties of NV centres[49] are unique since they provide long coherence times even at room temperature. Strictly speaking, diamond QC is based on singly negatively charged NV centres (NV^-). The electronic system of the NV centre provides an S=1 spin of which often only two states are used as a qubit. However, the three states can also be used for holonomic gates. The quantum information of the NV centre can be read out as the luminescence intensity upon excitation with a green laser, which is different for the different quantum states with a range of 20–30%. Another method with the potential for even higher SNR is the electrical readout, i.e., a photocurrent into a nearby electrode. Furthermore, (optical) spin initialisation with laser pulses is highly efficient. The NV centre couples to nuclear spins in the vicinity through hyperfine interaction in its $m_S=\pm1$ states. Besides the nuclear spin of the N atom making up the NV centre itself, ^{13}C atoms provide S=1/2 nuclear spins. Thus, additional qubits accompany every NV centre. The nuclear qubits yield much longer coherence times than the electronic NV qubit. The entanglement of the NV centre with its nuclear qubits is straightforward. Single NV centres can occur naturally in diamond, but pairs are already quite rare. NV centres as qubits and their coupled nuclear qubits as quantum information storage have been proposed for use in QPUs for over a decade[50]. SaxonQ is currently selling a room-temperature operation, portable/mobile, gate-based programmable NV quantum computer. The Australian/German company Quantum Brilliance is working on this same approach for a quantum computer as well as hybrid systems linking together NV-based quantum computers embedded in classical supercomputers.

European countries, notably Germany, are investing in building NV-centre-based quantum computers, with projects including QC-4-BW, DE-Brill, Spinnig, SPINUS, and AI4QT. The idea is to use optical excitation of vacancy spins (SnV, SiV, GeV and NV colour centres) in a diamond produced by chemical vapour deposition and, simultaneously, control the coupling to neighbouring nuclear spins (^{13}C isotope in the diamond) to stabilise the spin.

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[49] *Marcus W. Doherty et al., "The Nitrogen-Vacancy Colour Centre in Diamond," Physics Reports 528, no. 1 (July 2013): 1–45, https://doi.org/10.1016/j.physrep.2013.02.001.*

[50] *Sébastien Pezzagna and Jan Meijer, "Quantum Computer Based on Color Centers in Diamond," Applied Physics Reviews 8, no. 1 (March 2021): 011308, https://doi.org/10.1063/5.0007444.*

Road to 2035

To achieve scaling of an NV QPU to large numbers of qubits, many NV centres need to be coupled to each other to allow for entanglement. One approach is coupling through external optical resonators. In addition, the dipole-dipole coupling of NV centres close to each other enables the transfer of quantum information and entanglement. Depending on the temperature, a distance between NV centres in the 10–50 nm range is needed to arrive at reasonable coupling strengths in the 10–100 kHz range. This model requires control lines with similar structural dimensions. Ion implantation technology to artificially fabricate NV centres with high yield and quantum computers with arrays of NV centres has been patented in Europe. The design and stabilisation of the Fermi level are particularly important to ensure stable operation in the NV^- state.

NV quantum computers operate at room temperature and rely on a semiconductor chip/planar technology; thus, they have the potential advantage of small size and portability. However, at low temperatures of 5–10 K, offering even larger coherence times, other mechanisms of control and readout can be employed and lead to systems with even higher fidelity.

Near term (2025–2029)

- Increase the number of qubits to several hundred by coupling many NV centres;
- Improve readout efficiency and gate fidelities;
- Reduce overall system size;
- Implement suitable QEC codes.

Long term (2030–2035)

- Integrate the NV technology with CMOS controls;
- Increase the number of physical qubits into the range several thousand to a million;
- Increase the number of logical qubits to several hundred.

Qubit Environment and Packaging

The correct functionality of quantum computers is dependent on a carefully crafted qubit environment and packaging conditions. This critical topic is discussed in detail in Chapter 6 – Enabling Technologies.

Qubit Control and Characterisation

Overview

Optimal operation of quantum computers requires the control and characterisation of qubits.

Qubit control is the optimised manipulation of individual qubits to achieve longer coherence times, and the careful orchestration of qubit pairs to achieve better gate performance. The topic is crucial for the optimal deployment of NISQ-era quantum computers, as well as fault-tolerant architectures. Qubit control can broadly be broken down into qubit control hardware and qubit control software. Several European companies provide qubit control technology. Hardware providers include Creotech, Qblox, and Zurich Instruments. Software providers include QUARTIQ, QuantrolOx, Riverlane, and Qruise.

Current challenges in qubit control include:

Optimising signal routing;

Increasing qubit readout speed and efficiency;

Characterising and mitigating noise sources;

Managing a growing number of signals in an efficient and scalable manner;

Bringing control and measurement electronics closer to physical qubits.

As quantum computers grow in qubit number, qubit control systems will need to address larger quantities of qubits, while reducing noise and crosstalk but retaining high accuracy and low latency. Powerful FPGA-based controllers are currently used in the core of qubit control systems. Future applications could be based on dedicated ASICs and different purpose-oriented control layers adapted to the operating environment.

Qubit characterisation involves measuring the properties of individual qubits and the quality of information transfer between pairs of qubits. Combined, these characteristics provide a complete understanding of the quantum system, which is an essential step in the development cycle and fabrication process for new QPUs. Several companies, such as Orange Quantum Systems, QuantrolOx, and Qruise, supply products and services that automate and optimise qubit characterisation and calibration.

QPU interconnections: Most quantum computer manufacturers are already exploring ways of linking QPUs together to accelerate scaling of processor sizes. The challenge is particularly acute for matter-based qubit systems that operate at microwave frequencies and therefore require cryogenic temperatures to maintain a suitably low thermal environment (e.g., superconducting qubits). A new approach being developed to move away from the usual thermal noise challenge is to translate quantum information from about 5 GHz (microwave frequencies) to about 200 THz (optical frequencies), which allows the information to operate virtually noise-free at room temperature. Moreover, the information can be communicated over distances of kilometres via optical fibre. This technological shift transforms QPUs from isolated monolithic devices with increasing heat load and complexity into a flexible, reconfigurable, and scalable network. QphoX and Miraex are developing hardware to efficiently and silently convert single photons between microwave and optical frequencies, and thus enable future interconnections between cryogenic QPUs.

Road to 2035

- The main ambitions are:
- Increase the number of qubits that can be simultaneously controlled in line with the development of QPUs over the next three, six, and nine years;
- Increase the integration of these control devices (user interfaces, qubit interfaces);
- On the hardware side: optimise control signal management and make it scalable alongside the development of new, interconnected QPUs; improve the speed of operation, in particular to allow for fast feedback loops between qubit readout and control relevant for error correction; reduce noise injected from the control system side; increase the level of integration with the qubit's immediate environment; include qubit control elements in the semiconductor stack for serial manufacturing;

- Reduce lead times and costs by reducing the dependency on materials and components from non-European sources.

Standardisation is fundamental for the future of qubit control. There are currently many approaches to qubit probing and synchronisation. An agreed framework for qubit control could lead to faster iterations of hardware designs and more rapid technology sector growth.

Quantum Error Correction

Overview

For useful quantum algorithms to run on large-scale quantum computers, the system must be able to efficiently manage the intrinsic noise in the quantum hardware (introduced by the decoherence of qubit states, photon loss, the non-ideal behaviour of quantum manipulation processes, and other sources). Therefore, it is of utmost importance to develop efficient quantum transitions with as little loss as possible. This first stage, achieving optimum performance from the quantum-enabling hardware, is essential before launching the second stage, in which an error correction strategy is implemented. Reducing phase noise to a minimum for the oscillators in the RF and optical domain is paramount, along with the reduction of acoustic vibration, electrical or optical switching noise, and other technical noise sources.

In fact, noise limits the number of operations that can be performed before the information stored in the qubits is overwhelmed. Progress is being made by adopting software-based mitigation strategies that can partially compensate for the noise that accumulates during algorithm execution.

Another alternative is QEC – error-correcting codes are being developed that allow highly complex quantum algorithms to provide reliable outputs even on noisy hardware. These codes use multiple physical qubits to encode information stored in a single logical qubit and require repeated fast measurements of a subset of these qubits to decode and correct potential errors. Performing such operations at speed can require decoders to be implemented in FPGA or ASIC hardware, closely interfacing with the control hardware connected to the qubits. In September 2023, Riverlane produced the world's first decoder ASIC, using the surface code combined with new “parallelisation” techniques that enable the simultaneous processing of error-prone data. They also released the decoder IP which can be used in any quantum computer, and which is being updated via regular releases. Other companies, such as QC Design, launched in 2023, are also entering this space, helping build a foundation that all hardware companies across qubit types can use for error correction and thus opening the pathway to scalable QC. Last but not least, Qblox has integrated a realtime decoder into its control stack demonstrating decoding within the allotted time for the most stringent case of superconducting qubits.

Some error correction codes may also need specific qubit manipulation functionalities, such as the execution of mid-circuit qubit measurement and reset, or fast calibration. Furthermore, managing a very large number of qubits is likely to require multiple hardware backends controlling submodules of qubit arrays and equipped with distributed processing units, calling for the development of IRs with instruction synchronisation and coordination capabilities. The realisation of large-scale, error-corrected quantum computers thus requires close synergy between software development down to the qubit control level and improvements in classical hardware backends and quantum hardware, i.e., a full QEC stack. In addition to Riverlane, other European companies such as ParityQC are working on the development of specific architectures for FTQC.

One downside of error correction codes is the need to increase the number of qubits to implement the code. Some qubit technologies are able to self-correct a single two-qubit error (bit flip) thanks to special hardware designs, such as superconductive bosonic codes. Other architectures allowing long-distance qubit interconnections via photonic links can use “non-local” error correction codes (low-density parity checks), a technique which reduces the logical-to-physical qubit ratio compared to standard approaches such as surface codes.

Current challenges in QEC include:

- Designing error correction codes optimised according to qubit topology and noise profile, suppressing the logical error rate below the physical error rate;
- Performing realtime, fast decoding without critically slowing down computation;
- Demonstrating quantum memory functionalities and the ability to preserve information stored in a logical qubit far beyond the typical decoherence time of the physical qubit;
  Demonstrating logical operations between multiple logical qubits.

Road to 2035

The main ambitions are:

- Demonstrate realtime error correction cycles suppressing the logical error rate below the physical error rate for each of the main qubit technologies;
- Demonstrate QEC algorithms capable of handling > 2 and > 10 logical qubits;
- Develop error correction chips that integrate seamlessly with qubit systems for different qubit types to create systems that can scale to at least a trillion error-free quantum operations.

Quantum Software

Quantum Operating Systems, Quantum Algorithm Compilers

Overview

The quantum OS is the software that manages the classical and quantum hardware used to characterise and control the qubits. It oversees the execution of quantum algorithms at the machine level by optimising hardware resources and provides users with an interface for entering instructions and receiving output from the quantum computer.

The compiler is an important module in the OS, consistent with classical representations of the computing stack. Quantum algorithm compilers translate a quantum algorithm from a high-level source programming language to a lower-level language. This process can be repeated multiple times through the quantum stack using a chain of different compilers, until the algorithm is translated to a sequence of instructions that can be executed by the QC hardware. There are many source programming languages available for writing quantum algorithms. However, the target language, i.e., the set of instructions executable by the quantum hardware, depends strongly on the chosen qubit technology and the appropriate classical control hardware. Several European companies are involved at the forefront of developing quantum compilers able to automatically adapt and optimise quantum gate sequences based on the technical requirements of different hardware platforms.

Current trends in compiler development involve using one or more IRs to connect multiple source languages to multiple target languages. The IR simplifies the various compilation tasks for individual compiler developers. It should ease migration and compatibility between high-level and low-level hardware-specific languages, including those low-level languages that describe the quantum algorithm as a sequence of pulses instead of gates. Ideally, the IR should be independent of the source language and target hardware and lend itself to code optimisation to reduce hardware requirements and execution times. However, there is a risk of not fully capturing the hardware capabilities and making concessions on performance in order to be as universal as possible. On the other hand, lower-level compilers that automatically adapt and optimise the intermediate code for the target platform are now becoming increasingly available. A major challenge is to find the right balance between providing an easy-to-use environment for end users (who are less interested in the specifics of the hardware) and offering lower-level access for hardware developers to optimise hardware performance. The development of powerful IRs should happen in tandem with the development of scalable and reliable qubit control systems (see Section 2.5).

Scientists from INRIA, Université Paris-Saclay and Quandela developed the LOv-calculus[51], which is a graphical language for reasoning about linear optical circuits of the kind used in photonic QC. Its visualisation capabilities are analogous to quantum circuits depicting qubit and logic gate operations, but it represents processes at a level closer to the photonic hardware, depicting, e.g., waveguides, beam splitters, phase-shifters. At a deeper level, it comes equipped with a powerful set of graphical equations and rewrite rules. These allow any photonic circuit to be simplified to a compact normal form. Simplification can be performed in a fully automated way, and is implemented, e.g., in Perceval (Quandela's programming framework). Benefits of the calculus are not limited to photonics: since qubit circuits can be encoded and decoded to and from photonic circuits, these simplification tools also translate to qubit circuits[52].

Another major challenge in the development of compilers is hybrid design: enabling the use of quantum and classical hardware to execute different portions of a computational task. Typical compiler workflows include optimising a gate sequence to make efficient use of the available hardware resources, while taking into account connectivity, fidelity of individual gates, total gate count, and total clock time. Hybrid design will include additional features. ParityQC is one company specialising in this type of solution, which involves the development of novel building blocks as well as compilers.

In addition to the use of compilers to optimise the gate sequences, each individual gate must itself be optimised, a process done by low-level control instructions (see Section 2.5). The low-level control instructions required to manipulate and measure a qubit are usually specific to the qubit technology, but they still lend themselves to a degree of abstraction through the use of general metadata, making the instruction set portable across multiple technologies. Current trends see software and hardware developers collaborating to identify a general abstract representation of the hardware stack that is as close to qubits as possible. An example of this is a consortium of UK companies led by Riverlane and including OQC. This approach allows portability of the quantum OS and application software and helps to define a commonly accepted framework to simplify future hardware and software development. Ideally, IRs should also be scalable, to accommodate the future control instruction requirements of new

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[51] *Alexandre Clément et al., "LOv-Calculus: A Graphical Language for Linear Optical Quantum Circuits," 2022, https://doi.org/10.48550/ARXIV.2204.11787.*

[52] *Alexandre Clément et al., "A Complete Equational Theory for Quantum Circuits" (arXiv, June 21, 2022), https://doi.org/10.48550/arXiv.2206.10577.*

technologies. Several initiatives around the world are currently exploring the standardisation of IRs.

A major bottleneck, affecting the development of all layers of the QC stack and the QT sector in general, is the talent shortage (See Chapter 7 – Workforce Development). It is crucial for all quantum companies to be able to attract experts with skills spanning quantum physics, quantum information theory, computer science with a focus on complexity theory and compilers, and software engineering. A comprehensive understanding of the challenges ahead is essential to creating effective scalable solutions for quantum OSs.

Finally, when designing environments for developing quantum programs, attention should be paid to building environments suitable for developing certified quantum programs. Such certification will be especially necessary for certain critical applications with prescribed safety and security requirements. This means, in particular, ensuring:

- A clear separation between code and proof;
- Specification of scale invariance and proof;
- A high degree of proof automation.

The environments should allow quantum programs to be written in a natural, textbook style. Key features include:

- A new domain-specific language for quantum programs;
- A new logic specification language.

Road to 2035

Near term (2025–2029)

- Develop quantum compilers with automatic scheduling capabilities, to incorporate calibration and QEC coding and decoding routines in the main quantum algorithm;
- Improve the capabilities of quantum compilers to optimise quantum circuits for different hardware platforms automatically;
- Adopt design automation principles and AI/ML methods to improve the quality and scalability of the compiler output;
- Develop OSs supporting hardware architectures with increasing numbers of qubits, in alignment with the corresponding roadmaps for QC hardware (Section 2.10.1);
- Demonstrate distributed programming capabilities on multiple hardware control backends;
- Standardise an IR framework that works across multiple technologies.

Long term (2030–2035)

- Continue to scale up OS capabilities in alignment with the corresponding roadmaps for QC hardware (Section 2.10.1).

Quantum APIs and Cloud Access

Overview

Quantum APIs and cloud access form the transition layer between users and quantum machines in the QC stack. This layer includes general-purpose quantum SDKs that are used to implement quantum algorithms at the quantum gate level (for gate-based systems, and the equivalent for quantum annealers). Almost all commonly used general-purpose quantum SDKs are developed by US companies. This has very profound implications for Europe, particularly in terms of technological autonomy. We urge European leaders to support European enterprises for quantum software and quantum applications by issuing solid strategic plans, articulated through strong financial commitments and clear roadmaps for the implementation of the strategy. It is in some ways surprising that although Europe is a world leader for experts specialised in quantum software and quantum applications, this has not translated into leadership in quantum SDKs, with the exception of a small number of companies (for instance, Qilimanjaro with its Qibo framework, Multiverse Computing, and Eviden).

Quantum programming languages and SDKs increasingly offer convenient features intended to make life easier for software developers, such as predefined subroutines with commonly used gate sequences, or support for automatic correction of temporary effects on ancilla qubits. The toolkits also provide increased support for the upper layers of the stack.

Another important aspect is the integration of quantum and classical computing. This is particularly advantageous for hybrid algorithms, which will be the first to be used in real applications in the near future. The main challenge is integration into the resource management and scheduling systems of HPC centres and cloud providers, taking into account the very different timescales of quantum jobs and typical classical HPC or cloud jobs, and the necessary coupling between these. Quantum cloud providers around the world are increasingly offering the possibility of running fully integrated hybrid algorithms in the cloud, whereas previously only the quantum part was run by the quantum provider while the classical part had to be run on the customer's premises or in a different cloud instance, leading to long waiting times. Europe is also leading the way for on-premises solutions, by funding research projects on integrating commercially available quantum computers into HPC centres.

However, the current reality is that the most powerful quantum computers in the world are not on European soil (with very few exceptions). This means that for European enterprises to harness the power of these computers, which implies integrating them into their production systems, the enterprises need to send their data outside the EU. Careful review and analysis of European data regulations and laws (such as the European General Data Protection Regulation) and national laws and regulations is essential to ensure that companies remain compliant without losing access to these computers.

Road to 2035

European success in providing cloud-based access to quantum computers and the necessary APIs is an essential focus for the coming decade. Both substantial investment from policymakers and the involvement of large-scale end users will be necessary to help European companies rival the large US companies that already dominate the space (e.g., IBM). The involvement of domain experts from industrial end users must be emphasised as an essential ingredient for success: large European companies make up the largest category of QuIC members and are seeking to anticipate the quantum shift. Supporting these companies in the exploitation of Europe-made QC solutions could offer a competitive advantage to European businesses addressing the QC value chain through all layers of the QC stack.

Near term (2025–2029)

- Integrate quantum computers with large-scale computing infrastructure (HPC systems, cloud);
- Improve availability of European quantum hardware in the cloud, operated by European cloud providers to ensure European autonomy;
- Urge companies in industry to accelerate their transition to European cloud architectures;
- Establish mechanisms for supporting industrial companies and quantum companies during the transition to European cloud architectures;
- Provide legal guidelines and clarifications for sharing data in the cloud to companies outside the EU.

Quantum Algorithms

Overview

Quantum algorithms, unlike their classical counterparts, are designed to take advantage of the fundamental features of quantum physics, namely superposition, entanglement, tunnelling, and interference. More than half of the 100+ known QC algorithms offer super-polynomial performance improvements over classical algorithms[53]. These are quantum algorithms that have been shown theoretically to have an advantage over their classical counterparts.

Traditionally, gate-based quantum computers have been programmed by quantum experts at the level of individual gates (qubit control layer), well below the algorithmic layer. More recently, libraries of quantum algorithms have been developed, making QC more accessible to developers and enabling a wider range of programmers to develop software for quantum computers. This development is essential as work continues on achieving quantum advantage for economically relevant applications.

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[53] *Stephen Jordan, "Quantum Algorithm Zoo," October 2022, https://quantumalgorithmzoo.org/.*

However, making QC more generally accessible must go beyond widening access to quantum computers and programmers, by bringing quantum solutions to businesses and society. This will enable the tangible value of quantum solutions to be propagated to society at large. A prominent example of how this can be done is Multiverse Computing, a quantum software and applications company that makes use of quantum and quantum-inspired technologies in real applications for corporate customers across a broad range of sectors such as finance, engineering, manufacturing, energy, aerospace, and cybersecurity.

Careful selection and coordination of quantum manipulation, communicated from the software layer to individual qubits, remains essential to get the most out of NISQ-era quantum computers. Several European projects are addressing this need by collecting reference implementations for certain use cases. There are many companies in Europe (mostly SMEs) that focus on implementing and optimising algorithms for customers; some of them also develop specialised software toolkits for certain classes of use case (e.g., quantum chemistry, ML, finance) that interested parties can use themselves.

Some startups are working on platforms to automatically generate quantum gate sequences from a high-level specification of the problem and/or from classical source code. While this work is still at an early stage, if successful it could revolutionise quantum programming in the future. A German consortium of industry and academic specialists is developing PlanQK[54], an app store for quantum-based services, where developers will offer their services, and users will be able to make simple use of these services.

Finally, one challenge remaining is the development of disruptive quantum algorithms to efficiently perform certain tasks. This will require new talent from academic research teams, capable of bridging concepts from quantum physics and mathematics. A new theoretical framework building on the rich literature of quantum algorithms for solving algebraic problems would pave the way for the quantisation of many algorithms in ML and numerical methods that use group operations.

Another promising branch of quantum algorithms is to be found in quantum-inspired classical algorithms. Namely, in addition to algorithms specifically designed for the use and operation of quantum computers (and their quantum-mechanical properties), it is possible to take inspiration from these quantum-mechanical features to rethink and improve algorithms designed to run on classical hardware. Furthermore, quantum-inspired hardware allows classical hardware to emulate a quantum computer to extract business value in the short term for optimisation problems.

Several QuIC members with this focus have developed quantum-enhanced and quantum-inspired application suites that are beginning to show the power of this

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[54] *"PlanQK – Platform and Ecosystem for Quantum-Inspired Artificial Intelligence," accessed December 29, 2023, https://planqk.de/en/.*

technology. These include Quanscient, which develops quantum algorithms and multiphysics (computational fluid dynamics) simulation software; Multiverse Computing, which works on industry problems across several verticals using quantum-inspired tensor network algorithms that exhibit business advantage in quantum optimisation and ML; and Eviden, with its Qaptiva, a quantum application development platform used to develop and test quantum algorithms on a classical emulator, optimise them for different QPU types of any technology, and emulate the behaviour of different QPUs. The number of QC use cases will expand as access to cloud platforms for QC increases over the next few years.

Road to 2035

As with quantum APIs and cloud access (see Section 2.7.2), the involvement of end-user domain experts will be essential to developing application-specific algorithms. Close collaboration between commercial quantum software solution providers and end users could not only help Europe strengthen its global position in the quantum algorithm layer but would also have a positive trickle-down effect on the lower layers of the QC stack.

Near term (2025–2029)

- Build collections of use cases with reference implementations of quantum algorithms and data preparation. These use cases must be mostly industry-oriented and solve real problems, ideally now; if that is impossible, there should be a clear roadmap including integration in production systems as one of the key goals;
- Support the adoption of quantum solutions in industry through stimulus programmes;
- Help European companies develop quantum algorithms through measures such as facilitating their access to industrial companies of any size and offering financial support adapted to their needs;
- Build supporting software for developing and implementing quantum algorithms – e.g., by automatically generating gate sequences;
- Build a Europe-wide platform for quantum-based services.

Long term (2030–2035)

- Continue support for the adoption of quantum solutions in industry and help for European companies to develop quantum algorithms;
- Emphasise integration of quantum solutions into the production systems and architecture of the main European corporations across a broad range of sectors, prioritising those promising the greatest business advantage and strategic relevance – for example, finance, energy, manufacturing and life sciences;

- Develop standards for software development processes in hybrid IT systems;
- Offer a steadily growing number of quantum-based services;
- Build an integrated workflow for the software life cycle using hybrid quantum systems.

Classical Quantum Emulators and Simulators

Overview

Emulating quantum computers on classical computers, either locally or in the cloud, allows quantum algorithms with a limited number of qubits to be developed and tested without needing to access a real quantum computer. Although emulation is much slower than running the algorithm on quantum hardware, it can provide access to some information that is not available on a real quantum computer as a matter of principle (such as the full state vectors of the quantum-mechanical wave function), so there are advantages for development and debugging.

Many general-purpose quantum SDKs allow quantum computer emulation. One of the world's most powerful quantum emulators is available through Eviden as a computer appliance comprising software and (classical) hardware. This appliance can emulate more than 40 qubits exactly and more than 100 qubits approximately, depending on the algorithm and emulator used, with optional GPU acceleration. It is designed to be hardware-agnostic and can interface with other common quantum SDKs as well as with real quantum hardware. Therefore, it can serve as an emulator and a universal quantum programming and integration platform. It is being used increasingly in HPC centres for this purpose.

From a quantum software perspective, the main points have already been covered above. It is important to emphasise, however, that the success of the European quantum ecosystem overall depends on adoption by industrial companies. If Europe stands by while the quantum ship sails, the EU will find itself in a challenging situation in future years.

Road to 2035

Near term (2025–2029)

- Integrate classical quantum emulators and simulators with large-scale computing infrastructure (HPC systems, cloud);
- Improve integration of classical quantum emulators and simulators with real QPUs for use as a universal quantum programming and integration platform;
- Improve the availability of European classical quantum emulators and simulators in the cloud, operated by European cloud providers, to ensure European autonomy.

Applications: User Community

Overview

The European community of large companies and institutions, such as RTOs and academic bodies, is rapidly becoming interested in QC. QuIC already counts among its members 30 large companies and approximately 25 RTOs and academic institutions, most of which are interested in exploring and understanding QC. Some companies have organised QC challenges in order to stimulate the development of different and efficient solutions based on quantum computers. These include the Airbus (2019)[55] and BMW (2020)[56] Quantum Computing Challenges. Combined, these indicators point to a particularly fertile user ecosystem, giving European QC solution providers an advantage over competitors in other geographic locations.

Intelligence has begun to emerge from the commercial user community. Figure 2-9 shows the quantum domains most relevant to industry needs, together with a histogram of use cases from a variety of industries.

The performance limitations of current quantum computers and simulators prevent some use cases from being addressed in the short term. However, these use cases can serve as ambitious goals to further catalyse the development of quantum computers.

Quantum solutions to industrially relevant problems will be a first step. Developing quantum computers that can outperform the most powerful conventional computers and solve problems that are impossible for today's HPC systems remains the long-term goal of end users.

Road to 2035

The road to 2035 follows two parallel tracks: one aimed at facilitating interaction between users and experts in quantum algorithms; the other at improving the skills of current users and preparing the next generation of QC professionals. The latter topic is covered extensively in Chapter 7 – Workforce Development. The ingredients of the former are provided below.

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[55] *"Airbus Quantum Computing Challenge | Airbus," July 2, 2021, https://www.airbus.com/en/innovation/disruptive-concepts/quantum-technologies/airbus-quantum-computing-challenge.*

[56] *"BMW Group Quantum Computing Challenge: The Winners Have Been Decided.," accessed January 6, 2023, https://www.press.bmwgroup.com/global/article/detail/T0362463EN/bmw-group-quantum-computing-challenge:-the-winners-have-been-decided?language=en.*

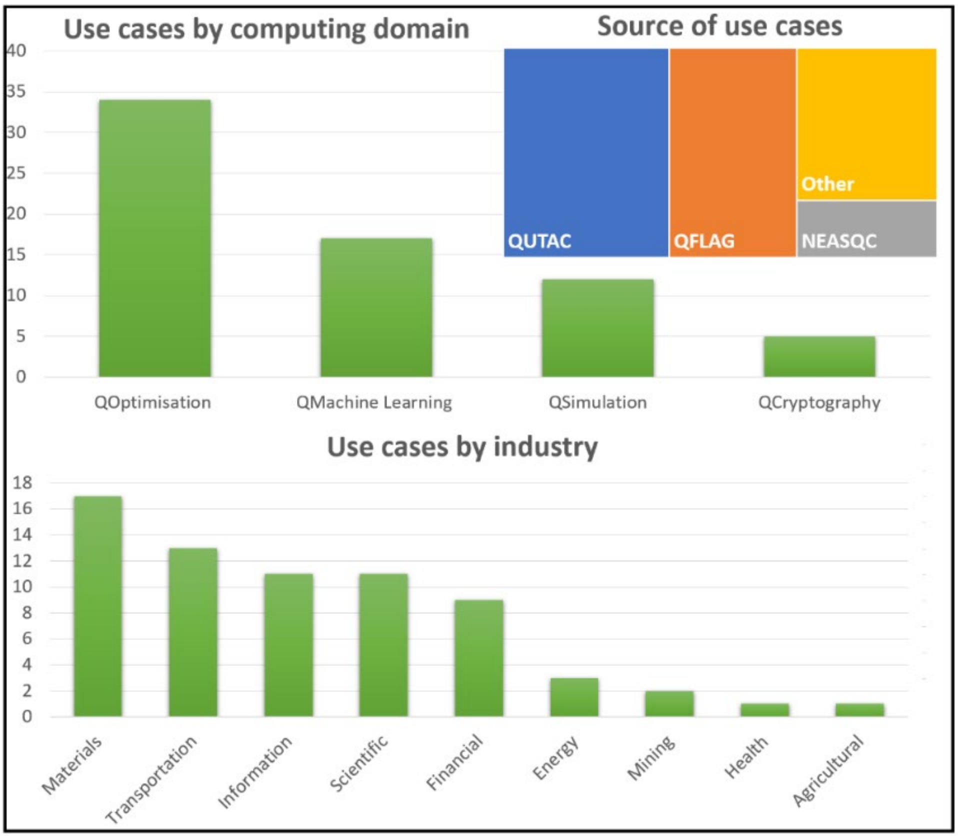

Figure 2-5: Industrial needs for QC[57]

Near term (2025–2029)

Integrate QC systems into the infrastructure of national and European HPC centres and provide key services:

- Provide access to industry, academia, and European startups;
- Serve as collaborative hubs between users and quantum algorithm developers;
- Facilitate procurement of products and services from QC solution providers;
- Capture tangible value through quantum and quantum-inspired use cases, which will act as a driver for quantum adoption in businesses and kickstart a virtuous circle.

Success is likely to occur in a series of small steps starting with “toy” problems and growing as the capabilities of quantum computers expand. Even a few qubits can be used to discover new insights not directly available using classical computers.

Long term (2030–2035)

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[57] *Data in figure based on Quantum Technology and Application Consortium – QUTAC et al., “Industry Quantum Computing Applications,” EPJ Quantum Technology 8, no. 1 (December 2021): 25, https://doi.org/10.1140/epjqt/s40507-021-00114-x.., the NEASQC project (https://www.neasqc.eu/), and an internal survey of QuIC members.*

- See national (and European) HPC centres equipped with integrated QC solutions and interconnecting their systems using the EuroQCI network for distributed computing capabilities.

Road to 2035

The following is a summary of the “Road to 2035” subsections in this chapter, which should be consulted for more details.

Quantum Computing Hardware

Superconducting

- Improve quality (fidelities) and scale (number) of the qubits using 3D architectures;
- Develop more efficient cryogenic units;
- Develop industrial-scale fabrication facilities;
- Research into materials, fabrication techniques and processing methods.

Spin qubits

- Develop higher quality single-qubit and multi-qubits
  - Using improved semiconductor materials;
  - Improve production process in general as well as in existing semiconductor foundries;
  - Smaller-dimension lithographic nodes;
  - Develop 3D packaging to reduce need for swap sequences.
- Improve single-qubit and multi-qubit readout fidelity;
- Incorporate error correction cryoelectronics enabling QPUs based on logical qubits;
- Selection of the optimum operating temperature (15 mK to 3.6 K), qubit physical architectures (2D/3D), qubit addressability, novel error correction codes, connectivity to classical electronics, and low-power-consumption ADC and RF circuits;
- Develop software compilers that accommodate the architecture.

Trapped ions

- Increase the qubit count for a single QPU beyond 1000 qubits;
- Lower error rates for initialisation, readout, and manipulation;
- Integration of optical elements and electronics in the vicinity of the trap (ultra-high-vacuum environment);
- Improve gate speeds, connectivity, and processor architectures;
- Lower the operating temperature from room temperature to 4 K to improve gate quality;
- Interconnections between QPUs, e.g., by ion transport or photonic coupling, to build distributed quantum computers (future QC clusters);

- Develop comprehensive automation for 24/7 operation.

Neutral atoms

- Digital QPU;
- High level of parallelisation of gates;
- Explore fault-tolerant architectures;
- Develop QRAM designs.

Photons

- Efficient sources (single and entangled photons) and detectors;
- Increase single-photon purity (indistinguishability);
- Increase fidelity of cluster states;
- Increase switching speed and numbers of outputs of photonic routers;
- Compatibility of wavelengths between ICs and sources (telecommunications C-band and 935 nm);
- Reduce photon losses;
- Develop compilers, assemblers and libraries for the platforms;
- Improve reproducibility and large-scale production of single-photon semiconductor emitters;
- Integrate sources, circuits, and detectors on-chip;
- Have multiple identical single-photon emitters and routers to distribute up to 1000 single photons in ICs with hundreds of modes each;
- Interconnect several optical QPUs via optical links and entanglement distribution;
- Feed-forward control on detectors and ICs.

NV diamond

- Increase the number of physical qubits into the range several thousand to a million;
- Increase the number of logical qubits to several hundred;
- Integrate the technology with CMOS controls;
- Improve readout efficiency and gate fidelities;
- Reduce overall system size;
- Develop and standardise QEC codes.

Qubit Control

- Increase the number of qubits that can be simultaneously controlled;
- Improve the integration of control devices;
- Optimise control signal management and make it scalable;
- Improve the speed of operation;
- Reduce noise;
- Reduce dependency on materials and components from non-European sources;
- Standardise a framework for qubit control.

Quantum Error Correction

- Use error correction to suppress the logical error rate below the physical error rate for all modalities.

Quantum Software

Quantum OSs, quantum algorithm compilers

- Incorporate calibration and QEC routines into the main algorithm;
- Optimise quantum circuits for different hardware platforms automatically;
- Support hardware architectures with increasing numbers of qubits;
- Distributed programming capabilities on multiple hardware control backends;
- Standardise an IR framework.

Quantum APIs and cloud access

- Integrate quantum computers with large-scale computing infrastructure (HPC systems, cloud);
- Improve availability of European quantum hardware in the cloud, operated by European cloud providers;
- Support the transition of industrial companies to European cloud architectures;
- Provide legal guidelines and clarifications for sharing data in the cloud to companies outside the EU.

Quantum algorithms

- Close collaboration between quantum software providers and end users;
- Build collections of use cases with reference implementations of quantum algorithms and data preparation;
- Support the development and adoption of quantum solutions in industry through stimulus programmes;
- Build supporting software and develop standards for software development processes;
- Build a Europe-wide platform for quantum-based services.

Classical Quantum Emulators and Simulators

- Develop a NISQ-compatible approximate simulator, capable of simulating > 100 qubits with a controllable error;
- Integrate classical quantum emulators and simulators with large-scale computing infrastructure (HPC systems, cloud);
- Improve integration of classical quantum emulators and simulators with real QPUs for use as a universal quantum programming and integration platform;

- Improve availability of European classical quantum emulators and simulators in the cloud, operated by European cloud providers.

Applications: User Community

- Interaction between users and experts in quantum algorithms;
- Education;
- HPC/QC Integration;
- Facilitate procurement of products and services from QC solution providers;
- Create value through quantum and quantum-inspired use cases to drive quantum adoption in business;
- Interconnect the quantum computers installed at European HPC centres using the EuroQCI network for distributed computing capabilities.

Key Messages

Quantum Computing Hardware

During the past year, the European QC industry reached several significant milestones driven by early funding decisions that supported these developments. Progress will continue as several companies have published aggressive roadmaps backed by VC and EU funding.

In all modalities, the number of physical qubits is currently doubling annually, restrained somewhat due to the myriad components needed to build complete systems. In parallel, vigorous efforts continue to improve the quality of the qubits via manufacturing improvements and iterative design changes.

Early benchmarks focused on hardware-level “quantum volume” measurements, with the most comprehensive papers funded and published by QED-C under Tom Lubinski’s direction[58]. The latest area of focus is attempts to compare QC and hybrid QC platforms using standardised application-oriented benchmarks. The first publications on this topic came from Roche and BMW[59]; more recently, a comprehensive set of benchmarks has been published by NEASQC[60]. Several initiatives on designing benchmarks have already started in Europe, such as Bench-

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[58] *Thomas Lubinski et al., “Application-Oriented Performance Benchmarks for Quantum Computing,” IEEE Transactions on Quantum Engineering 4 (2023): 1–32, https://doi.org/10.1109/TQE.2023.3253761.*

[59] *“Chemistry Simulation Benchmarks (Quantum Computing Technical Dossier)” (BMW Group, Munich, Germany and Hoffman-La Roche, Basel, Switzerland, 2021).*

[60] *“NEASQC | About the Project,” NEASQC, accessed December 29, 2023, https://www.neasqc.eu/about-the-project/.*

QC[61], QPack[62], Q-score[63] and CUCO[64]. As these efforts mature and additional projects (BACQ[65]) deliver their results, we will be able to compare the performance of the quantum computers more readily.

The recently funded Qu-Pilot and Qu-Test EU projects are a welcome additional support. It will be necessary to extend their timelines beyond the current 41-month period and to enable a sustainable capacity to ensure that companies using these facilities can bring their products to market.

The industry partners also have several concerns regarding the handling of IP surrounding the pilot lines, discussed in more detail in Chapter 9. In particular, it is important to bring in industry participation as early as possible and craft a common approach to IP management for all pilot lines, right from this early stage. There is an impression that IP for previous pilot lines (e.g., in photonics) was managed inconsistently between the various RTOs and universities, risking unpleasant legal trouble.

Accordingly, when developing these technologies, it may be necessary to give some consideration to IP protection and avoidance of cross-pollination of IP between partners in the consortium. Open-source licences of the design kits combined with the ability for companies to include additional protected features may help address these issues. However, special arrangements may also be necessary per separate partnership. Ultimately, it is likely that licensing and transferring the completed pilot line to one or more companies will be necessary to ensure the long-term supply of specialised components.

Each modality also requires ongoing development in enabling technologies (cryogenics, photonics, cryoelectronics and RF/microwave electronics, FPGA, etc), so support is also needed for these core technologies within the overall EU funding plans (e.g., the European Chips Act). At this stage, some key technologies need to be imported from other jurisdictions (and vice versa), and although from a strategic or security viewpoint, it may seem sensible for the EU to develop local alternatives, the

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[61] *"Bench-QC – Application-Driven Benchmarking of Quantum Computers - Fraunhofer IKS," Fraunhofer Institute for Cognitive Systems IKS, accessed December 29, 2023, https://www.iks.fraunhofer.de/en/projects/bench-qc-application-driven-benchmarking-of-quantum-computers.html.*

[62] *Huub Donkers et al., "QPack Scores: Quantitative Performance Metrics for Application-Oriented Quantum Computer Benchmarking" (arXiv, May 24, 2022), http://arxiv.org/abs/2205.12142.*

[63] *"Q-Score," Atos, accessed December 29, 2023, https://atos.net/en/solutions/q-score.*

[64] *"What Is CUCO? - CUCO Project," March 23, 2022, https://www.cuco.tech/en/home/.*

[65] *"BACQ: Delivering an Application-Oriented Benchmark Suite for Objective Multi-Criteria Evaluation of Quantum Computing Performance, a Key to Industrial Uses | LNE, Laboratoire National de Métrologie et d'essais," accessed December 29, 2023, https://www.lne.fr/en/press-releases/bacq-delivering-application-oriented-benchmark-suite-objective-multi-criteria.*

costs may be prohibitive and such projects have a very high risk of failure. It is likely that a more effective approach to ensuring supply stability will be by means of international trade agreements and support for the strategic location of critical resources (e.g., silicon foundries) by international companies.

Subject to the successful implementation of the outlined strategy, the consensus of QuIC members is that fault-tolerant quantum computers will be available by 2035, and several companies are in fact confident that they can achieve this significantly earlier.

Quantum Computing Software

It is essential to widen and strengthen the accessibility of QC resources to industry to foster upskilling of the workforce and develop applications to progress toward quantum advantage. One way to achieve this could be to allow the commercial use of EuroHPC infrastructure for a reasonable fee.

Standardised interfaces are needed to access the various QC resources uniformly. In the interest of European autonomy, having a commonly adopted European software stack would be helpful. It should be open source, with standardised interfaces between the layers. Supporting this activity could also enable standardised interfaces to access the various QC (EuroHPC) resources uniformly.

In addition, end users need to be supported to increase the adoption of QTs. Maximising the utility of quantum computers will require additional computing algorithms, and packages that incorporate the new algorithms together with existing algorithms within application-focused libraries.

The software will need to keep pace with the increasing number of qubits. This is especially true for components such as compilers and software for qubit control and calibration. As it will no longer be feasible to manually address thousands or even millions of qubits, automation techniques will become increasingly important.

A hardware-universal set of application benchmarks is needed to facilitate comparisons between different qubit modalities. In addition, application-specific benchmarks should be developed to assess the scalability potential of each modality.

Quantum Simulation

General Overview

Definition of Terminology

There is often some confusion about whether the term “quantum simulation” refers to the simulation of quantum systems or to the simulation of QC on classical computers. This ambiguity is even more pronounced when referring to the devices, i.e., “quantum simulators”. Our terminology was clarified at the beginning of Chapter 2.

We now clarify some additional terminology used in this section: “analogue” makes reference to continuous time control (as opposed to non-continuous, discrete, digital control) of a system; “adiabatic” refers to a process whose timescale is very slow compared to that of the internal dynamics of the system, so that if the system starts at a certain energy level (e.g. the ground state) it will still be at that same energy level at some other point in time; and “annealing” is an algorithm (rather than a computational paradigm) that can be used to solve computational problems that are encoded in the ground state of some Hamiltonian.

This chapter deals with quantum simulation in the sense of simulating quantum systems using a quantum computer, which is described in more detail in the following overview.

Brief Overview

Quantum simulation determines the physical properties of static or time-evolving quantum systems, ranging from molecules and chemical reactions to physical phenomena in particle physics or material science. These calculations are typically carried out on classical computers using simulation methods. These rely on a series of approximations necessary to reduce the runtime and resources from the exponentially large degrees of freedom that the nature of the quantum system implies, to make the computation feasible.

However, due to the complexity of quantum mechanics, it is difficult to calculate these properties on classical computers, even with approximations. Indeed, it is impossible to calculate exactly for systems consisting of more than 30 particles. Carrying out the calculation on a digital quantum computer is possible in principle, but in many cases, the number and quality of qubits available in NISQ machines are insufficient. It is also hard to determine these properties experimentally for many systems of interest as these systems are difficult to manipulate. This is where quantum simulators come into play. These quantum devices exhibit similar properties to the systems of interest but are easier to program and control through a set of tuneable parameters. On these machines, the relevant properties are determined in an analogue fashion (i.e., by continuous (non-digital) control of certain parameters), which is why quantum simulators are often also called “analogue quantum computers”. They are not intended to be universal computers, however: they can only be used to study problems following the same mathematical formalism as the actual quantum system implemented in the device unless the system is fully programmable. Nevertheless, there are many valuable applications for quantum simulation, including basic science, materials research, quantum chemistry, and other areas.

One of the advantages of these platforms is their robustness, up to certain levels, against errors, due to the non-digital and slow control systems used for the algorithms. We can therefore expect relevant problems to be solvable earlier using quantum simulators. The quantum simulation stack is quite similar to the one depicted in Figure 2-2: QC stack, but it does not include a specific layer associated with QEC:

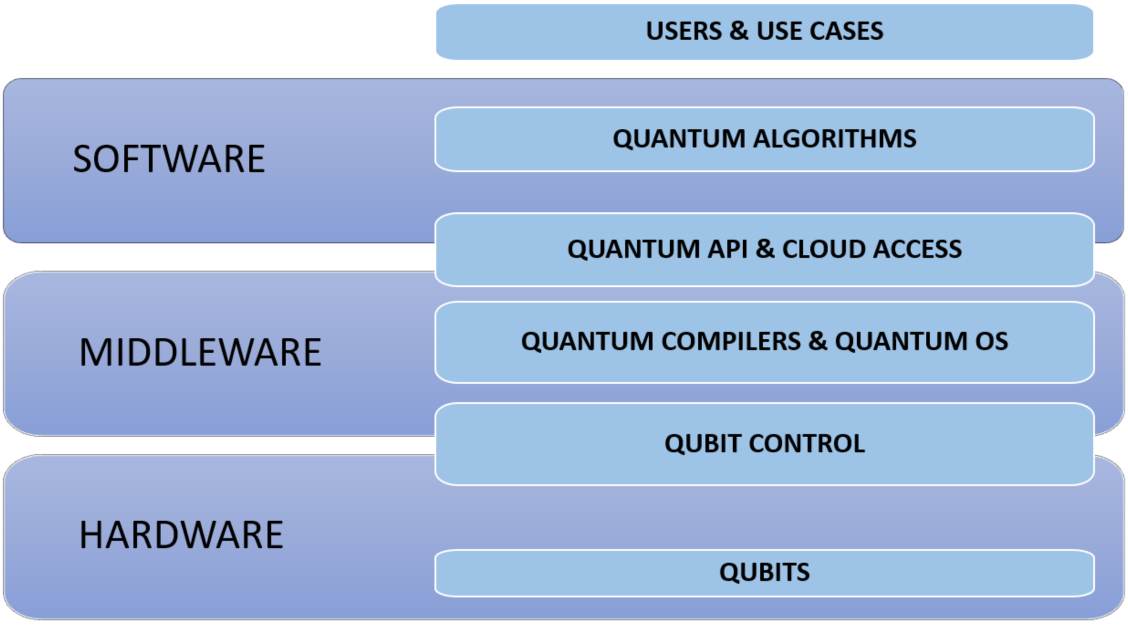

Fig 3-1: Quantum simulation stack

Current quantum annealers can be seen as a specific type of quantum simulator capable of solving Ising or QUBO problems by adiabatically determining the ground state of the corresponding Hamiltonian. However, expanding the annealer’s capabilities to simulate a broader range of quantum systems beyond this model would be interesting. Moreover, the quantum Ising Hamiltonian is *stoquastic*[66]. On the other hand, the equilibrium properties of Hamiltonians that fall outside this category (i.e., Hamiltonians containing non-stoquastic interactions) are more susceptible to

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[66] *Hamiltonians where all the off-diagonal elements in the standard basis are real and non-positive are called “stoquastic”.*

instabilities in classical simulations with quantum Monte Carlo methods, commonly accepted as the most significant classical competition to QuA.

There are different physical realisations of quantum simulators, such as superconducting qubits, spin qubits and neutral atoms; these are discussed in more detail in the following sections.

Quantum Simulation Hardware

Superconducting

Overview

In light of the enormous potential of quantum computers, large research institutions and companies are racing to demonstrate quantum advantage for more and more practical applications. A significant focus is being placed on gate-based models of QC. It is, however, unlikely that such quantum devices will be able to outperform classical machines in the near term, as the technological challenges required to implement error correction protocols on these devices are still far from being overcome. Instead, some academic and industry players are exploring ways to approach quantum advantage differently by considering the *analogue* model of QC. The algorithms that run under this paradigm can be based either on AQC or, more broadly, on the annealing algorithm. These approaches encode the solution of the problem in the ground state of the system’s Hamiltonian, or apply the quantum simulation of non-equilibrium dynamics, which allows the system to evolve through its natural dynamics along all its possible states and codifies the solution as the state of the system after a given time, through measurement of the desired observable.

The equivalence between the adiabatic and the gate-based models of QC has been formally proven. Therefore, any quantum circuit can be mapped to a target Hamiltonian to solve it via AQC and vice versa, with a polynomial overhead in the computation time. The direct consequence is that since the gate model is universal, the adiabatic model is also a universal form of QC, assuming one can encode arbitrary Hamiltonians in the quantum device. The analogue simulation, on the other hand, targets specific problems typically based on the study of the dynamics of a physical system or its use for ML applications, as it allows for the processing of a larger amount of data due to the exponentially large space offered by the quantum nature of the qubits, as seen in quantum reservoir algorithms.

The objective of a quantum annealer is to evolve the quantum system towards the ground state of the target Hamiltonian as in analogue QC, but allowing the evolution to be non-adiabatic; this means escaping the ground state to reach higher excited states. Most quantum annealers can solve certain optimisation problems that can be encoded in an Ising model but not other kinds of Hamiltonians and are, therefore, not universal. Suitable problems for quantum annealers include many industrial computational challenges that involve finding effective solutions to large and complex optimisation problems. These problems may be found in sectors such as logistics, finance, the chemical and pharmaceutical industries, and materials science, among others. Quantum annealers are, therefore, promising candidates for providing better-than-classical solutions to problems of this kind in the near future. There are already quantum annealers from D-Wave available on the market today that are larger (i.e., have more qubits) than any other available gate-based quantum computer. However, such devices have limited quantum properties due to the short coherence times of their qubits.

D-Wave’s technological achievement in terms of hardware (5000 qubits and 35,000 couplers) must certainly be recognised. However, the company’s design fails to incorporate significant technological advances of the past decades in the field of flux qubits. In particular, the flux qubit systems that are currently being proposed have longer coherence times and allow for richer control. Potentially, it may become possible to encode more complex Hamiltonian models than the Ising one, leading to the possibility of simulating universal, fully programmable Hamiltonians.

The Spanish startup Qilimanjaro is the leading QC company in Europe developing full-stack analogue quantum computers, with an architecture based on high-quality superconducting qubits that offer much greater coherence, thus ensuring the quantum effects persist through the entire computation. Importantly, this architecture is being developed to allow for the possibility of tuning richer interactions to simulate Hamiltonians beyond the Ising model, thus allowing for arbitrary simulation of quantum Hamiltonians, such as those relevant to chemistry problems. These systems enable a broader set of challenges to be addressed, allowing implementation of both adiabatic and quantum simulation algorithms.

The electronics control setup needed for analogue QC is similar to that for digital QC, as it is also the case that arbitrary shaped microwave pulses are used to control the QPU and to read out the information stored. However, a major difference between analogue and digital control is that most of the control channels for analogue QC have sub-GHz bandwidths, whereas for digital QPUs all control channels are in the Ghz bandwidth. As the price of microwave electronics correlates strongly with the frequency ranges being used, the cost of the electronics needed to control analogue QPUs may be lower than for their digital counterparts.

Road to 2035

Technical ambitions for the coming years in the field of superconducting qubits and simulation are:

- Improve the coherence times of flux qubits by a factor of 10, reaching hundreds of µs;
- Improve architectures to achieve better qubit interconnectivity and minimise encoding overhead;
- Implement tuneable non-stoquastic couplings that go beyond the Ising model;

- Implement chip configurations that allow for scalable, dense connectivity while minimising crosstalk;
- Identify encodings that go beyond QUBO models (such as those that employ non-stoquastic Hamiltonians);
- Intensify basic research on the requirements for, and design of, universal annealing-based quantum computers which have the potential to be complementary to fault-tolerant gate-based quantum computers;
- Offer the first cloud-accessible superconducting qubit-based coherent analogue device in the world with 5 qubits (2024), 10 qubits (2025), 20 qubits (2026), doubling each subsequent year, with coherence times of 1–100 µs;
- Develop quantum chips for specific dedicated applications that allow a wide variety of Hamiltonians to be encoded, including quantum Hamiltonians beyond the transverse Ising model;
- Further basic research into flux qubit circuit design with the long-term goal (2035) of designing and fabricating a universal quantum simulator based on superconducting qubits with coherence times of the order of 400 µs.

Spin Qubits

Overview

Section 2.3.2 discussed the current developmental status of semiconductor spin qubits. This section reviews research on applying spin qubits for quantum simulation applications.

Using subsets of emerging spin qubit technologies can offer interesting research opportunities. Recent examples of research using early technology implementations include engineering topological states in atom-based semiconductor quantum dots (Silicon Quantum Computing)[67], topological order detection and qubit encoding in Su–Schrieffer–Heeger type quantum dot arrays[68] (University College Dublin) and solving nonlinear differential equations with differentiable quantum circuits[69] (QUDOS).

Road to 2035

A key focus within the spin qubit research community is designs for universal quantum gate computers. Several companies are focusing on algorithm research and the modelling of quantum systems to run algorithms on universal quantum computers.

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[67] *M. Kiczynski et al., “Engineering Topological States in Atom-Based Semiconductor Quantum Dots,” Nature 606, no. 7915 (June 23, 2022): 694–99, https://doi.org/10.1038/s41586-022-04706-0.*

[68] *Nikolaos Petropoulos et al., “Topological Order Detection and Qubit Encoding in Su–Schrieffer–Heeger Type Quantum Dot Arrays,” Journal of Applied Physics 131, no. 7 (February 21, 2022): 074401, https://doi.org/10.1063/5.0082214.*

[69] *Oleksandr Kyriienko, Annie E. Paine, and Vincent E. Elfving, “Solving Nonlinear Differential Equations with Differentiable Quantum Circuits,” Physical Review A 103, no. 5 (May 17, 2021): 052416, https://doi.org/10.1103/PhysRevA.103.052416.*

However, it is also likely that new companies will emerge to take advantage of spin qubits and apply them in creative ways to solve quantum simulation problems. Ongoing research support is certainly warranted.

Trapped Ions

Overview

One of the most promising short-term applications of QC is the VQE algorithm: a hybrid quantum/classical algorithm with the crucial property that the quantum part of the algorithm consists of very small circuits compared to other quantum algorithms. This makes VQE a very promising application for NISQ computers that are unable to successfully execute large circuits. The main application of VQE is in computational chemistry, for describing interactions between molecules which are themselves quantum systems. A VQE proof of concept was implemented in 2020 for a trapped-ion quantum computer, used to minimise the quantum resources required to estimate the ground-state energy of the water molecule (H_2O) using 11 qubits and 143 entangling gates[70]. This level of resource requirements could make meaningful applications in computational chemistry possible within the near-term performance targets for trapped-ion NISQ computers. Interesting applications with enormous potential impacts, social as well as industrial, range from targeted drug design with potential for individualised treatment to more efficient (in cost and time) approval mechanisms. Other relevant insights and applications can be expected from material physics; e.g., improving our understanding of limits in solar cells and high-temperature superconductivity.

Another application domain where trapped-ion computing is expected to come into its own is the broad area of optimisation and related problems that can be solved with coherent QuA techniques, as discussed previously in the context of superconducting qubits. Activities in this field are currently being led by eleQtron, using their platform of microwave-controlled trapped ions. Application possibilities are widespread, ranging from portfolio optimisation in finance to waste minimisation in material cutting.

Road to 2035

Efforts should be focused on tailoring and optimising annealing protocols to make full use of the intricate connectivity of microwave-controlled ions. Industry-relevant use cases should also be examined, first on small-scale QPUs with a few tens of qubits, and subsequently with progressively larger, more capable QPUs.

In addition, simplified VQE models should be implemented on ion-trap-based quantum computers, and potential for industrial applications should be investigated.

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[70] *Yunseong Nam et al., "Ground-State Energy Estimation of the Water Molecule on a Trapped-Ion Quantum Computer," Npj Quantum Information 6, no. 1 (April 3, 2020): 33, https://doi.org/10.1038/s41534-020-0259-3.*

Neutral Atoms

Overview

Neutral-atom computing in analogue mode is a natural setting for quantum simulation implementations. For example, each qubit can directly represent a quantum spin in spin models, and the term “simulation” can be taken quite literally (simulating a quantum system directly with a quantum system) in the case of analogue quantum simulation.

Neutral-atom processors operating in analogue mode have enabled researchers to probe the entanglement frontier and advance scientific research. One example is a 2021 key study[71] of quantum magnetism using approximately 200 qubits. Pasqal has an R&D prototype operating in analogue mode in the dozens of qubits range, with an industrial machine currently under construction. Analogue QC can also be used to solve optimisation problems or perform quantum ML[72]. Pasqal has also developed Pulser[73], an open-source Python library for controlling neutral-atom devices at the laser pulse level. Future work will focus on extending the library’s capabilities and making it a standard for neutral-atom processors. Connecting this library to other tools further up the stack is also essential.

Future work on analogue neutral-atom QPUs will focus on noise suppression, increasing the total qubit count, and extending the quantum simulation capabilities of these devices.

Road to 2035

The long-term future of QC is not yet completely known and cannot be said to be set in stone for any of the technologies. It is, however, clear that in some way, the coherence time of qubits and the fidelity of quantum operations need to be drastically improved. Although technology and engineering can push the boundaries further and further, the time requirements of deep quantum simulation scale exponentially and ultimately physics will be the blocking factor. While specific digital gates can be made fault-tolerant, no method is known for making general analogue operations fault-tolerant. Therefore, it is expected that even neutral-atom simulators will perform quantum simulation in a digital mode of operation, e.g., using Trotterization, and that fault-tolerant digital neutral-atom quantum computers will need to be developed. Neutral-atom quantum computers scale well in the number of qubits, which is a

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[71] *Pascal Scholl et al., “Quantum Simulation of 2D Antiferromagnets with Hundreds of Rydberg Atoms,” Nature 595, no. 7866 (July 8, 2021): 233–38, https://doi.org/10.1038/s41586-021-03585-1.*

[72] *Loïc Henriet et al., “Quantum Computing with Neutral Atoms,” Quantum 4 (September 21, 2020): 327, https://doi.org/10.22331/q-2020-09-21-327.*

[73] *Henrique Silvério et al., “Pulser: An Open-Source Package for the Design of Pulse Sequences in Programmable Neutral-Atom Arrays,” 2021, https://doi.org/10.48550/ARXIV.2104.15044.*

requirement for fault tolerance. It is therefore expected that quantum simulation on neutral-atom quantum computers is also a promising direction for the longer term.

Quantum Simulation Software

Quantum Operating Systems and Compilers

Overview

The quantum OS of a quantum simulator is the software that manages the characterisation and control of the simulator hardware. Quantum simulators are analogue devices and do not use quantum gates unless required for some pre- or post-processing of the simulation. A compiler translates quantum algorithms from a high-level source programming language, usually at a Hamiltonian level, to a set of instructions based on a sequence of signals that define the schedule of the algorithm, which is executed by the hardware. For more advanced use, the quantum simulator can be programmed directly at the pulse level, which is always specific to a particular device.

Road to 2035

It is necessary to develop software that can be used for fast compilation from Hamiltonian level algorithms into analogue schedules, including techniques for efficiently mapping algorithmic to physical qubits and crosstalk reduction.

Quantum APIs and Cloud Access

Overview

Quantum APIs and cloud access form the transition layer between users and quantum machines in the quantum simulation stack. APIs for quantum simulators typically accept either parameters of specific problems which can be solved by the simulator, or sequences of pulses for direct control of the hardware. Most of the well-known general-purpose quantum SDKs are device-specific and do not include support for programming quantum simulators. However, there is important work ongoing into developing open-source hardware and computational model-agnostic APIs such as Qibo, co-developed by Qilimanjaro.

Like digital quantum computers, quantum simulators can be either installed on-premises or accessed via the cloud. Although the API calls and data structures are different, the integration itself can be achieved in a similar way. The integration with HPC systems is currently being developed in EU-funded research projects.

Road to 2035

In light of the above, we can identify the following goals for the long-term horizon:

- Improve availability of European quantum simulators in Europe-based clouds;
- Achieve integration of quantum simulators with HPC systems;
- Create a unified API/SDK for using quantum simulators at the use case level.

Quantum Algorithms

Quantum simulators evaluate the Hamiltonian of a specific quantum system available in hardware. They are programmable in that the parameters of this Hamiltonian can be manipulated, with newer developments allowing the evaluation of a broader range of Hamiltonians than just those native to the hardware (i.e., where only problems that can be mapped to the Hamiltonians available on the device can be solved). Most current quantum simulators focused on annealing are limited to solving problems that the QUBO and Ising formalisms can represent. However, richer algorithms can be encoded with a more versatile platform that allows for non-stochastic tuneable couplers and coherent qubits such as the ones being developed by Qilimanjaro. The challenges lie in offering flexibility in tuning the parameters that codify the system's Hamiltonian to be simulated, and in achieving interactions between qubits that go beyond the effective coupling in the z direction.

Using Digital Quantum Computers for Quantum Simulation

It is quite common to use digital quantum computers for quantum simulation. Many quantum algorithms are known for this purpose. One advantage of this approach is that digital quantum computers are universal, which means the same machine can be used to solve different types of problems, while a dedicated quantum simulator is restricted to solving only specific types of problems. Digital QC is also much more widespread than analogue QC, meaning that know-how is more widely available. However, when it comes to simulating the dynamics of a quantum system (i.e., when the process of interest is analogue), digital computers intrinsically accumulate additional errors coming from the discretisation of time.

Classical Quantum Emulators and Simulators for Quantum Simulation

Overview

Most commonly used quantum SDKs focus on digital gate-based QC and do not support the emulation of quantum simulators. One notable exception is the emulator available from Eviden, which supports analogue QC and simulated QuA. Other options are to emulate a digital quantum computer performing quantum simulation or use “standard” classical software packages to solve quantum-mechanical problems (e.g., quantum chemistry software).

Road to 2035

Several commercial and open-source program suites for computational quantum chemistry exist (e.g., Jaguar). The computational resources are extensive, but approximations and simplified models constrain their usefulness. As quantum simulators evolve, some of these program suites will incorporate the new technology, mapping the quantum description of the chemical problem into the quantum description of the device. However, computational chemistry using classical quantum emulators is still at an early stage of development.

Applications: User Community

Overview

Quantum simulation is mainly used to model physical problems, so it is no surprise that the main areas of application are the life sciences sector, quantum chemistry, and materials research. Use cases include drug discovery, nitrogen fixation, protein folding, new materials design, and molecular similarity.

Quantum simulation is used for this type of problem because the simulation hardware closely resembles the life science problems under investigation, sometimes using the same atomic or chemical components. This means that the system can be designed to evolve naturally in the quantum simulator, such that the outcomes observed provide direct insights into the problems under study. While classical counterparts must use theoretical models of the behaviour of the physical system to address this type of problem, this is not necessary with a quantum simulator. Quantum simulation is also expected to have an advantage over digital QC for applications of this type, at least in the near future, as the impact of noise on the results is less pronounced.

Academia is currently engaged in joint research with industry to tackle increasingly large problems and establish the limits of this approach for current technology.

Road to 2035

The long-term objective for this technology is to continue developing the hardware to achieve quantum advantage.

Road to 2035

The following is a summary of the "Road to 2035" subsections in this chapter, which should be consulted for more details.

Quantum Simulation Hardware

Superconducting

- Improve the coherence times of flux qubits by a factor of 10 (reaching hundreds of μs);
- Improve architectures to achieve better qubit interconnectivity and minimise encoding overhead;
- Implement tuneable non-stoquastic couplings to simulate problems beyond the Ising model;
- Identify encodings that go beyond QUBO models;
- Develop universal annealing-based quantum computers;
- Double the number of qubits every year;
- Design and implement benchmarks;
- Develop quantum chips for specific dedicated applications.

Spin qubits

- Apply spin qubits in creative ways to solve quantum simulation problems.

Trapped ions

- Optimise annealing protocols to make use of the connectivity;
- Study industry-relevant use cases with progressively larger QPUs;
- Implement simplified VQE models on ion-trap-based quantum computers and investigate their potential for industrial applications.

Neutral atoms

- Successful demonstration of quantum ML on graphs;
- QPU with 1000 qubits working in analogue mode.

Quantum Simulation Software

Quantum OSs and compilers

- Develop software that allows for fast compilation methods from Hamiltonian level algorithms into analogue schedules, including techniques for efficiently mapping algorithmic to physical qubits and crosstalk reduction.

Quantum APIs and cloud access

- Improve the availability of European quantum simulators in Europe-based clouds;
- Achieve integration of quantum simulators with HPC systems;
- Create a unified API/SDK for using quantum simulators at the use case level.

Classical Quantum Emulators and Simulators for Quantum Simulation

- Program suites for, e.g., computational chemistry that map the quantum description of the original problem into the quantum description of the quantum simulation device.

Applications: User Community

- Continue developing the hardware until quantum advantage is reached.

Key Messages

- Quantum simulators are quantum devices that exhibit properties similar to particular quantum systems but are easier to program and control through tuneable parameters;
- Quantum simulators are also called "analogue quantum computers" since their properties are determined by continuous control of specific parameters (as opposed to digital (gate-based) quantum computers);
- Most quantum annealers are used to solve complex optimisation problems;
- Quantum annealers are promising candidates to provide quantum advantage for solving scientific problems in quantum chemistry, materials research, high-energy physics and other fundamental areas;
- Analogue platforms are more robust against errors due to the non-digital and slow control systems applied to the algorithms;
- Although analogue quantum computers are not universal, superconducting flux qubits (thanks to their long coherence times and rich tunability) raise the possibility of encoding complex, arbitrary Hamiltonians, leading to universality;
- The co-design of quantum chips customised to a particular application makes the need for relevant industry use-case identification even more important than general-purpose digital chip design;
- When defining benchmarks, there is a need to go beyond "quantum volume" and define specific metrics for analogue QC, focusing not only on the number of qubits but also on their quality (coherences), their interactions (beyond *z*-*z*), and connectivity (full connectivity or methods to achieve it). These benchmarks must also include energy consumption metrics;
- Electronics requirements for analogue quantum computers are much less costly (a few hundred MHz) than for digital (order of GHz);
- Key messages listed in Section 2.11 also apply to quantum simulators (e.g., pilot line funding and advances in enabling technologies).

Quantum Communications

General Overview

Humanity is creating more data and more valuable digital data, touching all aspects of government, industry, and society. This leads to an increased interest in malicious activities such as obtaining unauthorised access, destroying data, or compromising its integrity. There is an entire industry, including academic research, working to prevent and mitigate attacks on our data. Various studies suggest there is currently a global cybersecurity market in the order of € 150 billion[74].

Within a few years, cybercriminals might have access to a quantum computer powerful enough to attack the asymmetric part of contemporary cryptography based on the DLOG and integer factorisation hard problems, which are used to distribute private keys and to authenticate communication partners. This would shake the foundations of our modern data transmission networks. Although it is currently difficult to estimate a timescale for the arrival of a quantum computer with enough fault-tolerant qubits to break current cryptography (2030 has been suggested as a possible horizon for this event[75]), the latent risk to secure communications is already clear. Thus, in order to ensure long-term security, it is essential to act now. A long period of time is usually needed for new security paradigms to be adopted and deployed. In addition, it is already possible to store encrypted data today for decryption at a later date, when powerful enough quantum computers are available. Symmetric cryptography is also prone to quantum attacks such as Grover's search or the quantum algebraic attack, reducing its security level (security level is halved). However, official estimates indicate that symmetric algorithms such as AES-256 or OTPs will be valid for longer than cryptosystems relying on DLOG and integer factorisation.

Today, we already have concepts developed to a high level of sophistication for countering the quantum computer threat, based on PQC and QComm. These correspond to two security building blocks with different capabilities that are expected to work together to contribute to a quantum-secure world. Note that these technologies are not competing but complementary.

The first of these two building blocks involves replacing legacy cryptographic algorithms with new, "quantum-safe" algorithms. This class of PQC cryptosystems relies on computational complexity (for existing and known algorithms) for security and is accordingly resilient against known classical and quantum computer attacks. This

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[74] *"Cybersecurity - Worldwide | Statista Market Forecast," Statista, December 2022, https://www.statista.com/outlook/tmo/cybersecurity/worldwide.*

[75] *Kristina Rundquist, "Cloud Security Alliance Sets Countdown Clock to Quantum," March 9, 2022, https://www.businesswire.com/news/home/20220309005135/en/Cloud-Security-Alliance-Sets-Countdown-Clock-to-Quantum.*

computational complexity relates to the hardness of the mathematical problems on which the cryptosystem design is based. Resilience is a measure of the feasibility of solving a problem with the respective computing resources – classical or quantum. Security levels can be derived for either case. PQC is currently undergoing an intensive standardisation effort. Most of the finalist candidate PQC algorithms in NIST's standardisation process were proposed by cryptographers from European research institutes and companies. During 2022, NIST completed the selection process for the algorithms to make up the PQC NIST standard. During 2022, NIST completed the selection process for the algorithms to make up the PQC NIST standard; during 2023, these were incorporated into drafts which are now undergoing a feedback process and will be used in various secure applications over the subsequent years.

The second building block strategy is based on QComm, which refers to the field of transmitting and distributing information using photons in the quantum regime. QComm leverages quantum physics – in particular, the no-cloning theorem, which is exploited to send information encoded in single photons (or few of them) such that any attempt to copy the information is detectable. With additional optical and electronic technology, it is already possible to support cybersecurity applications that rely on secure key distribution and RNG, and we anticipate the coming of the quantum internet (connecting quantum computers, quantum sensors), which will be able to synchronise quantum clocks and long-baseline telescopes – as well as many more applications not yet conceived of.

Adding these quantum channels to an existing authenticated digital structure allows it to be used as a quantum network. Communication parties can exchange secret keys securely using QKD services. The received keys can be used to perform different cryptographic functions, and the results transmitted through the classical channels.

The two approaches, PQC and QKD, have different capabilities. While PQC can have a wide variety of cryptographic functions and can already be deployed in a wide variety of systems, its reliance on the hardness of mathematical problems means there is always a latent risk of exposure to new quantum algorithms. On the other hand, QKD generates and distributes keys based on the principles of quantum physics. This technology, used for secure key exchange, relies on quantum physical phenomena and it is thus immune to attacks from both classical and quantum computers, making it a future-proof solution. However, the adoption of QKD requires additional hardware and a costly infrastructure, which slows down its implementation. It is foreseen that a quantum-secure world will be built upon a layered security approach, combining different building blocks from the classical, PQC, and QKD domains.

A further cybersecurity application based on QT is the QRNG, which leverages quantum physics to develop a TRNG. Unlike non-quantum TRNGs, the entropy (i.e., the source of the randomness) is not generated in a chaotic (i.e., uncontrolled) way. QRNGs can be fully modelled, and are thus maximally controlled, yet still generate a "surprise", which is then processed to generate private and secret keys. QRNGs are discussed in Section 4.3. QRNGs also add value to classical symmetric cryptography, as the entropy of an RNG determines the true security level of the related encryption.

Measuring the randomness of an RNG is a challenge in itself. Some security agencies have published tests and TRNG frameworks. Defining equivalent frameworks for QRNGs is ongoing research.

While QKD technology is becoming mature and applicable, research is also progressing on the next generation of quantum network technology, the quantum internet. The goal is to deliver fully entangled quantum networks that are able to connect quantum computers, QPUs and quantum sensors. The core functionality is the end-to-end distribution of entanglement, which is typically achieved with quantum repeaters and quantum memories to extend the distances. It is expected that the technology will increase its TRL in the coming years as testbeds are launched to develop and industrialise a variety of products and use cases. A leading consortium in this field in Europe is the Quantum Internet Alliance.

As our focus is on the industrial aspects of QComm, we mainly cover QKD and QRNGs in this chapter. We begin by classifying several QKD technologies for terrestrial (i.e., fibre-based, free-space) and satellite-based QKD, and discuss the status of network architectures, standardisation, and security certification. This is followed by a review of the industry roadmap for QRNG. To conclude the chapter, we identify several open challenges in the QComm industry and potential strategies to counter them.

Quantum Communication Networks (Products and Services – QKD and PQC)

From the user point of view, the main functionality of QKD is to deliver identical, private keys to two remote sites. Using the technology, it is possible to define a shared key while bounding information leakage to the external world as tightly as desired, independently of the computational capabilities of an attacker. This is because the security of the key is not dependent on the computational power of the adversary. The key sharing can be done either via optical fibre or free-space ground-to-ground optical links (Section 4.2.1), or via free-space connections to satellites (Section 4.2.2). In the long run, a combination of fibre-based and satellite-based QKD is expected.

Independent of the implementation and the medium used to transport the photons, a QKD system can be described as composed of two boxes deployed at two distant sites (see Figure 4-1). The sites are often labelled Alice and Bob. The two boxes are connected via a quantum channel and one or several classical channels, where quantum and classical refer to the regime of the communication: the quantum channel transports quantum information encoded in single (or few) photons, and the classical channels transport classical information encoded in optical pulses with standard telecommunications intensities (in the order of mW) or any other technology (e.g., electrical, RF). The boxes implement the QKD protocol via quantum and classical communication. The result is that a shared symmetric key is output via an interface for further (cryptographic) use.

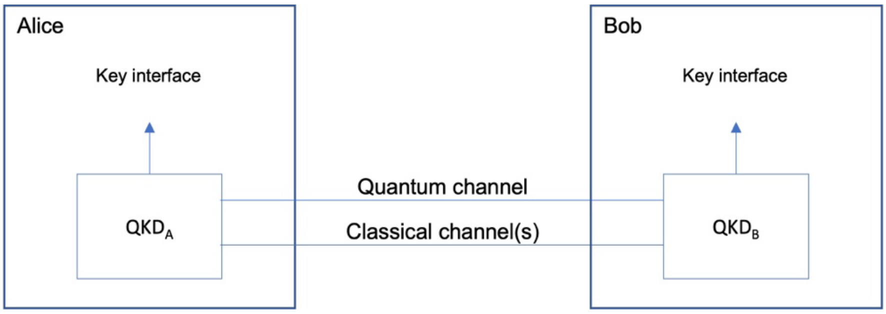

Figure 4-1: The basic concept of a single QKD link

Due to losses in fibres or the absence of direct free-space links (limiting QKD links to around 150 km), it is not generally possible for two arbitrary points to be covered by a single QKD link. Links between sites further apart are achieved by building up a network of “Trusted Nodes” (TNs). A TN is an intermediate node comprising two or more end points of single QKD links. Secret keys that need to be distributed between other nodes in the network can be relayed through the TN. The security assumptions inside the TN are stronger than between the TNs, which requires some level of trust in the correct and uncorrupted functioning of the TN. The simplest topology with a single TN is illustrated in Figure 4-2. The figure shows key forwarding as an example of how TNs can be used to extend the effective range of QKD. The model can be extended to an arbitrary number of TNs, connected with point-to-point QKD links. In this way, large QKD networks become feasible (e.g., networks with fibre connections in combination with satellites). Scalability comes from standardised network architectures including control and management, standardised interfaces to allow for interoperability, and efficient implementations of the key forwarding functions. TNs need to be hosted within a secure boundary, designed to prevent tampering and other attacks from unauthorised parties.

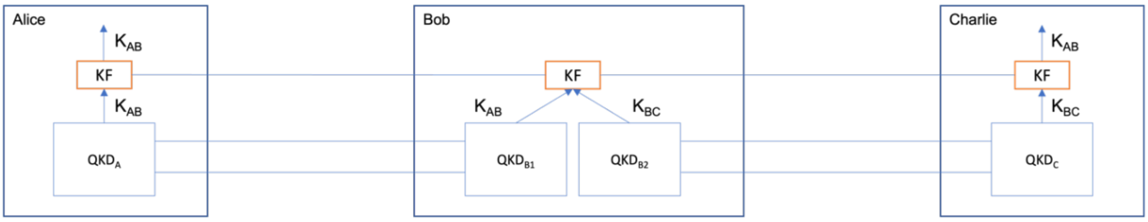

Figure 4-2: Simple key forwarding example, giving Bob a TN to cover larger distances between the two key users Alice and Charlie. Direct QKD links between Alice and Bob and Bob and Charlie (K_{AB} and K_{BC} respectively) deliver keys to a key forwarding module (KF). K_{BC} is then used as an OTP to transport K_{AB} to Charlie. As a result, identical shared keys are distributed to Alice and Charlie

A future development is promised by the quantum repeater paradigm, in which TNs like those shown in Figure 4-2 are replaced by quantum repeaters which no longer require the security boundaries. Essentially, quantum repeaters make it possible to transform entanglement (or, more precisely, quantum correlations) between Alice and Bob, and between Bob and Charlie, into entanglement between Alice and Charlie. This can then be used to directly implement a QKD protocol between Alice and Charlie without the need to trust Bob. It is this technology that will form the basis of the quantum internet and some zero-trust communication scenarios. Today, the most advanced research and demonstrations of quantum repeaters are at TRL 3 (i.e., research to prove feasibility) with several open questions to be researched. The QKD industry is therefore focusing on the TN paradigm, knowing that the "trust" needed can be significantly reduced to a level comparable to other security risks in the network architecture. However, research on this topic must be continued and is supported by the QKD industry.

As mentioned in the overview, QKD and PQC are two paradigms based respectively on physical and mathematical principles. As discussed in numerous research and white papers, neither PQC nor QKD has been researched to its full extent, and security questions are still being investigated. It is beyond the scope of this document to discuss these open questions. We note, however, that it is expected that future solutions will be based on a combination of QKD and PQC, as well as legacy cryptography, depending on the use case and the available resources. In the simplest case, this means that QKD- and PQC-based keys are made available to the users Alice and Bob. They agree on a secure combination of the keys (e.g., by applying an XOR operation on both keys) such that it is necessary to know both keys to learn about the derived key. In some cases, QKD keys cannot be delivered to end points like mobile devices. For these cases, more complex hybridisation schemes can be used. For example, algorithmic cryptography to establish end-to-end security while QKD is used to additionally secure the backbone of the transport network, as implemented for part of the 5G network in South Korea[76].

QKD network development in Europe

An important European initiative towards ultra-secure communications and the future quantum internet is the EuroQCI: the aim of the project is to build an ultra-secure QCI spanning the entire EU, including overseas territories. This initiative was announced in a declaration made in June 2019, which was signed by the 27 EU Member States. The Member States are working with the EC and the ESA to design, develop, and deploy the EuroQCI. Leading European industries, several of whom are members of QuIC, are also participating in the design of the EuroQCI[77]. The EuroQCI will integrate QTs and quantum systems into terrestrial fibre-optic communications networks. Early field-deployed fibre-based QKD demonstrations have been realised, including cross-border QKD links between EU Member States. The EuroQCI will also include a space-based segment to ensure full coverage across the EU and other continents. The ESA, through its SAGA programme, is responsible for designing the space backbone of the

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[76] *"SK Telecom Continues to Arm Its 5G Network with Quantum Cryptography Technologies," SK Telecom, March 18, 2019, https://www.sktelecom.com/en/press/press_detail.do?idx=1385&currentPage=3&type=all&keyword=quantum%20.*

[77] *"A Consortium of European Digital Players to Design the Future EU Quantum Internet | Airbus," May 2021, https://www.airbus.com/en/newsroom/press-releases/2021-05-a-consortium-of-european-digital-players-to-design-the-future-eu.*

EuroQCI. The objective is to produce a EuroQCI demonstrator and offer an initial operational service by 2027. It will be an integral part of IRIS², the new EU space-based secure communication system[78].

To this end, several European consortia have been established under the EuroQCI initiative to advance the maturity level of QKD and related technologies. An important project is the PETRUS consortium coordinating the EuroQCI, which includes several QuIC members and will ensure the interoperability of the quantum network and alignment across deployments by the different EU Member States.

Comparison to international activities

In terms of scope and ambition, there are two regions outside Europe that can be considered leaders in terms of protecting public (and private) critical infrastructure using QKD: China and South Korea. Singapore has also recently been further developing its internal QKD capabilities.

China has implemented and tested several ambitious QKD projects with the strategic objective of serving national information security. The newly constructed Beijing–Shanghai backbone provides a secure QComm backbone linking Beijing and Shanghai, passing through several cities, spanning a total length of > 2000 km of fibre-optic cable and a satellite link covering 2600 km between two observatories[79]. Following the first demonstration of space-to-ground QKD[80], China is working on significant improvements to its satellite-based QKD capabilities, with the goal of building more versatile, ultra-long-distance quantum links via geosynchronous satellites. The integration of fibre and free-space QKD links will make it possible to extend the range of QKD networks, allowing QComm across more than 4000 km.

Following on from testbeds deployed in 2020, in 2022 South Korea launched a large governmental project to connect 48 public institutions with a national QKD network. The core of the network will be composed of dozens of QKD links in a connected multi-ring topology. Singapore, meanwhile, is following a similar path to Europe: it is planning testbeds to prepare for a subsequent production network for governmental use.

In the remainder of this section, we discuss first terrestrial and then satellite QKD. We expect that in future both paradigms will work together to provide continental or even global QKD services. However, we underline that the individual building blocks are at

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[78] *https://defence-industry-space.ec.europa.eu/eu-space-policy/iris2_en*

[79] *Yu-Ao Chen et al., "An Integrated Space-to-Ground Quantum Communication Network over 4,600 Kilometres," Nature 589, no. 7841 (January 14, 2021): 214–19, https://doi.org/10.1038/s41586-020-03093-8.*

[80] *Sheng-Kai Liao et al., "Satellite-to-Ground Quantum Key Distribution," Nature 549, no. 7670 (September 7, 2017): 43–47, https://doi.org/10.1038/nature23655.*

different TRLs. This implies different levels of technical risk and different timescales. Decisions regarding the network architecture or security requirements, as well as evolving user requirements, will have a significant impact on the roles of both fibre-based and satellite-based QKD.

Terrestrial Segment

Overview

Since the first QKD protocol in 1984 and the first experimental demonstrations, different QKD concepts and implementations have been proposed and demonstrated. We start by giving a brief overview of the different solutions that have been at least demonstrated outside the lab. Each approach has advantages and disadvantages for individual modules (optics, analogue electronics, processing) and regarding performance (SKR and dynamic range) and industrial scalability. In the following section, we consider QKD links connected via a fibre channel. In a limited set of cases, free-space ground-to-ground optical links may be adopted to overcome a lack of deployed fibre, or to implement mobile or temporary nodes. The technologies needed for this type of connection, and the related challenges, are closer to those used in OGSs and discussed in Section 4.2.2.

DV QKD was the first QKD paradigm and is the most advanced in terms of TRL, industrialisation, and security proofs. Available high-end products reach an SKR of 100 Kb/s to 1 Mb/s at 50 km, and 1 Kb/s or more at around 120 km. Other designs with lower price and reduced performance are available. A critical component of DV QKD is the SPD, which is currently a relatively large and expensive bulk component. DV QKD reached TRL 9 a few years ago.

CV QKD is the QKD concept closest to coherent communication of the telecommunications industry, which means there are advantages for industrialisation of the optical setup. CV QKD does not reach the performance of DV QKD for long distances, but rather provides reliable performance for short-distance nodes within dense metropolitan networks. It is expected to provide gradually more cost-effective solutions. In earlier demonstrations, the performance of CV QKD based on local oscillator distribution between Alice and Bob was comparable to that of commercial DV QKD devices, with a complete security proof. The recent published evolutions are based on the use of an independent local oscillator at Bob and digital signal processing, and they offer at least an order of magnitude increase in the SKR, by using commercial coherent telecommunications equipment. CV QKD has a TRL between 7 and 8, with systems already commercially available.

MDI QKD is composed of two DV senders and one receiver, where there is no need to trust the receiver station. In a configuration where the receiver is a separate third node placed in between the two (or more) senders, theoretically the same dynamic range can be achieved. MDI QKD has been demonstrated in Europe in the Netherlands and Italy. MDI QKD is currently at TRL 5 to 7 and can now bridge distances > 200 km.

TF QKD is a modified MDI QKD scheme that facilitates transmission over larger distances. Field demonstrations of prototypes suggest that distances of 600–800 km are possible, with an SKR in the order of 1 b/s. Admittedly, this has been achieved with highly complex and expensive optics. TF QKD is currently at TRL 5 to 6.

EB QKD is based on a source of entangled photon pairs and two connected receiver stations. As in MDI QKD, the source can be an untrusted standalone box as a third node in between the receivers, or integrated in one of the receiver nodes. In TN networks, the main practical advantage of EB QKD is the absence of state preparation optics and electronics; for quantum-repeater-based networks, entanglement is, conceptually, a necessary ingredient. EB QKD has TRL 5 to 6.

Products and services

The available QKD products have now been industrialised to an extent that allows the industry to serve a market of innovators and early adopters. The commercially offered systems are typically mountable in 19-inch racks. They are one rack unit or more in height and are adapted to datacentre conditions. The most-deployed systems worldwide and in Europe are DV QKD solutions based on the BB84 or coherent one-way protocols. CV QKD is starting to be commercialised and deployed by some companies, and is expected to continue gaining presence within metropolitan networks. Other technologies are also available as commercial or pre-commercial products.

To build up QKD networks going beyond a single point-to-point link, software is needed to distribute the key via the network, potentially passing through several TNs. This software is partially indicated in Figure 4-2 as the KF modules present in every node. However, the operation of an entire network also requires control and management capabilities. These network capabilities must be designed. Current standardisation activities worldwide are working on approved network architecture concepts and interoperable interfaces between modules. Adapting the TRL scale to the network level, fibre-based QKD networks are around TRL 5 in Europe.

Challenges of the terrestrial QKD industry

1. Security challenges – the benefit of quantum mechanics within QKD and QRNG applies only to the quantum components of the devices. As soon as the token or keys leave the quantum component, classical IT security challenges apply. Key management is usually implemented in non-quantum components of the system. Cybercrime has typically leant towards “advanced persistent attacks”, also called multi-stage attacks, which target highly critical information in secure systems. These attacks typically involve multiple stages over a long time period. Secret keys are a popular target as they can unlock access to much more highly critical information. Countermeasures are based on various security monitoring mechanisms, and these will need to be considered for quantum security devices as well.

2. The most mature QKD products that are available today can be used in production environments, but the capital and operational expenditure are too high to generate a large market including private companies. Clearly, hardware costs will decrease as the production volume is increased, but achieving this also requires better technology at the component level. Importantly, the ability to integrate optical components into PICs will make it possible to scale up production capabilities and reduce the SWaP-C of QKD hardware. Many optical components of the different QKD technologies are available in PIC technology libraries. However, further development is needed in some cases where the specifications for QKD lie beyond the current state of the art. Other elements, like SPADs or entangled photon pair generation, need more basic research before they can be included in industrialised PICs. These are important enabling technologies (see Chapter 6) also relevant to other industries (inside and outside QT), and research policymakers should accordingly pay particular attention to this area. To some extent, this is already happening through smaller and larger initiatives like the European Chips Act.
3. Products for a single point-to-point QKD link can be used in production use cases like DCI technology to secure OSI layers 1 to 3, thanks to commercially available standardised interfaces to QKD-ready encryptors. Large TN QKD networks exhibit increased complexity and new challenges. For example, standardised interfaces are needed for interoperability and to avoid vendor lockin. Furthermore, the network must be scalable; that is, the configuration work and operational effort should scale adequately with the network size, and the cost of adding new links or merging two networks should not exceed a reasonable level. The QKD community has built up some useful experience in this area through OpenQKD, while standardisation work (e.g., at ETSI and ITU-T – see Chapter 8 – Standards) has produced applicable interfaces and conceptual insights. These programmes must be continued to allow further collaborations on testbed deployments like the EuroQCI phase 1, and standardisation activities. Europe must reinforce its historical leadership position here.
4. The security of QKD is based on watertight mathematical proofs. The end user is typically not in a position to verify the correctness of the QKD models and the implementation, and independent evaluations and audits are therefore essential to establishing trust. As outlined in Chapter 8, standardisation and certification activities started around 10 years ago. Today, Europe is on track to begin the first QKD security certification within a few years. However, policymakers in different areas must reinforce efforts to ensure quantum-secure solutions can be provided on time. Specifically, there is a shortage of trained academics and experts to work on the foundations of QKD security. There is need for more interdisciplinary collaboration between the QKD and security communities, which traditionally come from different areas (physics and mathematics/engineering respectively). Finally, investment is needed in the “certification ecosystem” composed of national authorities and accredited evaluation laboratories. Projects in this area are underway, but must be accelerated and supported by additional public funding and incentives for interdisciplinary collaboration.
5. Security, in particular cybersecurity, is traditionally an underfunded field despite its importance. In all private and public sectors, other topics with more direct impact or revenue compete with security, which in the best case just preserves the status quo

of not being attacked or compromised. QKD comes with two additional challenges. Firstly, although the future quantum computer threat may be intellectually understood, the need to act on it now is systematically underestimated. Migration to quantum-safe systems will take several years, and the risk of the intercept-now-decrypt-later attack (intercepting transmitted data before the arrival of a powerful quantum computer, for decryption at a later date) has also not been adequately acknowledged. Secondly, QKD remains a difficult-to-implement solution. However, experts often merely look at the current state of the art and fail to recognise the potential of technological developments within the next few years. Integration with PQC must also be further studied and analysed. Ultimately, PQC and QKD will play a crucial part in long-term security for sensitive and classified data. Policymakers must be aware of the timescales and these challenges and lay the foundations for long-term funding and support for QKD. Alongside public investment, this also means recommendations and later regulations for the use of QKD-based solutions in areas where private and public information is processed and transferred.

6. Generally, the QKD industry welcomes and supports research in several directions alongside the points mentioned above. In addition to foundational research to bring quantum repeaters to a higher TRL, almost every aspect of QKD can benefit from research: components like sources, modulators, detectors, and their integration in PICs; research into integration of QKD into the optical transport network (e.g., multiplexing of quantum signals with third-party classical signals on fibres); improved hybridisation schemes and use cases for combined QKD/PQC; better security proofs that allow higher SKRs under the same security assumptions; etc.

Road to 2035

The goal of this section is to present our best estimate for the future of terrestrial QKD, subject to the assumption that enough private and public investment is available.

Immediate future (to 2025)

- QKD products are being industrialised, allowing for tens to hundreds of manufactured QKD links per year;
- QKD networks with dozens of QKD links will be built up. Some of them will continue to be operated in test mode, while a few will be used in production;
- QKD network architectures are being demonstrated and will become ready to be validated for governmental use cases;
- Products will enter the market with general-purpose product certification (EU directives, etc.);
- QKD security certification is under preparation: background documents, evaluation methods;
- Adoption of quantum keys and PQC by encryptors operating at OSI layers 1 to 4 begins;
- CV and EB QKD products will reach TRL 9.

Near term (2025–2029)

- MDI and TF QKD products will reach TRL 9;
- QKD networks will reach sizes of hundreds of nodes. Testbeds will be replaced by production networks;
- QKD products will evolve from general-purpose devices to specialised products, ranging from low-cost and low-performance devices for access networks or local private networks to long-range, high-key-rate devices;
- Integration of optical and electronic components will become advanced enough to allow for medium-size production series with volumes of thousands of pairs per year;
- The first QKD products will be certified;
- Quantum keys and PQC will be adopted and/or integrated by apparatus operating at the various OSI layers;
- Quantum internet will start by connecting two quantum computers that are in the same metropolitan area – benefits will be limited, compared to the computational power of the standalone products.

Long term (2030–2035)

- Widespread deployment of QKD and PQC;
- It will be possible to connect quantum computers located in the same region into networks with combined computational power substantially greater than the sum of the individual devices;
- Adoption of entanglement-based communication, together with new QComm services such as the quantum internet, in niche applications (where high costs and limited key rates are acceptable).

Space Segment

Overview

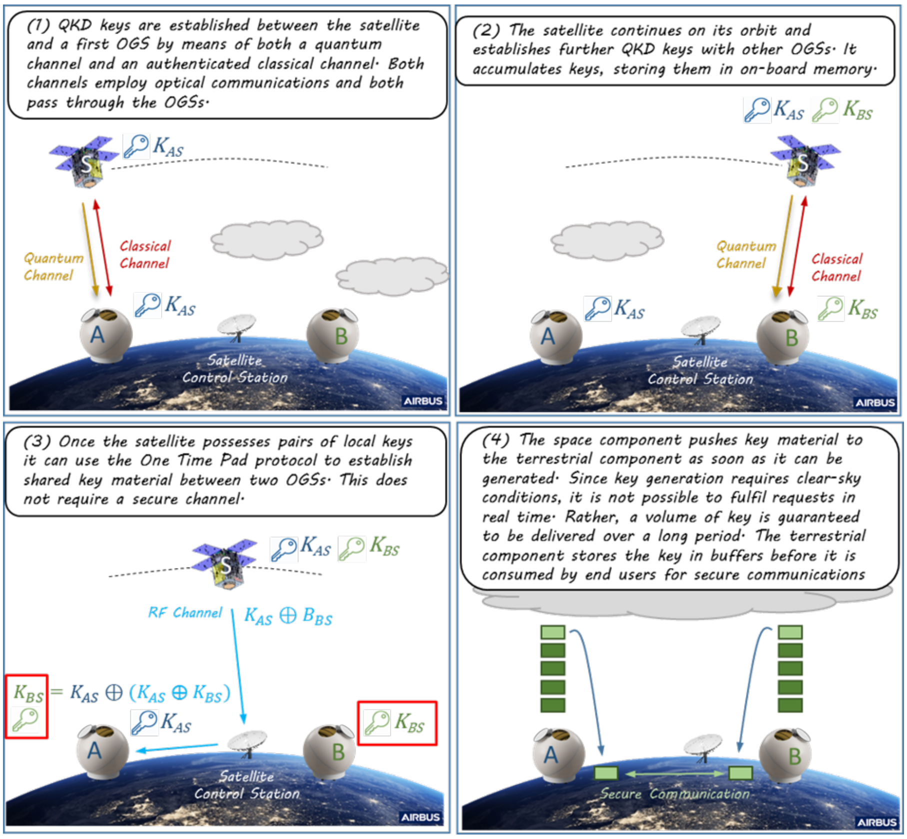
Terrestrial QKD suffers from an inherent range limitation associated with the loss mechanisms of optical fibres. An alternative to increasing the range by use of TNs is to employ a QKD space segment. The Chinese Micius mission successfully demonstrated both PM and EB QKD from an LEO range. There is now a European space QKD initiative in the form of the SAGA programme, which is aiming for a preliminary operational mission by 2027.

The following sections cover both PM and EB QKD operations in space.

PM satellite services

This section briefly describes the operational concept of a PM satellite service. Figure 4-3 illustrates how a mutual key can be established for two OGSs, labelled Alice (A) and Bob (B).

1. The standard PM protocol (typically a DV protocol due to higher robustness against turbulence) is employed to generate a mutual key, K_{AS}, between the satellite (S) and Alice. This uses both a unidirectional quantum channel and a bidirectional classical channel (required for synchronisation, state-shifting, error correction, and privacy amplification). The classical channel needs to be an authenticated channel in order to avoid man-in-the-middle attacks. Clear sky conditions are needed to generate K_{AS}.
2. Once K_{AS} has been established, the satellite continues along its orbit until an appropriate opportunity occurs to generate a second key, this time interacting with Bob, K_{BS}.
3. Now that the satellite possesses both keys it can use, e.g., K_{AS} to transmit K_{BS}. This is performed using an ITS protocol such as the OTP, as in the illustration. This key distribution can take place over any reliable channel such as the RF ground link and it can take place at a later time.
4. Importantly, secure key material must be generated in an opportunistic fashion and cannot be generated in real time on demand due to orbital and meteorological constraints. It must therefore be stored by the terrestrial component in buffers and exploited when required for secure exchanges by end users. Since some sites can suffer from cloudy conditions over a period of several weeks, the key lifetime must be of at least this order of magnitude.



(1) QKD keys are established between the satellite and a first OGS by means of both a quantum channel and an authenticated classical channel. Both channels employ optical communications and both pass through the OGSs.

(2) The satellite continues on its orbit and establishes further QKD keys with other OGSs. It accumulates keys, storing them in on-board memory.

(3) Once the satellite possesses pairs of local keys it can use the One Time Pad protocol to establish shared key material between two OGSs. This does not require a secure channel.

(4) The space component pushes key material to the terrestrial component as soon as it can be generated. Since key generation requires clear-sky conditions, it is not possible to fulfil requests in real time. Rather, a volume of key is guaranteed to be delivered over a long period. The terrestrial component stores the key in buffers before it is consumed by end users for secure communications

Figure 4-3: OpsCon for a PM QKD satellite system

EB QKD satellite services

The operational concept of an EB QKD satellite service is simpler to illustrate and is shown in Figure 4-4. The entangled photon source is mounted on the satellite, transmitting entangled photons to A and B. Keys can therefore be generated in real time. This obviates the need for delayed key transmission. EB QKD also presents the distinct advantage that the satellite does not need to be “trusted” by the two OGSs. However, EB QKD places some quite severe constraints on the system operations. Firstly, channel losses have a greater impact since both of the entangled photons need to arrive at their destination, so that combination of the two low detection probabilities leads to an extremely low expected SKR. This difficulty is compounded by the fact that two satellite telescopes are required, resulting in smaller apertures due to accommodation reasons, and consequently more divergent beams. Secondly, the satellite must be simultaneously visible to both A and B, placing a limit on their separation unless the satellite occupies a higher orbit at the expense of a lower SKR.

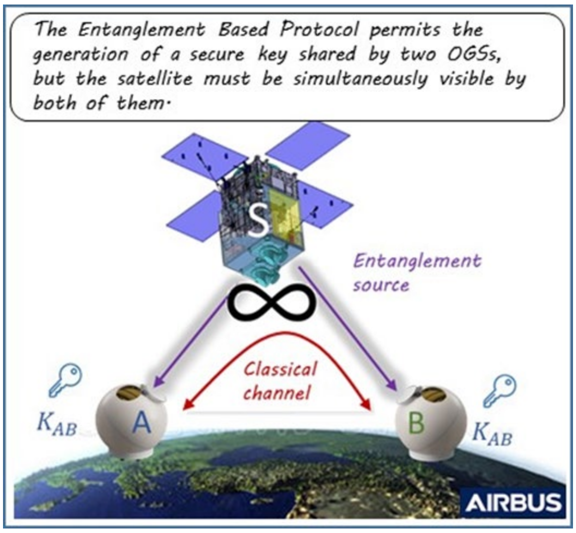


Figure 4-4: OpsCon for an EB QKD-based satellite system

Road to 2035

The following two sections identify some of the main developments required for the near-term (2025–2029) and long-term (2030–2035) horizons.

Near term (2025–2029)

- **Integrated QCI terrestrial and space segment**: A space QKD component is seen as a complementary solution to a terrestrial QKD component. Terrestrial QKD offers a higher SKR but has an inherent range limitation (currently approx. 100 km for practical implementations) due to inherent fibre losses, whereas space QKD offers long-range communications at a lower SKR[81]. Significant system architecture studies have been performed by the major space system integrators, in each case working in the framework of EC/ESA projects and ensuring coherent specifications for both the terrestrial and space components. The overall system forms a QCI.

- **Increase capacity**: In order to provide useful services to multiple end users without becoming a bottleneck in the QCI, the QKD space component must support a high SKR. Two main approaches have been proposed. The first approach is to implement simple low-cost and low-capacity QKD satellites (using compact optical terminals) deployed in very large numbers. However, this approach presents some limitations: it may require the use of "classical" ISLs which compromise security, it cannot serve compact user terminals and it might not be compatible with truly secure, certifiable satellite payloads (comprising crypto boxes, radiated emissions protection, etc.). The second approach is to deploy high-capacity satellites in small numbers. This approach presents the advantage of eliminating the above problems, is compatible with small user terminals and is more coherent with a high-security space programme. However, in order to implement a high-capacity satellite, it is necessary to have not only a high-rate QKD source but also large-diameter space telescope optics, which is technically challenging but greatly assisted by the existence of heritage equipment. A further consequence of the need for high capacity is a preference for LEO systems since, despite some disadvantages, they suffer less path loss and offer far higher system capacities.
- **Use of heritage equipment**: Much of the equipment required for the implementation of high-capacity QKD satellites already exists in the framework of classical optical communications and Earth observation missions. Firstly, optical communications already employ satellite terminals with diameters in the tens of cm. Such larger-diameter terminals have been developed for feeder link applications with geostationary satellites and have a limited scan range. This limitation can be compensated by the use of agile Earth observation satellites. Finally, heritage solutions in the area of synchronisation and data processing can also be employed advantageously for developing the space segment of the QKD system. It is therefore possible to leverage the extensive investment and existing technology but, in each case, some customisation activities will be necessary.
- **Certification of implementations**: Another key topic following the initial demonstrator missions is the need for a certified system, as certification is a necessary condition for a system to be exploitable for government use in national security agency recommendations. The impact of certification is that all definition and development work is required to take place within a security framework such as a Project Security Instruction. This can have significant consequences for working methods and the development infrastructure.
- **Standardisation**: Yet another important topic on the roadmap to the implementation of an exploitable system is the need for standardisation. Initial

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[81] Transmission in a link with length *L* scales as: tfibre=t_0 exp(-α*L*) and tfree-space=β/L^2 (with α and β dimensionless parameters of the channel). For example for *L*=1000 km, typical losses are tfibre=200 dB versus tfree-space=30–40 dB.

activities have already started in the framework of the ETSI, the ITU, and the ISO (see Chapter 8 – Standards). Further work will be required in order to ensure interoperability and security compliance.

- **System issues – end-to-end key delivery**: QKD is inherently a link-level solution, although secure methods do exist for providing network-wide key distribution while preserving the desirable property of ITS. For efficient network management in general and for space QKD in particular, optimised key distribution methods will be needed. For the space component, this includes the tasking of satellites to satisfy inhomogeneous customer key needs in a changeable environment (due to clouds, atmospheric perturbations, and background noise).
- **Simplified user terminals**: Another key topic for the deployment of QKD up to the end user is the need for compact and affordable ground terminals. Achieving this is possible with higher capacity satellites, since a large satellite telescope permits a small ground telescope while preserving a good link budget. Another important enabler for simplified user terminals is the development of low-cost, high-performance, and easy-to-use SPDs. The wish list of properties that such detectors should possess includes large surface areas, to allow efficient telescope coupling without the need for coupling into fibre guiding to a small detector surface.
- **Parallel PM and EB developments**: Studies have been performed to compare the respective merits of PM and EB protocols. The conclusion is that they are in fact complementary approaches. PM offers the higher SKRs required to satisfy user requirements using current technology. EB permits operations with “untrusted” satellites and, importantly, has potential to evolve to provide entanglement distribution for future quantum information networks. It is necessary to pursue the two approaches.
- **Fully operational systems**: The horizon 2025–2029 should see the arrival of fully operational systems and their uptake by users. This is anticipated to take place in both the institutional and the private sectors. The exploitation of these satellite systems is expected to result in the identification of new use cases and potentially new requirements and further evolution.

Long term (2030–2035)

- **Space component within a quantum information network**: The EB geometry shown in Figure 4-4 illustrates how a satellite can be employed as a means of distributing entanglement over large distances, which is one of the key ingredients of a quantum repeater, along with entanglement purification, quantum memories, and entanglement swapping. The optimal mix of space infrastructure and terrestrial infrastructure will depend on terrestrial repeaters, needed to overcome the range limitation and facilitate scaling of practical systems.
- **Alternative implementations**: Future technological improvements will make way for alternative implementations that are currently impossible. The feasibility of concepts such as on-board quantum repeaters, quantum ISLs, MDI QKD for satellites, etc., will need to be reassessed as advances are made. We can also anticipate greater synergy between QComm and the QT missions that will increasingly be embarked on satellites – such as quantum sensors, quantum navigation, and, potentially, QC.

Quantum Randomness Generation

Overview

Random numbers are essential in a broad range of applications, including cryptography, gaming, and Monte Carlo simulations. Random numbers are consumed daily in vast amounts and the inadequate generation of these random numbers may lead to security vulnerabilities, fraud, or performance inefficiencies. For this reason, generating and using randomness properly is fundamental to our digital society. There are two main categories of RNG. The first alternative is to use an algorithm to generate pseudo-random numbers (PRNG). The second alternative is to measure a random physical process to generate truly random numbers (TRNG). Although PRNGs are very easy to deploy in any programmable device, TRNGs are necessary to produce the cryptographic keys that provide security in cryptography applications. Typically, a combination of TRNGs and PRNGs is used in practice, leveraging the security of complex and slow hardware-based TRNGs and the speed and simplicity of software-based PRNGs.

QRNGs are a specific type of TRNG that are based on measuring a quantum physical process. The fundamental advantage of QRNGs is that they leverage one of the most basic features of quantum physics: quantum indeterminacy. This makes them the strongest technical solution to the challenge of producing unpredictable digits. In addition, QRNGs provide other technical advantages such as faster randomness generation rates (tens of Gb per second have been generated with QRNGs) and measurable quality. Paradoxically, the fact that QRNGs can be modelled with an inherently unpredictable quantum process allows QRNG makers to provide very accurate means to assess the quality of these devices. This is not possible with non-quantum TRNGs, and therefore this capability constitutes a strong differentiator for QTs in randomness generation.

Standards and challenges for adoption

In contrast to other QTs, QRNGs can be deployed in fully operational environments using current standards and certification processes. This is because QRNGs can be understood as TRNGs. While there are efforts to develop QRNG-specific standards, and, in fact, an ITU-T recommendation already provides a description of what a quantum entropy source is, the market still follows the TRNG standards NIST SP800-90 (US) and BSI AIS31 (Germany – Bundesamt für Sicherheit in der Informationstechnik). These standards have plenty of similarities, with the main difference being that AIS31 requires a stronger analysis of the properties of the physical system. Both industry and academia are paying more attention to studying the physical dynamics of TRNGs (i.e., trying to understand the question of why a TRNG system is random), reflecting growing awareness of a need to demonstrate the quality and origin of the randomness produced by an RNG.

Among the main challenges for adoption of QRNG technology, we identify the following:

1. **Size**: Current TRNGs can be embedded as an IP core in an ASIC. That means QRNGs must offer a convenient, small, and easily deployable alternative;
2. **Cost**: Due to the fact that TRNGs can typically be licensed within an ASIC design, their cost tends to be low. QRNGs provide technical advantages, but cost scaling is essential to access larger markets;
3. **Performance**: Many emerging quantum-safe protocols, such as QKD, require increasingly high speeds of quantum randomness generation, ranging from hundreds of Mb/s to multiple Gb/s and even tens of Gb/s;
4. **Quantum-specific standards**: The lack of dedicated quantum standards means that QRNG must compete head-on with existing and market-dominant TRNGs. New standards to capture the unique value of inherently unpredictable and measurable randomness sources would accelerate the adoption of QRNGs.

Use cases

- **Random state generation for PM QKD protocols**: QRNGs are used to select the random state to be sent by a PM QKD device. Typically, multiple random bits are required for each state, therefore requiring the QRNG to produce bits at rates 4 to 5 times faster than the QKD device itself.
- **Entropy generation for PQC**: Computational security systems, like those based on conventional cryptography (RSA, etc.), and PQC require lots of random numbers. As the amount of information exchanged increases and as new algorithms emerge that require longer keys, the amount of randomness required also increases. QRNGs can be used together with all types of cryptography, meeting quality and performance requirements. Specific applications range from certificate generation to initialisation vectors or nonces.
- **Decentralised randomness beacons**: Randomness beacons are emerging with multiple applications in gambling, web3, blockchain, zero-knowledge proofs, and cryptography. QRNGs are the ideal cryptographic sources for generating the values to be distributed through these public sources of randomness. Physical noise sources are typically complemented by other software techniques to provide the cryptographic properties required for particular randomness beacons.
- **Online gaming**: Online games, for instance online casinos, require randomness as a fundamental part of the game. It is in the interest of the online gaming companies and their users to ensure that there are no biases or predictability, thus avoiding unfair usage by either the operators or malicious users who can exploit weak randomness to gain competitive advantage and misappropriate other users' money.
- **High-performance simulations**: QRNGs are also starting to be used in Monte Carlo simulations, providing a source of randomness with zero patterns, and eliminating any co-dependency (correlation) risks. Deployment of the technology at scale for this market is a challenge, as there is very strong competition with software techniques.

Road to 2035

Generally, QRNG as technology has already been at TRL 9 for some years, but it must be further developed to increase market share. There are four main aspects of the development and commercialisation of QRNG products, relating to scientific, technological, and industrial capabilities. Specifically:

1. **Smaller and cheaper solutions**, so that QRNGs can be embedded in large-scale deployments and even consumer devices. This requires single-chip solutions that integrate the quantum entropy source technology (e.g., photonics) and the digital and analogue electronics together on a single chip or in another compact form factor. Main KPIs for this initiative are size and cost;
2. **Faster solutions**, so that QRNGs can enable a new class of high-rate quantum-safe solutions, as in QKD. Main KPIs: speed and form factor;
3. **Standardised entropy monitoring**, so that buyers can embed different QRNG devices and monitor their quality using standard interfaces. KPIs: standard and adoption;
4. **Sovereignty of technology (fabrication)**: EU fabrication to produce chip-based QRNG and modules in the EU, facilitating supply to high-security governmental and space markets and ensuring production autonomy.

Immediate future (to 2025)

- Smaller and cheaper solutions: Current technology becomes further industrialised to allow for production costs below € 1 per QRNG chip;
- Faster solutions: Commercially available multi-Gb/s modules widely available for QKD systems and infrastructure (1–10 Gb/s);
- Standardised entropy monitoring: First entropy monitoring standard.

Near term (2025–2029)

- Smaller and cheaper solutions:
  - Integrated photonics technology enables the development of a monolithic QRNG chip solution including readout and post-processing electronics;
  - (from 2028): QRNGs can be implemented as IP core in opto-electronic integrated chips, similar to today's non-quantum TRNGs;
- Faster solutions: Commercially available 10–20 Gb/s modules and space-qualified QRNG modules;
- Standardised entropy monitoring: Entropy monitoring adopted in telecommunications and government industries.

Long term (2030–2035)

- Faster solutions: Commercially available 10 Gb/s chipsets, including streamlined production of integrated chips and modules for high-end applications;
- Standardised entropy monitoring: Entropy monitoring widely adopted in the industry.

Road to 2035

The following is a summary of the “Road to 2035” subsections in this chapter, which should be consulted for more details.

Quantum Communication Networks

Terrestrial Segment

Immediate future (to 2025)

- QKD products are being industrialised, allowing for tens to hundreds of manufactured QKD links per year;
- QKD networks with dozens of QKD links will be built up. Some of them will continue to be operated in test mode, while a few will be used in production;
- QKD network architectures are being demonstrated and will become ready to be validated for governmental use cases;
- Products will enter the market with general-purpose product certification (EU directives, etc.);
- QKD security certification is under preparation: background documents, evaluation methods;
- Adoption of quantum keys and PQC by encryptors operating at OSI layers 1 to 4 begins;
- CV and EB QKD products will reach TRL 9.

Near term (2025–2029)

- MDI and TF QKD products will reach TRL 9;
- QKD networks will reach sizes of hundreds of nodes. Testbeds will be replaced by production networks;
- QKD products will evolve from general-purpose devices to specialised products, ranging from low-cost and low-performance devices for access networks or local private networks to long-range, high-key-rate devices;
- Integration of optical and electronic components will become advanced enough to allow for medium-size production series with volumes of thousands of pairs per year;
- The first QKD products will be certified;
- Quantum keys and PQC will be adopted and/or integrated by apparatus operating at the various OSI layers;
- Quantum internet will start by connecting two quantum computers that are in the same metropolitan area – benefits will be limited, compared to the computational power of the standalone products.

Long term (2030–2035)

- Widespread deployment of QKD and PQC;

- It will be possible to connect quantum computers located in the same region into networks with combined computational power substantially greater than the sum of the individual devices;
- Adoption of entanglement-based communication, together with new QComm services such as the quantum internet, in niche applications (where high costs and limited key rates are acceptable).

Space Segment

Near term (2025–2029)

- **Integrated QCI terrestrial and space segment**: A space QKD component is seen as a complementary solution to a terrestrial QKD component. Terrestrial QKD offers a higher SKR but has an inherent range limitation (currently approx. 100 km for practical implementations) due to inherent fibre losses, whereas space QKD offers long-range communications at a lower SKR. Significant system architecture studies have been performed by the major space system integrators, in each case working in the framework of EC/ESA projects and ensuring coherent specifications for both the terrestrial and space components. The overall system forms a QCI.
- **Increase capacity**: In order to provide useful services to multiple end users without becoming a bottleneck in the QCI, the QKD space component must support a high SKR. Two main approaches have been proposed. The first approach is to implement simple low-cost and low-capacity QKD satellites (using compact optical terminals) deployed in very large numbers. However, this approach presents some limitations: it may require the use of “classical” ISLs which compromise security, it cannot serve compact user terminals and it might not be compatible with truly secure, certifiable satellite payloads (comprising crypto boxes, radiated emissions protection, etc.). The second approach is to deploy high-capacity satellites in small numbers. This approach presents the advantage of eliminating the above problems, is compatible with small user terminals and is more coherent with a high-security space programme. However, in order to implement a high-capacity satellite, it is necessary to have not only a high-rate QKD source but also large-diameter space telescope optics, which is technically challenging but greatly assisted by the existence of heritage equipment. A further consequence of the need for high capacity is a preference for LEO systems since, despite some disadvantages, they suffer less path loss and offer far higher system capacities.
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- **Certification of implementations**: Another key topic following the initial demonstrator missions is the need for a certified system, as certification is a necessary condition for a system to be exploitable for government use in national security agency recommendations. The impact of certification is that all definition and development work is required to take place within a security framework such as a Project Security Instruction. This can have significant consequences for working methods and the development infrastructure.
- **Standardisation**: Yet another important topic on the roadmap to the implementation of an exploitable system is the need for standardisation. Initial activities have already started in the framework of the ETSI, the ITU, and the ISO (see Chapter 8 – Standards). Further work will be required in order to ensure interoperability and security compliance.
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Long term (2030–2035)

- **Space component within a quantum information network**: The EB geometry shown in Figure 4-4 illustrates how a satellite can be employed as a means of distributing entanglement over large distances, which is one of the key ingredients of a quantum repeater, along with entanglement purification, quantum memories, and entanglement swapping. The optimal mix of space infrastructure and terrestrial infrastructure will depend on terrestrial repeaters, needed to overcome the range limitation and facilitate scaling of practical systems.

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Quantum Randomness Generation

Immediate future (to 2025)

- Smaller and cheaper solutions: Current technology becomes further industrialised to allow for production costs below € 1 per QRNG chip;
- Faster solutions: Commercially available multi-Gb/s modules widely available for QKD systems and infrastructure (1–10 Gb/s);
- Standardised entropy monitoring: First entropy monitoring standard.

Near term (2025–2029)

- Smaller and cheaper solutions:
  - Integrated photonics technology enables the development of a monolithic QRNG chip solution including readout and post-processing electronics;
  - (from 2028): QRNGs can be implemented as IP core in opto-electronic integrated chips, similar to today's non-quantum TRNGs;
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- Standardised entropy monitoring: Entropy monitoring adopted in telecommunications and government industries.

Long term (2030–2035)

- Faster solutions: Commercially available 10 Gb/s chipsets, including streamlined production of integrated chips and modules for high-end applications;
- Standardised entropy monitoring: Entropy monitoring widely adopted in the industry.

QuIC Member Activities in Quantum Communication

Many members of QuIC are active in QComm. Here we present a short self-description of some of these members.

Airbus is a world-leading aerospace company with over 134,000 employees worldwide. Our portfolio includes civil and military aircraft (planes, helicopters and unmanned vehicles), space systems and secure communication systems. We are highly active in the three main areas of QT preparing for early adoption for aerospace applications. **QComm**: Lead and participation in major EC and ESA projects (QOSAC, OQTAVO, QUBITS, SAGA PHASE A, PETRUS, FRANCE QCI, etc.). We target being the prime integrator for QKD space systems and a provider of control & management layers and KMSs for terrestrial QCIs. **QC**: Several major QC projects and collaborations with major players. Airbus is preparing QC as an end user and is structuring its applications in four use case families including quantum simulation, quantum optimisation, quantum ML and quantum solvers. Recent activities include the EQUALITY project funded by the Horizon Programme, preparing quantum algorithm workflows for aerospace applications. **Quantum Sensing**: Airbus works on sensor development in several aerospace areas such as quantum-assisted navigation, quantum-enhanced testing, quantum imaging and space applications such as quantum space gravimetry (CARIOQA). Airbus addresses several quantum sensor technologies including NV-centre magnetometers, cold-atom interferometers and Rydberg sensors. Airbus aims to improve products in all its divisions using quantum sensors and to be the prime integrator for space-based quantum sensor missions.

Creotech is a Polish SME with a focus on electronics and systems engineering and manufacturing. Together with partners, it is developing DV QKD hardware and key components as part of EuroQCI. Creotech is also leading a project for the development of a large-area high-rate SPD for QKD ground stations as part of the ESA SAGA programme.

The mission of **Nutshell Quantum-Safe** is to secure Europe’s data in transit with the best QKD. Initiated by ID Quantique, the spinoff is now an independent company controlled by EU citizens. We develop and commercialise QKD systems. We offer service and customer support to maximise the value of QKD for the users. Our R&D team works on security certification of QKD devices, and on further hardware and software development to prepare for large-scale deployment and usage of QKD in Europe and worldwide. We are an enthusiastic team based in Vienna, Austria.

Quside is a QT startup delivering advanced randomness solutions to help customers build stronger cryptographic solutions and more efficient computation capabilities. Quside has multiple products in the market, including QRNG chips and modules, with unique entropy monitoring capabilities, and randomness processing units. The company, which spun off from ICFO in 2017, now has a team of more than 40 professionals and has recently secured Series A investment with leading European deep tech investors. Quside is a member of the Quarter and QSNP[82] consortia, from the EuroQCI and QFlag programmes.

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[82] *“Launch of Quantum Secure Networks Partnership (QSNP),” Quantum Flagship, accessed January 29, 2024, https://qt.eu/news/2023/2023-03-21_launch-of-quantum-secure-networks-partnership-qsnp.*

Tecnobit (Grupo Oesía) has more than 15 years of experience in the field of secure communications, providing services and products such as encryptors and KMSs to different clients. In the field of QComm, Tecnobit is part of two European consortia: Quarter and EuroQCI-Spain. Within Quarter, Tecnobit provides the security metrics needed for the QKD modules and the secure industrialisation of this disruptive technology. EuroQCI-Spain will deploy the QCI in Spain. In the space segment, Tecnobit is a member of the CARAMUEL consortium, which aims to launch the first geostationary QKD satellite.

ThinkQuantum, spinoff of the University of Padua, offers optical and quantum solutions for cybersecurity, such as QKD platforms and QRNG systems for telecommunication networks and in the space domain (satellite payload and OGS). The company covers the full value chain from development and manufacturing to design and commissioning of standard systems and tailored solutions. ThinkQuantum, based in Italy with an Italian shareholder structure, offers a reliable European supply chain. As an EU27 company, eligible according to the most up-to-date Connecting Europe Facility criteria, ThinkQuantum has been granted a variety of projects by the EC and the ESA.

European market overview

Further active QuIC members in QComm are:

Company	**Type**
Adva Network Security	Large
AROBS Polska	SME
AUREA	SME
CryptoNext Security	SME
GMV	Large
ID Quantique	Large
Indra Sistemas	Large
KEEQuant	SME
KETS Quantum Security	SME
LuxQuanta	SME
MPD	SME
Miraex	SME

QphoX	SME
Quant-X	SME
Quantum Delta NL	RTO
Quantum Telecommunications Italy	SME
RedWave Labs	SME
Syndesis	SME
Thales	Large

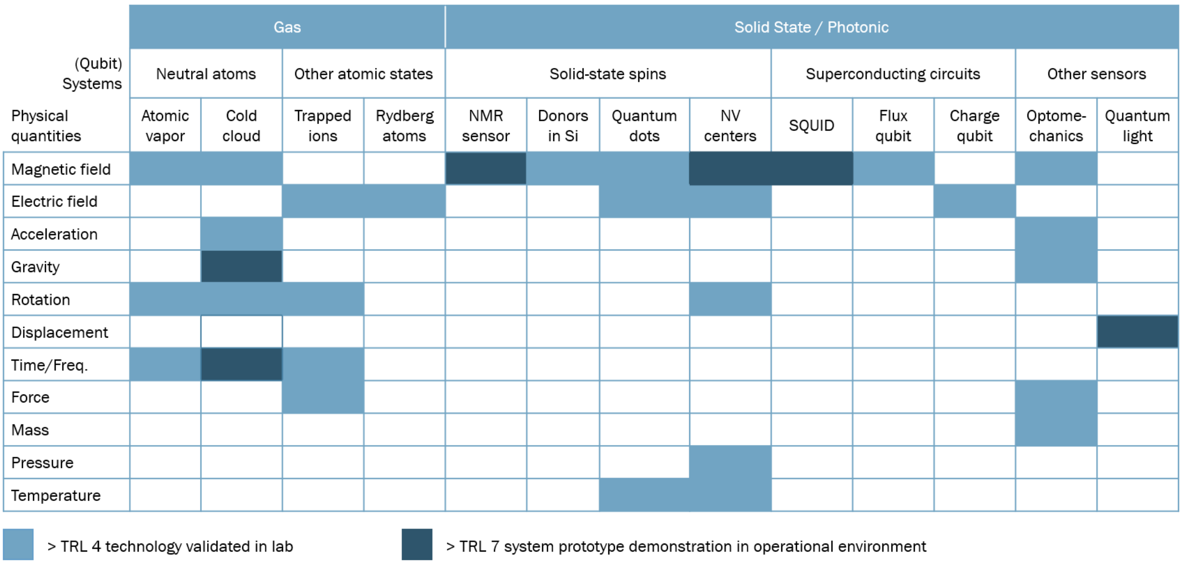
Quantum Sensing and Metrology

General Overview

Quantum sensing and quantum metrology are based on exploiting the quantum properties of nature, quantum phenomena, quantum states, their universality and intrinsic reproducibility, the quantisation of associated physical quantities, or their high sensitivity to environmental changes. Coupling a simple quantum system with an external physical quantity modifies the system’s properties, thereby allowing the measurement of this quantity.

In most cases, quantum sensors use the interference properties of simple quantum systems. In the simplest case, these are qubits, i.e., systems with two basis states. The qubits are initialised in a prepared superposition state and then coupled to the external physical quantity to be measured. The coupling alters the phase of this superposition in a way that can be measured quantitatively. In many cases, these quantum measurements can then be mapped to the value of the external physical quantity, achieving increased absolute and relative accuracy compared to measurements by classical means. There are other possibilities, for instance, relaxometry, where the lifetime of an excited state is decreased by magnetic noise, which gives access to some properties of the sample.

The wide variety of quantum systems used as sensors are typically classified into two main categories: gas and solid-state (see Figure 5-1). All have specific properties and are sensitive to different physical quantities, which make them suitable for particular applications (e.g., cold atoms for gravimetry; defects in diamond or SiC for high-resolution magnetometry). Furthermore, the various platforms and applications have very different TRLs: some products are already commercially available, while other platforms are still at an early stage of development. In this section, we provide an overview of quantum sensor applications. For each, we describe the technology platforms used, the current state of the art, and what developments are expected in the near, medium, and long terms.



	Gas				Solid State / Photonic								
(Qubit) Systems	Neutral atoms		Other atomic states		Solid-state spins				Superconducting circuits			Other sensors	
Physical quantities	Atomic vapor	Cold cloud	Trapped ions	Rydberg atoms	NMR sensor	Donors in Si	Quantum dots	NV centers	SQUID	Flux qubit	Charge qubit	Optome-chanics	Quantum light
Magnetic field	🟦	🟦			⬛	🟦	🟦	⬛	⬛	🟦		🟦	
Electric field			🟦	🟦			🟦	🟦			🟦		
Acceleration		🟦										🟦	
Gravity		⬛										🟦	
Rotation	🟦	🟦	🟦					🟦					
Displacement													⬛
Time/Freq.	🟦	⬛	🟦										
Force			🟦									🟦	
Mass												🟦	
Pressure								🟦					
Temperature							🟦	🟦					

🟦 > TRL 4 technology validated in lab

⬛ > TRL 7 system prototype demonstration in operational environment

Figure 5-1: Overview of the quantum systems currently used for quantum sensing and the quantities they measure, compiled by TNO

The Promise of Quantum Sensors

The primary objective of quantum sensing is to harness the quantum properties of simple quantum systems to improve the sensitivity of sensors, render them more robust, and enable them to reach better SWaP-C characteristics. There are many ways to do so: the simplest option is to exploit the system's coherence, i.e., its ability to oscillate between the two states reversibly. This translates into an increased interaction time and, thus, greater sensitivity. Another option is to move beyond using a single quantum object (or multiple, unrelated instances of such objects) and instead engineer a many-body quantum state designed to detect the quantity of interest with greater precision, accuracy, bandwidth, or some other attribute of merit. This can also be achieved by engineering quantum states (squeezing) to overcome conventional noise limits (standard quantum limits). An example is squeezed light interferometry, which increases sensitivity – for instance, in the observation of gravitational waves (gravitational-wave detector in Germany, GEO600, Laser Interferometer Gravitational-wave Observatory in the US, LIGO).

A further aim of quantum sensing is to offer new capabilities that classical sensors cannot provide. One example is nanoscale magnetic sensing and imaging, enabled by single NV scanning tips or similar single-spin systems. Moreover, depending on the application, this technology can be exploited without the need of cryogenics, vacuums and magnetic shielding. Using quantum sensors can also simplify and improve the conditions relating to the sensor usage, compared with classical sensors. For example, the cold-atom gravimeters make measurements based on physical constants and do not require regular calibration.

In addition, quantum metrology devices, including sensors and measurement standards, are integral to the definition and dissemination of SI units as they provide universal and highly reproducible references for the physical constants defining these units (e.g., the Planck constant, the elementary charge, the unperturbed ground-state hyperfine transition frequency of the ^{133}Cs atom), based on quantum phenomena (quantisation of atomic energy levels (time), QHE (electrical resistance), Josephson effect (electrical voltage)). Prominent examples of these universal and highly reproducible quantum metrology devices are cold-atom clocks, quantum electrical standards based on solid-state quantum phenomena (Josephson effect, QHE) and associated quantum instrumentation (SQUID, etc.).

Advantages of Quantum Sensors

Quantum sensors offer several advantages over their classical counterparts: they have higher sensitivity because they exploit the inherent quantum properties of matter, tuned in such a way as to be extremely sensitive to the targeted environmental characteristic to be measured. However, to exploit this enhanced sensitivity, quantum sensors need to be shielded from potential noise, which corrupts their performance – notably, due to measurement decoherence; this limits the number of oscillations between the two states and, thus, the interaction time with the measured quantity. Some excellent results have already been obtained in this respect. However, there is still room for improvement: for example, by increasing the purity and quality of the host materials for solid-state sensors, optimising the environment for gas sensors (reducing blackbody radiation, residual gas pressure, undesirable electromagnetic fields, mutual interactions, etc.), or enhancing the interactions required for interrogating the quantum system (reducing side-effects, ensuring better control of the interrogating laser pulses, etc.). Solid-state sensors provide stable measurement solutions that are relatively easy to build, integrate, and use due to their spatially confined configurations and the fact that many of them are able to operate at room temperature. Solid-state sensors based on a single spin, such as the NV centres at the end of an atomic-force microscopy tip, provide nanoscale spatial resolution as well as near-zero perturbation of the device they are measuring. Sensors using a set of spins, e.g., NV centres deposited in a layer close to the surface of the diamond crystal, allow for the parallel measurement provided by optical imaging and, consequently, more rapid measurement than scanning sensors. In addition, their rapid response times permit the instantaneous measurement of time-varying quantities. Atomic gas sensors can reach a very high sensitivity by integrating the signals of many atoms at the expense of a spatially confined implementation. They provide measurements based on physical constants. Being self-referenced and immune to drift over time, they have the added advantage of not requiring recalibration. Products that can function autonomously with little or no human intervention, such as atomic clocks and ground-based gravimeters, already exist.

From an industrial perspective, it is necessary to consider the technical performance and the practical aspects of sensing solutions (e.g., SWaP-C, reliability, performance in challenging environments such as mobile or flying platforms with vibrations, noise and temperature variations, and cosmic radiation). For example, the chip-scale atomic clock, although underperforming compared to a lab-scale conventional atomic clock, has more potential applications in the short term due to its ease of integration, low weight, compact form factor, and lower cost than the standard atomic clock systems. SQUID-based sensors made of high-critical-temperature superconductors dramatically reduce the burden of cryogenics and can be packaged in less than 1 litre, with a consumption of just 10 W, opening the door to portable applications for magnetic sensing and imaging. In addition, many quantum techniques offer interesting possibilities for building compact, robust, reliable, integrated sensors at room temperature that have long-term stability.

Products and Services

Use Cases and Trends

Quantum sensing and metrology involve, by far, the broadest set of QT (hardware) domains. Therefore, there are also a large number of possible use cases. First, we provide an overview, and then in the next section, we describe some use cases in more detail.

Biological applications include a range of use cases: detecting metabolic activity and identifying specific metabolites in less than 100 living cells, or nuclear spin detection for characterising molecules in volumes of a few femtolitres using NV-centre techniques (e.g., NVision) as well as free radical production from metabolic activity. Another biological use case is the remote assessment of heart disease in clinical applications (Bosch). Finally, there are several approaches for neurosignals that combine magnetic field sensing with temperature.

RF sensing and processing: Analysis of the electromagnetic spectrum to detect transient signals based on NV centres and rare earth ions. RF spectrum monitoring for instantaneous reallocation of communications frequency bands (cognitive radio) and future 5G deployment. Rydberg atoms in vapour cells offering high broadband sensitivity and polarisation detection capabilities are also currently being studied. SQIFs (Thales) based on high-T_c superconductors are truly wide band (from DC to tens of GHz) and sensitive devices that can be up to 1000 times smaller than classical antennas.

Object detection and ranging for classical LiDAR and radar applications based on high-performance atomic clocks and photonic detection systems. In the long term, entanglement could enable a quantum radar or quantum LiDAR system that is theoretically more robust against spoofing. Current experimental limitations, relating mainly to suitable sources and detection schemes, suggest medium-term applications for close-range surveillance. For LiDAR, using the rapid response of current photonic detection systems (e.g., SPADs and SNSPDs), time-of-flight measurements can be resolved at centimetre scales, with further precision possible using interferometric sensing techniques.

Quantum sensors can be used as a tool for **quantum information** (qubit characterisation). Qnami is developing a scanning NV microscope to analyse quantum materials and superconductors targeted at the QC industry and research activities.

NDT for magnetic materials and generally for materials science is being developed with single NV scanning tips with high spatial resolution or sets of NV centres with parallel measurement. Example use cases include characterising small currents to control microelectronic circuits for the semiconductor industry or automated test equipment based on integrated NV sensors (Qnami, QZabre). Another use case is the measurement of defects (such as cracks, corrosion, loss of material, and fatigue) in metals in the energy and aerospace industries. Indeed, fatigue on alloys has been tracked with NVs and OPMs.

There are a large number of use cases for **high-precision atomic clocks**. High-stability cold-atom microwave clocks have many applications in time and frequency metrology, timescale generation, and synchronisation. Current trends focus on optimising robustness and SWaP-C to promote mobile or long-life applications and operations in demanding environmental conditions (e.g., aerospace) and increasing the fundamental frequency to the optical domain for higher performance. For the latter, a frequency comb allows optical frequencies to be translated into RF signals if relevant to the user.

Many **metrology use cases,** such as chronometric geodesy, the connection of height reference systems on the European scale, and the exploitation of fibre networks for time and frequency dissemination, are possible through the development of high-performance and transportable optical clocks. Optical clocks can provide stable optical frequency references that enable increased data transfer density in fibre networks and may play a key role in the synchronisation of future quantum networks. Furthermore, the availability of accurate timestamps at each network node could render telecommunications or power grid networks less vulnerable to GNSS disruptions. GNSS signals are currently important for synchronising such networks but are susceptible to jamming and spoofing.

In the field of positioning, high-precision atomic clocks and quantum-based gyroscopes or inertial sensors have several applications. Terrestrial navigation is enabled by distributing timing signals with sub-ns accuracy, enabling position determination at cm scale, which is highly desirable for self-driving cars. An optical clock on board a moving platform (e.g., boat, drone, aeroplane, or satellite) could detect spoofed GNSS signals based on their mismatched timestamps. Knowing that the GNSS signals are compromised, the vehicle could switch to alternative navigation modes, e.g., inertial navigation. Optical clocks on board GNSS satellites would improve the waiting time between synchronisation cycles with ground clocks and the accuracy of navigation signals. 3D measurement of the position and orientation of objects in indoor and outdoor applications based on CMOS-integrated control electronics will be enabled by NV-centre magnetometry (Bosch). Determining the position and orientation of autonomous systems such as vehicles, satellites, or drones will be enabled by atomic gyroscopes (Bosch).

Rotational sensing for **seismology**, earthquake engineering and geodesy will also be made possible by transportable optical clocks, inertial sensors with atomic interferometry, and high-performance frequency transfer of optical references. Here, atomic clocks and atomic interferometers can provide complementary measurements of potential differences on larger scales and local gradients.

Gravity surveys, the detection of underground infrastructure or cavities, and the exploration of natural resources in civil engineering, archaeology, geodesy, and hydrology will be enhanced with the development of unmanned ground-based mobile gradiometers. Airborne gravimeters will enable geological-tectonic mapping, geodetic surveys, oceanography, and deposit exploration. Sea-floor gravimeters will facilitate marine gravity surveys, reservoir management, and deposit exploration. The first in-field quantum gravimeters based on atomic interferometry are already commercially available (Exail). Using of QT gravity surveys has excellent potential because of the modular approach and stability/sensitivity, which means such a system can be deployed on land, sea, air and space-based platforms. There will obviously be varying requirements for the systems engineering depending on the deployment modality, but in each case these systems can offer some operational advantage.

Selected Use Cases

The following use cases are a selection of the most economically interesting industry applications across multiple sectors. This list of commercial applications for quantum sensing and metrology is not exhaustive.

Determination of the position and orientation of self-driving vehicles

Description: In some situations where GNSS or visual guidance cannot be used or where accuracy is low (e.g., in a tunnel or narrow streets surrounded by tall buildings), self-driving cars rely on gyroscopes and inertial navigation systems. Several technologies are under consideration. The most advanced system is a gyroscope based on NMR of Xe nuclei and optical spin-exchange pumping via Rb to detect rotation. The high accuracy and drift stability make this a suitable candidate for use in autonomous cars, and a potential alternative to existing gyroscopic technologies (fibre-optic gyroscope, hemispherical resonator gyroscope, micro-electro-mechanical system). Another possible technology is NV centres in diamond coupled to ^{14}N nuclear spin. Significant improvement in the sensitivity has been demonstrated recently, making this technology a foreseeable alternative. Another sector is mining where it is possible to use techniques based on on NMR and magnetic field sensing to guide the drill operator.

QT: Atomic interferometers, NV centres, clocks

Customers: Automotive sector, oil & gas industry

Navigation using Earth's magnetic field

Description: Satellite geopositioning signals such as GPS are not always satisfactory; for instance, there is a risk of signal loss in mountains, underground, or in underwater situations. The terrestrial magnetic field can be a good alternative solution using NV technology. There is potential for a compact and reliable navigation device based on the Earth's magnetic field map. Similarly, vapour cells oriented along the *x*, *y*, and *z* axes, or SQIF sensors could also be possible techniques for monitoring Earth's magnetic field.

QT: NV centres, atomic vapour, SQIFs

Customers: Civil aviation, defence industry, oceanographers, mountain cave explorers

Positioning and navigation in deep space with small atomic clocks

Description: Navigating in space requires Earth-based navigators to relay a signal to the spacecraft and back and very accurate clocks at the Earth station to measure how long the journey took. The Earth station uses this "bounce time" to calculate information about the spacecraft's position, speed, and heading, based upon which the manoeuvres are calculated and sent to the spacecraft. Using this method for a spacecraft near Jupiter would be impractical since the bounce time is about an hour and a half. A solution to this problem is to equip the spacecraft with its own small, trapped-ion atomic clock, send the reference signal from Earth to the spacecraft, and then perform the position, speed, and heading calculations on board, effectively eliminating the need for calculations from the Earth station.

The trapped-ion atomic clock is attractive to the space industry because of its low sensitivity to variations in radiation, temperature, and magnetic fields. Recent advances have also reduced the size and power requirements, making this technology a candidate for deep space navigation or an aid to scientific radio observations.

QT: Optical atomic clocks, trapped ions

Customers: Governmental space agencies

Human brain-machine interface with magnetometers

Description: In the future, there will be new applications for magnetometers based on negatively charged NV centres in diamond, for example, in areas such as the brain-machine interface, as they outperform their classical peers in the sensitivity they achieve. These magnetometers can also detect direct- and alternating-current fields with high sensitivity and cover a high dynamic range. They can record neural activity potentials in the low-frequency range, which has been demonstrated in a controlled laboratory setting (due to the magnetometers' sensitivity to environmental conditions).

Nano-MRI using NV centres in diamond is a new technique to bring the resolution of MRI to the nanometre scale. Nano-MRI can be used for molecular imaging, i.e., the *in-vivo* visualisation of molecular processes at the nanoscale resolution. Given this high resolution, nano-MRI could potentially be used for neuron *in-vivo* imaging. Low-critical-temperature SQUIDs have been used for years in magnetoencephalography and would also be suitable for human-machine interfaces. Low-T_c SQUIDs do, however, suffer from the disadvantage that they have to be cooled to below 4 K. Using high-T_C SQIFs with similar sensitivity but compact cryogenics could solve this issue. In contrast, NV centres operate at room temperature. OPMs based on atomic vapours can achieve higher sensitivity than NV centres at the expense of lower spatial resolution.

QT: Magnetometers based on NV centres, SQUIDs, SQIFS, OPMs

Customers: Healthcare providers

Magnetocardiography

Description: Measurement of the magnetic fields generated by cardiac currents is possible due to a technique known as magnetocardiography.

The basic idea is that the magnitude of a magnetic field (“external field”) is measured by its interaction with the (usually nuclear) magnetic moments of atoms in a vapour cell for OPM or spins in NV centres. The magnetic moments react by performing a Larmor precession. The frequency of this precession is proportional to the magnitude of the external magnetic field and can be measured with resonance techniques. In the case of SQIFs, the sensor is sensitive to the flux that threads the SQIF’s loops.

These techniques allow an in-depth study of the origin and evolution of cardiac abnormalities such as valve flutter, fibrillation, and tachycardia. OPMs are also used for magnetoencephalography. While NV centres in diamond and SQIFs can measure the direction of the magnetic field and its magnitude, OPMs only have access to the magnitude. On the other hand, OPMs and SQIFs typically have a higher sensitivity than NV-centre-based magnetometers.

QT: OPMs, NV centres, SQIFs

Customers: Healthcare providers

Biomedical tests

Description: Functionalised nanodiamonds address several applications in biomedical tests. Excessive free radical production by a cell is the main cause of ageing or transmutation of the cell. NV technology will make it possible to quantify the free radicals and characterise the antioxidant properties of products acting against them. Nanodiamonds are biochemically neutral and stable carriers and are good for biomedical applications. Specific diseases can be detected by means of their associated biomarkers. By attaching specific biomarkers to nanodiamonds by functionalisation and applying a magnetic field to the samples being tested, it is possible to induce the NV centres in nanodiamonds to generate quantifiable fluorescence signals indicating the biomarkers, thereby providing reliable detection of, e.g., viral diseases or cancers. Magnetic nanoparticles can also be functionalised for *in-situ* and *ex-vivo* detection based on clusters of NV centres.

QT: NV centres

Customers: Cosmetics industry, food industry, hospitals, biomedical testing laboratories

Exploration of underground resources with atomic gravimeters

Description: At present, our ability to identify characteristics of the subsoil in underground exploration using classical technology is restricted by the technology's limited range of resolution and depth. Using QT allows us to explore new approaches to this problem.

One such novel technique involves atomic gravimeters based on matter-wave interferometry measurements with a Bose-Einstein condensate of free-falling Rb atoms, coherently partitioned, and brought to interference. Slight changes in the way the atoms fall indicate subsurface density that can be due to cavities, hydrological effects, or the presence of minerals or other resources. This technique allows more precise exploration of underground resources, with use cases such as mineral prospecting, groundwater management, or volcano monitoring.

Another technique is based on transportable optical clocks that can be used to monitor the vertical deformation of surfaces to characterise geological processes (e.g., tectonic deformation, and groundwater depletion). Such processes occur on timescales ranging from hours to years and are consequently difficult to measure with current technologies such as GNSS or interferometric synthetic aperture radar measurements, which are sensitive to atmospheric perturbations.

QT: Atomic gravimeters based on cold-atom or ultra-cold-atom systems, optical clocks

Customers: Mining, geology, defence industry, institutes for volcanology, geodesy, and earth science and earth observation

Measurement and monitoring of Earth's gravitational field

Description: Satellite-based instruments to measure and monitor the static or time-varying components of Earth's gravitational field with higher sensitivity, and spatial resolution using cold-atom interferometers such as accelerometers or gravity gradiometers will make it possible to observe processes that are currently difficult to capture, including the melting of glaciers and changes in the water cycle, which are highly relevant to climate research.

QT: Cold-atom interferometry

Customers: Space agencies, climate research institutes

Automated test equipment based on integrated NV sensors

Description: High-sensitivity and high-resolution instruments are necessary for various industrial process tests. Due to their high spatial resolution, room-temperature operation, and use in vector magnetometry, NV centres open new perspectives for industrial testing for quality assurance – which represents a huge portion of the production cost of various complex mixed-signal ICs. Using NV sensors to measure magnetic field patterns and automatically trace electrical currents in the microchip could potentially help to detect manufacturing defects and thus reduce manufacturing costs.

The high sensitivity and stability of magnetometers using diamonds with NV centres will enable early detection of defects (such as cracks, fatigue, corrosion, loss of material) in metallic materials used in harsh mechanical or pressure and temperature conditions, and will offer safety improvements – for example, in industrial plants for producing energy and in the aerospace industry. These techniques will also significantly reduce the environmental impact compared to the current dye-penetrating solutions. Moreover, OPMs and NVs can trace the fatigue process, for instance loss of plasticity, with the potential of extending the life cycle of the material and optimising recycling processes.

QT: NV centres, OPMs

Customers: Electronics manufacturers, aerospace industry, energy-producing industries (oil & gas, nuclear, etc.)

RF detection

Description: The detection of rapidly changing RF signals, as generated by many modern communications systems, means performing a time-frequency analysis over a very wide bandwidth, ideally several tens of GHz. However, conventional electronics detectors are generally limited to an instantaneous bandwidth of only a few hundred MHz. Several alternative techniques are possible. One is to use NV centres in diamond, applying a controlled magnetic field gradient over the diamond crystal. The Zeeman-split ground state levels ($m = \pm1$) can be tuned with a static magnetic field and brought into resonance with the signal to be detected. In this way, an image of the instantaneous spectrum can be produced. Another possible technique, instead of NV centres, is the use of Rydberg atoms. This technique probes RF signals using a pair of laser beams appropriately tuned relative to atomic states.

Classical RF antennas are limited because their size depends on the wavelength to be detected. This restricts their bandwidth and, for lower frequencies, imposes sizes of tens or hundreds of metres. The SQIF technology makes it possible to break free of this limitation by having a compact, ultra-wide-band (DC to 100 GHz), and ultrasensitive sensor. Rydberg atoms also offer high-sensitivity detection from MHz up to THz, but with a limited instantaneous bandwidth. Other technologies like NV centres or OPMs can be employed with less sensitivity and/or bandwidth.

QT: NV centres, Rydberg atoms, OPMs, SQIFs

Customers: Electronics manufacturers

Road to 2035

In Section 5.3.1, we discuss the industrial roadmap for quantum sensing and metrology over three and six years, using the application categories introduced in Section 5.2.1. In Section 5.3.2, we summarise our findings and lay out the roadmap to 2035.

Quantum Sensors in Industry

Quantum sensors are relevant to almost all areas of industry. There are a considerable number of applications in the **instrumentation** field. Some products intended for materials research have reached TRL 9 and are already available on the market, such as the NV scanning microscopes from Qnami and QZabre. Materials science can also use these products to characterise various types of materials according to the magnetic field they produce. They can operate at low and high temperatures, depending on the application. The WAINMAG-ST magnetometer (based on NV technology) developed by KWAN-TEK[83] has also reached TRL 6. It provides high-sensitivity detection of a strong magnetic field. Other products based on optically active NV centres are in development. Wide-field NV imagers are being developed for various applications in condensed matter and materials science and in the semiconductor industry to monitor defects in microelectronic circuits. These are attracting interest from key industry partners, such as ZEISS and Infineon, and TRL 9 should be achievable within six years. A microscopic NV diamond-sensing platform based on detection via NV centres in various diamond samples is being developed by NVision. It includes a scalable global orchestration software suite and is expected to reach TRL 9 in six years. Derivatives of this initial product for NDT and navigation applications are currently at TRL 5–6. TRL 8 or 9, plus commercialisation, is expected to be reached within three years for all identified use cases.

Atomic gas cells are another promising platform for instrumentation. Miniature atomic magnetometers based on vapour cells are at TRL 4–5. Atomic vapour cells for magnetocardiography have reached TRL 9. Devices developed for magnetoencephalography based on atomic gas cell quantum sensors have also reached TRL 9. A related application is the use of polarised gases for lung imaging. This technique has also reached TRL 9.

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[83] *formerly WAINVAM-E*

There are several applications in **biology**. Platforms based on NV centres for sensing microscopic cell metabolism and for nanoscale spectroscopy are currently being developed by NVision (TRL 3); these are expected to reach TRL 6 in three years. Magnetocardiography sensors for remote monitoring of heart activity for clinical applications are under pre-development at Bosch (TRL 3), expected to reach TRL 7 in three years and to have commercial products on the market in six years. KWAN-TEK has developed an NV-nanodiamond based lateral flow assay solution to detect the presence of pathogens in biological samples (e.g., viral or cancerous substances), with a high sensitivity.

RF sensing and processing is another area of application for quantum sensors. The SQIF, based on high-temperature superconducting materials, is being refined by Thales to produce small RF antennas. These are currently at TRL 3 and should reach TRL 5 in three years and TRL 6 in six years. Instantaneous RF spectrum analysis is an important application for Thales. To this end, two approaches are being investigated: the first is SHB techniques, based on rare earth ion-doped crystals; these have reached TRL 5, and are expected to reach TRL 6 in three years and TRL 7 in six years. The second approach uses NV centres in diamond to measure the incoming RF field and analyse its spectrum directly. The current status is TRL 3, while TRL 5 is expected to be reached in three years and TRL 6 in six years.

Quantum sensors are also useful for **radar applications**. Optical clocks for QT-enabled radar systems are at TRL 4–5 and are expected to reach TRL 5–6 in three years and pass TRL 6 in six years. The use of quantum measurements and/or entanglement for improved SNR in radar is currently at a lower level of development (TRL 1–2), but is expected to reach TRL 3–4 in three years and TRL 4–5 in six years.

Another important application area is **time/frequency measurement and navigation**. In this area, there are many ongoing activities to develop atomic clocks. High-stability microwave clocks based on cold atoms should reach TRL 5 in three years. Based on coherent population trapping using a dual-frequency laser, Cs atomic clocks developed by Thales have reached TRL 3 and are expected to reach TRL 5 in three years and TRL 7 in six years. Other systems based on Rb are already at high TRL. Miniature atomic clocks developed by CSEM are at TRL 6. Transportable Sr-neutral optical clocks should be at TRL 5 in six years. Several laboratories are working on a transportable Yb clock. TOPTICA Photonics is developing transportable single-ion Yb+ optical clocks with a stability factor ten times higher than that of hydrogen masers; these are currently at TRL 3 and should reach TRL 5 in six years. Airbus and the ESA are developing a set of high-performance Cs-H maser space clocks, known as ACES (Atomic Clock Ensemble in Space), scheduled for launch in 2024. The ESA, Airbus, and CSEM are developing an ultra-high-stability optical oscillator for space applications (currently at TRL 6).

Accelerometers and gyroscopes based on atom interferometry are used for navigation applications. Inertial measurement devices based on cold atoms on a chip are being developed. At Thales, these have reached TRL 3 and should reach TRL 4 in three years and TRL 5 in six years. Exail is exploring other approaches based on free-falling cold atoms in a strap-down configuration and should reach TRL 5 within three years.

3D positioning based on NV-centre magnetometry developed by Bosch is at TRL 2 and should reach TRL 4 in three years and TRL 7 in six years. NMR gyroscopes for autonomous vehicles are at TRL 3 and should reach TRL 5 in three years and TRL 8 in six years.

Quantum sensors are also used for **gravimetry** because atoms are sensitive to the gravitational field. Unmanned ground-based mobile gradiometers using cold atoms, airborne gravimeters, and sea-floor gravimeters are all expected to reach TRL 5–8 in three years. Field-operated marine and airborne gravimetry have been demonstrated and are expected to reach TRL 7+ within three years. A first-generation quantum gravimeter developed by Exail is commercially available (TRL 8–9) and used in various applications such as volcano monitoring. Nevertheless, significant R&D still remains to develop next-generation sensors with improved SWaP-C and transportability. Gravimeters will be deployed in networks of several instruments to provide spatially resolved gravity images. For satellite-based applications, experiments conducted on sounding rockets and on the International Space Station have been successful (DLR). Related subsystems are currently under development to reach TRL 5 in three to five years, paving the way for a dedicated exploration mission based on cold-atom interferometry by 2030 to demonstrate improved absolute precision.

Quantum devices are also used in **metrology** for quantum standards and sensors, and it has been possible to disseminate the SI with the highest accuracy since its redefinition in 2018 (LNE). For electrical voltage measurements, commercial products based on Josephson junctions already exist. Electrical resistance standards based on the QHE are currently under development but are generally at a lower TRL (TRL 4) than Josephson devices. For the definition of the SI ampere, a direct combination of QHE and Josephson quantum standards has produced excellent results (LNE). TRL 4 is expected within three years and TRL 8–9 within six years. The SI second (unit of time), which has been the basis of six of the seven SI units since 2018, is determined using the frequency standards mentioned above.

Quantum magnetometers are being developed for NDT of metallic materials with greater potential for sensitivity, reliability, compactness, and ease of use *in situ*. KWAN-TEK is developing an NV magnetometer (currently at TRL 4) and aims to have the first industrial application for metal defect sensing within two years.

Summary

Quantum sensors have many applications in instrumentation, biology, RF detection, processing, detection and telemetry applications, time/frequency measurement and navigation, gravimetry, and metrology. There are three main classes of quantum sensors, based respectively on solid-state physics, on atomic gases and on quantum states of light. In the solid-state category, most platforms based on NV centres in diamond have reached TRL 3, SQIFs are at TRL 5, and SHB techniques are at TRL 5. In the atomic gases category, vapour cell sensors are at TRL 3, cold atoms on a chip are at TRL 4, and cold-atom clocks are at TRL 4–5. Quantum states of light are mostly used in big instruments such as gravitational-wave detectors. Today, there are just a few products that have reached the market, such as ground-based quantum gravimeters (based on cold atoms) and nanometre resolution microscopes (based on NV diamond scanning tips). As the technology progresses due to extensive ongoing R&D work, a wider range of quantum sensors is expected to reach the market within the next few years. The roadmap below represents the objectives for this R&D work, classified into low (1–3), medium (4–6) and high (7–9) TRLs and are described below over short-, medium- and long-term horizons.

Short term (2025–2027)

- Achieve a high TRL for some applications of atomic vapour cells such as magnetocardiography;
- Achieve a medium TRL for solid-state sensors based on NV centres in diamond/SiC, SHB, SQIF, or other techniques to detect magnetic fields, RF fields, etc. Targeted application areas are the medical industry, instrumentation, biology, and RF detection;
- Achieve a medium TRL for atomic clocks (both high-stability microwave clocks and optical clocks) based on cold atoms or atomic vapour cells;
- Achieve a medium TRL for positioning sensors, based on, e.g., cold atoms or NV centres in diamond;
- Achieve a medium TRL for the combination of QHE and Josephson junction standards for metrology;
- Target a medium TRL for improving the SNR in radar using quantum measurements and/or entanglement;
- Target a medium TRL for RF-sensing Rydberg atoms.

Medium term (2028–2029)

- Achieve a high TRL and commercialisation for most of the quantum sensors based on defects in diamond/SiC and atomic vapour cells, for applications in the semiconductor industry, biology, medical diagnostics, etc.;
- Achieve a high TRL for RF sensors and spectrum analysers based on NV centres in diamond, SHB or SQIF;
- Achieve a high TRL for optical atomic clocks;
- Achieve a high TRL for the combination of QHE and Josephson junction standards for metrology;
- Achieve a medium TRL for RF-sensing Rydberg atoms;
- Achieve a medium TRL for transportable optical atomic clocks;
- Achieve a medium TRL for inertial measurement units based on cold-atom systems and for quantum inertial navigation systems for multiple deployment modes (e.g., land/sea/air);
- Achieve a medium TRL for a space gravimetry pathfinder;
- Achieve a medium TRL for improved SNR in radar using quantum measurements and/or entanglement;
- In general, reach the commercialisation of quantum sensors for instrumentation.

Long term (2030–2035)

- Reach large market uptake of all quantum sensors based on solid-state physics and atomic gases. Applications include instrumentation, biology, RF sensing and processing, radar applications, time/frequency measurement and navigation, gravimetry, metrology, etc., where QT can add new functionality and offer higher sensitivity than classical sensors;
- Integration of quantum sensors into larger systems as key elements of the overall system performance, leveraging the added value of these QTs;
- Use of quantum sensors in harsh environments such as space;
- Use of quantum sensors for consumer applications.

Key Messages

- Continue to fund research (EC targets)
  - Support activities that promote industrialisation and the creation of a supply chain for high-end products and mass-market products;
  - Implement the quantum sensing toolbox.
- Incentivise startups to engage with end users to better specify the performance requirements for the technology and identify to what extent the performance level of a given technology is able to meet the requirements;
- Remain aware that components produced in the EU27 have a cost and we should be ready to pay the price
  - Perform a risk assessment of critical technologies, to establish which technologies must be strategically produced in Europe. Evaluate the cost of this strategy and be ready to pay the cost of components that may not be competitive in the global market.
- Incentivise the use of EU27 components, in particular in systems produced for European organisations
  - Coordinate with European manufacturers to discuss regulations that could help them develop their products, particularly for systems produced for European organisations. Such regulations should be applied only if European manufacturers are ready to supply and ensure their products meet standards and requirements. The timing between regulation and production should be carefully analysed. An example of this kind of support is the European Chips Act.
- Strengthen the link between the roadmap for quantum sensing and metrology and the photonics roadmap
  - Ensure coordination of the roadmaps of other initiatives such as Photonics21 to ensure that the relevant enabling technologies are supported coherently by all of them;
  - In the calls to action for EC quantum projects, include a task for coordination with other groups – for example, for the next CSA of QFlag.
- Stimulate private funding from investors;
- Encourage coordination between startups and RTOs or technological facilities to facilitate reaching the market at a lower cost and time.

Enabling Technologies

General Overview

“Enabling technologies” refers to the physical components that are crucial to developing basic quantum applications. The enabling technologies for QTs consist of all necessary ingredients for building the quantum pillars. The quantum pillars comprise classical and quantum components that are used for the creation, maintenance, and manipulation of quantum states. Depending on the QT application (i.e., QC, QComm, sensing or metrology), the relevant enabling technologies take different forms: cryogenics and vacuum environments, control electronics, laser sources, detectors, etc. (see Figure 6-1). Although some of these technologies are also relevant to other fields (e.g., lasers for other industrial processes), some enabling technologies are specifically dedicated to QTs and developed in response to the needs of the quantum industry. However, due to similar requirements across qubit platforms, some enabling technologies, such as control electronics, may be horizontal across QT markets.

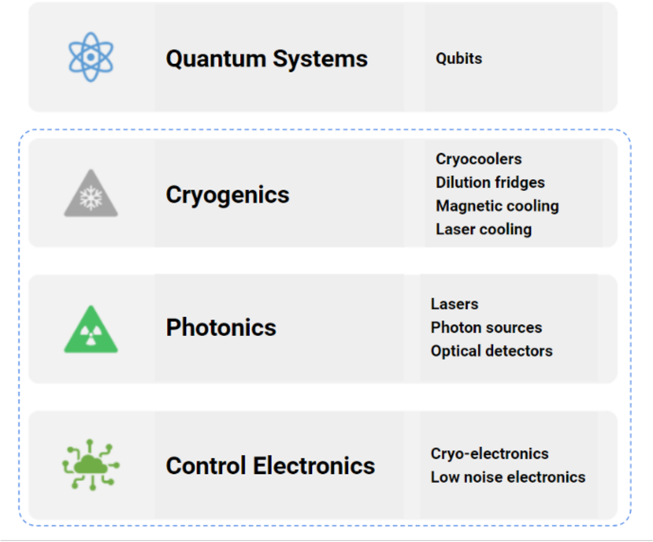

Figure 6-1: Enabling technologies for QTs

Enabling Technology Industry

European companies have a history of being commercially successful key suppliers of enabling technologies for the private and academic environment, dominating the global marketplace for decades in some cases. Europe’s historic strength in such deep tech niches has been built and maintained thanks to the culture of close cooperation between institutional laboratories and the industry, with a highly skilled workforce and interactions with customers on the international market.

Developing enabling technology at the right pace is as crucial as the development of the quantum systems (qubits) themselves if the QTs are to reach the critical point of quantum advantage and produce first use cases that are relevant for the wider industrial sector. R&D work is necessary for quantum systems themselves, of course, but it is also essential for high-end, high-tech enabling technologies. We believe strongly that only by anticipating the rapid and growing demand for components and systems in the quantum supply chain will it be possible to reap the full socio-economic benefit of the second quantum revolution, with the emergence of a robust quantum market and European industrial leaders.

Although the academic world is primarily presently at the forefront of technological innovation breakthroughs, Europe has all the assets to nurture the emergence of world-class industrial players in the quantum supply chains of the future.

Finally, it is important to note that several enabling technologies that are important for QTs are not currently available in Europe. The absence of European supply creates a risk of dependency and thus a vulnerability in the existing supply chain, and might possibly limit Europe's capacity to expand and develop new technologies. These gaps need to be filled for critical enabling technologies in cryogenics, photonics and control electronics. Enabling technologies are an important pillar of the quantum industry value chain and development of these technologies will make a significant contribution to all three main pillars: QC, QComm, sensing and metrology.

In the next sections, we discuss the status of the primary enabling technologies for QT.

Cryogenics

Most QTs need low temperatures and cooling power to operate, as a suitable thermal environment needs to be maintained for electrical equipment and electronics such as detectors, photonic materials, photon sources, optical crystals, and for control and readout of qubits. In the particular cases of solid-state superconducting qubits and CMOS qubits, ultra-deep cryogenics is part of the computer stack structure, maintaining the mK temperatures essential for exploiting the quantum properties of matter, avoiding noise from thermal sources and increasing qubit coherence times. Although cryogenics for quantum states are typically associated first and foremost with cooling, they are also used in advanced setups that feature high-vacuum and mechanically, electromagnetically, and thermally stable environments. Therefore, the choice of the right cryogenic system from the various available technologies, described further in this section, involves considerations beyond temperature and power requirements as some system features such as cycle speed, size and scalability may be crucial to determining the overall effectiveness.

There is a strong EU supply chain for cryogenics with several leading players. However, gaps exist, for instance, some of the critical components and raw materials for cryocooler systems.

We give an overview of the various technologies available to respond to QT needs:

Mechanical cryocoolers for variable temperatures across a broad range and as low as 3 K: this closed-loop technology relies either on a GM cycle, or on a PT.

- In a **GM cycle cryocooler**, the regenerator is displaced, as in a Stirling engine. Essentially, a rotation valve is used to alternate the high/low pressure and cause displacement of the regenerator. This displacement induces vibrations on the cold end, which is a drawback of the machine. Its advantages are its simplicity and flexibility – the cryocooler can be installed in any position relative to gravity. The displacer is equipped with moving seals that must be replaced regularly (approx. every 20,000 h).
- In a **PT cryocooler**, the displacer is replaced by a single open tube acting like a "piston" to allow the gas to flow into the regenerator. Several techniques are available to control the gas displacement. The main advantage of PTs is that they do not have a moving part in the cold end. These machines are known to induce less vibration and be more robust.
- The cryocooler (either PT or GM) needs to be integrated with a compressor and a cryostat, usually customised for a dedicated application.

There are numerous integrators of cryocoolers selling standard cryostats on the market: Oxford Instruments, Lake Shore, Montana Instruments, Cryo Industries of America, ARS, Attocube, Absolut System, Cryomech, MyCryoFirm, and kiutra, to name a few. However, there are only a few companies selling low-power cryocoolers. The market for two-stage GM or PT cryocoolers (either 4 K or 10 K) is dominated by Cryomech (US) and Sumitomo (Japan), with a focus on He recovery systems (He recondensing or liquefaction), cryopumping, and MRI applications.

In Europe, the only existing provider of PT technology for laboratory and on-ground applications is TransMIT in Germany. In England, Oxford Cryosystems produces two-stage GM cryocoolers (10 K) for crystallography and applications in astrophysics instrumentation.

Consequently, developing a Europe-based cryocooler is important for EU autonomy and there is huge potential for building and marketing this cryogenic equipment. The main actors engaged in this field are Absolut System (development and integration of cryocoolers), TransMIT (two-stage PT development at 4 K), Oxford Cryosystems (two-stage GM cryocoolers at 10 K), and Entropy (laboratory cryogenics).

Cryostats based on dilution refrigeration for ultra-deep cryogenics below the 500 mK range and as low as 5 mK.

- This cryostat technology relies on the association of PT mechanical cryocoolers with a dry dilution system of a gas and liquid mixture of two He isotopes: ^{4}He and ^{3}He. The dilution component is adjacent to the piston of the PT cryocoolers – this helps to minimise vibrations, which could otherwise have a negative impact on the qubits.

- The largest dilution refrigerators currently available on the market have limited volumes at mK temperatures, are in the 250–1000 mm diameter cryostat range and offer cooling capacities of approximately 40 µW at 20 mK.
- In some cases, laboratories may instead use ^{3}He cryostats: these have the best cold performance above 10 mK, but require a larger stock of He.

The main market players in the field of dilution refrigeration are Bluefors, Oxford Instruments, CryoConcept, FormFactor, and Leiden Cryogenics.

Scaling up the current technologies in terms of size, cooling power and energy efficiency is a challenge that industry must tackle as the number of physical qubits in the systems grows. Concurrently with engineering progress for QC qubit platforms, the cryogenic system architectures will need to be optimised in terms of temperature and power. Two parallel routes can be taken to overcome the challenges of cryogenic cabling when scaling up dilution refrigerators: firstly, increasing the cold power of the fridges; and secondly, exploring new generations of cabling that would take less space and/or generate less heat.

Cryostats based on magnetic refrigeration: magnetic refrigeration, also referred to as ADR, is a well-established technique that can be used to generate sub-K temperatures by exploiting the magnetic field dependence of the entropy of a spin system. By combining mechanical cryocoolers and ADR, cooling into the sub-K regime (e.g., < 1 K) with moderate cooling power (e.g., 100 µW at 500 mK) and with minimum “one-shot” temperatures of, e.g., 50 mK, can be implemented at scale and without ^{3}He. The technology continues to progress rapidly.

Rapid characterisation of quantum hardware: the above sections describe various cooling technologies mainly in view of their use for the long-term cooling of QTs. Beyond this use case, rapid testing and characterisation of quantum hardware at low temperatures is required for R&D and quality assurance. To facilitate this task and prevent it becoming a bottleneck, some providers (e.g., FormFactor/HPD, Bluefors/Afore, kiutra) have designed cryostats with a focus on high throughput.

Laser cooling of quantum sensors operating at around 100 K is another field where cooling technology is used, to bring the nanoparticles to the low temperatures needed for studying their properties and taking measurements. Due to the prevailing constraints of miniaturisation and zero vibration that apply here, the most relevant technique is typically optical or laser cooling by fluorescence (also known as the anti-Stokes effect).

In the field of **space application**, the development of more compact cryogenic systems is another crucial element for the progress of QTs. Systems requirements include lower optimised electrical power (< 1 kW, including the compressors needed for the cryocoolers), and robustness to harsher environments away from laboratory conditions. The technologies developed for space cryogenics offer good insights into potential building blocks that could be used to develop optimised cryogenics for embedded QTs. The various technologies needed are available in Europe – for example: CEA, Air Liquide, Thales Cryogenics, Absolut System, Honeywell Hymatic, and MSSL (at UCL).

Road to 2035

Near term (2025–2029)

- Scale up size and cold power of cryogenics solutions (cryostats and cryocoolers);
- Interface several cooling technologies to offer a large amount of cooling power at low temperature;
- Improve the electrical efficiency of the cryogenic system;
- Develop compact and optimised cryogenic systems;
- Develop faster and easy-to-use testing solutions for quantum R&D.

Long term (2030–2035)

- Scale up integrated cryogenics architecture and systems for solid-state quantum chips;
- Develop industrial cryogenics architecture for cloud quantum services;
- Reduce heat load resulting from quantum chip wiring for control and readout.

Photonics

Photonics is an important enabling technology for all the pillars of QT: computing, communication, and sensing and metrology. The photon's unique properties make it an ideal candidate as a flying qubit, for manipulation of single quantum states, and as a detectable signal in the interaction with matter.

As enabling technologies, **advanced lasers and photonic circuits** mostly support the development of cold-atom/ion-based QTs.

Advanced photon counters are key for developing and implementing fibre- and space-based QComm, linear optical QC, and quantum imaging. High-performance SPDs, with near-perfect efficiency, low noise, and ultra-high temporal accuracy, will enable the accurate characterisation and development of the quantum internet and QC technologies such as quantum memories, quantum relays, and photonic entanglement sources. Such high-performance detectors will also permit the extension of QComm channels, through improvements to the SNR and multiplexing opportunities. In addition, quasi-ideal detector efficiency will establish the foundation of an expanded repertoire of QComm protocols with strong technical specifications, such as MDI QKD, while photon-number-resolving detectors will enable extended QC schemes based on knowledge of the photonic Fock states used.

Lasers for atom cooling and single-photon or entangled-photon emission will be crucial to almost all future quantum systems, whether for quantum sensing, QC, or QComm.

The main challenge for photonics as enabling technology for the advance and commercialisation of QTs will be the diversity of demands relating to different applications. For example, the target specifications for photonics are very different for tools involving individual atoms (e.g., in trapped-ion QC or in quantum sensing) than when operating at the level of a few photons (e.g., QComm or photonic QC).

Many of the tools of QT are based on photonics. Confocal laser scanning microscopes to study optically active qubits are under development and should reach TRL 9 in six years. A microcavity scanning platform and microscope based on an optical-sensor scanning array is currently under development. It uses enhanced light-matter interactions inside an optical microresonator and is expected to reach TRL 7 in three years.

Finally, we note that in photonics, some critical components cannot be sourced in Europe (e.g., nonlinear crystal to build single-pass frequency converters), which creates a risk of dependency and thus a vulnerability for the existing strong European laser industry.

Lasers

Lasers have been used in material processing, medicine, spectroscopy, satellite laser ranging, and many more applications for the past six decades. More recently, they have become crucial to QC experiments using cold atoms and ions; QComm and QKD; and in quantum sensing experiments. Two decades after the invention of the laser, research groups were making use of this technology for laser cooling experiments, initially on biological cells, but also on atoms and ions, which paved the way for trapping and manipulation of single atoms and ions – a technique that is now making the transition from the laboratory into commercialisation.

A promising candidate for QC and quantum simulation is the use of **cold neutral atoms** or **charged ions**. Ions are typically trapped in electromagnetic traps – these use a rapidly varying electrical field to trap single ions or groups of ions in a crystal configuration. To achieve this, the ions need to be cooled using sympathetic cooling or produced within the trap by laser ionisation followed by laser cooling: this first slows the ions so that they do not escape from the trap due to their own motion and then cools them to the motional ground state of the trap. The process requires frequency-agile narrow-band ultrastable CW lasers in the UV, visible, and infrared ranges, at specific frequencies determined by the atomic transitions in the ion. Typically, other narrow transitions need to be controlled with lasers simultaneously, including repumping transitions and sub-Hz level clock transitions. Neutral atoms can be trapped in arrays using optical lattices or optical tweezers produced by high-power narrow-band lasers with extremely good intensity noise. For these atoms to be used as qubits, they require lasers for gate operations, including laser cooling, repumping, state transition, clock transitions, lattice lasers, and sometimes Rydberg transition lasers. The CW lasers need to meet a whole set of criteria including high stability, high robustness, frequencies ranging from the UV into the infrared ranges, and narrow linewidth.

To achieve the SWaP-C requirements, semiconductor-based solutions and higher integration will be necessary. However, small volume production in mainly academic or institutional fabrication plants remains a challenge. High-power, narrow-band, phase- or intensity-stable solid-state or dual-frequency fibre lasers are at TRL 3 and should reach TRL 7 in three years and TRL 9 in six years. Integrated laser systems (cooling laser, lattice laser, low noise electronics) are at TRL 2 and are expected to reach TRL 6 in three years and TRL 9 in six years. Clock lasers (narrow linewidth (Hz) lasers coupled to an ultrastable optical cavity) should reach TRL 9 in six years. Stabilised lasers for atomic cells, optical frequency combs, and optical cavities are at TRL 5–6 and may reach TRL 9 within three years.

Typical sources include external cavity diode lasers (e.g., TOPTICA Photonics, MOGLabs, Sacher Lasertechnik), solid-state lasers (M Squared, Sirah, Coherent, etc.), and customised fibre lasers (e.g., NKT Photonics). One of the main challenges is the stabilisation of these lasers – sometimes to the Hz level at carrier frequencies of hundreds of THz. The technique of optical cavity stabilisation has moved from the laboratory into a commercial product (e.g., Menlo Systems, TOPTICA Photonics) and is a crucial component in neutral-atom-based quantum computers as well as optical atomic clocks ("quantum clocks"). Many lasers can also be referenced to optical frequency combs (e.g., Menlo Systems, TOPTICA Photonics), thus benefiting from both the narrow linewidth and the absolute stability of these combs. Optical frequency combs have also been used as the "clockwork" in optical atomic clocks over the last twenty years allowing stability transfer to the 10^{-21} level. Atomic clocks themselves are being used worldwide in quantum metrology and sensing and have the highest accuracy of any clock (or any measurable physical quantity), on the 10^{-18} level.

Both CW and pulsed lasers are used for **QComm applications**, both for generation of entangled states (e.g., in parametric down-conversion) and as flying qubits (e.g., for entanglement distribution between spatially separated trapped atoms). This technology paves the way for long-distance QComm and QKD via fibre-optic networks or satellite. The most important challenge in this field is the quantum entanglement of different spectral bands determined by the QComm or QKD approach with telecom wavelengths for long-distance transfer.

For **space applications**, it may be necessary to research and develop lasers customised specifically for use in the harsh space environment (temperature, shock, vibration, and radiation) and longer lifetimes.

Single-Photon Sources

Single-photon sources are essential components for QComm (notably DV QKD), some types of photonic QC, and future quantum internet infrastructures. Some of the approaches used to generate single photons may also be used to generate pairs of entangled photons, which are needed for quantum LiDAR and EB QKD, as well as emerging techniques in quantum-enhanced microscopy and spectroscopy. The ideal single-photon source has the following properties:

- Deterministic: consistently emits a photon in a controlled manner “on demand” at a time arbitrarily chosen by the user (unlike probabilistic sources, which emit randomly and may not emit any photons for the majority of trials). A truly deterministic single-photon source would enable significant advances in photonic QC;
- Indistinguishable: each emitted photon is high purity and indistinguishable from the others; they have the same frequency and there are well-defined states in spatial, temporal, and spectral modes;
- Low probability of multi-photon emission: ideally, the probability of emitting a discrete single photon is 100%, with 0% probability of multi-photon emission;
- High repetition rate/brightness: emission rates are very fast – i.e., many single photons can be produced per unit time;
- Ability to generate entangled pairs: some applications (e.g., EB QKD) require the production of entangled photons;
- Integrated: on-chip integration of single-photon sources would be highly desirable for integrated photonics.

Optical Detectors

Optical detectors are core elements of many QComm, QC, and quantum internet technologies. There are two different types:

High-performance SPDs are fundamental to a great deal of QCI and quantum internet infrastructure technology, such as quantum relays and quantum repeaters, and are also enablers for a wider variety of QKD schemes, such as MDI QKD. Photonic QC also relies on highly efficient SPDs.

Single-photon counters for QComm, QC, gas detection, and LiDAR already exist commercially, with current wavelength ranges of 350–900 nm for Si-based APDs, 900 nm–1.7 µm for InGaAs APDs, and 700 nm–2 µm for SNSPDs.

To support future free-space and space-based QComm, this operational range should be extended to 300 nm. SNSPDs (visible, near-infrared, telecommunications, and UV wavelengths) are already commercially available at TRL 9, with detection efficiency < 95%, time resolution of 30 ps or better, and excellent noise performance (dark counts < 1 cps for visible detection, < 100 cps for infrared detection). The main players in Europe are Single Quantum, AUREA, MPD, and ID Quantique.

Integrated Photonics

PICs are a key enabling technology for future commercialisation and exploitation of QTs. The objective is to use them to miniaturise photonic systems and improve the SWaP-C on optical systems, while guaranteeing compatibility with the fabrication processes used in the semiconductor industry (or very similar processes). Extension of the operational wavelength ranges towards visible and UV would enable PICs to be used for QTs based on neutral atoms, ions, spins and NV centres. Furthermore, PICs offer an intrinsic stability and robustness, due to their monolithic integration of photonic components.

To date, foundries are commercialising various platforms such as Si on-insulator, SiN, $LiNbO_3$ on-insulator, AlO, InP.

The primary challenge faced by many QTs using photonics is the optical losses resulting from the use of PICs and the maximum input optical power. Among other things, these losses can limit the useful system size for quantum photonic circuits or the quality of integrated laser sources.

Fibres

A new generation of fibres will be the key to successful realisation of several quantum applications. Progress on fibre amplifiers is relevant for amplifying optical frequencies that match the transition and trapping frequencies of atoms used in quantum computers, or for sensing applications.

It is crucial for Europe to develop its own, fully vertical, supply chain for these fibres, covering the full process from glass synthesis and preform production to drawing of rare-earth-doped fibres, together with fibre characterisation and fibre post-processing. Work to date has mainly focused on Yb in its ionic form Yb3+, in response to the growing need for an average power of 1 µm for many industrial, scientific, and medical applications. The development of less conventional doped or co-doped fibres (Nd, Tm, Tm-Ho, Er, Bi, etc.) will open up possibilities for amplifiers able to amplify directly at frequencies relevant to quantum applications, in combination with ad-hoc frequency converters. Expertise in fibre microstructuring (distributed filtering) to privilege unconventional wavelength laser emission will help expand the spectral agility: an example here is fibre doped with Nd – this spontaneously emits at wavelengths of around 1060 nm as conventional fibre and is able to emit intense 922 nm frequencies when suitably microstructured. It can then be frequency-doubled to 461 nm and used for laser cooling of Sr atoms.

There is one emerging class of fibre that is expected to play a central role in the quantum systems of the future. HCPCFs, made of a hollow air core embedded in a photonic crystal lattice, enable enhanced light/matter interaction over theoretically unlimited distances (fibre lengths), and are likely to emerge as a disruptive innovation in the context of the ongoing quantum photonics revolution.

Indeed, this interaction between quantum objects (photons, atoms, ions, and molecules) has already been exploited in a new class of HCPCF-based photonics objects that will boost the QT supply chain at several steps. Examples include miniaturised microwave clocks based on Rb- or Cs-atom-filled HCPCFs, and Rb-filled HCPCFs for quantum memories.

Road to 2035

Near term (2025–2029)

Lasers

- Rack-mounted lasers reaching frequencies from the UV to the infrared ranges;
- Analysis and optimisation of critical parameters such as stability and phase noise in different laser types;
- Towards higher TRL for CW lasers, pulsed lasers, cavity stabilisation, frequency combs.

Single-photon sources

- Improve performance of SPDs.

Advanced optical detectors

- Fix the final efficiency gap to reach > 99%-efficiency detectors at 1550 nm. For most quantum applications, it is critical to have SPDs with the highest efficiency;
- Optimisation for different wavelengths (since some quantum applications need different wavelengths, such as QC solutions requiring 900 nm or 600 nm);
- Increase detector size for space QKD, since the smallest spot size is in the order of 500 µm when coupled to a telescope.

Integrated photonics

- Set up medium-scale production facilities to improve chip fabrication;
- Develop improved cryogenic-compatible photonic packaging for large-scale PICs;
- Reduce overall losses (coupling losses and on-chip losses);
- Achieve photonic integration of large-scale advanced detectors (such as SNSPDs);
- Commercialisation of integrated building blocks for standard wavelengths of ionic and atomic interactions;
- Scalable on-chip sources for single-photon generation and squeezed states of light;
- Development of low-loss optical modulators and switches (< 0.1 dB/element, 1–10 GHz).

Long term (2030–2035)

Lasers

- Continue development owards optical frequency synthesis on demand;
- Higher-power, low-phase-noise lasers with high mean time between failures at all frequencies;
- Miniaturisation of lasers, cavity-stabilised lasers, and optical frequency combs.

Single-photon sources

- Improve miniaturisation.

Advanced optical detectors

- Real photon-number-resolving detectors;
- Count rate in the tens of GHz;
- Ultralow time jitter.

Integrated photonics

- Integration of fabrication processes in high-end foundries;
- Establish assembly lines for cryogenic packaging of PICs.

Control Electronics

Control electronics is a **fundamental building block for all QTs**. As quantum systems scale up, with the transition from NISQ to fault-tolerant architectures, an increasing number of programs and control signals need to be distributed to an increasing number of control channels. This makes the quantum control stack of critical importance, as this is the central hub between the user and the qubits, between nodes in a quantum network and between quantum computers and classical HPC supercomputers.

The variety of use cases requires a **versatile control-system** architecture to support a multitude of experimental conditions. The electronics drives the preparation, manipulation, detection, readout (measurement) of the quantum states achieved in different system architectures. On top of that, it is responsible for the communication of information from one part or module of the control stack to another. This information may consist of measurement outcomes for conditional feedback and QEC, time and entanglement generation measurements in a quantum network, as well as measurements and instructions into the feedback loop of hybrid algorithms and HPC computation.

The centrality in the stack and the similarity of requirements across qubit modalities makes the current control electronics **horizontal** in the market and in the technology. Development in one area of QT (QC, QComm, sensing and metrology) and qubit modality can rapidly spread to other areas. Control electronics depends on parameters such as speed, low noise, and operating bandwidth that are relatively specific to the application and quantum system. Frequencies for the electronics range from DC to tens of GHz and beyond, encompassing many of the different qubit modalities. For example, both superconducting qubits and spin qubits require few-GHz control and DC biasing. Even when optical components and lasers are needed, for example for colour-centre qubits, there is still a need for modulation by a few hundred MHz, falling into the supported range of many control systems.

Low noise is one of the key attributes for control electronics and requires particular attention. The control signal phase noise, 1/f noise and detection electronics input noise may directly influence qubit fidelities. The high-performance characteristics of individual qubit control and readout lines represent one of the key cost drivers for electronics development and adoption; hence, it is essential to explore novel approaches to operation that will facilitate an economical scale-up of quantum devices. As fidelity and performance continue to improve, the demands on control electronics technology will become steadily higher. In the specific case of quantum sensors, which were covered in Section 5.1, the key to optimising the performance is low-noise electronics. Notably, Thales has had considerable success with low-noise RF electronics; these include antennas for NV centres, cold atoms, and SQIF-based devices.

Room-temperature Control Electronics

The focus to date for private sector developers, manufacturers, and suppliers (e.g., Qblox, Zurich Instruments, Creotech) has been on developing (mainly FPGA-based) electronics operating at room temperature. This means that current commercially available solutions operate outside the immediate qubit environment. This makes it possible to leverage high-TRL technologies developed over decades to build a control stack that is highly flexible and effective for the qubit counts foreseeable for the next few years.

It is thus important that FPGA boards and RF sources are strategically available and accessible for building the blocks of the QT stack. FPGAs are a technology available from the US, but there is no supplier in the EU. The key components of an FPGA are transistor chips, which are also not available within Europe. Current chip technology from the biggest US supplier Xilinx uses 16 nm transistor technology and has 35 billion transistors.

The currently available control solutions are typically **modular**, **highly flexible** and **scalable** on the order of 100+ qubits. Support for HPC integration and for FTQC is advancing. In particular, there has been fast progress towards realtime decoding for FTQC (e.g., Qblox, Riverlane). To go beyond 100–1000 qubits, higher density control with an increasing number of channels per unit volume will be needed. This will be made possible by the ongoing progress on RF components and control chips. Furthermore, to support error correction involving large numbers of qubits, more efficient communication feedback loops will be required between qubit readout and control system response, especially in the hardware layer of the stack but also in software.

Moving towards scales of several thousand qubits, dedicated ASIC solutions will be required. This development will depend on the underlying economy of scale that is expected to emerge as the size of quantum computer chips increases. Increasing the level of integration through ASIC solutions and multiplexing must also happen in tandem with optimised and smarter signal management, matching or improving the state of the art based on non-ASIC solutions and consistently with evolving QPU architectures – e.g., interconnected or segmented chips.

Cryoelectronics

The current approach, in which all control electronics are configured to room temperature, will eventually need revisiting, and there are several proposals for ways to move forward.

The path to large-scale systems can be broken down into various steps: cooling the part of the electronics close to the quantum chip to low temperatures requires the development of cryoelectronics; better control efficiency could be achieved by frequency-multiplexed qubit control and readout, and this could result in the development of dedicated ASIC control chips that would drastically improve the performance of control electronics.

At least one European company (Equal1) and several research groups (TU Delft, EPFL Lausanne) have developed control electronics operating at between 3 K and 4 K, and there are publications on electronic circuits operating at 100 mK. These developments pave the way for further integration and systems that can control thousands of qubits.

For several qubit platforms, especially those based on trapped ions and cold atoms, integration of both control electronics and optical components (for light transmission and detection) with the qubit environment is crucial for further progress. Achieving this requires further improvement of the quality of waveguides for a broad range of frequencies, improvements to the efficiency of APDs or SNSPDs for wavelengths corresponding to the relevant transitions in atoms and ions, and integration of these optoelectronic components into the semiconductor stack of the QPU.

Road to 2035

Near term (2025–2029)

- Progress on control electronics compatible with scaling up quantum systems to 1000+ qubits;
- Higher density of control channels;
- Improve noise performance of electronic devices that control and readout quantum states, alongside progress on qubit lifetimes;
- Integrate with quantum networks, as well as HPC resources;
- Increase TRL of ambient electronics that will reduce the complexity of control electronics and energy consumption:
    - Low temperatures;
    - Integrated cryoelectronics in close proximity to qubits.

Long term (2030–2035)

- Develop electronics for several thousand qubits:
    - Room temperature;
    - Cryogenic temperature;
- Develop ASICs for dedicated quantum control;
- Scale up support for feedback operations and realtime QEC.

Road to 2035

The following is a summary of the “Road to 2035” subsections in this chapter, which should be consulted for more details.

Cryogenics

Near term (2025–2029)

- Scale up size and cold power of cryogenics solutions (cryostats and cryocoolers);
- Interface several cooling technologies to offer a large amount of cooling power at low temperature;
- Improve the electrical efficiency of the cryogenic system;
- Develop compact and optimised cryogenic systems;
- Develop faster and easy-to-use testing solutions for quantum R&D.

Long term (2030–2035)

- Scale up integrated cryogenics architecture and systems for solid-state quantum chips;
- Develop industrial cryogenics architecture for cloud quantum services;
- Reduce heat load resulting from quantum chip wiring for control and readout.

Photonics

Near term (2025–2029)

Lasers

- Rack-mounted lasers reaching frequencies from the UV to the infrared ranges;
- Analysis and optimisation of critical parameters such as stability and phase noise in different laser types;
- Towards higher TRL for CW lasers, pulsed lasers, cavity stabilisation, frequency combs.

Single-photon sources

- Improve performance of SPDs.

Advanced optical detectors

- Fix the final efficiency gap to reach > 99%-efficiency detectors at 1550 nm. For most quantum applications, it is critical to have SPDs with the highest efficiency;
- Optimisation for different wavelengths (since some quantum applications need different wavelengths, such as QC solutions requiring 900 nm or 600 nm);
- Increase detector size for space QKD, since the smallest spot size is in the order of 500 µm when coupled to a telescope.

Integrated photonics

- Set up medium-scale production facilities to improve chip fabrication;
- Develop improved cryogenic-compatible photonic packaging for large-scale PICs;
- Reduce overall losses (coupling losses and on-chip losses);
- Achieve photonic integration of large-scale advanced detectors (such as SNSPDs);
- Commercialisation of integrated building blocks for standard wavelengths of ionic and atomic interactions;
- Scalable on-chip sources for single-photon generation and squeezed states of light;
- Development of low-loss optical modulators and switches (< 0.1 dB/element, 1–10 GHz).

Long term (2030–2035)

Lasers

- Continue development owards optical frequency synthesis on demand;
- Higher-power, low-phase-noise lasers with high mean time between failures at all frequencies;
- Miniaturisation of lasers, cavity-stabilised lasers, and optical frequency combs.

Single-photon sources

- Improve miniaturisation.

Advanced optical detectors

- Real photon-number-resolving detectors;
- Count rate in the tens of GHz;
- Ultralow time jitter.

Integrated photonics

- Integration of fabrication processes in high-end foundries;
- Establish assembly lines for cryogenic packaging of PICs.

Control Electronics

Near term (2025–2029)

- Progress on control electronics compatible with scaling up quantum systems to 1000+ qubits;
- Higher density of control channels;
- Improve noise performance of electronic devices that control and readout quantum states, alongside progress on qubit lifetimes;
- Integrate with quantum networks, as well as HPC resources;
- Increase TRL of ambient electronics that will reduce the complexity of control electronics and energy consumption:
  - Low temperatures;
  - Integrated cryoelectronics in close proximity to qubits.

Long term (2030–2035)

- Develop electronics for several thousand qubits:
  - Room temperature;
  - Cryogenic temperature;
- Develop ASICs for dedicated quantum control;
- Scale up support for feedback operations and realtime QEC.

Key Messages

R&D work is essential for high-end, high-tech enabling technologies, in anticipation of rapid and growing demand for components and systems in the quantum supply chain. Enabling technologies (cryogenics, photonics and control electronics) are an important pillar of the quantum industry value chain and development of these technologies will make a significant contribution to all three main pillars: QC, QComm, sensing and metrology.

Several enabling technologies that are important for QTs are not currently available in Europe. The absence of European supply creates a risk of dependency and thus a vulnerability in the existing supply chain, and might possibly limit Europe's capacity to expand and develop new technologies. These gaps need to be filled for critical enabling technologies in cryogenics, photonics and control electronics.

Europe has all the assets to nurture the emergence of world-class industrial players in the quantum supply chains of the future.

Workforce Development

General Overview

A fundamental understanding of quantum-mechanical phenomena is transformative for the way we think about and approach the applications of QT in computation, communication, and sensing. This requires new subject matter to be incorporated in educational and training programmes. New talent needs to be trained to meet the challenges that will arise with the adoption of these technologies. Attention must also be paid to diversity within the workforce. In addition, new programmes should go beyond the schoolroom or university lecture theatre to include vocational training. Due to the complex and interdisciplinary nature of QTs, training should involve a multidisciplinary skill set, essential to mastering the future challenges of the second quantum revolution.

In recent years, there has been a boom in QT startups across the globe. This means there is a burgeoning job market in search of talent. What does this market look like? We can review both current demand and the expected growth over the coming decades, assessing the question of whether there is or will be an adequate talent pool to meet the needs of the expanding quantum industry.

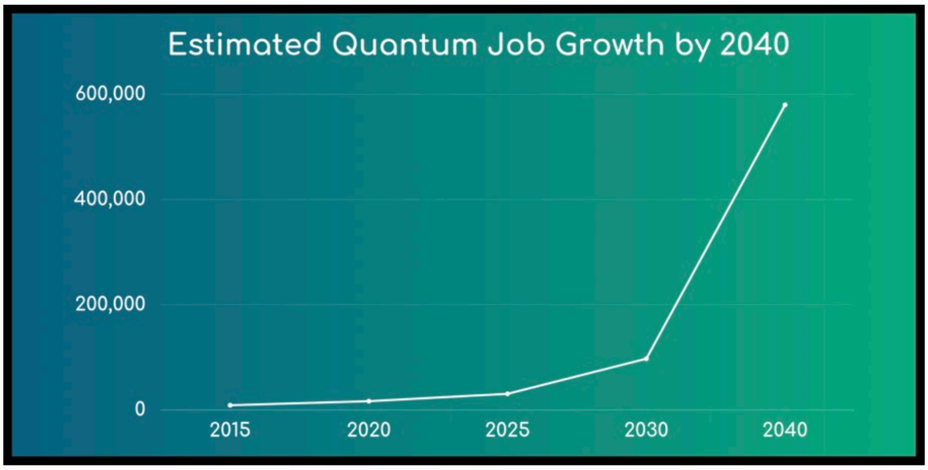

Figure 7-1: Global quantum workforce forecast[84]

For the present day, a talent shortage has already been identified. One way to resolve this could be to upskill professionals who already have quantum competences. This solution will be discussed in more detail in Section 7.4. There are also several

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[84] *Araceli Venegas-Gomez, "The Quantum Ecosystem and Its Future Workforce: A Journey through the Funding, the Hype, the Opportunities, and the Risks Related to the Emerging Field of Quantum Technologies,"* PhotonicsViews *17, no. 6 (December 2020): 34–38, https://doi.org/10.1002/phvs.202000044.*

educational programmes already in place with a focus on QTs, mainly postgraduate master's programmes; these are discussed in Section 7.3.

The gap between the talent pool and demand from the job market is expected to widen considerably over the long term[85]. Closing this gap will require engagement on both sides of the coin: on the one hand, educational programmes at school and university level to introduce QTs and quantum concepts to the students who will become tomorrow's workforce; on the other hand, preparing industry for this future workforce. Combining these aspects allows us to define a long-term strategy – and following this strategy is crucial if the world is to be ready for this emerging technology.

We can break down the overall strategy into two main phases:

1. The short term: reskilling the existing workforce and talent;
2. The long term: developing and adapting educational programmes and raising the profile of QT through the academic world.

Earlier chapters have discussed industry use cases in the areas of materials science, engineering and design, and manufacturing and logistics, with topics including optimisation, ML, simulation, and cryptography as domains where QT will be important. The following fields (not an exhaustive list) are now considered critical elements of a QT education:

- Theoretical and applied computer science (e.g., complexity theory, operations research);
- The basics of quantum information (e.g., the basics of QC operation and control, error mitigation, quantum algorithms, quantum SDKs, evaluation of application-relevant hardware features);
- Experimental quantum science;
- Electronics and laser engineering;
- Photonics technologies and optical communication;
- Business skills (e.g., identification of customer needs, familiarity with production and operational processes, understanding the customer's business and technical limitations).

Both industry and academia need to develop new interdisciplinary educational programmes at the intersection of physics, engineering, computing, and business, at all levels from undergraduate to postgraduate and professional, and at the same time begin to integrate quantum physics into existing educational programmes. It is vital to prepare a workforce who can combine low-level quantum knowledge with expertise in industry.

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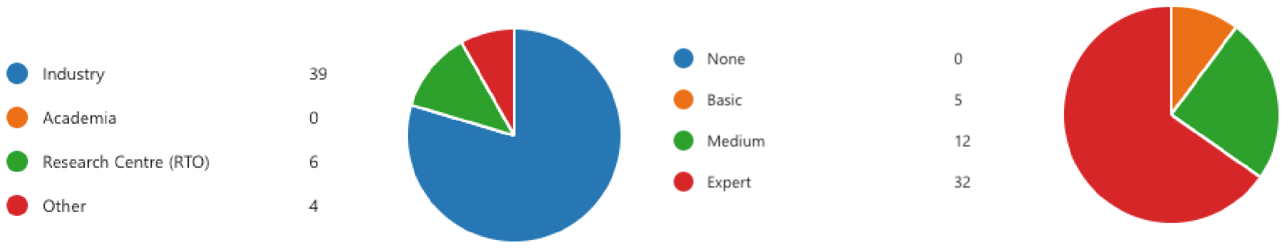
[85] *Venegas-Gomez.*

Recent research[86] indicates that the list of roles for the quantum industry is expected to remain fairly consistent for the next five years, through all disciplines. The Education WG at QuIC conducted a survey of QuIC members to gather information regarding education and skills in QTs, considering both current and future perspectives. The main result of this showed that the needs in quantum span a broad remit of skills and educational requirements. There were 49 responses to the survey. Additional interviews were also held to build up a more fine-grained picture of how end users and other companies in the European quantum ecosystem are being educated in this field and help to understand the present and future hiring situation.

A selection of the survey results is shown in Figure 7-3, Figure 7-4, and Figure 7-5 below.



QuIC Survey: profile of respondents

QuIC Survey: respondents' quantum expertise

Figure 7-2: Profile and quantum expertise of the QuIC survey respondents

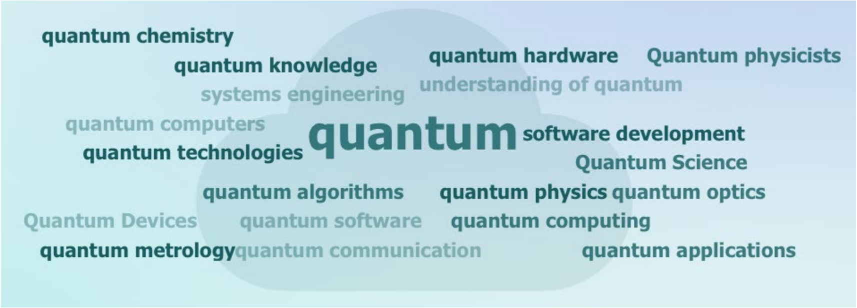


Figure 7-3: Answers to the survey question: “What are the skills/competences you need in your institution/company regarding quantum technologies?”

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[86] *Maninder, “Overview of Quantum Initiatives Worldwide 2023.”*

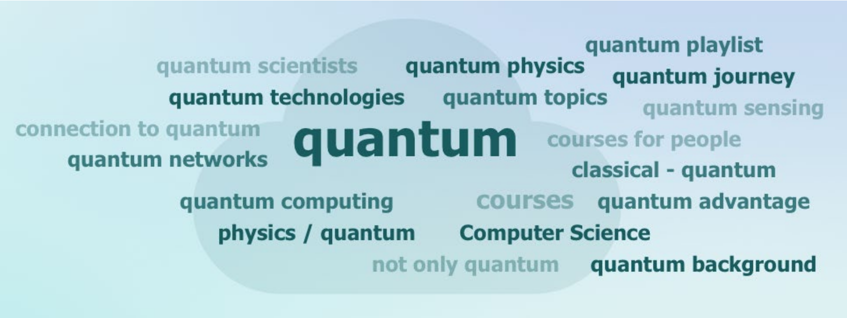

Figure 7-4: Answers to the survey question: "What kind of educational support (e.g., additional educational resources) would you need to develop your current and future talent within your institution/company?"

A non-exhaustive list of skills required in the future workforce for QTs was prepared by the group and is presented in Table 7-1.

Technology (product/service)	**Skills required**
QC Hardware Architecture	Knowledge of recent and future physical systems and platforms used for quantum information processing (e.g., ions, atoms, electrons, superconductors, photons, etc.) and enabling technologies needed to build a QC system.
QC Software Architecture	Design concepts and architectures, and build business solutions for complex computational problems on quantum computers, based on business requirements.
QC Business Solutions	Promote awareness of QC; identify and adopt the right solutions based on customer-specific functional and non-functional requirements.
QC Software Development	Understand the fundamentals of QC and quantum programming languages, SDKs, and their interactions in an application architecture.
Quantum Information Science	Understand how traditional disciplines like physics, mathematics, computing, and engineering can be harnessed to dramatically improve the acquisition, transmission, and processing of information.
Quantum Chemistry	Knowledge of computational chemistry; application of quantum mechanics to chemical systems.
Quantum Optimisation	Understand and create quantum algorithms to solve optimisation problems.

Quantum ML	Understand ML algorithms and apply them to QC algorithms.
Quantum Sensing	Understand the use of a quantum system, quantum properties, or quantum phenomena to perform the measurement of a physical quantity; ability to interpret these measurements in the context of business requirements.
QC Vendors and Public-Cloud Services	Familiar with the contemporary landscape of companies offering QC products and services; understand how their solutions are used.
QC Circuit Compilation	Convert between different device architectures and optimise the quantum circuit for a given target system.
QC Assembly and Pulse-Level R&D	Experience in the construction, control, use, tuning, or low-level programming of quantum computers.
QComm	Competence in quantum information theory and QComm – in particular, topics such as QKD and the quantum internet.
FTQC	Ability to work with QEC, e.g., schemes such as surface codes.
Variational Quantum Algorithms for QC	Understand variational, parametric, and approximate algorithms. Familiarity with parametric circuits (sometimes known as ansatz), for example in ML and optimisation frameworks. Understand the use of the variational principle in the construction of QC algorithms.
QC Simulators (Quantum Virtual Machines)	Can use, code, and optimise QC simulators, build and work with noise models, and simulate the quantum-mechanical effects of quantum devices and circuits.
QuA	Familiar with QuA theory, the application of QuA to optimisation, and other problems.
Enabling Technologies	Engineering skills in electronics, optics, and photonics.

Table 7-1: Required skills for the future quantum workforce

Building and operating QC hardware requires interdisciplinary skills from quantum physics, thermodynamics, photonics, electronics, control theory, signal processing, and computing. The conditions under which quantum phenomena occur, making QC feasible, are extremely specific – e.g., cryogenic temperatures.

On the software side, the key skills required include the underlying logic, data representation, computational algorithms, complexity theory, and data access. We need entirely novel algorithms and methods in all domains of our computer technology if we are to exploit QC to its full advantage. Since we use computers extensively in all aspects of our lives and industry, this transformation will demand expertise from almost all fields of engineering. At the same time, the development of algorithms for quantum computers requires skills from every field of classical computing, dovetailed with a deep understanding of quantum physics. We will need to bring together expertise in mathematical optimisation, ML, statistics, quantum chemistry, quantum information theory, and many others. In addition, realising quantum advantage will require leveraging domain knowledge relevant to the specific application areas, such as materials science, battery design, or weather forecasting.

Although quantum physics is the foundation of QT, the development of low-level quantum algorithms requires strong mathematical and computer science skills. In addition, there are many layers of QT and the translation of business problems into algorithms that can bring quantum benefits, including our current tendency to underestimate the power of quantum techniques. Training people with the skills to work within this layered system is a major prerequisite for the widespread uptake and successful implementation of QC in real business use cases.

The design and development of a technology architecture for a QC solution requires a wide range of software engineering and domain-specific skills. Software architects need to understand how high-level quantum algorithms work, in order to design effective solutions around them. To create benefits for real-world quantum applications, we must first understand the technology, so that we can carefully select and integrate the right components to meet given requirements. The same applies to cryptographic algorithm solutions.

QT architects, solution integrators, and software developers will need a wide range of new skills. These will include familiarity with SDKs and libraries, quantum hardware devices and services, existing algorithms and their applications, and integration mechanisms. Quantum sensing is the use of a particular quantum system to measure a physical quantity. Therefore, a basic understanding of quantum phenomena and an experimental background in the field are fundamental to developing this technology. However, experience in other areas of optics and photonics can always be usefully applied for quantum sensing, by building on the classical foundation with targeted training in the novel technologies (e.g., atomic clocks, magnetic sensors, or quantum imaging devices). In addition, as the technology becomes more robust, there will be growing demand for software skills to create specific models of these sensors, and for data scientists.

As an example, KWAN-TEK has developed a solution for hands-on education in QTs, which consists of an open and flexible experimental platform aimed at university curricula (bachelor, master, PhD), engineering schools, and large corporations for continuous training of their engineers. Students can work with laboratory equipment and carry out experiments to help them physically appreciate the concepts of quantum mechanics and optics, such as spin resonance and the Zeeman effect, observation of hyperfine coupling, longitudinal relaxation time T_1, Rabi oscillations, and Ramsey fringes.

To sum up, it is important to be aware of the resources that are (or will be) in place to prepare our future quantum workforce, ranging from specific educational programmes to events and even games.

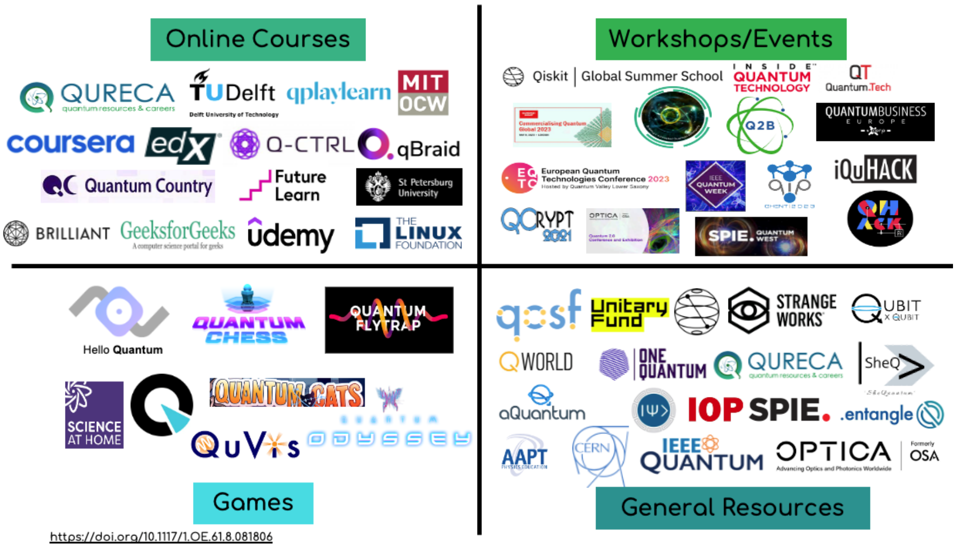

Figure 7-5: A selection of resources relating to QTs[87]

Recruiting and Retaining International Talent

The rise in QT investment has intensified the demand for a diverse and expert quantum workforce. As the technology progresses, it is highly critical to carefully analyse the supply and demand model for quantum expertise. QURECA projects there will be 600,000 new jobs by 2040[88], but not enough people with the right skills and expertise to fill these positions. Educating the future workforce is a long-term endeavour, while upskilling talent in related disciplines could help to fill the gap in the short term. Established companies and quantum startups are pouring energy into training, attracting, and retaining talent from a wide variety of disciplines and skill sets.

A key element of ensuring a robust and diverse talent pipeline must be fostering international collaboration and recruiting foreign talent. Government officials and policymakers should develop and execute strategies not only to recruit international talent, but furthermore to create opportunities for skills growth in order to develop a competent quantum workforce.

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[87] *Source: Maninder Kaur and Araceli Venegas-Gomez, "Defining the Quantum Workforce Landscape: A Review of Global Quantum Education Initiatives," Optical Engineering 61, no. 08 (May 19, 2022), https://doi.org/10.1117/1.OE.61.8.081806..*

[88] *Venegas-Gomez, "The Quantum Ecosystem and Its Future Workforce."*

This is a highly complex, challenging task that needs to be addressed now. The EU needs to establish a detailed timeline and roadmap for the long term. Support from government and public bodies is key. Measures to educate, recruit, and reskill talent will be fundamental to Europe's path to become a quantum leader.

The quantum skills shortage is a well-known bottleneck and there have been many initiatives worldwide making inroads into tackling this problem. In order to overcome this shortage in Europe, not only should specific educational programmes be developed, but we should also ensure that Europe can compete with other countries in terms of professional opportunities, salaries, and career development.

Europe has the potential to attract highly qualified specialists. However, immigration controls and export control regulations often prevent non-European specialists from working in Europe outside an academic setting. Given the size of the actual market, which is still a small niche, provisions for work visas generally do not yet list QT specialists, making it even harder to develop a thriving European ecosystem and workforce.

Therefore, it is essential that national and European regulations are put in place to attract talent and to ensure that these skills remain in Europe.

Academic Education and Outreach

Overview

The required skills are delivered through traditional educational programmes closely aligned to the theory relevant to a particular QT. At pre-university level, outreach activities offered by academic institutions and products designed to introduce the basics of QC are crucial (e.g., Qureka! Box[89] from QURECA, a hands-on tool and methodology for teachers and professionals). At university level, programmes can range from a bachelor's degree in engineering to a doctorate in physics or other disciplines. More than ever, it is clear that it is not just physicists that are in demand: there is a growing call for computer scientists who have gained experience in the design and implementation of quantum algorithms.

When considering educational activities concerning QTs, we can distinguish between two types of programmes:

New learning paths: new programmes created to meet the demand generated by research and industry in terms of skills and requirements.

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[89] https://qureca.com/qureka-box/

Modification of current learning paths: modification of current programmes to add new subjects/modules to meet the growing need for interdisciplinary research perspectives and industry demands.

There is unquestionably a demand for new master's programmes to train a workforce in QT for industry. This is especially true within computer science and engineering departments. The main goal of the new quantum programmes must be to educate students with the best possible immersion and employability opportunities. The main advantages of this type of programme are that the curriculum can be designed to align with the criteria required by industry and to closely match the quantum requirements. At present, development of quantum programmes is largely confined to university-specific activities, with no coordination on a national or international level.

However, in recent years, universities and other institutions around the world have started to put together new programmes in QTs or quantum engineering. An overview of European master's programmes with a focus in QTs is shown in Figure 7-7. At European level, the DigiQ project, funded by DIGITAL, is expected to become a turning point in higher education and training in QTs in Europe, spawning a total of 16 new specialised master's programmes.

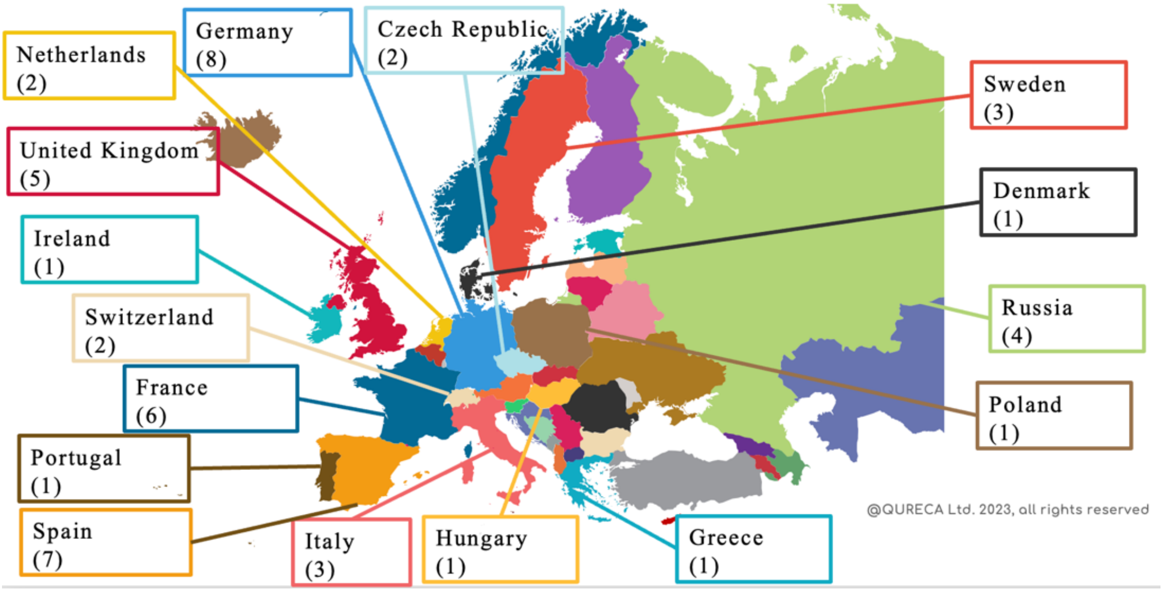

Figure 7-6: Current overview of master's programmes in Europe with a focus on QTs[90]

Another important role in the research and training ecosystem is played by RTOs: organisations whose primary purpose is to provide R&D, technology, and innovation services to governments, businesses, and other clients. They include public entities such as national laboratories and other research institutions – which can be both

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[90] *Source: Kaur and Venegas-Gomez, "Defining the Quantum Workforce Landscape."*

developers and consumers of QTs – and private entities with significant public funding that provide research and technical consulting services. Examples include clocks in metrology labs and quantum computers in HPC facilities.

RTOs play a unique role in the research and training ecosystem, often acting as intermediaries between companies and universities, providing research and technical services at a scale and with a level of reliability that other players cannot offer (in the case of national laboratories and facilities), and serving a key function in bridging the gap between basic research and market innovation.

RTO staff, who may include graduate students, post-doctoral researchers, and senior scientific staff, can constitute an important pool of highly qualified personnel with experience in basic research and in innovation, IP development and protection, and collaboration and engagement with industry. RTOs have an important role in meeting the training needs of industry and producing agile, modular graduate students and researchers well positioned to adapt to the future demands on the quantum workforce. Public grants to support both research and education in QC technology are important to enable knowledge development.

Overall, the creation of new learning programmes will be a major part of the roadmap for training new people in these business areas. The second quantum revolution requires entirely new, very specific skills. As we train people to enter the new talent pool, we need to ensure they have all the tools and resources at their disposal to be able to develop these skills. The roadmap for creating a learning path is:

1. Identify the size of workforce and the skills required for a specific QT;
2. Carry out an in-depth analysis of student profiles to see how best to match industry requirements with student needs, including the duration of the training;
3. Create learning paths that match industry requirements with student needs;
4. Identify educational institutions capable of providing such competences. It will be necessary to train educators in the new quantum skills;
5. Determine the additional resources needed to deliver the quantum curricula, including skills, hardware, and software;
6. Plan to place these students in professional career paths, where they can grow and contribute to the development and adoption of QTs.

Modifying existing learning programmes is as important as creating new ones. The most important modification would be to insert quantum concepts into the existing curricula for computer science, telecommunications, and related disciplines. Therefore, the steps that current programmes should take to integrate quantum themes into existing learning paths are:

1. Recognise the skills required for a specific QT (QC, quantum simulation, QComm, or sensing) from both the classical and quantum worlds. Survey existing companies to find out what they expect from entry-level employees and the anticipated number

of new hires for each QT (this will be aligned with the current QTEdu Competence Framework[91] and its qualification profiles[92]);
2. Draw up a thorough analysis of existing programmes to identify the key areas of science already included;
3. Identify competences that need to be incorporated into the programmes to meet industry needs;
4. Determine the resources required to modify existing programmes;
5. Modify the programmes to meet the vision by removing unnecessary modules and adding essential ones. For example, add early courses to build awareness and stimulate interest in quantum applications.

There is a range of activities and programmes in place, intended to address educational themes at all levels. An overview of these activities can be found on the European QT Education Portal[93].

Road to 2035

The aim of broadening the scope and options for learning about QTs at secondary and university levels is to ensure a steady stream of students are trained with skills in QTs. New graduates should enter the workforce equipped to take up positions in the quantum industry and academia. To achieve the goal of preparing future graduates for working on and with QTs, a twofold approach is essential: on the one hand, there must be a coherent path from an early first contact with the quantum world to a deeper understanding of quantum topics, ultimately to a quantum-related degree and further specialised training (e.g., in a PhD project); no one should “fall through the gaps” because the opportunities they need are not available. On the other hand, entry points should be available at every stage of education, to draw in students whose main focus is not a specifically quantum-related subject, but who are interested in understanding certain aspects of QT, e.g., for assessing potential quantum applications, managing quantum-related projects, and other similar tasks.

In light of these objectives, we can outline the following roadmap:

Near term (2025–2029)

- Develop and deploy additional training courses for teachers and other educators to spark student interest in quantum-related subjects;

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[91] *“QTEdu,” QTEdu | European Competence Framework, accessed January 6, 2024, https://qtedu.eu/european-competence-framework-quantum-technologies.*

[92] *“QTEdu,” QTEdu | Qualification Profiles for Quantum Technologies, accessed December 29, 2023, https://qtedu.eu/qualification-profiles-quantum-technologies.*

[93] *“QTEdu,” accessed December 29, 2023, https://qtedu.eu/.*

- Establish basic and advanced courses on quantum mechanics, QTs, and QC for a wide variety of STEM majors beyond physics – engineering and computer science in particular, but also e.g., economics;
- Facilitate collaborations between quantum companies and academia for joint student and thesis projects;
- Establish collaborations between academic institutions working on quantum topics, both to enhance European networking in R&D and to facilitate shared education on QTs – virtual courses, short courses (e.g., summer schools), visiting lecturers, etc.

Long term (2030–2035)

- Add quantum phenomena and their technological impact as standard topics in secondary curricula;
- Create QT hubs shared by several academic institutions to pool competences and serve as contact points with industry.

By 2035, education on quantum phenomena and QTs should be widely available in Europe on multiple levels from secondary education to PhD level.

Professional Training/Reskilling

Overview

Training and development of the existing workforce are central pillars of the quantum education roadmap, especially since QT is likely to transform the nature of work in some professions. Industry needs educational programmes that will not disrupt day-to-day business. Since upskilling today's workforce is a major requirement for tomorrow's QT, it is essential for educational institutions to design industry-specific professional training programmes. These programmes will not require an extensive background in quantum physics; rather, they will be aimed at delivering a broad understanding of the field as a whole, combined with the ability to translate business problems into QT. At present, there is only a need to upskill specific employees within a company; however, the demand is expected to widen steadily over the coming years as we train people to use QT, particularly quantum computers, effectively.

Past experience of establishing new learning programmes within industry will be valuable to developing these new programmes. In the medium to long term, there will be a need for more continuous training and practical experience; in the short term, identifying people or institutions with the right skills and experiences is essential. The following measures are proposed to meet industry demand:

- Set concrete learning objectives aligned to the skills required;
- Define the populations (disciplines, job families) who need to acquire these skills, and classify them by priority. This includes identifying the disciplines/roles or situations where training is most important, as well as identifying the personnel who

need complete reskilling (this will be aligned with the current QTEdu Competence Framework);
- Define the level of mastery that will be targeted (from awareness level to expert level to active practitioners);
- Link up companies looking to reskill their staff with companies offering appropriate expertise (e.g., quantum computer manufacturers, training bodies);
- Design learning approaches adapted to the learning objectives (based on the 70/20/10 model) in each pathway and for each level, and leverage existing resources in the market (academic modules, MOOCs, etc.);
- Establish a long-term map with a vision of the specific skills and roles to be created in the industry, classified by the different QTs and sectors of activity.

The quantity of people to be trained and the speed of transformation will depend on the industrial and business models and the evolution of the quantum workforce. Overall, these programmes must be modular, flexible and adaptable in order to respond to potentially rapidly changing requirements as the various competing QT platforms develop and mature, and new applications emerge. It is also important to develop industrial and academic programmes that attract and retain a wide range of diverse talent, respect gender balance, and offer attractive pathways to and support for underrepresented groups entering the field. This is essential for promoting equitable access to the training programmes and to ensure that the resulting quantum workforce benefits from the incorporation of people from diverse backgrounds and experiences.

Vocational education is developed and delivered by different entities: industry, academia, research institutions, and online or in-person training organisations. These various entities play an important bridging role for vocational training, offering broader training and acting as a link between companies and the workforce. The education offered by industry is currently delivered by QT companies (startups and large enterprises) or service providers. However, these courses focus on the main product or service offered by the company and lack the necessary broad overview. Specialist training companies, such as QURECA, offer training to companies and individuals ranging from an introductory level to business-focused educational programmes. These companies also place candidates with specific skills in emerging roles within the quantum industry. There are many open-access resources that provide training and education on QTs, particularly in the field of QC. Many of these resources are provided by research institutions, but some are made available by private companies, often from outside the EU. It is essential for European stakeholders (i.e., European universities and educational centres, companies, research centres, governments, regulatory bodies) to be actively engaged in shaping and defining the way we use and interact with QTs and program quantum computers.

Also funded by DIGITAL, the QTIndu project[94] is focused on reskilling the current workforce; in particular, through development of a training programme with several courses at different levels, addressing each of the three axes (business sectors, stakeholders, application areas).

Road to 2035

Industry and academia must work together to incorporate such training programmes to ensure industry is immersed in QTs as fully as possible.

In light of these objectives, we can outline the following roadmap:

Short term (2025–2027)

- Companies have a preliminary understanding of how QTs can impact their own business;
- Training opportunities are available to reskill employees in QT;
- Clear professional development paths are made available within businesses for professionals who want to work on QTs, aligning with corporate strategies.

Medium term (2028–2029)

- Companies have a broader understanding of how QTs can impact their business;
- Companies develop collaborations within the wider ecosystem to enhance the overall quantum knowledge;
- Strong relationships established between academia and industry;
- Work begins on closing the gaps between industry needs and academic progress.

Long term (2030–2035)

- Companies have a clear grasp of QTs, how the technologies can impact their business, and how to reap maximum benefits from QTs for their target market;
- Clearly defined internal training strategies are on offer, with a focus on adapting QTs to interact with the ecosystem of the specific company;
- Professional development opportunities are available to convert any “classical” role to a “quantum” role.

By 2035, companies should be fully immersed in QTs, by having skill development options for specific departments and areas. Companies that fail to reach this milestone will find themselves trailing behind, without the skills and capacity to benefit effectively from the competitive advantage of the new disruptive technology.

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[94] *“QTIndu Project - Quantum Technologies Courses for Industry,” QTIndu Project, accessed December 29, 2023, https://qtindu.eu/.*

Road to 2035

Academic education and outreach

Near term (2025–2029)

- Develop and deploy additional training courses for teachers and other educators to spark student interest in quantum-related subjects;
- Establish basic and advanced courses on quantum mechanics, QTs, and QC for a wide variety of STEM majors beyond physics – engineering and computer science in particular, but also e.g., economics;
- Facilitate collaborations between quantum companies and academia for joint student and thesis projects;
- Establish collaborations between academic institutions working on quantum topics, both to enhance European networking in R&D and to facilitate shared education on QTs – virtual courses, short courses (e.g., summer schools), visiting lecturers, etc.

Long term (2030–2035)

- Add quantum phenomena and their technological impact as standard topics in secondary curricula;
- Create QT hubs shared by several academic institutions to pool competences and serve as contact points with industry.

By 2035, education on quantum phenomena and QTs should be widely available in Europe on multiple levels from secondary education to PhD level.

Professional training/reskilling

Short term (2025–2027)

- Companies have a preliminary understanding of how QTs can impact their own business;
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- Clear professional development paths are made available within businesses for professionals who want to work on QTs, aligning with corporate strategies.

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- Companies have a broader understanding of how QTs can impact their business;
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- Companies have a clear grasp of QTs, how the technologies can impact their business, and how to reap maximum benefits from QTs for their target market;
- Clearly defined internal training strategies are on offer, with a focus on adapting QTs to interact with the ecosystem of the specific company;
- Professional development opportunities are available to convert any “classical” role to a “quantum” role.

Key Messages

- QT educational programs at all levels need to ensure a steady stream of students are trained with skills in QTs, preparing the future workforce in the field;
- Outreach activities are essential – in particular, bringing quantum to educators will ensure awareness of quantum career options;
- In the medium and long term, we are looking at less specialised profiles (engineering and other disciplines). In the short term, doctorate programs are the leading path to enter the job market in QT;
- Industry and academia must work together to incorporate training programmes to ensure industry is immersed in QTs as fully as possible;
- Attraction and retention of talent is of utmost importance, especially in the short term due to the scarcity of skills;
- Setting concrete learning objectives aligned to the skills required is key;
- Alignment with the current QTEdu Competence Framework is vital both when building new quantum educational programmes and when looking at skills needed for specific roles;
- Design and learning approaches must be adapted to the learning objectives, from schools to industry;

Companies need to start setting a long-term map with a vision of the specific skills and roles to be created, classified by the different QTs and sectors of activity.

Names and Nomenclature in Standardisation

Initiatives		
JTC	Joint Technical Committee	
MSP	European Multi-Stakeholder Platform on ICT Standardisation	
International		
IEC	International Electrotechnical Commission	
IEEE SA	Institute of Electrical and Electronics Engineers Standards Association	
IETF	Internet Engineering Task Force	
IMEKO	International Measurement Confederation	
ISO	International Organization for Standardization	
ITU	International Telecommunication Union	
ITU FG-QIT4N	ITU Focus Group on Quantum Information Technology for Networks	
ITU SG	ITU Study Group	
ITU-T	ITU Telecommunication Standardization Sector	
QIRG	Quantum Internet Research Group	
Europe		
CEN	European Committee for Standardisation	
CEN-CENELEC	European Committee for Electrotechnical Standardisation	

CEN-CENELEC FGQT	CEN-CENELEC Focus Group on Quantum Technologies	
DIN	Deutsches Institut für Normung	
EMN-Q	European Metrology Network for Quantum technologies	
ETSI	European Telecommunications Standards Institute	Active worldwide
ETSI ISG QKD	ETSI Industry Specification Group on Quantum Key Distribution for Users	
ETSI ISG QSC	ETSI Industry Specification Group on Quantum-Safe Cryptography	
ETSI TC CYBER WG QSC9	ETSI Technical Committee Cyber Security Working Group for Quantum-Safe Cryptography	
EURAMET	European Association of National Metrology Institutes	
JRC	EC Joint Research Centre	
SESEC	Seconded European Standardisation Expert for China	
US		
ANSI	American National Standards Institute	
ASME	American Society of Mechanical Engineers	
ASTM	American Society for Testing and Materials	
NIST	(American) National Institute of Standards and Technology	
UL	Underwriter Laboratories	
National – Asia		
CCSA	China Communications Standards Association	China
CESI	China Electronics Standardization Institute	China

CNIS	Chinese National Institute of Standardisation	China
CRYPTREC	Cryptographic Research and Evaluation Committee	Japan
NICT	National Institute of Information and Communications Technology	Japan
NIM	Chinese National Institute of Metrology	China
SAC	Chinese Standards Association	China
National – Europe		
AFNOR	Association Française de Normalisation	France
BSI	British Standards Institution	UK
INRIM	Istituto Nazionale di Ricerca Metrologica	Italy
NEN	Stichting Koninklijk Nederlands Normalisatie Instituut	Netherlands
NPL	National Physical Laboratory	UK
PTB	Physikalisch-Technische Bundesanstalt	Germany

General Overview

Industrial standards are essential for new technologies, since they ensure the interoperability of equipment and protocols in complex systems and stimulate supply chains for components and systems. The EC emphasises the importance of standardisation activities and supports initiatives like the High-Level Forum on European Standardisation, the European MSP, the MSP Task Force Rolling Plan for ICT standardisation, and others to ensure a coordinated representation of European interests in international standardisation forums.

As with any new technology, standardisation helps to improve QTs by establishing a common ground for terminology, key control characteristics, performance, measurement, analysis, and comparisons of different technologies. QTs, having originated mainly in academic contexts and in many cases requiring highly specific and expensive dedicated systems, are moving steadily towards technological maturity and wider industrial adoption. Currently, industry interest in QT is relatively fragmented due to the variety of applications. There are insufficient reference facilities, and few or no established standards. As QTs move towards technological and market maturity with higher TRLs, the importance of building a solid industrial base, including developing new standards and in some cases new regulations, becomes greater. An evolving standardisation process is crucial for the field to mature and to achieve interoperability between different systems, technologies, ecosystems, and companies. The existence of standards supports the tests and measurements necessary to validate quantum-enabled measurement systems and procedures. Standardisation also brings significant benefits in the area of interoperability and enhanced cooperation. Furthermore, standardisation is key to innovation, competitiveness, and adoption of QTs.

Standards can play an important part in enabling the integration of quantum devices into wider complex systems. By standardising interfaces between the different technology layers of a complex system design (including hardware, hardware-related software, control systems, and system software through to OSs and user software, including graphical interfaces), these interfaces become easier to access and companies can shift their focus to just certain parts of the overall QT stack. For example, in order for QKD technologies to be commercialised and become fully integrated into current communications infrastructures, development of industry-wide standards to allow interfacing with existing devices is necessary.

Even in QC, although it is still in its infancy and there is need for freedom to innovate and to proliferate, there are areas in which standards would be helpful. For example, performance benchmarks for the equipment and infrastructure required to support QC and quantum measurements, and interfaces to determine how different hardware components work together and how different software components interact with other software and hardware components can all help towards securing end-user confidence and supporting a viable supply chain.

Supply chains for QTs are emerging, focusing on commercially available components for enabling technologies and QT research infrastructures. Standards are essential ingredients for a sustainable business sector. They give customers and suppliers a common starting point and language when discussing demand/supply. They can therefore help each company to occupy a particular position in a value chain and have clear interfaces with their respective suppliers and customers, thereby supporting a broad ecosystem of individual solution providers and alleviating the need to develop full-stack solutions.

Standards help to bridge the gap between research and the market and increase the probability of market uptake of technological innovation. Of course, the process of standardisation will become more complex as the market for QTs grows, and other, nontechnical, issues come into play, such as the management of international trade and export control, patent positions and SEPs, competition, anti-monopoly rules, etc.

While standardisation can be seen as a resource-consuming effort, especially for SMEs with scarce resources, it also opens up access to the technologies of others and frees the enterprise to concentrate on the parts of the technology stack where the SME has clear competitive advantage. As a full-stack provider, an SME would have significant development costs, interoperability issues, and would possibly also face fierce competition. Standardisation should thus be seen as a long-term investment, whereby the enterprise will be able to contribute its own technologies to the standards, which may then become SEPs and thus more valuable than pure implementation patents. Especially in the field of QC, this may prove to be a good choice, as the patented technologies in this area may not be easily detectable. Of course, it is also important for the SDOs to establish clear IPR policies to avoid possible royalty-stacking or patent holdup issues that might deter companies from participating in the standardisation work. The goal of these policies should be to establish clarity and transparency regarding IPR declarations and licensing commitments. Companies should also form, for example, patent pools or patent platforms outside the SDOs, to negotiate the related licenses and thus ensure that costs for adopting the standards are predictable and do not preclude technology adoption. Among other things, this may mean setting reasonable caps for royalty rates, and establishing fair rules for royalty distribution – for SMEs with smaller patent portfolios, rather than just using the proportion of the SEP to define each SEP owner's portion of the overall royalties, it may make sense to take into account how the SEP contributes to the standard.

Standardisation and mapping standardisation opportunities at a relatively early stage of the QT value chain will be beneficial. Within this context, the EC already promotes relevant projects (StandICT[95]), while the "Standardisation Booster"[96] is a relatively new Horizon Europe initiative to support standardisation activities within Horizon Europe research programmes[97]. Furthermore, in 2018 the EC launched its large-scale and long-term research initiative QFlag to support and foster the creation and development of a competitive European QT industry. In its Strategic Research Agenda, QFlag identified the importance of promoting coordinated, dedicated standardisation and certification efforts, such as the CEN-CENELEC FGQT[98], which launched JTC22-QT, the JTC on QTs, as a spinoff in early 2023.

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[95] *"Home | StandICT.Eu 2026," accessed December 29, 2023, https://standict.eu/.*

[96] *Horizon Europe Framework Programme, "Standardisation Booster for Fostering Exploitation of FP-Funded Research Results | HORIZON-WIDERA-2021-ERA-01-32," 2021, https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-widera-2021-era-01-32.*

[97] *"Standards Drive Innovation," accessed January 5, 2023, https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/standards-drive-innovation-2021-08-04_en.*

[98] *van Deventer et al., "Towards European Standards for Quantum Technologies."*

Standardisation activities in the field of QT have been increasing since 2008 and many SDOs like the ITU[99], ISO[100], IEC[101], ETSI[102], CEN-CENELEC[103] and others are currently working on QT standardisation activities, including:

- Security assessment, testing, and specification;
- Security – certification of QKD for market uptake;
- Interoperability – integration of QKD networks with other networks;
- Metrology – specification of certain quantum components;
- Physical standards and measurement protocols;
- Benchmarking and metrics for QC algorithms;
- Roadmap for standardisation of QTs;
- Exploratory studies on QTs;
- Architectures and terminologies;
- QKD testing and evaluation;
- Use cases;
- Guidelines and best practices;
- Interoperability and regulatory aspects.

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[99] *https://www.itu.int/*

[100] *https://www.iso.org/*

[101] *https://www.iec.ch/*

[102] *https://www.etsi.org/*

[103] *https://www.cencenelec.eu/*

Figure 8-1: The standardisation ecosystem for QTs

There is a need for greater coordination across the entire spectrum of SDOs, as early standardisation efforts were often fragmented and uncoordinated due to the breadth of interests involved. For example, the Common Criteria for Information Technology Security Evaluation (ISO/IEC 15408[104]) is an international standard for IT product security certification. Currently, both the ETSI ISG QKD (DGS/QKD-016: Common Criteria Protection Profile for QKD) and the ISO SC27 WG3 (ISO/IEC 23837-1: Information security and 23837-2: Test and evaluation methods) are working in parallel to standardise the ISO/EN 15408 "Common Criteria" security certification for QKD systems. These two WGs should coordinate their efforts to avoid developing two conflicting standards.

Standards are of paramount importance because they facilitate the establishment of regulation and certification processes, which will have significant repercussions throughout the ecosystem. It is therefore important to establish a standardisation roadmap for QTs, to identify which standards already exist and which standards will be needed for the various applications. However, a reluctance to engage in standardisation activities at early stages of the TRL scale has been observed among industrial and research communities. QuIC has established a Standards WG to act as an industry connection and to facilitate discussion on standards, to help channel

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[104] *"ISO/IEC DIS 15408-1(En), Information Security, Cybersecurity and Privacy Protection -- Evaluation Criteria for IT Security -- Part 1: Introduction and General Model," accessed January 5, 2023, https://www.iso.org/obp/ui/#iso:std:iso-iec:15408:-1:dis:ed-4:v1:en.*

common requirements to various standardisation bodies such as CENELEC, the ITU, the ETSI, the ISO, the IEEE, and the IEC, to identify standardisation needs coming from its industry members, to create a state-of-the-art living document on standardisation activities in QTs, and to write white papers.

More specifically, the WG foresees several key tasks in line with its objectives:

- To develop a living document, “State-of-the-art tracker on standardisation”, which will draw together the work of the main standardisation bodies;
- To establish a process and the necessary accompanying material in order to solicit standardisation needs from the broad European quantum industry;
- To support the activities of the SDOs, including coordinating the involvement of relevant European experts;
- To provide up-to-date information on global standardisation activities to the European quantum industry.

These tasks are quite substantial given the wide array of standardisation bodies and the variety of quantum systems currently in development. Accomplishing them, and thus establishing a standardisation framework to underpin QuIC’s objectives, will require significant financial investment and human capital.

The next section gives an overview of the activities of international and European SDOs with regard to QTs.

Standards Developing Organisations

International SDOs

Some international SDOs include:

IEC: www.iec.ch – The IEC is a global, not-for-profit membership organisation of more than 170 countries that coordinates the work of 20,000 experts around the world. QTs have already been a significant focus of IEC technical committees in areas such as lasers and semiconductors.

ISO: www.iso.org – The ISO is an international, independent, nongovernmental organisation with 166 national standards body members. The ISO/IEC JTC1 established a WG for QC in June 2020[105] This WG, subsequently renamed to Quantum information technology, will serve as a systems integration entity to focus on the JTC1 QC standardisation programme, identify gaps and opportunities, and develop deliverables in QC. Its current key work is the development of ISO/IEC AWI

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[105] *“Working Group 14 for Quantum Computing Was Established by ITO/IEC JTC1 in June 2020.,” JTC 1, accessed January 5, 2023, https://jtc1info.org/technology/working-groups/quantum-computing/.*

4879[106], "Quantum computing – terminology and vocabulary". As part of JTC1, the Software and Systems Engineering Subcommittee has established a study group on "Standards research for QC". In addition, the ISO/IEC JTC1 Subcommittee 27[107], which is best known for the ISO/IEC 27000 series of cybersecurity and privacy standards, is already investigating ways to develop quantum-resilient cryptography. The QKD work items come under the tasks of WG3 "Security evaluation, testing and specification". The two QKD security evaluation standards currently being developed in WG3, ISO/IEC 23837-1 and 2, are both "applications" of the Common Criteria paradigm to QKD.

ITU: www.itu.int – The ITU is the United Nations' specialist agency for ICT. The ITU is working on standards for QKD networks (networks of QKD devices and an overlay network) to enable the integration of QKD technology into large-scale ICT networks. Therefore, ITU standards for QKD networks address foundational concepts (ITU Y.3800[108]), functional requirements (ITU Y.3801[109]), architecture (ITU Y.3802[110]), key management (ITU Y.3803[111]), and control and management (ITU Y.3804[112]).

The ITU standards also provide a security framework for QKD networks (ITU X.1710[113]), key combination methods (ITU X.1714[114]), and the architecture of a quantum noise RNG (ITU X.1702[115]). These ITU standards will facilitate the integration of QKD networks into large-scale networks.

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[106] *ISO/IEC JTC 1 Information technology, "ISO/IEC DIS 4879," ISO, accessed January 5, 2023, https://www.iso.org/standard/80432.html.*

[107] *"ISO/IEC JTC 1/SC 27 - Information Security, Cybersecurity and Privacy Protection," ISO, February 2, 2023, https://www.iso.org/committee/45306.html.*

[108] *"Overview on Networks Supporting Quantum Key Distribution. ITU-T Y.3800 (10/2019).," 2019, https://handle.itu.int/11.1002/1000/13990.*

[109] *"Functional Requirements for Quantum Key Distribution Networks. ITU-T Y.3801 (04/2020)," ITU, 2020, https://handle.itu.int/11.1002/1000/14258.*

[110] *"Quantum Key Distribution Networks – Functional Architecture. ITU-T Y.3802 (12/2020)," ITU, 2020, https://handle.itu.int/11.1002/1000/14407.*

[111] *"Quantum Key Distribution Networks – Key Management. ITU-T Y.3803 (12/2020)," ITU, 2020, https://handle.itu.int/11.1002/1000/14408.*

[112] *"Quantum Key Distribution Networks – Control and Management. ITU-T Y.3804 (09/2020)," ITU, 2020, https://handle.itu.int/11.1002/1000/14409.*

[113] *"Security Framework for Quantum Key Distribution Networks. ITU-T X.1710 (10/2020)," ITU, 2020, https://handle.itu.int/11.1002/1000/14452.*

[114] *"Key Combination and Confidential Key Supply for Quantum Key Distribution Networks. ITU-T X.1714 (10/2020)," ITU, 2020, https://handle.itu.int/11.1002/1000/14453.*

[115] *"Quantum Noise Random Number Generator Architecture. ITU-T X.1702 (11/2019)," ITU, 2019, https://handle.itu.int/11.1002/1000/14095.*

Different ITU study groups are working on various standardisation issues:

- ITU SG1: Investigation of standards for QC, which is one of the priority technologies under JTC1’s Joint Advisory Group on Emerging Technology and Innovation;
- ITU-T SG13 [116] “Future networks”: General functional requirements for QKD networks;
- ITU SG SG17 [117] “Security”: cybersecurity, security management, security architectures, frameworks, and quantum-related communication at the international level;
- ITU FG-QIT4N[118]: established in September 2019 to discuss pre-standardisation issues in networks where quantum IT is relevant. FG-QIT4N has now finished its work and there is a recording available of the information session the editors held for SG11 and SG13[119]. Published versions of the FG-QIT4N deliverables are now available online, and there are direct links to each report on the FG-QIT4N publications page[120].

IETF: www.ietf.org – The IETF is an international SDO that works on the development and standardisation of internet protocols. The IETF established the QIRG in March 2019, with the aim of supporting the quantum internet and thus new remote communication and computing capabilities – such as quantum-secure communications, distributed QC, and quantum-enhanced physical sensor systems. QIRG aims to answer the question of how to design and build quantum networks. Its research areas include routing, resource allocation, connection establishment, interoperability, security, and design of an API that will serve the role that sockets play in classical networks.

IEEE SA: standards.ieee.org – The IEEE SA aims to raise standards to advance technology for humanity. Since 2017, the IEEE has established several standards working groups:

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[116] *“Study Group 13 at a Glance,” ITU, accessed January 5, 2023, https://www.itu.int:443/en/ITU-T/about/groups/Pages/sg13.aspx.*

[117] *“Study Group 17 at a Glance,” accessed January 5, 2023, https://www.itu.int/en/ITU-T/about/groups/Pages/sg17.aspx.*

[118] *“ITU-T Focus Group on Quantum Information Technology for Networks (FG-QIT4N),” ITU, accessed January 5, 2023, https://www.itu.int:443/en/ITU-T/focusgroups/qit4n/Pages/default.aspx.*

[119] *“Info Session on FG-QIT4N Deliverables to ITU-T Study Groups 11 and 13,” ITU, accessed January 5, 2023, https://www.itu.int:443/en/ITU-T/focusgroups/qit4n/Pages/SG11&13.aspx.*

[120] *“Focus Groups Publications,” ITU, accessed January 5, 2023, https://www.itu.int:443/en/publications/ITU-T/Pages/T-FG.aspx.*

- IEEE P1913[121] “Software-Defined Quantum Communication”: defines the protocol that enables the configuration of quantum devices in a communication network to dynamically create, modify, or remove quantum protocols or applications and facilitate cross-device information flow;
- IEEE P7130[122] “Standard for Quantum Technologies Definitions”: establishes a general terminology for QTs that can be used to ensure compatibility and interoperability in hardware and software projects;
- IEEE P7131[123] “Standard for Quantum Computing Performance Metrics & Performance Benchmarking”: covers QC performance metrics to standardise performance benchmarking of QC hardware and software;
- IEEE P2995[124] “Trial-Use Standard for a Quantum Algorithm Design and Development”: defines a standardised method for designing quantum algorithms. The methods defined apply to any type of algorithm that can be assimilated into quantum primitives and/or quantum applications;
- IEEE P3120[125] “Standard for Quantum Computing Architecture”;
- IEEE P3155[126] “Standard for Programmable Quantum Simulator”.

IMEKO: www.imeko.org – The IMEKO is a nongovernmental federation of 42 member organisations who are concerned with the advance of measurement technology. The IMEKO has established WG TC25 – Quantum Measurement and Quantum Information, whose objective is to provide a forum to discuss advances in quantum measurement, the QTs associated with these advances, and changes in international metrology infrastructure and applications. The expected outcomes of TC25 include an articulation of the role of QTs in the development and dissemination of standards and recommendations – for example, for the modernisation of the international metrology infrastructure to accommodate quantum standards and chip acceptance.

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[121] *“P1913. YANG Model for Software-Defined Quantum Communication,” P1913. YANG Model for Software-Defined Quantum Communication, accessed January 6, 2024, https://standards.ieee.org/ieee/1913/11105/.*

[122] *“P7130. Standard for Quantum Technologies Definitions,” IEEE Standards Association, accessed January 6, 2024, https://standards.ieee.org/ieee/7130/10680/.*

[123] *“P7131. Standard for Quantum Computing Performance Metrics & Performance Benchmarking,” IEEE Standards Association, accessed January 6, 2024, https://standards.ieee.org/ieee/7131/10681/.*

[124] *“P2995. Trial-Use Standard for a Quantum Algorithm Design and Development,” IEEE Standards Association, accessed January 6, 2024, https://standards.ieee.org/ieee/2995/10633/.*

[125] *“P3120. Standard for Quantum Computing Architecture,” IEEE Standards Association, accessed January 6, 2024, https://standards.ieee.org/ieee/3120/11359/.*

[126] *“P3155 - Programmable Quantum Simulator Working Group - Home,” accessed January 6, 2024, https://sagroups.ieee.org/3155/.*

European SDOs

The European SDOs, namely the CEN, CEN-CENELEC and the ETSI, are responsible for organising European standardisation activities. The ETSI is responsible for standardisation activities in the field of telecommunications at European level; CEN is responsible for all non-electronic activities and CEN-CENELEC for electrotechnical standardisation activities.

ETSI: www.etsi.org – The ETSI provides its members with an open, inclusive, and collaborative environment to support the timely development, ratification, and testing of globally applicable standards for ICT-enabled systems, applications, and services. ETSI has established the first two specific standardisation forums for QTs, dealing with standardisation of QComm:

- The ETSI ISG QKD was formed in 2008 and aims to connect European stakeholders from commerce, industry, and science. The group's focus is on standardisation issues in quantum cryptography, to enable digital keys to be shared privately without relying on computational complexity. In fact, the ISG QKD has members not just from Europe, but from all over the world (e.g., Japanese NICT). The ISG QKD is now working on various specifications:
  - Protection profile for QKD systems;
  - Protection against Trojan horse attacks in one-way QKD systems;
  - Characterisation of the optical output of QKD transmitter modules;
  - A control interface for software-defined networks;
  - A review of network architecture;
  - APIs in response to new network developments.

- The ETSI TC CYBER WG QSC9, a spinoff from the ETSI ISG QSC, deals with quantum-safe cryptographic primitives and protocols to connect state-of-the-art quantum algorithms and cryptography emerging from academia to the real-world needs of the industry.

These standards for QKD are listed in Table 8-1 below.

ETSI GS QKD 015 V2.1.1 (2022-04)	Control Interface for Software-Defined Networks[127]
ETSI GS QKD 004 V2.1.1 (2020-08)	Application Interface[128]

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[127] http://webapp.etsi.org/workprogram/Report_WorkItem.asp?WKI_ID=63881

[128] http://webapp.etsi.org/workprogram/Report_WorkItem.asp?WKI_ID=54395

ETSI GS QKD 012 V1.1.1 (2019-02)	Device and Communication Channel Parameters for QKD Deployment[129]
ETSI GS QKD 014 V1.1.1 (2019-02)	Protocol and data format of REST-based key delivery API[130]
ETSI GR QKD 007 V1.1.1 (2018-12)	Vocabulary[131]
ETSI GR QKD 003 V2.1.1 (2018-03)	Components and Internal Interfaces[132]
ETSI GS QKD 011 V1.1.1 (2016-05)	Component characterisation: characterising optical components for QKD systems[133]
ETSI GS QKD 005 V1.1.1 (2010-12)	Security Proofs [134] (both theoretical and implementation security)
ETSI GS QKD 008 V1.1.1 (2010-12)	QKD Module Security Specification[135]
ETSI GS QKD 002 V1.1.1 (2010-06)	Use Cases[136]

Table 8-1: A list of QKD standards published by the ETSI

CEN-CENELEC: www.cencenelec.eu – The joint report compiled by CEN-CENELEC and the JRC [137] recommended concrete actions to address the standardisation of QTs, including standardisation of terminology, the development of an EU roadmap for standardisation, and the start of regular collaboration based on light standardisation activities. Following these recommendations, a WG composed of CEN-CENELEC, the JRC, the DIN and the QFlag Coordination Office was set up for this purpose and led to the formation of the CEN-CENELEC FGQT. The group's

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[129] http://webapp.etsi.org/workprogram/Report_WorkItem.asp?WKI_ID=43812

[130] http://webapp.etsi.org/workprogram/Report_WorkItem.asp?WKI_ID=53603

[131] http://webapp.etsi.org/workprogram/Report_WorkItem.asp?WKI_ID=30486

[132] http://webapp.etsi.org/workprogram/Report_WorkItem.asp?WKI_ID=47929

[133] http://webapp.etsi.org/workprogram/Report_WorkItem.asp?WKI_ID=43376

[134] http://webapp.etsi.org/workprogram/Report_WorkItem.asp?WKI_ID=29098

[135] http://webapp.etsi.org/workprogram/Report_WorkItem.asp?WKI_ID=30487

[136] http://webapp.etsi.org/workprogram/Report_WorkItem.asp?WKI_ID=29096

[137] *European Commission. Joint Research Centre., Standards4Quantum: Making Quantum Technology Ready for Industry : Putting Science into Standards. (LU: Publications Office, 2020), https://data.europa.eu/doi/10.2760/882029.*

objective was to develop a European roadmap on the standardisation of QTs. The FGQT roadmap served as a guiding document to define topics, terminologies, and a structure of QTs. This work led to the creation of a new CEN-CENELEC JTC (JTC22/QT), which started its activities in 2023, working on the definition of standards with a scope of the entire field of QTs. The 2022 CEN-CENELEC FGQT article[138] published in a special issue of EPJ Quantum Technology[139] provides a broad overview of the current standardisation landscape for QTs, as well as standardisation gaps and needs.

EURAMET: www.euramet.org – EURAMET's mission is to develop and disseminate an integrated, cost-effective, and internationally competitive measurement infrastructure for Europe. In Europe, national metrology institutes (e.g., the NPL in the UK, PTB in Germany, and INRIM in Italy) are among those who contribute to standardisation activities in the field of quantum physics. In order to develop globally accepted measurement services for QTs and quantum devices, the European metrology institutes in the field of QT have formed the EMN-Q[140].

National SDOs

Each country has its own national standards bodies. In the EU, the most prominent national SDOs are probably the DIN in Germany, the NEN in the Netherlands, and the AFNOR in France. In the UK, the national SDOs that play a key role in QTs are the BSI and the NPL. In the US, the most relevant SDOs are:

- ANSI;
- ASME;
- ASTM;
- NIST;
- UL.

The NIST Cryptographic Technology Group[141] conducts research and produces guidelines, recommendations, and best practices for cryptographic algorithms, methods, and protocols.

In Japan, the SDOs related to QTs are:

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[138] *van Deventer et al., "Towards European Standards for Quantum Technologies."*

[139] *"EPJ Quantum Technology | Quantum Standardization," SpringerOpen, accessed January 5, 2023, https://epjquantumtechnology.springeropen.com/qs.*

[140] *"EURAMET: Quantum Technologies," accessed December 29, 2023, https://www.euramet.org/european-metrology-networks/quantum-technologies/.*

[141] *"About NIST's Cryptographic Technology Group | CSRC," accessed December 29, 2023, https://csrc.nist.gov/groups/computer-security-division/cryptographic-technology.*

- The CRYPTREC, which evaluates and recommends cryptographic algorithms for use in government and industry and thus the evaluation of QKD;
- The NICT, which works on QTs through its Quantum ICT Advanced Development Centre.

The European standards bodies (CEN, CENELEC, ETSI) have chosen to deepen exchanges with key partners in areas of strategic and growing economic importance, such as China. In 2006, the EU established the SESEC[142] project. Its general objective is to raise awareness in China for the European standardisation system, its values, and its assets.

In China, the standardisation ecosystem consists of:

- The SAC[143], which publishes notifications of national standards and related standardisation information;
- The CNIS[144], which provides standardisation research in various fields;
- The NIM[145], China's highest-level state-owned metrology research centre.

Two SDOs in China (CCSA[146] and CESI[147]) play key roles in quantum standardisation efforts. CCSA has a Special Task Group, ST7 (Quantum Communication and Information Technology), and leads the standardisation work on QComm in China, with various projects, reports and white papers[148] on QComm. CESI is responsible for SAC/TC28 (National Information Technology Standardization Technical Committee) which works on QComm issues in cooperation with ISO/IEC/JTC1. In addition, the SAC/TC578 National Quantum Computing and Metrology Standardization Technical Committee was established in 2019, working on QC terminology and responsible for four research projects.

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[142] https://sesec.eu/

[143] http://www.sac.gov.cn/sacen/

[144] https://en.cnis.ac.cn/

[145] www.nim.ac.cn

[146] http://www.ccsa.org.cn/english/

[147] http://www.cc.cesi.cn/

[148] *QuantumCTek, "White Paper on Quantum Secure Communication Technology Is Released," January 19, 2019, http://www.quantum-info.com/English/News/2019/2020/1013/616.html.*

Road to 2035: Standardisation Progress and Objectives

The above outline of SDO activities concerning QTs indicates a growing awareness of the need for standardisation of QTs worldwide. This is an indicator of increased maturity and strong interest in the practical applications and commercialisation of mature QTs. In addition, beyond standards, there are numerous white papers, pre-standards, and publications that address QTs. For example, the ETSI white paper on "Implementation Security of Quantum Cryptography"[149] summarises the current state of quantum cryptography implementation and discusses approaches to QKD; the FGQT published its first QT Standardization Roadmap in March 2023[150].

The Global System for Mobile Communications Association[151] published white paper Q_004 "Quantum Computing, Networking and Security"[152], which provides an overview of the current state of QTs and their associated maturity levels in terms of the TRL indicators, with particular reference to quantum security (QKD, QRNG, and the provision of quantum security as a service), QC, quantum networks and QComm, and quantum metrology. The OIDA Quantum Photonics Roadmap[153] clarifies the applications and timeframes for QTs (quantum sensing and metrology, QComm and QC) and details the improvements in the optical and photonic components needed to enable commercialisation (see Figure 8-2).

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[149] *Marco Lucamarini et al., "Implementation Security of Quantum Cryptography - Introduction, Challenges, Solutions," White Paper (ETSI, July 2018), https://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp27_qkd_imp_sec_FINAL.pdf.*

[150] *CEN-CENELEC FGQT, "Standardization Roadmap on Quantum Technologies" (CEN-CENELEC, March 2023), https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Quantum%20technologies/Documentation%20and%20Materials/fgqt_q04_standardizationroadmapquantumtechnologies_release1.pdf.*

[151] https://www.gsma.com/

[152] *GSMA, "Quantum Computing, Networking and Security – Version 1.0," White Paper (GSMA, March 2021), https://www.gsma.com/newsroom/wp-content/uploads//IG-11-Quantum-Computing-Networking-and-Security.pdf.*

[153] *OIDA, "OIDA Quantum Photonics Roadmap: Every Photon Counts," OIDA Reports, March 8, 2020, 3.*

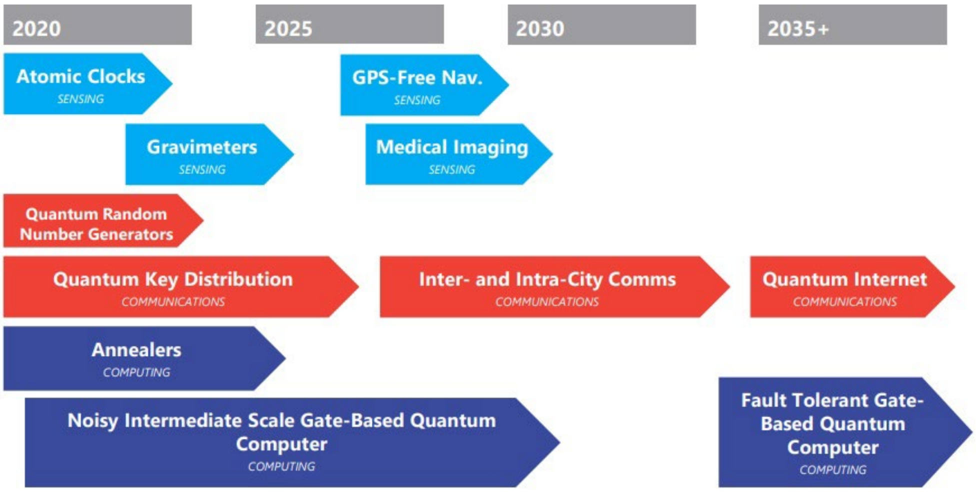

Figure 8-2: The OIDA Quantum Photonics Roadmap for QTs and related services[154]

Standardising QTs can be the foundation for significant market uptake by providing proofs of reliability, consistency, and interoperability with existing infrastructure, systems, and components. Standardisation not only concerns the requirements that form the basis of certification, but also addresses terminology, quality benchmarks, models, exchange protocols, etc.

Standardisation outputs serve different needs over the time the technology is being developed. In light of this, various projects have worked on classifying standardisation requirements and linking these needs with the TRLs[155,156].

At early-stage TRLs, standardisation needs include, in particular, a common language between different research groups, common metrics, and standardised measurement methods. The SDOs can support these needs with common agreed terminology, with metrology and testing methods, benchmarking models, etc.

During the prototyping development and evaluation phase (TRL 4–6), there is a need to prove and demonstrate the functionality of the technology. SDOs can support this need with common agreed functionality tests, quality metrics, guidelines, and best practices such as algorithms and systems.

As the technology becomes more mature (TRL > 6), it becomes necessary to support integration with existing technology and market distribution – in particular, by assuring customers of the quality of the technology. SDOs can support this need with

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[154] *Source: OIDA..*

[155] *Barbara Goldstein, "The Dream of a Common Language" (NIST, June 2021), https://www.itu.int/en/ITU-T/webinars/20210623/Documents/Goldstein%20Final.pdf?csf=1&e=GdALdj.*

[156] *CEN-CENELEC FGQT, "Standardization Roadmap on Quantum Technologies."*

interoperable protocols and interfaces to facilitate the integration process, as well as with certification processes.

We present a more simplified grouping of standardisation activities per TRL clusters (we adopted three TRL clusters: research, prototyping and market readiness) as shown in Figure 8-3. Standards are important for the development of technology, and the specific standards that are necessary to further support a specific technology can vary depending on the needs of the technology and its intended applications. Based on the TRLs of the various technologies, we suggest specific standards that need to be produced during the next decade. It is important to note that since standardisation is an ongoing process, the list of specific standards that need to be developed may grow and evolve as the technology itself and the needs of the industry evolve (as described in the SIR).

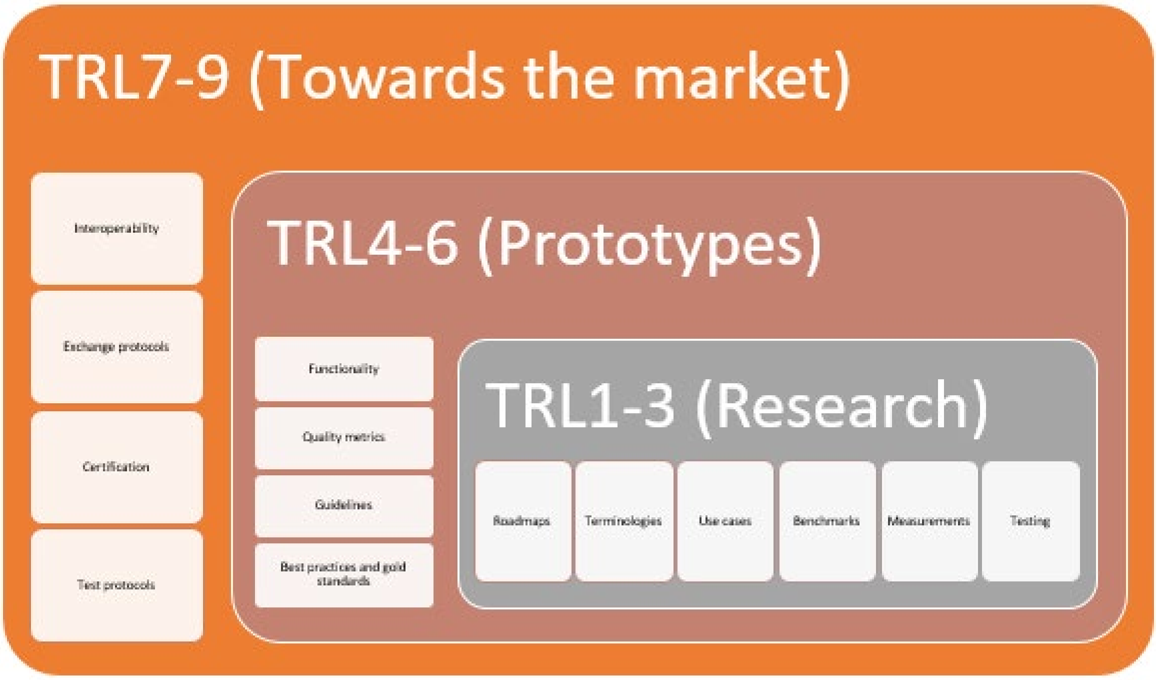

Figure 8-3: TRL-based standardisation clustering

Quantum Communications

The emergence of commercial-grade QKD and QRNG, and their uptake by early adopters in recent years, has resulted in an increased interest in QT standards and certification frameworks. In addition, new standards are needed to integrate QComm into networks and stimulate its commercialisation. The first wave of standardised quantum products concerned quantum cryptography, the process of securing communications, and the QKD security certification. The QKD standards that have been developed cover three main areas:

- Basic definitions (terminology, ontology, use cases);

- Security specifications and evaluation;
- Interoperability.

The standards that are indispensable to guarantee the interoperability of equipment and protocols in complex systems concern the definition of common interfaces.

For QKD, there are 22 published standards and 20 documents under development as follows:

- Several projects within the ETSI ISG QKD – results are published as a Group Specification;
- Several projects within the ITU's SG13 "Future Network" and SG17 "Security";
- ISO/IEC JTC1/SC7 – Software systems and systems engineering;
- ISO/IEC JTC1/SC27/WG3 – Work to begin on IT security techniques – security requirements, test methods and evaluation for QKD (Part 1: Requirements, and Part 2: Evaluation and test methods);
- IEC/TC65 is reviewing QKD in relation to the IEC 62443 series of standards;
- IEEE P1913 – Software-Defined Quantum Communication;
- IETF QIRG.

The complete list of documents can be found in the annex to the OpenQKD publication[157]. These standards cover the topics of QComm module security, fibre network interoperability, quantum network security, quantum-safe cryptography, and QKD terminology.

A roadmap for QComm standards development is shown in the table below.

TRL	TRL 1–3	TRL 4–6	TRL 7–9
QComm technologies	Quantum repeaters, quantum memories, quantum internet	QKD satellite systems	QKD systems, QRNGs
Indicative standardisation activities that need to be developed and support the	• Roadmaps • Terminology • Use cases • Measurements • Testing/benchmarking	• Functionality tests • Guidelines • Quality metrics	• Interoperability • Exchange protocols • Certification

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[157] *Marius Loeffler et al., "Current Standardisation Landscape and Existing Gaps in the Area of Quantum Key Distribution," White Paper (OpenQKD, December 2020), https://openqkd.eu/wp-content/uploads/2021/03/OPENQKD_CurrentStandardisationLandscapeAndExistingGapsInTheAreaOfQuantumKeyDistribution.pdf.*

specific technologies until 2035			

According to the OpenQKD report, there is a need for further development in the security certification of QKD modules, QKD networking, and satellite modules and networks. Both the European (e.g., the ETSI) and national agencies (e.g., the German DIN) demand the development of theoretical and implementation security proofs as well as evidence methods to create frameworks for measuring the security of QKD and QRNG devices. The associated theoretical security models must include the ε-parameter, which represents the probability with which an attacker can guess the secret information of the quantum system. ε-security proofs are a concept inherited from classical cryptography. Example security models include chosen plaintext attacks or chosen ciphertext attacks. Due to the physical nature of quantum security, a quantum ε-security proof must include physical aspects of the system.

Quantum Computing

QC is a domain in which some standardisation efforts have already been undertaken, but many new standardisation projects should be expected in the next few years. The standardisation activities listed below can support the various QC technologies on the road to 2035.

TRL	TRL 1–3	TRL 4–6	TRL 7–9
QC technologies	Prototype quantum computers	QC demonstrators	Deployed quantum computers, e.g. quantum annealers
Road to 2035: proposed standardisation activities	• Roadmaps • Terminology • Use cases • Measurements • Testing/benchmarking	• Functionality tests • Guidelines • Quality metrics	• Interoperability • Exchange protocols • Certification

Quantum Sensing

The first quantum products expected to require standardisation are precision timekeeping tools to further improve the security of communications. There is also a clear need for standards for sensing, imaging, and measurement. It is essential, therefore, that national metrology institutes should participate in the activities of the

SDOs. These efforts can be strengthened through engagement with the EMN-Q[158]. Based on the progress of the single-photon sources and SPDs and quantum sensors as described in the relevant sections of this SIR, we can cluster these technologies based on their existing TRL and their expected developments within the next decade as follows:

TRL	TRL 1–3	TRL 4–6	TRL 7–9
Quantum sensing technologies	3D positioning based on NV-centre magnetometry, NMR gyroscopes, accelerometers, and gyroscopes based on atom interferometry, atomic clocks (based on cold atoms, or coherent population trapping)	Miniature atomic magnetometers based on vapour cells, NV centres for sensing microscopic bio-entities and for nanoscale spectroscopy, NV sensors for medical applications, optical clocks for QT-enabled radar, ultra-high-stability optical oscillators for space applications	NV scanning microscopes, atomic vapour cells for magnetocardiography, relaxometers based on NV centres for biological use cases
Road to 2035: proposed standardisation activities	• Measurements • Testing/benchmarking	• Functionality tests • Quality metrics	• Test protocols • Certification

Key Messages

This chapter has highlighted the importance of standardisation in developing and bringing QTs to market, addressing several key points.

There is a noticeable global surge in the need for standardising QTs, a trend that mirrors the technological advance towards practical use and market viability.

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[158] *“EURAMET: Quantum Technologies.”*

Standardisation efforts vary across different stages of QT development. Early stages focus on establishing a common language and metrics, while mid-stage development shifts attention to functionality testing. The most advanced stages involve ensuring interoperability and establishing certification processes.

In the realm of QComm, the development of QKD and QRNG has underscored the necessity for establishing standards, particularly concerning security measures, certification and system interoperability.

QC is another area where standardisation is anticipated, with numerous initiatives (CEN-CENELEC JTC 22, IEEE, ISO/IEC) underway to set relevant standards. Similarly, in the domain of quantum sensing, the push for standardisation is gaining momentum, especially for technologies related to precision timekeeping and measurement tools.

For businesses, getting involved in standardisation processes is considered a key competitive advantage. Therefore, involvement with SDOs can be seen as crucial, particularly for SMEs, though it requires adequate financial support and effective communication of the benefits of standardisation.

Furthermore, it is important to create a supportive environment in QT by facilitating patent pools under fair, reasonable and non-discriminatory terms. This will ensure a balanced return on investment for innovators and affordable access for implementers, including SMEs and startups.

Finally, establishing and strengthening liaisons between SDOs is emphasised as a critical step. Such networks are vital for ensuring effective information exchange and collaboration, offering benefits to both large corporations and SMEs. This collaborative approach underscores the collective effort required to advance the standardisation of QTs effectively.

Intellectual Property

Patents

Overview

IP rights, in particular patents, are an important business tool for companies and organisations active in QT fields. IP not only provides an exclusive right to perform certain activities with respect to products and processes (making, using, selling, importing, distributing, etc.); it can also serve many other purposes. For example, an IP right can:

- Establish prior art, thus preventing others from patenting;
- Create a basis for licensing out technology;
- Form an intangible asset that can be used as collateral;
- Ensure control of the IP during a collaboration;
- Create leverage in negotiations;
- Serve as a marketing or advertising tool;
- Give access to special fiscal status under national legislation;
- Attract investors;
- Safeguard ownership of the technology when people leave the company;
- Strengthen the innovative image of a technology company;
- Promote and identify potential collaborations between companies or RTOs.

It is of the utmost importance that SMEs, in particular startups and spinoffs, understand how IP can be used in their organisations to gain and maintain competitive advantage.

Another mechanism for protecting technology is the trade secret. This approach relies on keeping certain knowledge about a piece of technology secret. A trade secret is not an exclusive right: it is based on contractual relationships, such as non-disclosure agreements or confidentiality clauses in labour contracts and commercial agreements (e.g., cooperation agreements, R&D agreements, etc.).

Reliance on trade secrets as the only means to protect an invention is rarely advisable. This is because of the nature of a trade secret:

- Once a trade secret is lost, i.e., becomes public, it is lost forever;
- A trade secret does not protect against third-party patents;
- Trade secrets are difficult to maintain in an environment with frequent employee turnover or multi-party collaborations.

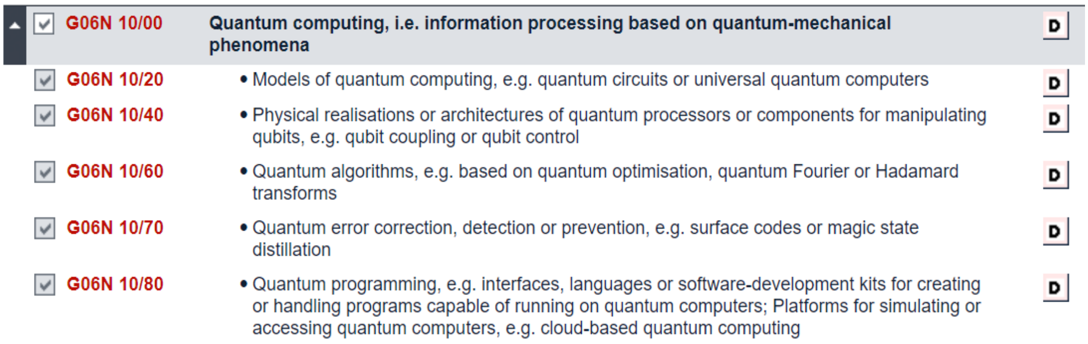
The WG IPT will identify best IP practices for inventions in the quantum industry. These should illustrate that patents and trade secrets are not mutually exclusive and that in technical fields (such as the quantum industry, photonics, and semiconductors), effective protection can be achieved by a combination of patents and trade secrets.

A sustainable IP strategy should be strongly linked to the organisation's business strategy and take into account all the tools needed.

Patentable Inventions in QT

Although there are, of course, many hardware-based QT inventions, a large share of novel work in this field is related to "software" (e.g., algorithms in the form of quantum circuits describing operations to be executed on a quantum computer) and protocols (e.g., QKD protocols). Patent applications for software and algorithms in quantum fields typically cover use cases (applications), algorithmic improvements, protocols, and control functions.

The Cooperative Patent Classification scheme used by the EPO lists topics like quantum algorithms, quantum circuits, error correction schemes, simulations, quantum ML and cloud-based QC.



☑	G06N 10/00	**Quantum computing, i.e. information processing based on quantum-mechanical phenomena**	D
☑	G06N 10/20	• Models of quantum computing, e.g. quantum circuits or universal quantum computers	D
☑	G06N 10/40	• Physical realisations or architectures of quantum processors or components for manipulating qubits, e.g. qubit coupling or qubit control	D
☑	G06N 10/60	• Quantum algorithms, e.g. based on quantum optimisation, quantum Fourier or Hadamard transforms	D
☑	G06N 10/70	• Quantum error correction, detection or prevention, e.g. surface codes or magic state distillation	D
☑	G06N 10/80	• Quantum programming, e.g. interfaces, languages or software-development kits for creating or handling programs capable of running on quantum computers; Platforms for simulating or accessing quantum computers, e.g. cloud-based quantum computing	D

Software and algorithms can be patented in Europe. The legal framework and rules are laid down in the EPO's Guidelines for Examination (the Guidelines). According to the Guidelines, computer-implemented inventions – software inventions, including inventions based on algorithms and AI – are patentable in Europe if an invention has "technical character".

Software as a high-level abstraction from the underlying hardware has technical character only if one of the two following situations applies:

- The software or algorithm is for a specific application[159] identified by the case law of the EPO Boards of Appeal as being "technical";

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[159] *Based on this rule, software in the medical field, image processing and encryption is technical and thus patentable, while software on natural language processing, logistics and finance is in principle not technical and thus not patentable.*

- The software is adapted to the internal functioning[160] of the computer.

These rules provide a relatively clear framework for what is patentable and what is not patentable. Software or an algorithm that runs on a conventional computer (CPU) can only be patented if it deals with a specific technical application. This situation is problematic in the sense that algorithmic innovations that have multiple applications (e.g., a clever convolutional neural network architecture) and are not adapted to the internal functioning of the computer cannot be patented in a generic way, only in specific ways, namely insofar as they are limited to “technical applications” as decided by the EPO.

Currently, the Guidelines do not provide explicit rules regarding software-related inventions in quantum domains. The recent decision G1/19 of the Enlarged Board of Appeal of the EPO regarding the patentability of simulations mentions that QC may make it possible to perform certain simulations by providing computer power which is not available from a standard computer.

Software and algorithms in quantum domains, including quantum ML, are new to the EPO and the Guidelines do not provide clear rules for how to deal with inventions in these fields. A recent EPO seminar concerning examination of inventions in quantum fields suggested that the rules for “conventional” (non-quantum) computer-implemented inventions should be applied to quantum in an analogous way.

The WG IPT has an established contact with the EPO and is maintaining an ongoing discussion on meaningful examination of quantum-related patent applications. The objective is to draw up clear rules regarding the possibilities for patenting quantum-related software and algorithms, so that quantum-related inventions, including software and algorithms, can be protected properly.

The Patent Landscape in QT

The WG IPT has conducted a patent landscape analysis, studying patents filed relating to QT.

The last ten years have seen a significant increase in the development of new IP in quantum research, resulting in a considerable number of patent applications and registrations. This reflects the increased interest in translating new research on QT into new quantum products.

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[160] *Based on this rule, software that is adapted to a specific computer architecture, e.g., the use of a GPU as a co-processor in AI applications or software that is adapted to run on a computer that has a parallel processing architecture is technical.*

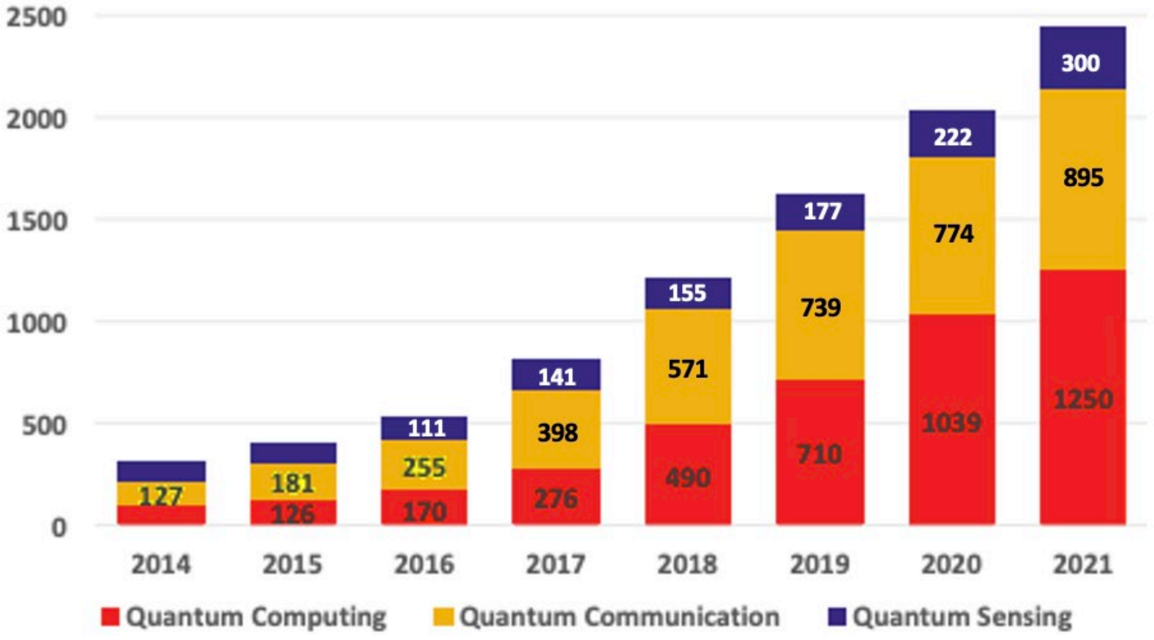

Figure 9-1: Patents filed in quantum sectors

The current patent landscape is dominated by QC, followed by QComm (including quantum cryptography and the quantum internet). At present, these patent families reflect nascent activities and are experiencing increased interest and funding from national initiatives or large groups, as well as startups, indicating the accelerating investment related to QT.

Turning to the European position in terms of patent activities, we must recognise that Europe is lagging far behind the US and China, **with less than 10% of worldwide patent families** (with at least one patent family kept alive). The global leaders in QT patents are, unsurprisingly, the US and China.

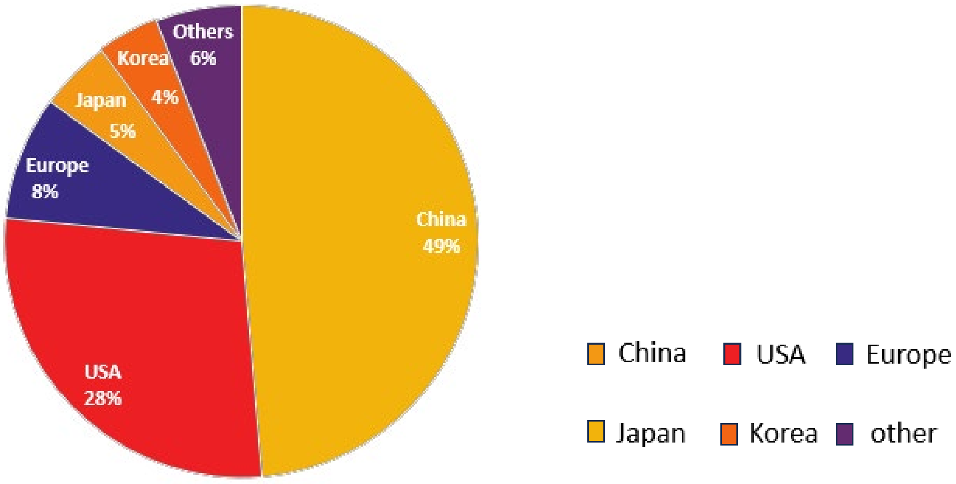

Figure 9-2: Percentage of the total number of patent families

China appears to have filed the lion's share (49%) of patents, but it is well known that very few patents initially filed in China are extended beyond China. However, even when we consider just patent families with patents pending in two (or more) countries (see Figure 9-3 below), Europe is clearly lagging.

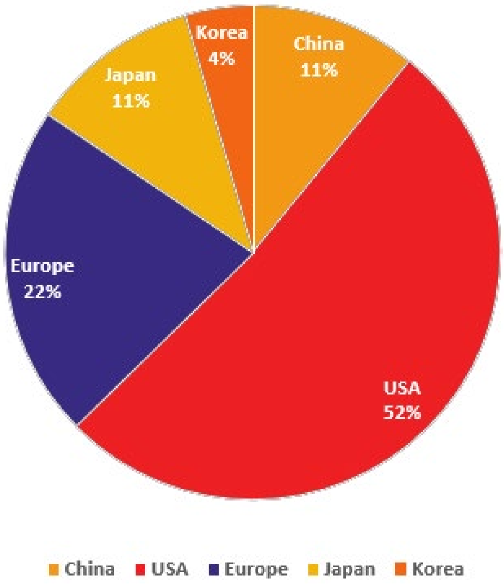

Figure 9-3: Percentage of the total number of patented inventions in two or more countries by country of origin

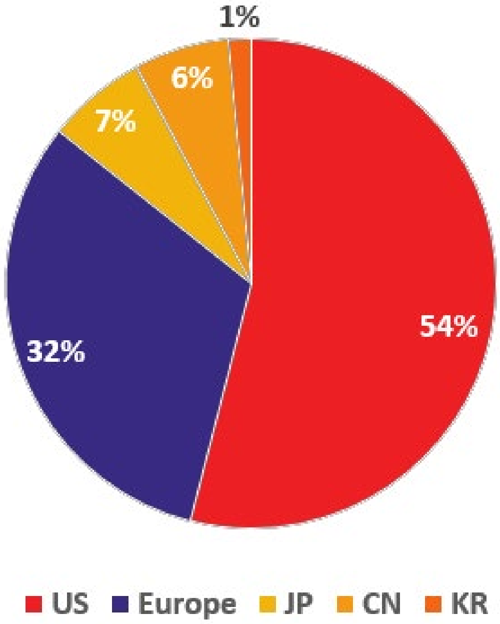

Figure 9-4: Percentage of the total number of patent families for European patents

If we look at the situation in the EPO states by country or region of origin (Figure 9-4), Europe is also lagging behind the US, with less than a third of "European" patents originating from a European country.

Clearly, these huge differences in patent output create a risk for Europe and the European companies, who may find themselves locked out of using the patented technologies.

The general takeaway from the analysis is that QuIC members must give heightened attention to IP protection, otherwise their future market position may deteriorate if they cannot use patents as leverage in business dealings.

It is consequently highly relevant to the autonomy and "sovereignty" of Europe and European companies that they work to significantly increase the number of patent families in the quantum world.

The WG IPT will continue monitoring the patent landscape. Through its contact with the EPO, the WG will keep up to date with patent filing information in QTs. A two-way exchange is envisaged: the WG IPT will inform and educate the QuIC members and will itself liaise with other relevant bodies (EPO and EU). For example, the QuIC WG will help the EPO in reviewing drafts of Patent Insight Reports on quantum topics (in particular, Patent Insight Reports on quantum metrology and sensing, QC, quantum simulation, and QComm).

Export Control

Regulations controlling exports from Europe to countries outside Europe will also need to be managed. This issue has recently become a hot topic with the possibility of including QC and enabling technologies, such as cryogenics, in the list of dual-use technologies subject to export control regulations under the Wassenaar Arrangement. Export controls are common in many areas of high technology and large companies are used to dealing with this issue. However, it could become a major problem for SMEs which are not equipped to deal with the legal and administrative issues involved. As yet, no decision has been taken on the Wassenaar Arrangement, and this is an opportunity for QuIC to express a common position from the European quantum industry.

In view of the above, monitoring export control regulations that apply to quantum is an important focus for the WG IPT. Export control regulations may prevent a company or RTO from importing or exporting equipment, software, or services (including hiring employees) from specific countries or to specific countries and thus present an impediment not only for the current development phase but also for future commercial exploitation. Equally important is to realise that the private investment community will reduce its engagement in the quantum startup field when political considerations start to limit commercial activities and restrict exit strategies.

A particular difficulty with export control regulations is that each country may formulate (within certain boundaries) its own policy. With regulations that vary from country to country, export control becomes difficult and non-transparent, particularly for smaller companies. As an example, there have been proposals in the US for imposing export controls on specific types of quantum computers, while certain cryogenic or laser equipment is already facing export control regulations.

The WG IPT has established an expert group on export control, using it as a platform to share experiences and best practices relating to export control issues.

Road to 2035

There are many challenges faced by European companies who need to build a successful business case in the quantum industry. QuIC and the WG IPT will support these companies by working towards the following goals:

A more balanced situation for European industry regarding patents

As part of its mission, QuIC seeks to understand the key challenges and identify solutions to improve the current patent situation and IP creation in QTs and related fields in Europe.

As such, IPT WG is working on different levels:

- Liaison with the EPO, so as to:
    - Build a shared view of the current European landscape;
    - Identify the obstacles to obtaining patents in Europe;
    - Promote EPO work and efforts regarding different types of training in QTs: for startups, R&D teams, academics, and patent attorneys.
- Helping build general knowledge regarding patenting in QT, especially targeting SMEs and startups.

Clear rules on patentability and build an IP community with strong competence in QTs

Clear rules on the patentability of inventions in QTs and patent attorneys and EPO examiners with strong competence in this field are essential to the IP creation process. These form a necessary framework for stimulating SMEs to protect their innovations using patents and to invest in building a patent portfolio. The EPO and the European IP Helpdesk can help achieving this.

Monitoring and recommendations for SEPs

SEPs play an important role in standardisation, especially for QComm and quantum cryptography, where interoperability between equipment is key. In light of this, WG IPT will liaise with the EU and with SDOs (such as ETSI, IEEE, ISO, etc.) to monitor and study the interplay of patents and standards for QTs and to formulate recommendations for QuIC members and/or relevant bodies.

In particular, it will monitor the developments on the draft EU SEP Regulation (COM(2023) 232 final – 27 April 2023), wherein the EC targets the dissemination of technology for the mutual benefit of SEP holders and implementers of standardised technology.

In the long term, QuIC may engage in the ongoing discussions at European and international level to establish reasonable remuneration criteria for IP developers involved in standards development in quantum domains.

Risk assessment for IP and export control regulations

As QTs become more mature, the risk of having to deal with export control regulations and IP issues will become more significant. As a consequence, the IP landscape and the nationality of the providers may become important criteria in the choice of the various elements of a supply chain.

Therefore, a risk assessment regarding IP and export control regulations for the whole supply chain (i.e., knowing which equipment/component or software may be at risk of facing these regulations or third-party IP issues) should form an integral part of the business plan of a company that is active in the quantum industry. In this assessment, each company should review its supply chain:

- In terms of potential patent infringement (freedom to operate) in and outside Europe;
- In terms of potential export control issues, especially for suppliers from outside Europe.

Key Messages

IP, in particular patenting, plays an essential role in the competitiveness of European companies within the global market of QT. In order to strengthen the IP position of companies in quantum domains, the following key points should be taken into account by policymakers:

- IP strategy for building a patent portfolio in quantum:
  - US and Japanese companies are substantially more active in filing patents than European companies, despite the fact that the scientific output related to QTs in Europe is at least at the same level as the US and Japan. This imbalance in patent filings in Europe compared to other important geographic regions may impose barriers for European companies looking to enter these markets and to exploit their technology within Europe. This imbalance also impacts the valuation of companies by investors.
  - European companies working in quantum, in particular SMEs, should be actively encouraged to improve their IP position and thereby their competitiveness. An IP strategy should be an essential part of the business plan and budget should be allocated specifically to executing this strategy.

- Interplay between RTOs and spinoffs: to give university spinoffs a head start in building a patent portfolio, the objective should always be a smooth transition of patents from the university to the spinoff. Investors will view a spinoff more favourably if it owns the IP. In light of this, it is advisable that initially agreed licensing and co-ownership schemes include a provision that IP can be transferred to the spinoff.

- Patentability of software-related inventions: a substantial proportion of startups and spinoffs develop applications for QC and QComm. These applications include software and algorithms, including AI-related algorithms. For these companies, it is important that effective patent protection for this kind of software application can be obtained in a similar way as in other important geographical areas such as the US and Japan. There is a need for harmonisation on this point and the EPO has an important role to play here.

Funding in Europe

General Overview

QTs are considered strategic technologies by several European nations and the EU institutions. The success of European startups and scaleups, who are Europe's future Google, Amazon and similar, depends on their access to capital. Adequate financial means are the lifeblood of companies when it comes to turning scientific leadership into industrial prowess. The European nations and the EU, like other governments across the globe, have set up funding mechanisms to support local quantum enterprises.

According to a recent investigation by McKinsey & Company[161], the EU is today home to roughly 25% of global startups and SMEs in the QT sector, on a par with the US. However, EU companies attract only 5% of private investments in the sector, a tenth of what similar companies in the US achieve. The EU lacks deep-pocketed VC groups with adequate expertise in QTs to support the competitive expansion of the European commercial QT market. Indeed, around 55% of the investments into European startups in 2021 and 65% in 2020 came from deep-pocketed US VC companies[162]. It is imperative that this imbalance is redressed.

The European Investment Bank (EIB), European Innovation Council (EIC), and the European Investment Fund (EIF), along with national-level public funding organisations, can play an instrumental role in levelling the access to capital in Europe relative to the US. The EU, together with several of its Member States, has set up funding mechanisms to support local quantum companies, notably through the EIB, EIC, and EIF. However, the implementation of EU funding instruments does not allow adequate funding for EU startups or, importantly, EU scaleups. The result is a worrying trend that must be reversed: the EU is failing to deploy capital in large enough sums or and sufficiently rapidly to keep pace with the growth of the QT sector. As an example, in 2022 the valuation of EU startups was a paltry 30% of their US equivalents, and the funds deployed in EU startups were half what was deployed for US startups[163]. EU quantum companies are, in effect, being placed at a disadvantage relative to their competitors in other regions of the world, including the US, Canada, the UK and China.

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[161] *McKinsey & Co., "Quantum Technology Monitor," September 2021, https://www.mckinsey.com/~/media/mckinsey/featured%20insights/the%20rise%20of%20quantum%20computing/quantum%20technology%20monitor/2021/mckinsey-quantum-technology-monitor-202109.pdf.*

[162] *Freya Pratty, "US Investment into Europe's Startups Hits an All Time High," Sifted, May 17, 2021, https://sifted.eu/articles/us-investment-europe/.*

[163] *PitchBook League Tables, completed deals, 2000–2022 .*

The challenging financial situation for EU quantum companies is exacerbated by the present economic downturn weighing on valuations of nascent tech companies[164]. VC funding for startups plunged by more than 50% in 2022–2023. This scarcity of capital could lead to an “extinction event” for the EU’s quantum scaleups, where companies holding collectively hundreds of patents and innovative IP are unable to secure funding and are either abandoned or sold to foreign competitors at discounted prices.

Supporting Academic Startups

We have noted elsewhere in this report that Europe’s scientific base is certainly on a par with other regions of the world, thanks to its strong RTOs, such as TNO in the Netherlands, imec in Belgium, VTT in Finland, CEA in France, and Fraunhofer in Germany. They have been the cradle for a number of European quantum companies.

However, many quantum companies (or potential academic startups) struggle to raise the funding they need. This is partly due to lack of business acumen on the part of their (mostly) young founders. However, some RTOs and universities unnecessarily complicate the negotiations with long and complex procedures including multiple signoffs and/or by placing restrictions on the use or ownership of IP that make the spinoffs unattractive to investors. There is also a need to provide training and mentoring services for the new founders with support from experienced business executives to enable the academic startups to thrive.

Road to 2035

Urgent and decisive action can reverse the trends and allow EU companies to remain top competitors in the global race for quantum commercialisation. Recommended actions include:

Raise the upper limit on direct equity investment from € 15 million to at least € 75 million in order to mobilise adequately sized co-investments for growth funding rounds (€ 100–250 million) to anchor European companies in Europe, rather than seeing them migrate their activities abroad;

Enable the EIB/EIC or other Europe-financed investment funds to take a “lead investor” role – namely, to set the financial terms for funding rounds and the composition of company boards. Such a measure has been successfully implemented by the Business Development Bank of Canada[165];

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[164] *“Venture Capital Funding in Start-Ups Halves as Tech Downturn Bites,” accessed December 29, 2023, https://www.ft.com/content/47747e24-01a4-431f-8ab6-da5fae62e480.*

[165] *“Business Development Bank of Canada - Investments, Portfolio & Company Exits,” Crunchbase, accessed December 29, 2023, https://www.crunchbase.com/organization/business-development-bank-of-canada/recent_investments.*

In addition to the previous recommended action, the EIB/EIC should deploy their capital in rounds led by existing private investors in the companies ("legacy" investors). Such a "large follower" strategy has been used by several foreign-government funding bodies, such as the UK's National Security Strategic Investment Fund in the recent investment rounds of Quantum Motion and Riverlane. In Riverlane's case, one of these legacy investors is Amadeus Capital, co-founded by EIC Board Member Hermann Hauser;

Simplify and accelerate the due diligence process of the EIC/EIB to be more in line with common practices from private capital investments (on the order of 4–6 months);

Advocate best practices (dos and don'ts) for public procurement programmes and their implementation within the EU, including at national Member State level. As a notable example, public procurement programmes should refrain from demanding exclusive ownership of IP developed in the course of manufacturing and delivering the agreed goods/services;

Pursue a measured implementation of the recent foreign direct investment screening framework (Regulation (EU) 2019/452) such that European quantum companies remain attractive targets for European and foreign investors alike, while maintaining Europe's strategic capability in the field. The balanced approach involves VC investments as well as future mergers and acquisitions;

Support the education of investors regarding the investment opportunities presented by QTs in general, and the EU quantum commercial ecosystem in particular;

Provide reliable and beneficial legal and financial frameworks for private investments;

Seek opportunities for investments through pension funds;

Promote the creation of initial public offering opportunities for large EU quantum companies with leading providers of EU stock exchanges, such as Euronext.

Europe has a once-in-many-generations opportunity to position itself as a global leader of a transformative technology. The EU has already recognised this as a pivotal moment, listing QTs as critical technologies for Europe's strategic future. It must also take note of the precarious financial conditions experienced by its startups and scaleups, and promptly adopt changes to allow its quantum stars to remain global frontrunners. If it fails to act decisively in this current moment, Europe risks losing the future quantum champions and with them, its position in this industry.

Key Messages

- There is a need to significantly increase the amount of funding available to Europe-based companies and also to increase the size of the funds to enable larger tickets;
- It is vital to encourage European investors to take on lead investor roles;

- It will be important to attract finance from funders that have not traditionally invested in QTs;
- Europe needs to be supporting academic startups through mentoring programmes and encouraging best practices for RTO and university spinoffs.

Quantum Technology Governance Principles

UN SDGs and Social Objectives

The United Nations' 17 Sustainable Development Goals (SDGs, also called the Global Goals), the European Green Deal, and EU Next Generation funds are all initiatives aimed at developing peace and prosperity around the world. Among other things, the SDGs are meant to serve as guidelines for businesses to operate in a sustainable manner.

These goals are:

1. No poverty;
2. Zero hunger;
3. Good health and well-being;
4. Quality education;
5. Gender equality;
6. Clean water and sanitation;
7. Affordable and clean energy;
8. Decent work and economic growth;
9. Industry, innovation and infrastructure;
10. Reduced inequalities;
11. Sustainable cities and communities;
12. Responsible consumption and production;
13. Climate action;
14. Life below water;
15. Life on land;
16. Peace, justice and strong institutions;
17. Partnerships for the Goals.

Table 11-1: The United Nations' 17 SDGs

Implementing sustainability measures has several benefits for companies. Firstly, several national regulatory bodies are making it mandatory to do so, and some governments are providing capital and tax benefits to enterprises that invest in sustainable activities. Brand reputation is affected by how sustainable a company is, due to social awareness of the issue. Last but not least, major investors are also increasingly mindful of how the companies in their portfolios perform on SDGs. Hence, a business acting sustainably attracts more funding.

Some companies and investors have set examples of impact, by investing in the promotion of a stakeholder economy. An ESG report is a document published by an organisation analysing the organisation's environmental, social, and governance impacts in the geographical areas where it is active. This report is a way for a company to be more transparent about the risks and opportunities it faces. It is a communication tool that plays a significant role in convincing sceptical observers that the company's actions are sincere and compliant with regulations, and that the company represents a secure investment.

As QTs move closer to providing quantum advantage in a range of industries, QuIC should lead efforts to underpin QTs to enable companies to achieve their environmental and social goals by identifying appropriate high-impact use cases.

The potential of QT to change the world is enormous. It has the potential to significantly affect several economic sectors, such as telecommunications, national security, medicine, agriculture, and finance. One of the main topics of discussion on sustainability is the potential of QTs to reduce the energy required for complex computations, even as demand continues to increase. At the same time, the promising processing capabilities of QC could enable new scientific solutions to be used in improving healthcare and better environmental models, part of the UN SDGs, while also bringing benefits for industry, innovation, and infrastructure (Goal 9).

Ethical Values

Emerging technologies have the power to disrupt society. There is a need to consider the social implications of new technologies before they reach full maturity. In the World Economic Forum, the Global Future Council on Quantum Economy aims to support businesses, governments and experts in “maximising the positive potential of this new form of computing and communication”[166]. Ethical concerns regarding QC have been discussed and global ethical “guidelines” are beginning to be drawn up with clear principles and approaches to mitigate the risks and unintended consequences from the outset. Some of these points have been discussed extensively within the QuIC community and are presented below.

Governance challenges

Challenges related to the governance of QT arise from its unique properties and capabilities. To effectively govern QTs, policymakers and regulators need to address these challenges and develop appropriate frameworks and regulations in parallel with the drive towards commercialisation in the NISQ era. Therefore, greater dissemination of information about quantum topics to these stakeholders should also become an essential part of the strategy. The rapid evolution of QTs requires flexible and adaptable governance frameworks that can accommodate emerging technologies and ensure their responsible use.

The complexity of the technology and its multiple application possibilities also pose additional challenges in terms of standardisation, interoperability, and certification.

Security concerns are also a crucial challenge in the governance of QTs. These technologies have the potential to significantly enhance fields such as cryptography and computational power, but they also introduce new vulnerabilities. Quantum

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[166] *“Global Future Council on the Future of Quantum Economy,” World Economic Forum, accessed January 8, 2023, https://www.weforum.org/communities/gfc-on-quantum-economy/.*

computers, for example, can break current encryption algorithms, raising concerns about data security and privacy.

Moreover, international collaboration and coordination will become increasingly important for the governance of QTs given that R&D is taking place in various countries. Relatedly, international collaboration can also help address challenges such as IP rights, technology transfer, and the prevention of unfair competition. By effectively addressing these challenges, appropriate governance of QTs can promote their responsible and secure use for the benefit of society.

Dual-use nature

Dual-use technology refers to technology that can be used for both peaceful civilian purposes and military applications. Different implementations can diverge in the degree to which they might be leverageable for dual-use purposes.

In general, the development of dual-use technology raises various ethical and security concerns. In specific domains, governments and international organisations attempt to closely monitor and regulate the export and transfer of certain technologies to prevent their misuse for military purposes. Companies and researchers involved in developing dual-use technologies find themselves in a position where they need to navigate complex legal and ethical considerations to ensure that their innovations are used for peaceful purposes. This gives rise to the challenge of designing effective regulatory models that do not stifle innovation.

Therefore, it is possible that some implementations of QT might require careful consideration, well-thought-out policies, and international cooperation to ensure that these technologies are used for the greater benefit of humanity while minimising the risks of misuse and harm.

Quantum ethics and policy

The quantum community needs to learn from the current discussions around AI and the impact that this type of technology can have on society, especially when it comes to inequalities and ethics. Quantum technologists have a responsibility to learn from AI and other deep tech fields that are more evolved and to be proactive in anticipating the ways quantum may be misused to harm vulnerable communities. We must ensure QT is designed and used for the greatest and most equitable public good.

In addition to QT addressing societal grand challenges, it is essential to also understand its application to everyday practices. The social purposes of potential users might be diverse when QTs are ready to be adopted by the market, with radical and unexpected innovations emerging. This may create a set of diverse affordances and constraints perceived by social actors and actualised as the use of QTs. Therefore, strategies for communicating about QT with the public are needed, to build trust in these new technologies and ensure benefits accrue to all parts of society in a responsible manner. Scientists, policymakers and communications experts should work together to create narratives around the usefulness of QTs, focused on practical problems that can be solved. The intertwining between the properties of QTs and the social intentions of their users could overcome cognitive biases and facilitate exploration how QTs could be integrated into achieving their daily activities, and this could in turn stimulate innovative practices. Thus, we must ensure that there is ongoing research and investigation in the empirical field to understand the social implications of QTs at the micro-level of usage and adoption.

It is important to take action now before it is too late. Otherwise, the effort required will become exponentially greater – as we have seen in fields such as AI, in which the underlying ethics discussion arrived too late to substantially influence the culture of design in the field. Once QTs are further integrated in different sectors of society, in large infrastructures and in investments in both public and private spheres, efforts to regulate them will become complicated by path dependency as well as pushback from the stakeholders involved (e.g., fundamental shifts to business practices might be required). This highlights the urgency of holding conversations about quantum ethics as soon as possible.

As QTs continue to advance, it is crucial for industry leaders to actively engage in the discussion surrounding quantum ethics. Sound reasons exist for industry actors to play a proactive role in such deliberations. Considering the current nascent and NISQ status of the technology, and its strategic importance for the EU, it would be sensible to pursue a realistic and evidence-based approach that moves towards developing achievable safeguards without stifling innovation prospects.

Technological sovereignty

The dual-use nature of QT and its potentially huge impact on almost all aspects of civil life also mean access to key technologies must be assured. Development of the EU-based quantum industry must have highest priority here, but it is also important to negotiate and regulate access to QTs owned by foreign allies.

Quantum information science and technology is crucial for the EU economy. It has the potential to drive innovation, stimulate economic growth, create job opportunities, and improve various sectors such as healthcare and cybersecurity while offering better solutions to optimisation problems. By further investing in and supporting R&D in this field and harnessing the power of QT, the EU can position itself as a global economic powerhouse and a leader in technological advances. By embracing digital sovereignty in QT, Europe can safeguard national security, control its own digital infrastructure and promote fair competition while protecting the rights of European citizens and the interests of the European industry.

Moreover, having control over its own digital infrastructure will allow the EU to shape the rules of the game and develop new policies that align with its values and interests. Taking a proactive approach will be essential for the EU to maintain its competitive advantage in the digital era and this could go hand in hand with action plans such as mapping critical components and dependency relationships.

Given the “collect now, decrypt later” risk, one of the additional reasons for digital autonomy when it comes to QT is to ensure the safety and security of EU citizens’ data.

The EU should develop and invest in robust cybersecurity measures, such as secure networks, encryption technologies, and incident response capabilities. This proactive approach will help to safeguard the EU’s critical infrastructure and sensitive data from potential threats and attacks.

It is important to work towards balanced and sensible policies in different domains, such as international export control and immigration, so as to ensure security, privacy, economic leadership and defence against cyber threats, and thus ensure that the EU can protect its citizens and maintain its digital sovereignty. By striking a balance between international cooperation and asserting its own interests, the EU will position itself to navigate the complex digital landscape and stimulate its continued growth and relevance in the quantum era.

The industry would be best positioned to lead and contribute to these discussions, given its expertise and knowledge regarding the actual capabilities of frontier tools and applications: it is best-placed to provide an informed assessment of potential implications and challenges that the technology could represent (without falling for either hype or doom scenarios). Additionally, industry players have a first-hand understanding of the realm of technological and engineering design possibilities. They can draw on their own experiences and the challenges they have encountered, giving them an excellent knowledge basis that could be used to inform the development of practice-oriented, effective ethical guidelines and regulations. The industry representatives must also be willing to take a collaborative approach, with multistakeholder deliberations involving academics, researchers and civil society in relevant aspects, while making sure that operability is not ignored when it comes to turning these discussions into guidelines and drawing up best practices to help ensure that QTs are used responsibly and ethically. Additionally, industry involvement will allow the creation of targeted, use-case-driven sets of best practices.

Inclusivity

The commercialisation of QTs holds immense potential for transforming various industries. To aid a positive transformation path, it is crucial to actively engage broader communities in the collaboration efforts. We list some of the ways that this can be done below:

- SMEs play a key role in the European economy and in social and economic inclusion. By **supporting quantum industry SMEs**, the EU can foster economic development in a wider range of geographic locations, including underserved areas. To address this issue, it is crucial to implement policies specifically targeting SMEs, such as reserving a certain capacity of HPCs for SME access. Such policies can coexist with policies that reserve access rights for research and academic institutions, and the additional time dedicated to SMEs will also boost European innovation in QT, since new discoveries are likely to emanate from these talent pools. Furthermore, these policies would also lower the barriers to entry for SMEs and enhance the competitiveness of the EU's QT ecosystem.

- To promote wider participation, it is essential to provide accessible and comprehensive **education and training programmes** on QT. These programmes should cater to individuals from diverse backgrounds, including students, professionals, and entrepreneurs, taking into account different education systems in the Member States (vocational training programmes, etc.). Beyond the classical higher education structure, offering additional online courses, certifications, and bootcamps can help bridge the knowledge gap and empower individuals to actively participate in the commercialisation process. This SIR document also analyses and provides recommendations on this in detail in Chapter 7 – Workforce Development.
- In order for the EU to remain competitive and foster growth in QT, it is also necessary to support **education and professional training for active policymakers**. The objective must be to help policymakers to navigate the complexities of this technology and drive responsible policymaking aligned with current legislation and regulations. By gaining a comprehensive understanding of the potential impacts of QTs, and the framework of ethical considerations and regulatory frameworks surrounding these emerging technologies, policymakers can help ensure society is able to harness the benefits of quantum while mitigating potential risks.
- One of the primary steps in engaging wider communities is to **raise awareness** about the potential benefits and applications of QT. This is also crucial to maximise the benefits of public consultations regarding policymaking processes on QTs. Some events might be designed to provide a basic understanding of QT as well as its impact on different sectors, and the opportunities it presents for businesses and individuals.
- Creating **dedicated collaboration platforms** could facilitate inclusive engagement in commercialisation of QTs. These platforms could serve as a space for networking, knowledge sharing, and collaboration among various stakeholders, including researchers, industry experts, entrepreneurs, and investors. By fostering an inclusive environment, these platforms could encourage the exchange of ideas and promote collaborative efforts.
- To foster a dynamic and fruitful knowledge exchange, it is worthwhile to build **strong partnerships between the public and private sectors**. European and national public authorities have a vital role to play in creating an enabling environment for commercialisation of QTs, through funding programmes, policy frameworks, and regulatory support. By collaborating with industry leaders, academia, and RTOs, governments can drive innovation and attract investments in the field. To promote healthy competition and low barriers to entry, it is also advisable to pay specific attention to the inclusion of SMEs in these processes.
- Building an inclusive ecosystem also involves reaching out to underrepresented groups and regions. Implementing **targeted outreach programmes** helps ensure inclusivity and diversity in the collaboration efforts such as initiatives focused on women in STEM, rural communities, and disadvantaged groups. By providing equal opportunities and resources, these programmes could help unlock the potential of a wider talent pool and foster innovation from diverse perspectives.

- There are also opportunities for taking the lead **on a more international dimension** to make QTs available for applications in LMICs. The immense potential of QTs, particularly QC, to revolutionise various fields, is highly relevant for LMICs. However, despite their potential, the availability and accessibility of QTs in LMICs remain limited. Europe now has the opportunity to take the lead at a more international level to bridge the gap between LMICs and QTs:
    - By establishing dedicated projects with a humanitarian goal, Europe could demonstrate leadership in this area;
    - These projects could focus on leveraging QTs to address critical challenges in LMICs, such as healthcare, agriculture, and energy. Such projects would have the potential to make QTs more accessible and impactful in LMICs, ultimately contributing to social and economic development in these countries;
    - Additionally, these projects would provide a platform for collaboration between Europe and LMICs, fostering knowledge exchange and capacity building. This collaboration could help accelerate the adoption of QTs in LMICs, enabling them to harness their full potential and contribute to the advancement of science and technology on a global scale.

An example initiative that seeks to provide inclusive access to QC, and aims at developing concrete solutions to achieve the SDGs, is the Open Quantum Institute, created by the Geneva Science and Diplomacy Anticipator in October 2023. In general, collaboration and engagement at all levels are key to ensuring a sustainable and impactful future for QT.

Commercialisation and open innovation

Implementing open innovation principles in development and commercialisation processes can significantly enhance an organisation's ability to drive innovation, accelerate time to market, and gain a competitive edge. By fostering a culture of collaboration, engaging in co-creation, and implementing effective governance mechanisms, organisations can tap into external knowledge, ideas, and resources to fuel their commercialisation projects. They create structures allowing them to focus on their core expertise, while benefiting from the expertise of partners in areas that are not their own core business. As part of engaging in open innovation, organisations can decide to embrace open IP strategies for some of their own inventions, and may leverage open innovation platforms. Making technology available under appropriate open-source licences directly benefits its creators by giving them increased exposure and publicity, plus the opportunity to build a user community and obtain critical feedback on their work. The open-source model can also help facilitate collaboration between organisations. In some cases, the successful establishment of an open-source technology might allow the European community to create a de-facto standard, and take the lead in specific technologies.

Another positive aspect of open innovation is that it also entails a strong collaborative environment across organisational boundaries. When multiple parties work together, differences relating to time schedules, work modes, choice of digital tools, and communication styles can become amplified. Therefore, managing inter-organisational collaboration becomes a critical element, including managing inter-organisational learning flows, flexible use of ICT, and temporary structuring of inter-organisational/inter-professional teams. Cultivating an appropriate corporate culture and workplace climate are also vital elements for successfully implementing inter-organisational collaboration and open innovation. Achieving this involves building inter-organisational trust, and establishing inclusivity and equality as the boundaries of the quantum ecosystem are increasingly expanded.

We underline that a commitment to open innovation does not necessarily imply involvement in all these activities, and in particular does not force the open sharing of IP. Indeed, it is very important that a commitment to open innovation does not infringe European, national or internal strategies and priorities regarding IP rights. By openly sharing IP, companies and organisations may inadvertently provide their competitors, including those from foreign nations, with valuable insights and technological innovations. This can result in dilution of the market share, reduced profitability, and a diminished ability to differentiate products or services from competitors.

Another risk of open IP strategies is the loss of control over how the IP is used. This is a particular issue for dual-use technology with a clear potential for misuse or unintended consequences. When technology is openly shared, it becomes accessible to a wide range of actors, including those with malicious intent. Patenting and IP issues for QTs were discussed in more detail in Chapter 9 – Intellectual Property.

Road to 2035

- **Policy frameworks:**
  - Establish comprehensive and clear frameworks to govern the development, export, and transfer of QTs;
  - Frameworks should be adaptable and responsive and address the potential risks and security concerns associated with the misuse of QTs.
- **International cooperation:**
  - Build collaboration and cooperation among countries and governments to establish international standards, share information, and develop common guidelines for the responsible use and transfer of QTs;
  - Work on systems and guidelines to help prevent the proliferation of these technologies to unauthorised entities or countries.

Key Messages

- **Environmental and social objectives:** Implementing sustainability measures aligns with global initiatives such as the UN's SDGs and the European Green Deal. Businesses benefit from sustainability not only by complying with regulatory requirements but also by enhancing brand reputation and attracting major investors.

As QTs advance, QuIC should lead efforts to align QTs with environmental and social goals, addressing high-impact use cases.

- **Ethical values:** The development of QTs necessitates a proactive consideration of ethical implications. The World Economic Forum's Global Future Council on Quantum Economy emphasises the importance of ethical guidelines. Relevant issues include:
  - **Governance challenges:** QTs pose unique governance challenges, requiring flexible frameworks to address rapid technological evolution. Security concerns, standardisation, and international collaboration are key aspects. Disseminating information to stakeholders, including investors, is vital. Effective governance can ensure responsible use and security in the development and deployment of QTs.
  - Addressing the risks of **dual-use technology**, promoting international collaboration, and overcoming governance challenges require a focus on ethical principles and global cooperation.
  - **Industry-led quantum ethics:** The industry would be best positioned to lead and contribute to these discussions, given its expertise and knowledge regarding the actual capabilities of frontier tools and applications: it is best-placed to provide an informed assessment of potential implications and challenges that the technology could represent (without falling for either hype or doom scenarios). Additionally, industry players have a first-hand understanding of the realm of technological and engineering design possibilities.
  - **Inclusivity and collaboration:** Inclusivity in commercialisation of QTs involves education, awareness, and collaboration. Providing comprehensive educational programmes, raising awareness, creating collaboration platforms, and fostering partnerships with the public and private sectors are essential for a sustainable and impactful future for QT. **Policymaker education** requires a twofold approach: a focus on QT literacy for those with non-technical backgrounds, in tandem with training and development of future policymakers following curricula in law and social science programmes, to ensure that they have the appropriate understanding to inform policy. Providing reserved access rights to HPCs **specifically for SMEs** (in addition to research institutions) will lower the barrier to entry to the quantum marketplace and foster competitiveness of the EU's QT ecosystem.
  - **Commercialisation and open innovation:** Open innovation principles enhance the ability of an organisation to drive innovation and gain a competitive edge. However, a commitment to open innovation should align with IP strategies and organisational priorities. Careful consideration of risks, including loss of control and competitive advantage, is crucial. Balancing openness with strategic goals ensures the positive impact of commercialisation of QTs.
- **Road to 2035:** The journey to 2035 involves establishing clear policy frameworks for the development and transfer of QTs. International cooperation is paramount, emphasising the need for collaborative efforts among countries to set standards and guidelines. Adaptable frameworks can address potential risks and security concerns associated with the misuse of QTs on a global scale. Regarding EU-level collaboration, the key steps will be forming a European Common Strategy that takes

into account Member States’ individual agendas, and encouraging joint research projects from different national agencies.

Conclusions

QTs can be grouped into five pillars: QC, quantum simulation, QComm, quantum sensing and metrology, and enabling technologies. Each of these pillars has its specific challenges, technical requirements, and development roadmap.

Countries around the globe have identified QTs as a strategic resource for their futures. This conclusion leads to geopolitical competition, pitting China, the US, all of Europe, and many other regions against each other. Although Europe has a long tradition of research in quantum physics, the US has a larger pool of private investments in QTs, and China has been providing the largest share of public investment to develop QTs. In this context of global competition, Europe must deploy the necessary financial resources, make available leading infrastructure, and facilitate the attraction and development of talent within the ecosystem.

Access to and subsidised use of pilot lines and test facilities are critical to accelerate the development of leading QTs. It is important to note that several enabling technologies critical to the fabrication of QTs are not currently available in Europe. The absence of a European supply creates a risk of dependency. These gaps need to be filled or otherwise identified to derisk.

In addition, European governments must act as early adopters of QTs. Acquisition programmes for quantum products and services to solve societal and business challenges must be implemented to stimulate demand. These programmes should further allow private users (businesses) to experiment with the use and benefits of QTs. This would have the added benefit of encouraging the development of industry standards. As QTs mature and are more widely adopted, the importance of standards will grow.

Another relevant topic is IP. A well-designed process for managing IP and licensing is fundamental and will bring significant commercial benefits to all industry players. European governments should create incentives for the generation of IP and promote cooperation between startups and large established companies. It is also important to establish a Europe-wide technology transfer process from universities and RTOs, based on past best practices.

It is clear that QTs have vast potential to change our world. They will impact a multitude of sectors, such as medicine and drug discovery, communications and privacy, energy and the environment, agriculture, finance, and national security. It is therefore imperative for policy- and decision-makers to take close note of the recommendations included in this report, and extend the range of support for the commercialisation of QTs in Europe.

Appendix: Technology Readiness Levels

The SIR uses the TRLs defined by the EC[167]

TRL 1 – Basic principles observed
TRL 2 – Technology concept formulated
TRL 3 – Experimental proof of concept
TRL 4 – Technology validated in lab
TRL 5 – Technology validated in relevant environment
(industrially relevant environment in the case of key enabling technologies)
TRL 6 – Technology demonstrated in relevant environment
(industrially relevant environment in the case of key enabling technologies)
TRL 7 – System prototype demonstration in operational environment
TRL 8 – System complete and qualified
TRL 9 – Actual system proven in operational environment
(competitive manufacturing in the case of key enabling technologies; or in space)

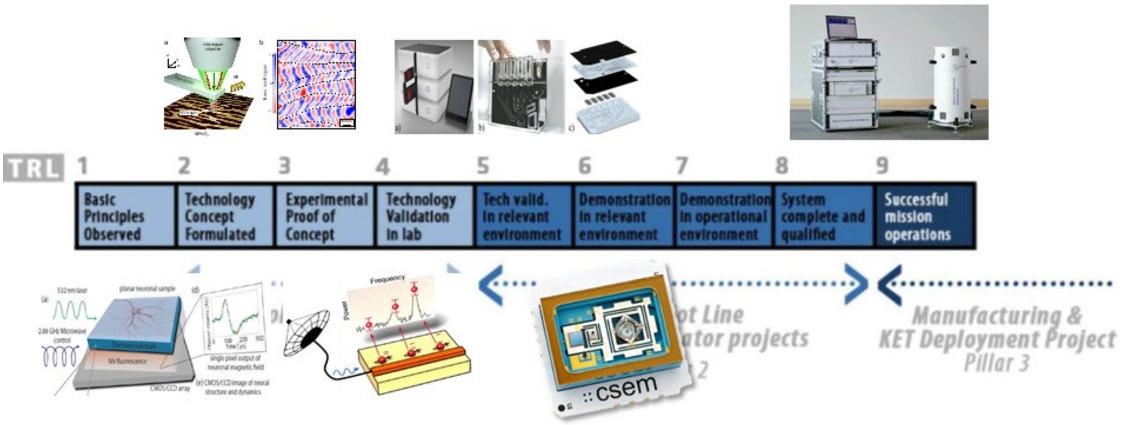

Figure 13-1: Technology Readiness Levels

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[167] *"HORIZON 2020 – WORK PROGRAMME 2014-2015; Annex G," December 19, 2014, https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf.*