Quantum computing technologies roadmap and assessment of emergent and promising quantum computing technologies

2021-2022

HPCQS has received funding from the European High-Performance Computing Joint Undertaking (JU) under grant agreement No 101018180. The JU receives support from the European Union's Horizon 2020 research and innovation programme and Germany, France, Italy, Ireland, Austria and Spain in equal parts.

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1 Introduction

Expectations on the outcome of the race towards quantum computing are still very high, and analysts show that the trend is not slowing down. According to the World Economic Forum, **public investments** in quantum technologies increased by **$3.2 billion in 2021** alone, and by **over $5.5 billion in the past decade**. These figures are probably lower than the reality, as not all of these investments are publicly disclosed. IDC projects that **investments in the quantum computing market will reach nearly $16.4 billion by the end of 2027**. The same analysts expect **customer spending on quantum computing to reach $8.6 billion by 2027**.

The various academic and industrial players involved in High Performance Computing - Quantum Computing (HPC-QC) are showing **progress** that supports this optimism. However, it’s still very **hard to decipher HPC-QC-related announcements**. The risk of overselling or misinterpretation is very high, as much of this information is exploratory and needs to be carefully analyzed by a handful of experts to make it available to a wider audience. At this stage in the history of quantum computing, **fact-checking** by experts is crucial. Scott Aaronson, in the US, and Olivier Ezratty, in Europe, are good examples of this fact-checking initiatives.

Also, **most players in the field are only beginning to consider the integration of quantum computing and high-performance computing.** These two worlds have long been clearly separated and are still in the early stages of their integration, so many announcements still refer exclusively to quantum computing. Nevertheless, it’s interesting to see that more and more companies are attending HPC conventions such as ISC22 (Hamburg, Germany, June 2022) and SC22 (Dallas, TX, November 2022), with panel sessions and conferences that address the topic of HPC-QC integration.

The information provided in this report mainly stems from **conversations of GENCI and its partners have had with players in the HPC and Quantum Computing industries**. It also comes from **publications that are listed in section 6 of this report**. It focusses specifically on developments in the HPC-QC technology landscape between late 2021 and early 2023 that could have an impact on HPCQS, and the partners involved in this project.

2 Description of Activities

2.1 HPC-QCS technological orientations for 2021-2022

During the start of the High Performance Computer and Quantum Simulator hybrid (HPCQS) project (end of 2021 - 2022), some main trends have been observed in the HPC-QC area. We start this report with an overview of these main topics.

a. Nobel Prize in physics highlights nascent quantum industry

The 2022 Novel Prize in Physics was awarded to Alain Aspect, John F. Clauser and Anton Zeilinger, for their respective **experiments on quantum entanglement**. All three managed to implement Bell's experiment to demonstrate that quantum entanglement is real. This led to breakthrough applications in various technological fields such as quantum communications and quantum computing. The announcement by the Royal Swedish Academy of Science brought an additional media coverage for the quantum computing industry.

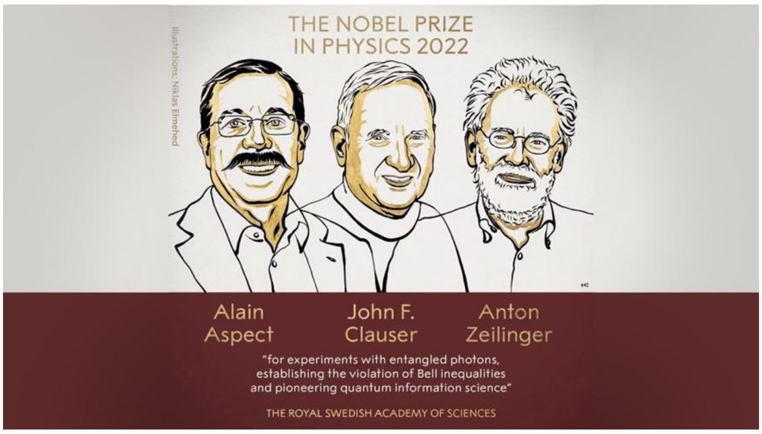


Figure 1 Presentation of the three 2022 Physics Nobel Prize laureates, Alain Aspect, John F. Clauser and Anton Zeilinger, produced by the Royal Swedish Academy of Sciences

b. Platform scalability is moving from scale-up to scale-out models

The number of qubits on a quantum computing device is still a very broadly observed and discussed metric, although it was demonstrated that this is widely insufficient to evaluate the performance of a platform and make fair cross-comparison between different platforms.

Distinction between scale-up and scale-out has emerged in 2022, with IBM's roadmap showing how they attempt to move from a one-QPU- (IBM Q System One, announced in 2019) to a multi-QPU-ready infrastructure (IBM Q System Two, to be launched in 2023 with a modular and flexible design, combining multiple processors into a single system with communication links, and optimized new cryostats allowing a 70% increase in wire density and a 5x reduction in price-per-line). Other players such as Rigetti went for the same approach that can be clearly identified in their roadmap as a shift from a one-chip to a multi-chip technology. At first, the QPUs will be connected through conventional electronics, so information will not be transferred from processor to processor in a quantum way. However, it is widely perceived as the first step towards modular quantum computing technologies, ultimately connected through quantum communication links, that would allow information to leverage quantum properties all through the system.

The objective of this new research field is to exploit quantum communication technologies to entangle several chips and thus provide more scalability. This distributed quantum computing paradigm requires coherent links in the form of a fiber-optic network with quantum repeaters or some fiber that goes through a ground station and a satellite network. These technologies have been demonstrated recently:

- 2017: Coherent quantum communications accomplished between nodes separated by 1,200 kilometers using the Chinese satellite Micius.
- March 2022: quantum repeater relays quantum information over 600 kilometers of fiber optics.

Several companies have emerged, worldwide, to support this scale-out trend by providing **quantum links and quantum memories**, such as **QPhox** (Netherlands) and **WeLinQ** (France). Numerous technical challenges will have to be overcome to achieve such connections, particularly for platforms that have strong cooling requirements, such as superconducting qubits. It's also important to **distinguish between intra-system homogeneous and inter-system heterogeneous quantum interconnects**. The challenges associated with both areas are likely to be different.

A **roadmap for quantum interconnect** was published by the **Q-NEXT** initiative led by Argonne National Laboratory (ANL, USA): https://publications.anl.gov/anlpubs/2022/12/179439.pdf

"Quantum communications, where coherent qubits are transferred over distances as large as hundreds of kilometers, will be an essential part of the quantum computing story in 2023", says Jack Hidary, CEO of SanboxAQ, a quantum technology company that was spun out of Alphabet in 2022.

"We have to entangle across these things," Sutor said. "We need to build a bigger quantum computer by being able to do quantum operations among smaller quantum cores, and this is how we will grow." Bob Sutor, ColdQuanta VP.

In order to make the most of the current scale of the devices, several organizations have initiated research on how to **split circuits in smaller ones that can run on current devices**. Then they will knit these circuits back together using classical post-processing. This type of trick has been pushed by **IBM**, through **its Circuit Knitting toolbox**, for example.

c. Qubit robustness is improving, as shown by new metrics

Apart from announcing a steady growth in the number of qubits on its superconducting platforms, IBM's new roadmap showcases **Heron, a new processor that will have 133 qubits –less than the 433-qubit Osprey chip – of the highest quality** (targeted two-qubit error rate of 99.99% instead of 99.9% on Osprey)**.** The latter should be demonstrated by a higher Quantum Volume and better Circuit Layer Operations Per Second (CLOPS) than those demonstrated by Osprey. The French start-up **Alice & Bob** announced they were able to multiply the qubit lifetime by a factor 100,000, demonstrating an **8-minute-long resistance to bit flip**, whereas the first world records were limited to a few milliseconds.

The Schrödinger superconducting qubits they are using are said to be less error prone, with a coherence time about 300 times longer than other technologies.

Progress is also being made in the field of **error correction and error mitigation**. One month after **Google Quantum AI**'s latest publication on the same topic, **Quantinuum** issued a new scientific paper showing **experiments where logical qubits outperformed physical qubits**. These results are said to provide a path towards scalability, qubit efficiency and fewer circuits for fault tolerance. **Keysight** provides its **True-Q error characterization and mitigation software** to support end-users achieve better performances. They signed a **partnership with Rigetti** in 2022 to support the hardware company in providing its users with a more reliable way to use its quantum computing devices. The **IBM and IonQ teams are also working on limiting the impact of noise on users'** experiments by predicting it and trying to compensate for it. They admit that performances are not ideal, but they hope to make progress as noise characterization improves. This could also reduce the resources needed to perform error correction. **PsiQuantum** announced in December 2022 that they had found a way to **optimize the use of resources** on their chips for error correction, which would allow a 50-fold improvement in the run-time efficiency of compiled applications.

Numerous benchmark initiatives arise, as we seek to decipher the relative performances of the first available systems, as well as the ones announced or forecasted by the various technology providers. The number of qubits available on a platform is still widely used as a baseline indicator of the scalability of a technology, but it has been shown to be misleading in terms of that platform's ability to perform actual computations. Therefore, we need to find additional parameters to evaluate and compare quantum computing technologies. According to BCG, "the key is designing benchmarks that are useful (they tell users what they need to know), scalable (they can expand and adapt to evolving technologies), and comprehensive (they cover all the relevant attributes)". Lawrence Berkeley National Laboratory (LBNL) chose to rely on a methodology that is as close as possible to the LINPACK method for ranking HPC systems in the TOP500 list. IBM provides a benchmark suite covering scale (number of qubits), quality and speed:

- Quality is measured by the "**Quantum Volume**", a metric that evaluates the maximum size square quantum circuit that a quantum processing unit (QPU) can reliably sample with a probability greater than 67%.
- **Circuit Layer Operations Per Second (CLOPS)** measure how fast a QPU can execute circuits.

Attempts have also been made to publish **application-oriented benchmark strategies** such as **Q-score** (Atos) to help end-users identify the most appropriate technology for their applications.

In April 2022, the US Defense Advanced Research Projects Agency (DARPA) announced that its Quantum Benchmarking program had selected Raytheon BBN ($2.9 millions), the University of Southern California (USC, $4.1 millions), and a team of five organizations including Aalto University, IonQ, University of Technology Sydney, University of Texas at Dallas, and Zapata Computing, to work on research projects and find new benchmark strategies.

In November 2022, **Terra Quantum** and **QMware**, two **Swiss quantum software startups**, published the results of an **application-oriented benchmark analysis of publicly available quantum processing units and quantum emulation platforms**. They used two algorithms: **Quantum Neural Network (QNN)** and **Hybrid Quantum Neural Network (HQNN).** They compared various metrics on the following platforms: **Rigetti Aspen M-2 (80 qubits), IBM Q Falcon r5.11 (27 qubits), IonQ Harmony (11 qubits) and OQC Lucy (8 qubits)**, as well as the **QMware HQC4020, AWS m5.24xlarge and AWS SV1** emulation environments. Benchmark metrics included **runtime, circuit fidelity and training costs**.

Systems benchmark ⟵⟶ Application benchmark

Origin	IBM		Sandia National Laboratories	UC Berkeley / Berkeley Lab	Atos	QED-C	Super.tech
Benchmark	Quantum Volume	Circuit Layer Ops / Second (CLOPS)	Mirror Circuits	Quantum LINPACK	Q-Score	App-Oriented Suite	SupermarQ Suite
Basis	Maximum size of square quantum circuits that can be implemented	Speed in executing layers of a parameterized model circuit	Executing quantum circuits forward and backward	Performance in a prerequisite task for linear algebra	Performance in solving a standard optimization problem	Executing common quantum algorithms / programs	Executing common quantum algorithms / programs plus error correction
Pros	✓ Inclusive measure of performance ✓ Practical measure of noise ✓ Cannot be "gamed" with classical improvements	✓ Evaluates speed of whole-machine operations ✓ Covers quantum-classical latency	✓ Captures significant error sources outside of gate error rates ✓ The forward-backward "mirror" execution makes the benchmarks easily verifiable	✓ Predicts efficacy in scientific computing applications	✓ Predicts efficacy in optimization applications	✓ Targeted toward practical applications ✓ Evaluates whole-machine operations	✓ Targeted toward practical applications ✓ Evaluates whole-machine operations ✓ Scalable for post-supremacy testing
Cons	✗ Non-square circuits can be predicted only directionally ✗ Applies only to near-term quantum computers	✗ May not measure speed in all applications ✗ No distinction between classical and quantum improvements	✗ Indirect measure of application performance	✗ Less useful for comparing computers that "pass" the test ✗ Restricted to linear algebra	✗ Restricted to optimization	✗ Applies only to near-term quantum computers ✗ No distinction between open and closed systems ✗ No distinction between classical and quantum improvements	✗ No distinction between classical and quantum improvements ✗ No distinction between open and closed systems

Source: IBM; Sandia National Laboratories; UC Berkeley; American Physical Society; Atos; Quantum Economic Development Consortium; Super.tech; BCG analysis.

Figure 2 Overview of the current state of quantum computer benchmark strategies, provided by BCG

d. The industry is becoming increasingly structured (partnerships, ecosystems)

The **market is becoming more structured**, with start-ups and specialization in all parts of the value chain: from the development of qubits and enabling technologies to the production of applications. It can be very difficult to keep track of all the new players emerging in various fields. The following table from CBInsights attempts to provide an overview of the start-ups that belong to the different categories in the value chain of the quantum computing industry. Of course, this can't be exhaustive and these tables need to be updated very frequently.

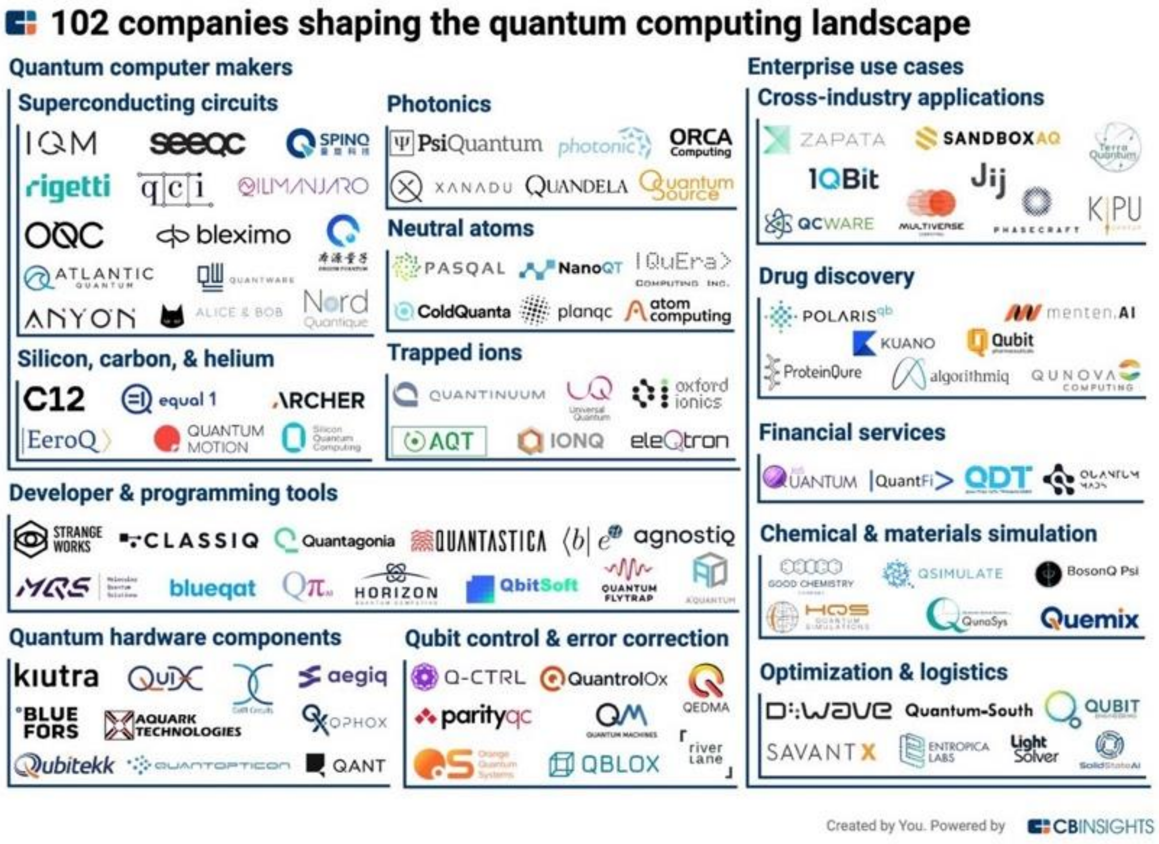


Figure 3 The 102 startups racing to commercialize quantum computing, by CBInsights, in October 2022

In addition, **numerous partnerships have emerged**, that make sense out of this diversity. For example, Atos has strengthened its ties with QPU providers like Pasqal (through HPCQS) or IQM, to ensure that these technologies are well integrated with their middleware. Nvidia launched CUDA Quantum with a very broad base of partners, to showcase the potential integration of numerous technologies with their HPC-QC approach. Other partnerships, such as those between Menten AI (biotechnology) and Xanadu, JPMorgan Chase and Toshiba, or E.ON and IBM, consist in leveraging a targeted technological expertise to explore the potential of quantum computing to solve a specific business use case.

Figure 4 Nvidia CUDA Quantum platform ecosystem presented at the TQCI EDF event in Paris on Jan. 11th, 2023

The industry has also seen a number of **mergers and acquisitions** that tend to enhance the ability of single players to add value to their customers. This is the case for Pasqal, which acquired Qu&Co in January 2022. The French and Dutch companies, which specialize in neutral-atom-based quantum hardware and quantum algorithms and software, respectively, have merged with the perspective of achieving a quantum advantage through their complementary technologies.

e. Convergence between HPC and quantum computing is becoming a reality

Access to hybrid HPC-QCS environment is becoming a reality. In Europe, it was materialized with the **launch of the European HPCQS project in December 2021**, led by Forschungszentrum Jülich (FZJ, Germany), which announced the acquisition, of **two 100+-qubit Pasqal neutral-atom quantum simulators** in June 2022. These devices, coupled with the JUWELS (Germany) and Joliot Curie (France), HPC systems, will be accessible by the end of 2023 for research purposes.

In 2019, **the Jülich UNified Infrastructure for Quantum computing (JUNIQ)** was established at the **Jülich Supercomputing Centre (JSC)** and has since been undergoing intensive development. Within JUNIQ, software tools, modeling concepts, algorithms, and prototype applications are developed. Currently, JUNIQ provides **access to a 5000+ qubit Advantage system of D-Wave Systems Inc. nicknamed JUPSI (JUelich Pioneer for Spin Interference)**, which is physically operated at JSC from January 2022 on. An access is also granted to most advanced software emulators of quantum computers running on supercomputers. At SC22, visitors of the JSC booth could live code JUPSI via JUNIQ. From the end of 2023, the Pasqal quantum simulator acquired in the EuroHPC JU project HPCQS will be added. The latter – like the D-Wave quantum annealer – will be installed in the **new vibration-free JUNIQ building**, which has been specifically designed and built in 2020/2021 at the Forschungszentrum Jülich (FZJ). A unique selling point of JUNIQ is the **tightest possible HPC-QC integration based on the modular supercomputing architecture concept**. It allows JUNIQ to provide a variety of quantum computing and hybrid quantum-HPC capabilities to researchers across Europe.

In the framework of the **Finnish Quantum-Computing Infrastructure (FiQCI)**, **VTT's 5-qubit quantum computer HELMI ("Pearl")** was connected in November 2022 with the **European supercomputer LUMI ("Snow"), hosted by CSC – IT Center for Science** in Finland. This is the first milestone on a road that will lead to a 50-qubit upgrade planned for 2024.

During the SC22 fair, the Munich-based **Leibniz Supercomputing Center** (Leibniz Rechenzentrum, LRZ) hosted the **Finnish startup IQM** on their booth. They wanted to promote **BMBF's €45.3-million Q-EXA project** on which they are collaborating with **Atos** (France) and **HQS** (Germany), to work on the integration between HPC and quantum computing. LRZ also hosted a dinner with IQM and they participated in a **workshop titled "Quantum Computing: A Future for HPC Acceleration?"** during which they discussed this topic with other experts in the field like Travis Humble, from Oak Ridge National Laboratory (ORNL, USA). **The first HPC-QC services in LRZ's Quantum Integration Center (QIC) should start in the coming months.**

2.2 Public initiatives and funding

Quantum computing has been identified as a critical and strategic technology by most governments. The emergence of this industry has been heavily funded in recent years. Here is an overview of recent public initiatives and funding announcements.

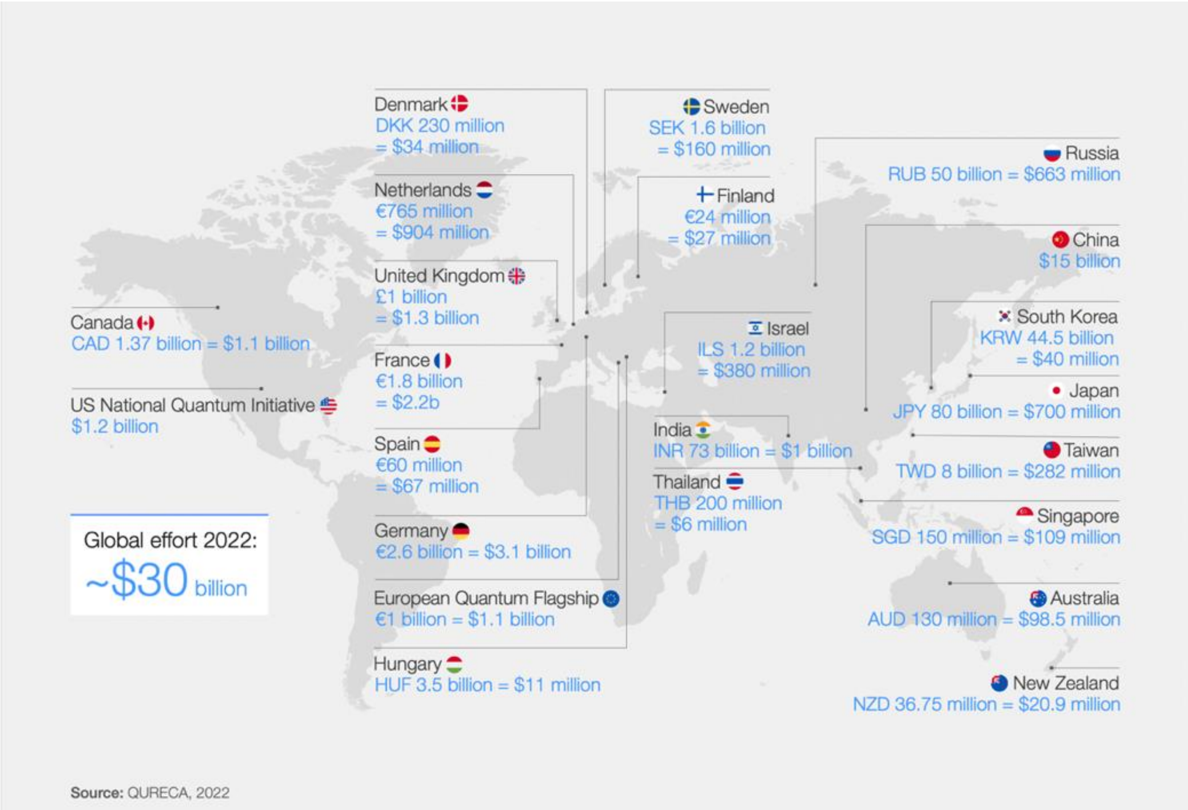


Figure 5 Overview of public funding for quantum computing worldwide, by the World Economic Forum in 2022

a. America

The **United States** government has strengthened its national program launched in late 2018: the National Quantum Initiative Act. In December 2022. The White House announced the appointment of fifteen experts in quantum information science who will form the **National Quantum Initiative Advisory Committee (NQIAC)**, which will advise President Biden on quantum-related topics. The US government's strategy also includes the creation of the **Quantum Economic Development Consortium (QED-C)**, which fosters the development of a quantum industry in the country. The **US CHIPS and Science Act**, passed in August 2022, includes a funding package to support quantum computing initiatives, workforce and infrastructure in the US, as well as measures to deny China access to American quantum computing technologies. Through the Department of Energy, six National Quantum Information Science (QIS) Research Centers have been established and numerous initiatives have been launched. It includes the **Quantum Computing User Program (QCUP)**, led by Oak Ridge National Laboratory, which provides users remote access to major commercial quantum computing devices. QCUP includes a user base of over 150 research scientists. GENCI and CEA met Travis Humble, Director of the Quantum Computing User Program, at SC22, and he was willing to collaborate with European centers to foster transatlantic collaborations and exchanges between users. The US is seeking collaborations with European countries on this topic, and the White House Office of Science and Technology Policy signed a **joint statement** with the French Ministry of Higher Education and Research in December 2022 **on cooperation in Quantum Information Science (QIS) and technology.**

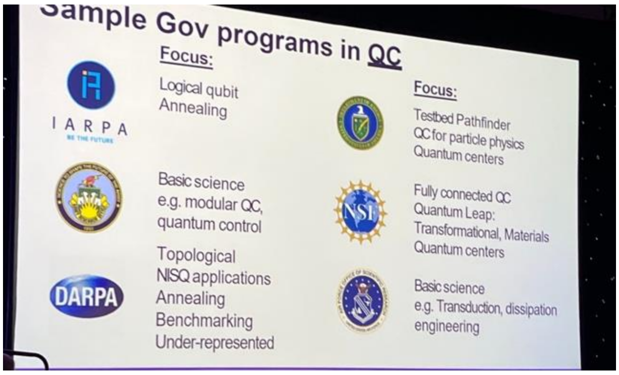


Figure 6 Presentation of US-based initiatives by Michael Metcalfe (University of Maryland) at SC22

Canada is not only home to Quantum Valley – an area in Ontario stretching roughly from Waterloo to Toronto – and to some outstanding players in the field such as D-Wave and Xanadu. It also pledged in January 2023 an **additional $360 million investment** in quantum technologies over seven years to support the implementation of its National Quantum Strategy. It focuses on expanding the country's strength in quantum research, innovation and commercialization. It covers all quantum technologies. The Business Development Bank of Canada launched the $200 million Deep Tech Venture Fund, which invested in Toronto-based Xanadu and Sherbrooke-based Nord Quantique in 2022, after previously investing in D-Wave. Provincial investment is also key in Canada, as the **Government of Quebec** has announced a $131 million investment in the creation of the **Sherbrooke Quantum Innovation Zone**, including $87.5 million to access state-of-the-art quantum computing infrastructure (IBM Q System One, Anyon Systems) and more than $8 million in quantum innovation projects of start-ups and SMEs. Other provincial governments such as **Ontario, Alberta** and **British Columbia** have launched similar programs.

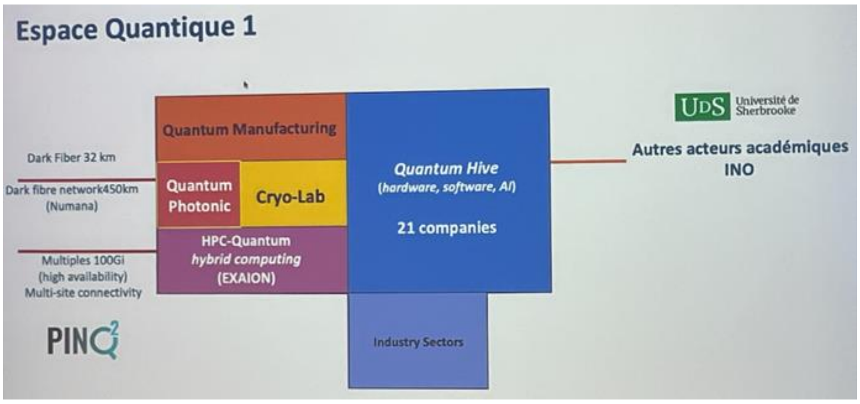


Figure 7 Description of the "1st Quantum Space" in the Sherbrooke Quantum Innovation Zone presented at the TQCI EDF event in Paris on Jan. 11th, 2023

b. Europe

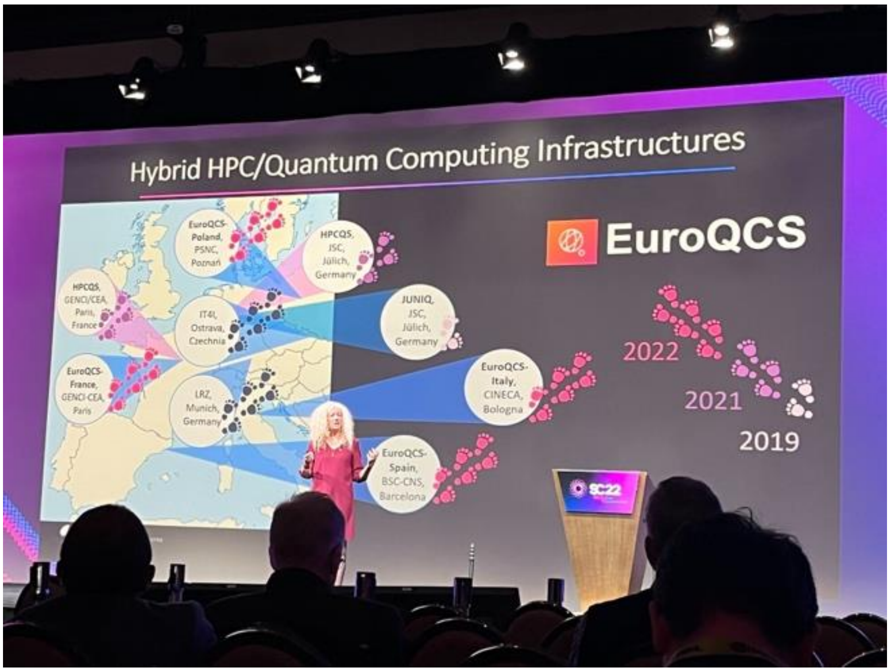


Figure 8 During her keynote at SC22, Kristel Michielsen (Forschungszentrum Jülich, Germany) presents the steps towards EuroQCS

The European High Performance Computing Joint Undertaking (EuroHPC JU) announced in October 2022 that they selected six sites across the European Union (EU) to host and operate their first EuroHPC quantum computers: IT4I (Czechia), LRZ (Germany), BSC-CNS (Spain), GENCI-CEA (France), CINECA (Italy), and PSNC (Poland). Here follows an outlook on the type of technologies that will be made available to European research communities through the six selected institutions, complementary to the two first 100+-qubit Pasqal simulation platforms acquired through HPCQS:

IT4I (Czechia)	Superconducting
LRZ (Germany)	Superconducting (error correction)
BSC-CNS (Spain)	Superconducting (annealing)
GENCI-CEA (France)	Photonic
CINECA (Italy)	Cold atoms
PSNC (Poland)	Trapped ions

In **Denmark**, the **Novo Nordisk Foundation Quantum Computing Programme** was announced in September 2022, allocating a **DKK 1.5-million grant** to develop a **universal fault-tolerant quantum computer within the next 10-12 years**.

France inaugurated the first piece of its National Quantum Strategy in January 2022, dedicated to the convergence between HPC and quantum computing – **France Hybrid HPC Quantum Initiative (HQI)**. Relying on a **physical platform** and an **ambitious research program**, this initiative will benefit from the **Pasqal quantum simulation device** acquired in the framework of HPCQS. It will also include access to the **photonic quantum computing device acquired in the context of the EuroQCS-France consortium**, co-funded by EuroHPC JU. End-users will also be supported through a **high-level support team (HLST),** the creation of a **"Houses of Quantum" label** and financial incentives to set up **industrial proofs of concepts**.

In 2021, the "Mission Quantum Computer" was launched in Germany. The goal of the Federal Government is the strategic expansion of quantum technology. **The Mission Quantum Computer is funded by the Federal Ministry of Education and Research (BMBF) with €1.1 billion**, and a total of **€2 billions** is available for the development of quantum technology **until 2025**. In addition to the BMBF, the Federal Ministry for Economic Affairs and Energy (BMWi), the Federal Ministry of Finance (BMF) and the Federal Chancellery (BKAmt) are also involved. **The BMWi provides a total of €878 millions for the development of quantum technologies and quantum computers and for their practical applications. The largest share of the funds, €740 millions, went to the German Aerospace Center (DLR).** Together with large industrial partners, small and medium-sized enterprises (SMEs), start-ups and research institutions, DLR will form two consortia whose task will be to **build a quantum computer in Germany and develop the corresponding software and applications**. As part of its €740 millions **Quantum Computing Initiative (QCI)**, the German Space Agency (DLR) has started to award million-euro contracts in 2022 to several providers to support the nascent industry:

- **€13 millions** awarded over 3 and a half years to **Advanced Quantum** from Allmersbach (Baden-Wurttemberg) and **Diatope** from Ummendorf (Baden-Wurttemberg) to develop qubits based on high-quality diamond layers with nitrogen-vacancy (NV) centres;
- **€14 millions** awarded to Dutch company **QuiX Quantum** to deliver a 64-qubit photonic quantum computer in four years.

The foundations for the quantum computing mission have already been laid in Germany since 2018 in various research projects funded by the BMBF under the **framework programme "Quantum Technologies - from Fundamentals to Market"**. In the "Mission quantum Computer" the next big step comes towards quantum computing and the construction of a first quantum computer.

In March 2022, **the University of Padua (Italy)** announced that it will host **the first general purpose trapped ion quantum computer in Italy,** thanks to the investment of the World Class Research Infrastructure (WCRI) in a project called **Quantum Computing and Simulation Center (QCSC),** led by the Padua Department of Physics and Astronomy with a consortium of partners, including CINECA and INFN (National Institute of Nuclear Physics).

In the Netherlands, after being awarded in April 2022 **€615 million from the Dutch Ministry of Economic Affairs and Climate Policy**, **Quantum Delta NL** – a public-private foundation – announced in November 2022 that they had just opened **the first location of the House of Quantum in Delft**. The first companies that joined the national quantum campus are Orange Quantum Systems, Qblox and Qphox.

Spain also launched a very ambitious program, called **"Quantum Spain"** in October 2021. It was created with an initial **€22-million funding** approved by the Council of Ministers. This amount will be **complemented by various European public and private initiatives to reach €60 million of investment**. This decentralized initiative involves 25 universities and HPC infrastructures in 14 autonomous communities, with the goal to promote and finance **a complete quantum infrastructure in Spain**. In January 2023, the **Galician Supercomputing Center (CESGA)** – a member of the Quantum Spain program – announced it will acquire a **€14-million quantum computer from Fujitsu** that will be installed this year, to complement the Atos Quantum Learning Machine (QLM) coupled with its Finisterrae III supercomputer.

The **United Kingdom's Ministry of Defence (MoD)** announced in June 2022 that it had just ordered its first quantum computer from London-based **ORCA computing**. The **PT-1 quantum computer** will be used by the MoD on-site to develop use cases as part of a one-year programme. *"Accessing our own quantum computing hardware will not only accelerate our understanding of quantum computing, but* *the computer's room-temperature operation will also give us the flexibility to use it in different locations for different requirements,"* said Stephen Till, fellow, Defence Science and Technology Laboratory, an executive agency of the MoD.

c. Middle East and Africa

Israel has been very active in the field through its state-owned **Israel Innovation Authority (IIA)**, which is funding 8 projects through its participation in the European network **QuantEra**. It has allocated **$28 million** to establish an **Israeli Quantum Computing Center (QCC)** over the next three years, exposing several technological approaches to entrepreneurs and research scientists. Among the partners of this initiative are Quantum Machines, Elbit Systems and Classiq (Israel), but also ParTec (Germany), QuantWare (Netherlands), ORCA Computing (UK) ColdQuanta and Super.tech (US). Israel and the USA will co-fund four joint quantum technology projects over the next four years, with IIA investing **$5.8 million** and the US National Science Foundation investing double that amount. Beginning of 2023, the IIA announced it would invest in a homegrown consortium to develop two quantum computing technologies – superconducting qubits and trapped ions.

The Doha-based Hamad bin Khalifa University (HBKU), announced in April 2022 the establishment of a **Qatar Center for Quantum Computing (QC2),** to secure **Qatar**'s strategic future on this technology and position it as a global player in this emerging technology.

The **Quantum Research Center (QRC)** at **Abu Dhabi's Technology Innovation Institute** is partnering with the Barcelona-based startup **Qilimanjaro.** They are currently developing a **5-qubit chip**, and announced they will reach **at least 30 qubits in the next two years**. NYU Abu Dhabi professors organized in April 2022 **UAE's first quantum computing hackathon**, which brought together more than 150 students.

d. Asia

Fujitsu and **RIKEN Research Institute (RIKEN Center for Quantum Computing – RQC)** announced in 2022 that they expect to deliver a superconducting quantum computer in the **spring of 2023**. Fujitsu will then become the first domestic company to commercialize a quantum computer in the country, as the first one was installed by IBM. Fujitsu's QPU will have **64 qubits** at first, and this number is expected to **grow to 1,000 qubits within 3 years**. This machine will be conceived and produced in Fujitsu's newly-built Wako City research center. *"The initial focus will be on applications for materials development, drug discovery, and finance,"* says Shintaro Sato, head of the quantum laboratory at Fujitsu Research.

In December, a paper was published by **24 Chinese research scientists** on ArXiv, titled "*Factoring integers with sublinear resources on a superconducting processor*", which caused a lot of discussions in the ecosystem. Indeed, the paper suggests that they **found a new approach to factor a large 2048-bit semi-prime number using a NISQ 372-physical-qubit device with around a thousand-gate depth**. This news was received by some readers as a threat to the RSA-2048 encryption code, which relies on the fact that this factoring problem is exponentially difficult to solve on a classical device. However, several responses, including Scott Aaronson's **mitigated the hype** by highlighting the fact that this method relies on the variational algorithm QAOA (Quantum Approximate Optimization Algorithm), which has not yet proven to yield any quantum speedup.

Korea's Vice Minister for Science, Technology and Innovation Joo Young-Chang recently stated in a conference that "Korea **lacks an industrial ecosystem in the quantum computing sector**, which widens its technological gap with the other advanced economies". The Korean government had introduced a **$37.6-million investment strategy for quantum technologies** in April 2021.

e. Australia

During SC22, the **Pawsey National Supercomputing Center**, located in Perth, hosted on their booth the start-up Quantum Brilliance. At a dinner co-organized by LRZ and IQM, Ugo Varetto, Pawsey's CTO, presented the installation of a **Quantum Billiance 2-qubit system** on their premises.

2.3 Main industry highlights

The evolution of the quantum computing industry has been tremendous in the past five years. This momentum should be further amplified as investments are expected to rise. IDC expects **investments** in this market to reach nearly **$16.4 billion by the end of 2027**. The same analysts project that the worldwide **customer spend** for quantum computing will grow to **$8.6 billion in 2027**.

a. QPU providers

In this section, we briefly review recent advances, trends and perspectives in the field of qubits.
Some further approaches to cloud access are mentioned and complement section c.

- **Cold atoms**

Company	QC Modality	Note/Comment
PASQAL	Analog	324 qubit processor gaining increasing commercial success but not yet generally available
QuEra	Analog	256 qubit machine publicly accessible via Bracket
planqc	Analog	Early-stage spin-out from Max Planck Institute; access to their machine not yet available
atom computing	Digital/Gate Based	100 qubit processor not yet generally available, but select beta customers utilizing
Infleqtion	Digital/Gate Based	100 qubit processor not yet generally available, but select beta customers utilizing

Figure 9 Summary of the main neutral-atom quantum platform providers and the state of their technology by Russ Fein - QuantumTechBlog, Jan. 17th 2023

Cold atom quantum simulators, such as those from **Pasqal**, **Atom Computing** and **QuEra** have joined other technologies in the cloud. **QuEra** made its 256-qubit Aquila available through **AWS Braket**. Most of these providers have announced that they are **willing to add gate-based quantum computing to quantum simulation**, through individual control of the cold atoms.

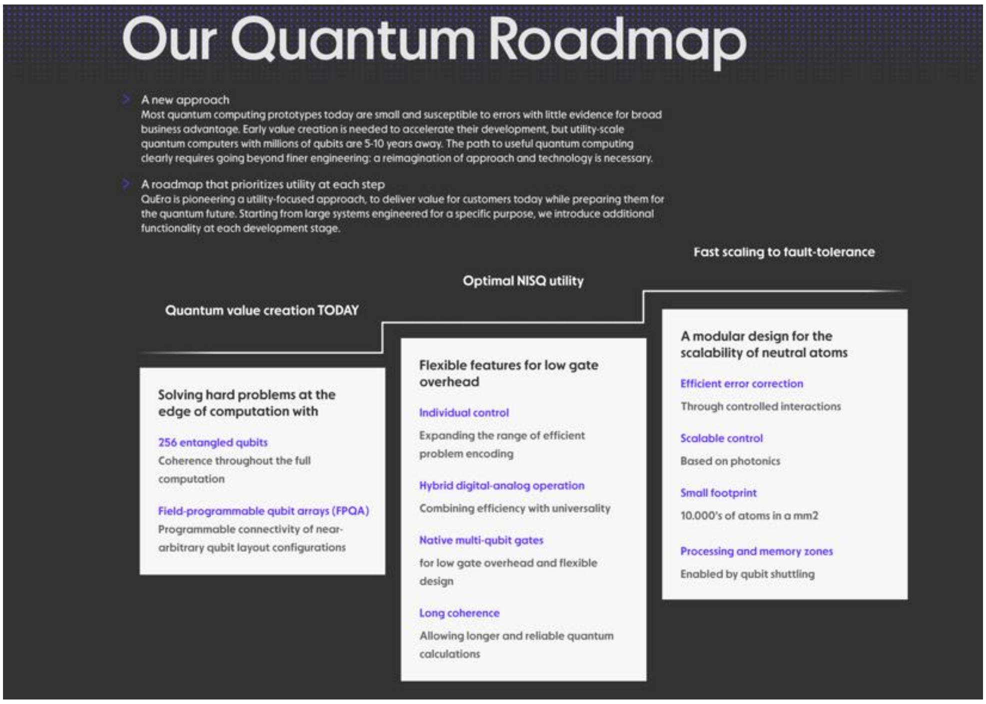


Figure 10 QuEra's roadmap towards Fault-Tolerant Quantum Computing

- **Superconducting qubits**

As part of the **D-Wave Clarity roadmap**, the Canadian company has announced it would provide access to the **Advantage 2 quantum annealing system** sometime in 2023/2024, with **7,000+ qubits** and a new topology allowing 20-way connectivity. It is also seeking to achieve **gate-based quantum computing** to expand the technology's application scope. We should hear more from them after their annual Qubits meeting on January 17-19, 2023.

IBM's new product roadmap for quantum computing was released in November 2022 during the annual IBM Quantum Summit. It features the **433-qubit Osprey** processor and the **1,121-qubit Condor** chip. They also announced their will to move **from a single-chip to a multi-chip approach**. The concept of the **higher-fidelity 133-qubit Heron** processor pushes the perspectives even further by presenting the possibility of a **modular architecture**, in which multiple processors could directly be connected to each other.

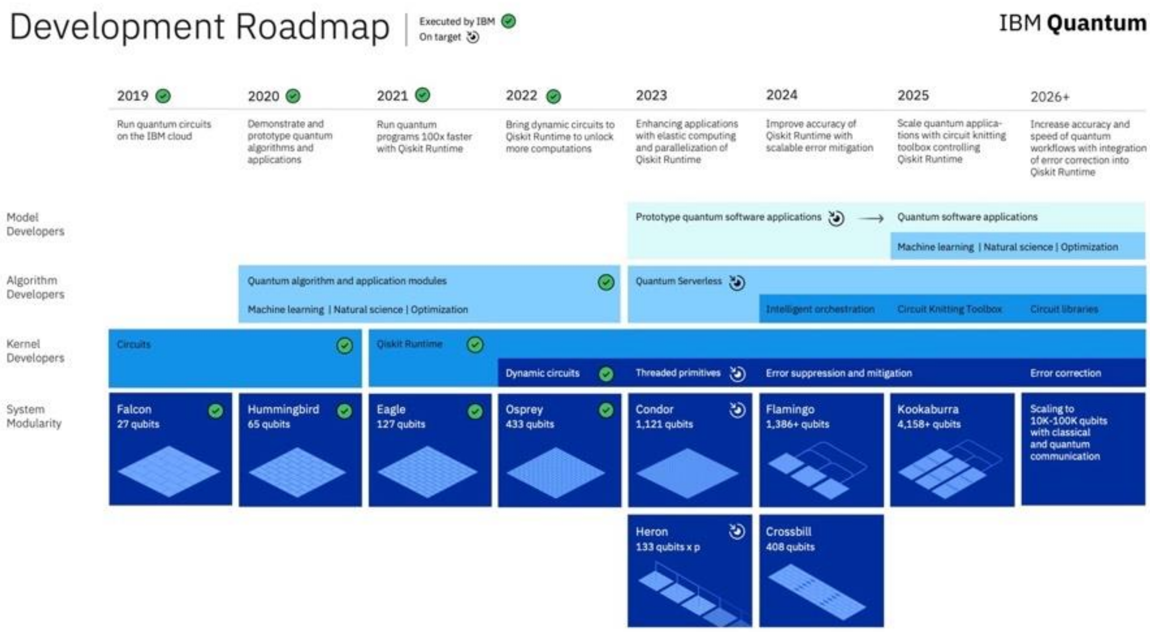


Figure 11 IBM roadmap for quantum computing

Rigetti expanded their roadmap to include the upcoming **84-qubit Ankaa** system (early 2023), a one-chip device, followed by the **336-qubit Lyra** system (later in 2023), which was described by Chad Rigetti (former CEO) as a **"constellation" of Ankaa dies**. The Californian company has partnerships to expose their technology both in Microsoft Azure and AWS, and is expanding its research collaborations with DOE laboratories such as Oak Ridge National Laboratory (ORNL), Lawrence Livermore National Laboratory (LLNL) and FermiLab.

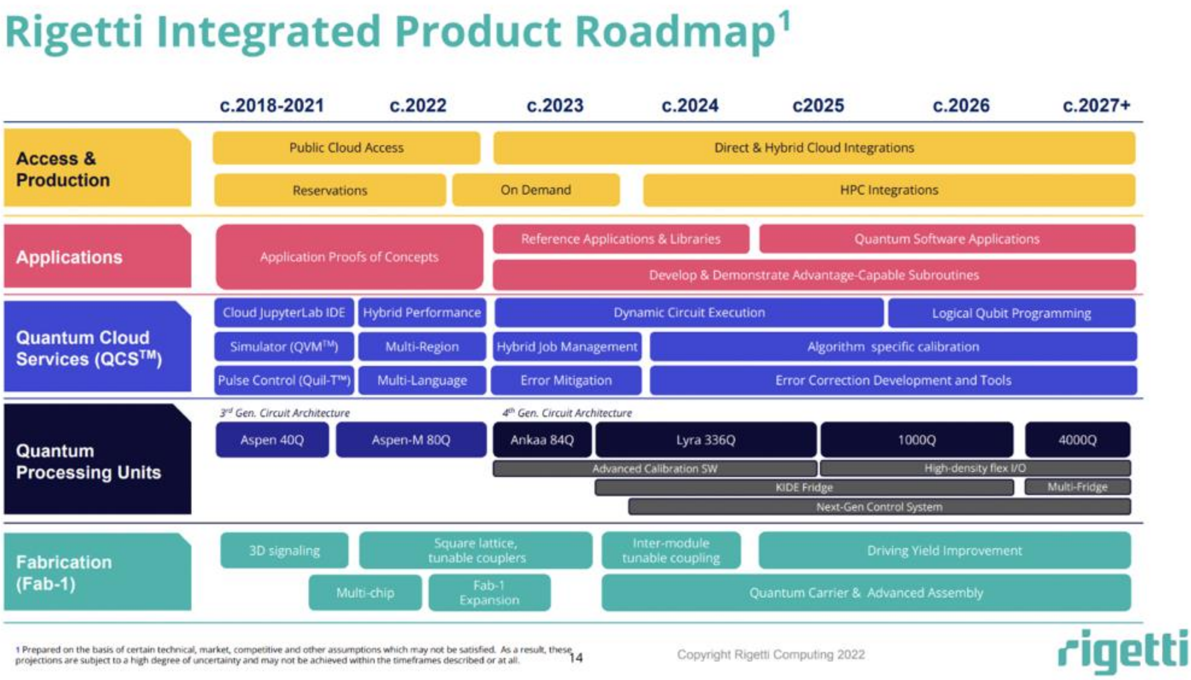


Figure 12 Rigetti's 2022 roadmap

The French company **Alice & Bob** raised €27 million in 2022 to move forward with the design of **superconducting cat qubits**. This technology is receiving a lot of attention because it promises to require fewer physical qubits to achieve a logical qubit (using cat qubits for solving bit-flip errors) than using other technological approaches (like surface codes). This superconducting cat qubit approach is also being investigated by the **AWS Center for Quantum Computing** in Pasadena.

Transmon qubits are the most widely used kind of superconducting qubits. However, **IQM** released a paper on a new type called "unimons". **Alibaba Group's DAMO research institute** also published a communication on using fluxonium to develop highly performing superconducting circuits. Both options could improve the coherence time and the fidelity of qubits compared to "mainstream" transmon qubits.

- **Photonic qubits**

In June 2022, **Xanadu** published a paper in Nature, in which they announced they had demonstrated a **quantum computational advantage** using 216 squeezed-state qubits on a platform called **Borealis**. They claimed it would take more than 9,000 years for the best supercomputers with the best algorithms in the world to perform that computation, compared to the 36 microseconds needed using Borealis.

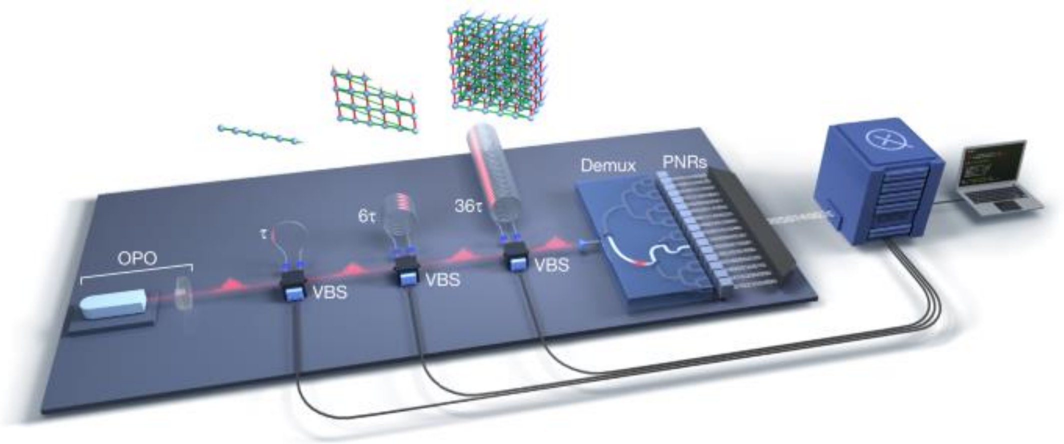


Figure 13 Description of the Borealis device used for the publication of the quantum computational advantage by Xanadu in Nature, June 2022

Quandela is a company created in 2017 by Pascale Senellart, Niccolo Somaschi and Valérian Giesz. It uses Linear Optics Quantum Computing, relying on the manipulation of single photons on fully reprogrammable universal interferometers.

Quandela released cloud access to a first QPU: **Ascella**, a universal 12-mode system. **Achernar**, a specialized 4-mode device is currently being deployed to perform QRNG.

In 2022 Quandela released a first programming and simulation environment called Perceval. It's a python-based software that allows users to get acquainted with Linear Optics Quantum Computing. We should expect to hear more from Quandela in the coming weeks as they recently mentioned the deployment of two new devices: **Altair**, a specialized 10-mode QPU, and **Bélénos**, which will reach 24 modes.

- **Silicon qubits**

Intel announced that their first **12-qubit Silicon chip** would be available in 2023.

In June 2022, the Australian company **Silicon Quantum Computing (SQC)** announced the **world's first integrated circuit manufactured at the atomic scale**, **two years ahead of schedule**. In the same period, they launched a $130-million Series A capital raising to fund the next phase of their development.

The creation of **Siquance**, a new start-up based in Grenoble (France) in the field of Silicon spin quantum computing hardware, was announced in December 2022. It was co-founded by Maud Vinet (CEO, formerly CEA-Leti), Tristan Meunier (CTO, formerly CNRS) and François Perruchot (COO, formerly CEA). The aim is to leverage the **FDSOI technology** and l**ong-term partnerships between industry and academia** in this field to build **reliable and scalable Silicon spin quantum computers**.

- **Trapped Ions**

In June 2022, **Quantinuum** announced an **upgrade on its H1-1 tapped-ion QPU, from 12 to 20 fully connected qubits** with improved features and qubit quality. JP Morgan simultaneously published a paper on the use of this device to perform an NLP algorithm for extractive text summarization.

The German company EleQtron, a spin-off of the Department of Quantum Optics at the University of Siegen, has raised **€50 million** in new funds. It was also part of the consortium that was awarded **sub-projects by the German Aerospace Center (DLR)** to develop a 10-qubit demonstrator by the end of 2023 and to study how to network individual chips to create a universal quantum computing architecture.

A new company called **Crystal Quantum Computing** has been founded in Paris to develop quantum computing platforms with **Rydberg trapped-ions**. Led by Quentin Bodart, a former postdoc of Stockholm University working on the QUASIRIO (QUAntum SImulation with Rydberg trapped IOns) project, it has not yet communicated much information to the public. We should hear more from them next year.

Main private funding of QPU providers in 2022, according to The Quantum Insider:

Company	Country	Technology	Amount	Details
Xanadu	Canada	CV photonics	$100 million USD	Series C financing $250 million USD raised in total Valuation $ 1 billion USD
Coldquanta	USA	Cold atoms	$110 million USD	Series B
Origin quantum	China		$148 million (1 billion Yuan)	Series B
IQM	Finland	Superconducting	€128 million	Series A2 Led by World Fund
D-Wave	Canada	Quantum annealing	$150 million USD	IPO on the NYSE
Silicon Quantum Computing	Australia	Silicon quantum dots	$130 million AUS	Already $83 million in seed backing

b. Middleware & HPC integration

Since 2016, **Atos** has been the main player working on HPC integration of quantum computing capabilities, through its appliance, the **Atos Quantum Learning Machine (QLM)**. The QLM was first positioned as an emulation platform that would support end-users in their discovery of quantum programming schemes. It is already widely used in HPC and research centers such as Forschungszentrum Jülich (Germany), ICHEC (Ireland), CEA-TGCC (France), LRZ (Germany), C-DAC (India), Argonne National Laboratory (ANL, USA), Oak Ridge National Laboratory (ORNL, USA) and SENAI-CIMATEC (Brazil). In the context of European and National projects such as HPCQS (EU), HQI (France Hybrid HPC Quantum Initiative, France) or Q-Exa (Germany), Atos is putting increasing efforts on the integrating modules to couple HPC clusters and QPUs. In HPCQS, they are collaborating with Pasqal (cold atoms, France), and they also announced a tighter partnership with IQM (superconducting, Finland) in 2022, to improve the integration of these technologies through the Atos QLM. IQM is also part of Atos' Scaler acceleration program, dedicated to open innovation for startups and SMEs.

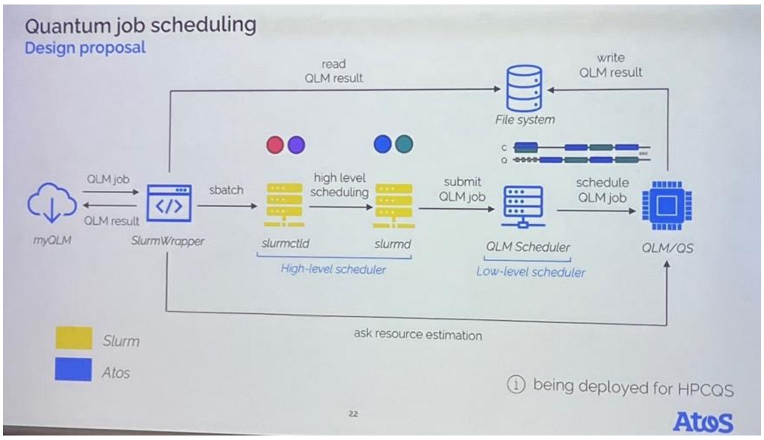


Figure 14 Design proposal for the integration of myQLM/Atos QLM with Slurm presented by Atos on Jan. 11th 2023 at TQCI EDF event

In 2021, **Nvidia** announced the release of **CuQuantum**, its quantum emulation environment, tightly integrated with Nvidia's own GPU chips. In 2022, this offering was dramatically expanded with the announcement of **CUDA Quantum**. CUDA Quantum is described as an "open, unified environment" that aims to make "quantum computing more accessible by creating a coherent hybrid quantum-classical programming model". Nvidia developed an aggressive partnership activity around CUDA Quantum. They combined this communication with new partnerships with hardware providers such as IQM (superconducting, Finland), Pasqal (cold atoms, France), Quantinuum (trapped ions, USA), Quantum Brilliance (NV centers, Australia) and Xanadu (photonics, Canada), to show the hardware-agnosticism of their offer. Nvidia has also launched a beta testing initiative for CUDA Quantum, relying on partners such as Forschungszentrum Jülich (FZJ, Germany), NERSC (USA) and Oak Ridge National Laboratory (ORNL, USA). They are working with specialized software providers such as Classiq, QCware and Zapata, to ensure that CUDA Quantum is compatible with these environments.

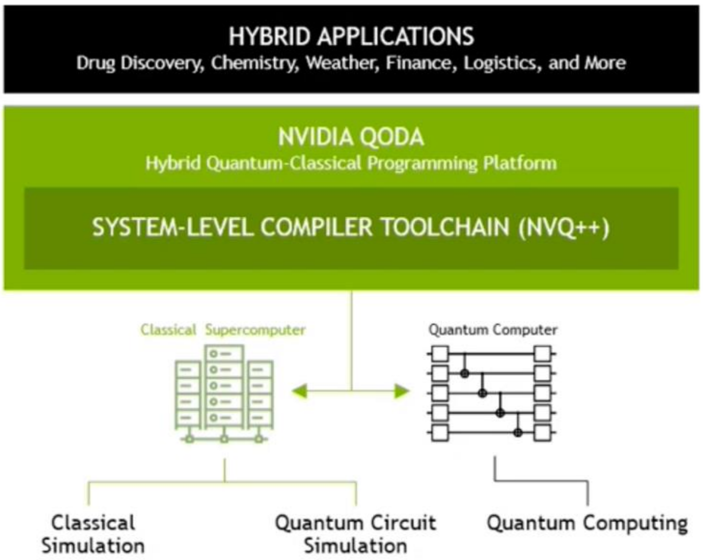


Figure 15 The Nvidia quantum computing stack

NEC was one of the first players to publish an article on solid-state (superconducting) qubits in Nature in 1999, so the topic of quantum computing is nothing new for the company. They explored the integration of quantum computing and quantum annealing in HPC workflows and found some examples of applications that would benefit from hybrid computing. As an example, they cited the preprocessing of amino acid to reduce the complexity of the set before feeding it to classical algorithms. They have a **reseller partnership with D-Wave**, and are therefore able to provide their customers time on a quantum annealing machine. They have also released a simulated quantum annealer that runs on vector processors: the **NEC Vector Annealing** offer.

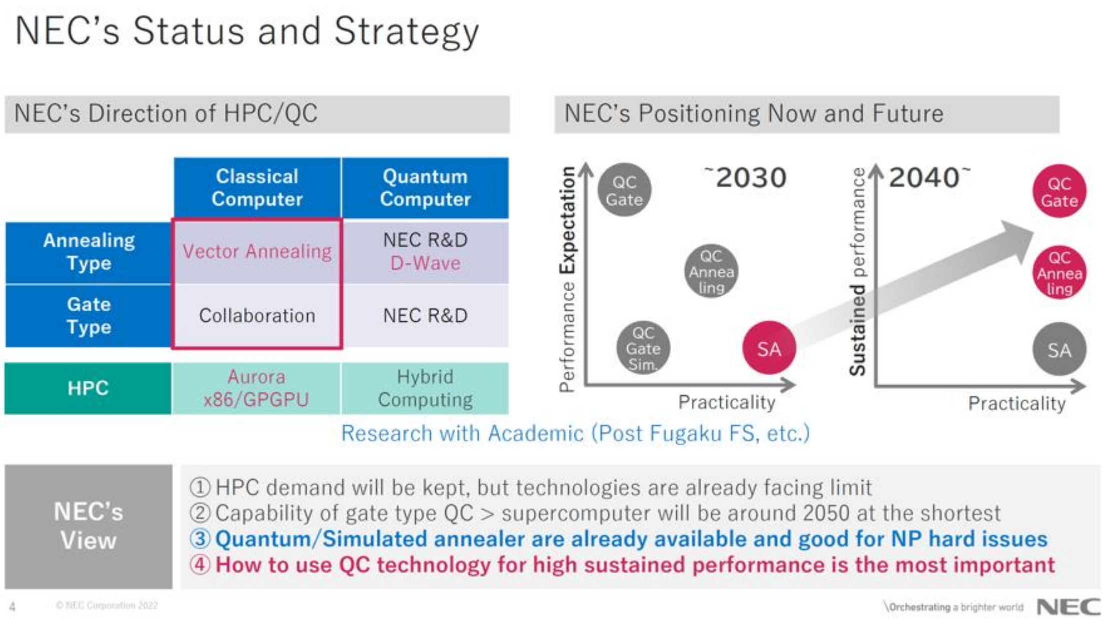


Figure 16 NEC's vision for hybrid quantum classical computing

HPE Labs have been involved with Silicon Photonics and Nitro Vacancy Diamonds for 15 years. They have also been involved in a DARPA project on Quantum-Inspired solutions. Numerous discussions with HPC and research centers motivated new investigations on how they could integrate QPUs in their HPC solutions. Currently, they have a few on-going customer projects in that field. They also have a

Pathfinder Venture Capital (VC) that invested in a few quantum computing companies, such as Classiq and IonQ.

c. Quantum computing offers of cloud providers

Hybrid quantum-classical computing has become a very important topic for most quantum cloud providers. That is also true for **AWS**, which released **Amazon Braket Hybrid Jobs** in late 2021 to facilitate the use of variational algorithms such as the Variational Quantum Eigensolver (VQE) and Quantum Approximate Optimization Algorithm (QAOA), as it optimizes the availability of the classical and quantum resources you need for the duration of your job.

There are also newcomers in this quantum computing cloud providers ecosystem. For example, the French company **OVHcloud** announced they would invest in quantum computing and open related services for their users, with the aim of developing a community of quantum developers. They organized a bit event in the Paris show venue Olympia in November2022, where they displayed an interview of Nobel Prize winner Alain Aspect, as well as a panel session including Christophe Legrand (Pasqal), Valérian Giesz (Quandela) and Maud Vinet (CEA-Leti, now Siquance). More information on their offer is expected to be available in 2023.

d. Software environments and algorithms

The Indian start-up **BosonQ Psi (BQP)** announced in January 2022 the launch of **BQPhy,** the **world's first quantum-powered Simulations-as-a-Service (Q-SaaS) computer-aided engineering (CAE) software** suite. It was available for early access as soon as Q2 2022. Among other fields of explorations, BQPhy could be leveraged to experiment **distributed quantum computing**.

Alphabet released a spin-off in March 2022, called **Sandbox AQ**, to provide Software-as-a-Service (SaaS) solutions based on Google's quantum computing and AI technologies. It is led by Jack Hidary, who founded the activity in Alphabet in 2016, and chaired by former Google CEO Eric Schmidt. Sandbox AQ destines its offering more specifically to telecom, finance, healthcare and cybersecurity customers. Its first public customers are **Vodafone Business** and **Softbank Mobile** – working with the latter on a post-**quantum cryptography use case.** One of the advisors of this newborn company is Admiral Michael Rodgers, former head of the National Security Agency (NSA).

The Israeli start-up **Classiq** is developing a **Quantum Algorithms Design (QAD)** solution to automate the conception and the optimization of quantum circuits and algorithms. It seduced **Samsung** and **Hewlett Packard Pathfinder**, who invested in the company.

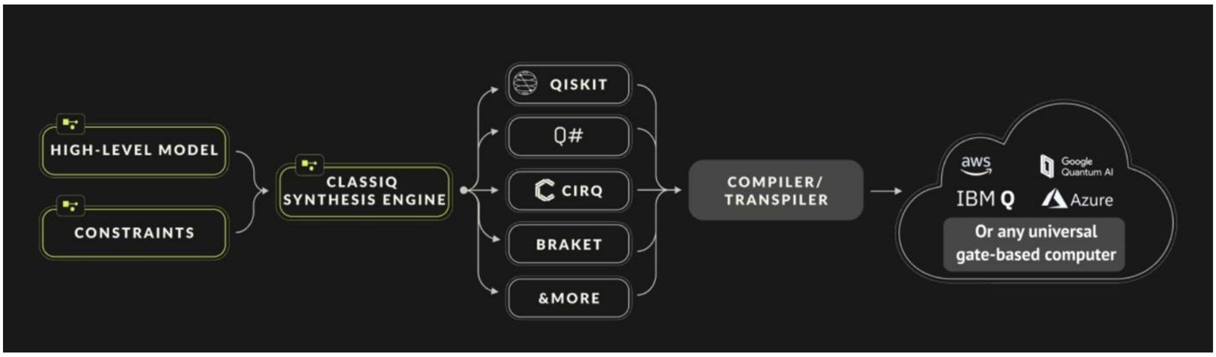


Figure 16 Presentation of the Classiq hardware-agnostic QAD workflow

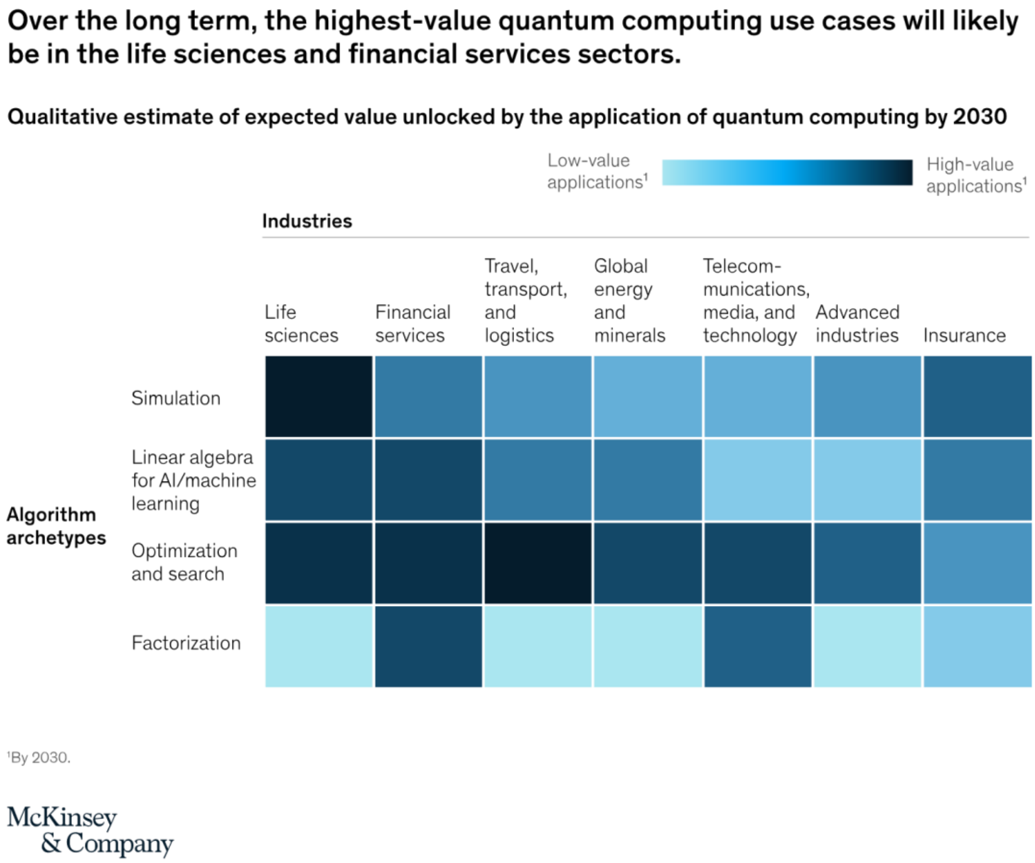
In France, several software and **consulting companies** have emerged, with the aim of providing solutions to support their customers in getting a quantum advantage. One of these companies, called **QbitSoft**, was created by former IBM France head of sales Olivier Pegeon. Paris-based **ColibriTD** also announced that they received funding from the Defense Ministry in France to work on a **combustion use case** with **Atos**.

The San-Sebastian-based **Multiverse Computing** was named a **Gartner 2022 Cool Vendor in Quantum Computing** in June 2022. The analysts stated that “advances in quantum software technologies and services enable integration of quantum solutions exploration in the financial services industry”. Multiverse provides quantum solutions for investment portfolio optimization and other finance applications through its **Singularity** product. They first leveraged quantum-inspired solutions and are now exploring quantum algorithms in partnership with hardware providers like **Xanadu** (Photonics, Canada) and **IQM** (Superconducting, Finland). They are now also trying to expand their activities to other industries, like the partnership they formed with **Bosch Automotive Electronics** in Madrid in July 2022 to explore manufacturing use cases.

Though a partnership with **Rolls-Royce** announced in January 2023, **Xanadu’s Pennylane** environment will expand its very popular algorithm libraries – Quantum Machine Learning (QML), quantum chemistry and quantum computing – to **support a new algorithm called the Quantum Singular Value Transformation (QSVT)**. This algorithm may be useful for potential aerospace applications like **materials chemistry** and **computational fluid dynamics (CFD)**.

e. Use cases - announcements of new industrial partnerships

For several years now, some pilot industries - pharmaceuticals, chemicals, automotive, finance - have been expected to be the first to benefit from quantum computing. Industrial end-users are beginning to embrace it and they are making progress. McKinsey estimates that **the potential of these industrial partnerships could reach $700 billion in value as early as 2035**. Gartner predicts that **20% of organizations will allocate budget for quantum computing projects by 2023**.



Here are a few examples of partnerships and exploration results that were announced in 2021-2022.

Quantum Random Number Generation (QRNG)

QRNG is an early application of existing quantum computing with a **forecasted market of $1.2 billion in 2028** (and $4.4 billion by 2032) – according to analyst Inside Quantum Technology Research. The generation of higher quality randomness, certified by the laws of quantum physics, could support the **implementation of more resilient cryptography**, for example. It is currently being investigated by **Zapata Computing (USA)**, but also by hardware companies like **Quandela (photonics, France)**.

- **Quantum Chemistry**

In April 2022, **TotalEnergies** and **Quantinuum** have presented a new paper detailing a potential use of quantum computers to describe the binding of molecular carbon dioxide with a material actively researched for carbon capture, called Metal-Organic Framework (MOF). This could support many companies in their efforts to achieve a net-zero balance and is part of TotalEnergies and Quantinuum's multi-year project on **carbon capture, utilization and storage (CCUS). Volkswagen** and **Xanadu** have also announced a multi-year research programme to optimize the computing power of quantum algorithms for **battery materials simulation**. The aim is to overcome the computational limitations of existing classical methods such as density functional theory to develop more powerful batteries.

- **Logistics and optimization**

Logistics and optimization are areas where some quantum computing approaches are very promising. A concrete example is the **partnership between D-Wave Systems and the Port of Los Angeles**. They have collaborated on a **logistics use case** and implemented a quantum-powered solution to optimize the cargo traffic on Pier 300. Through an extensive use of D-Wave's quantum annealer, cargo handling by the rubber tyred gantry (RTG) cranes has **improved by 60%**, and the time it takes for trucks to pick up containers has reduced by 12%. **NEC Corporation** and **NEC Fielding, Ltd,** which provides maintenance services for ICT equipment, have announced in September 2022 that they would introduce a delivery planning system for maintenance parts that leverages quantum computing technology in the 23 wards of Tokyo in October 2022. This service will rely on the **NEC Vector Annealing Service** and is expected to reduce the work of planning next-day delivery of maintenance parts **from two hours to roughly 12 minutes**, thus dramatically increasing operational efficiency. **China Mobile**, the world's largest telecom carrier in terms of mobile subscribers, signed a partnership with **Origin Quantum**, to leverage the superconducting **OriginQWuyuan**, based in Hefei, to solve **network optimization use cases**, among others.

- **Finance**

Financial applications of quantum computing is still a very active research field. **JPMorgan Chase** explained how they used a 20-qubit **Quantinuum** H-series quantum computer to carry out constrained optimization experiments applied to NLP for document summarization. This work could have numerous applications in many industries. **HSBC** announced a partnership with **IBM** to investigate the use of quantum computing to increase the level of accuracy of fraud detection. **Caixa Bank** has collaborated with **D-Wave Systems** to conduct improved investment portfolio hedging. In September 2022, Dr. Will Zeng, **Goldman Sachs'** head of quantum research, wrote in a blog post: *"derivatives are so common in finance that even a small improvement in pricing them, or in calculating related quantities, could be very valuable"*. They relied on partnerships with **IBM** and then **Microsoft** to explore this field.

- **Computational Fluid Dynamics (CFD)**

CFD can be found in numerous industries, with codes that have been improved over decades. Major parts of these workflows consist in **solving large systems of partial differential equations** (PDE). This is not necessarily a low-hanging fruit on the quantum computing algorithms side, as the most well-known algorithm discovered to solve these is HHL (Harrow, Hassidim, Lloyd) – and it requires numerous high-quality qubits. There could however be nearer-term methods to improve the resolution of these problems, and two projects were announced in September 2022 in this field. The first one brings together **Pasqal** (neutral-atom quantum simulation, France), **Airbus** and **ONERA** to study quantum algorithms for plane design CFD. The second one tackles combustion CFD and will be carried out by **Quandela** (photonics, France), **MBDA** and **ONERA**. Both projects were funded by the **Paris region** through an initiative called **Pack Quantique Ile-de-France**. **Classiq** (Israel) and **Rolls-Royce** (UK) also announced a collaboration on CFD algorithms in October 2022.

3 Results

The data exposed in this report are coming both from **direct discussions and conferences**, and from **public information available online**. Confidentiality of information is key in our respective relationships with the quantum computing industry, so no sensitive or confidential data was included here.

This monitoring of the various fields related to the quantum computing industry in all geographical regions has supported HPCQS's reflections on the development of quantum computing technologies. It also assisted them in adjusting the focus of their efforts to support their user communities.

A key take-away of this technology watch is that **collection and analysis of data must necessarily be shared among several partners**. The aim is to **process information and opinions on a regular basis** to ensure that they are subsequently shared with other partners. Having a shared dynamic collaboration environment would foster the participation of many partners.

At a time when numerous updates are published on the technical progress of quantum computing, it is also important to **check the facts** proclaimed by the various players. Individuals such as Olivier Ezratty in France, and Scott Aaronson in the US play a pivotal role in **deciphering communications** and trying to **mitigate the hype**.

4 Conclusions

Deciphering communications related to quantum computers has not become easier as the technology evolves and numerous new options become available. New discussion points have emerged or intensified. Some are linked to the current state of art, such as the **Quantum Energy Initiative**, which promotes the inclusion of energy efficiency as a metric of technological success. Others ask the public to **shift their focus from pure scalability to actual usability**. Some announcements, such as the one in January 2023 about a potential threat to RSA-2048, still trigger a wave of panic and then **must be dissected and mitigated by "*fact checkers*".**

The **maturity of the quantum computing industry** has definitely moved forward in recent months. **Several hardware providers have announced that they are now building factories** to produce their chips, such as IonQ in the Seattle region (January 2023), or Quandela in Massy, based on the UFOQO (Optical quantum computers factory and farm, 2022) project. The European Investment Bank also granted IQM €35 million to support the construction a quantum-dedicated fabrication facility in Espoo, Finland. **This shows how confident these players are in their ability to add value to customers with their technology.**

Building on these **positive signals**, we will undoubtedly see **a lot of progress in HPC-QCS integration** in the coming months.

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