a cea SPOT study in partnership with futuribles

QUANTUM 2042

Public report

Prospective Study on the Impacts of Quantum Computing in 2042

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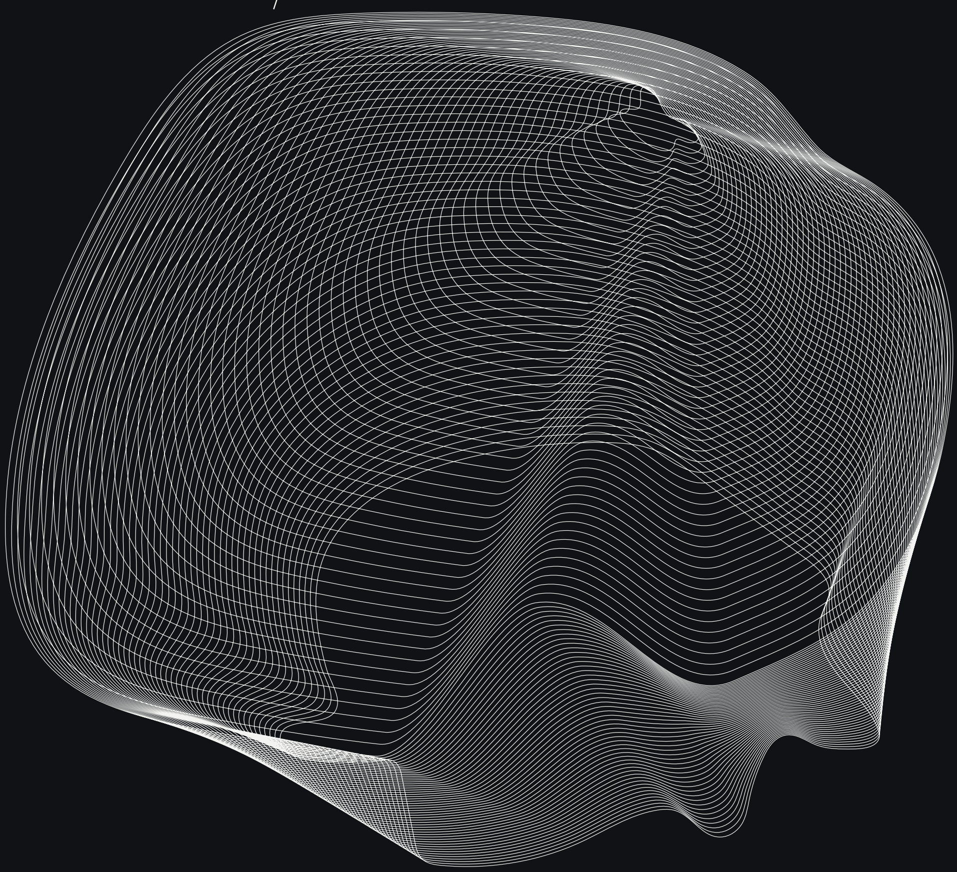

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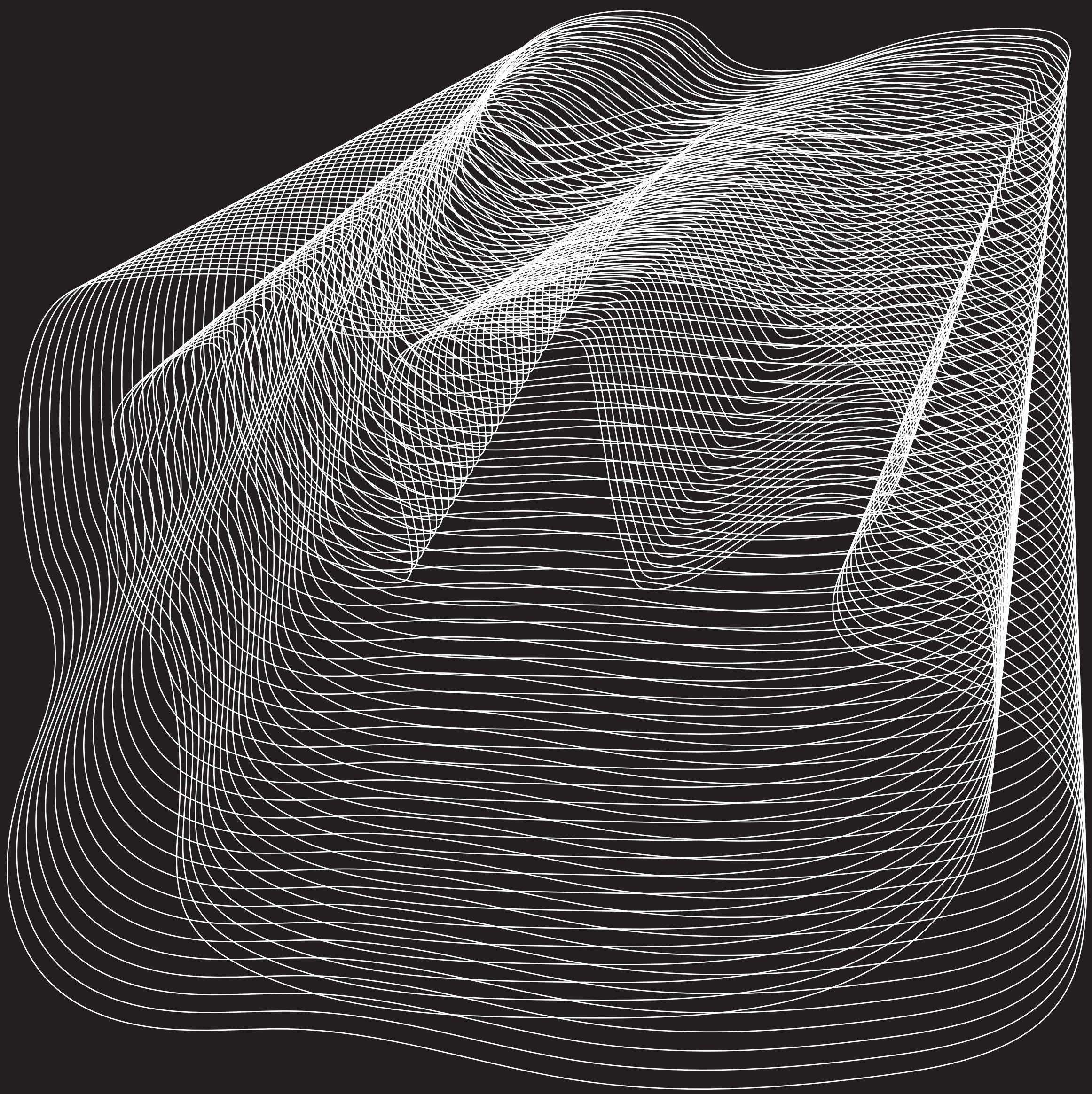


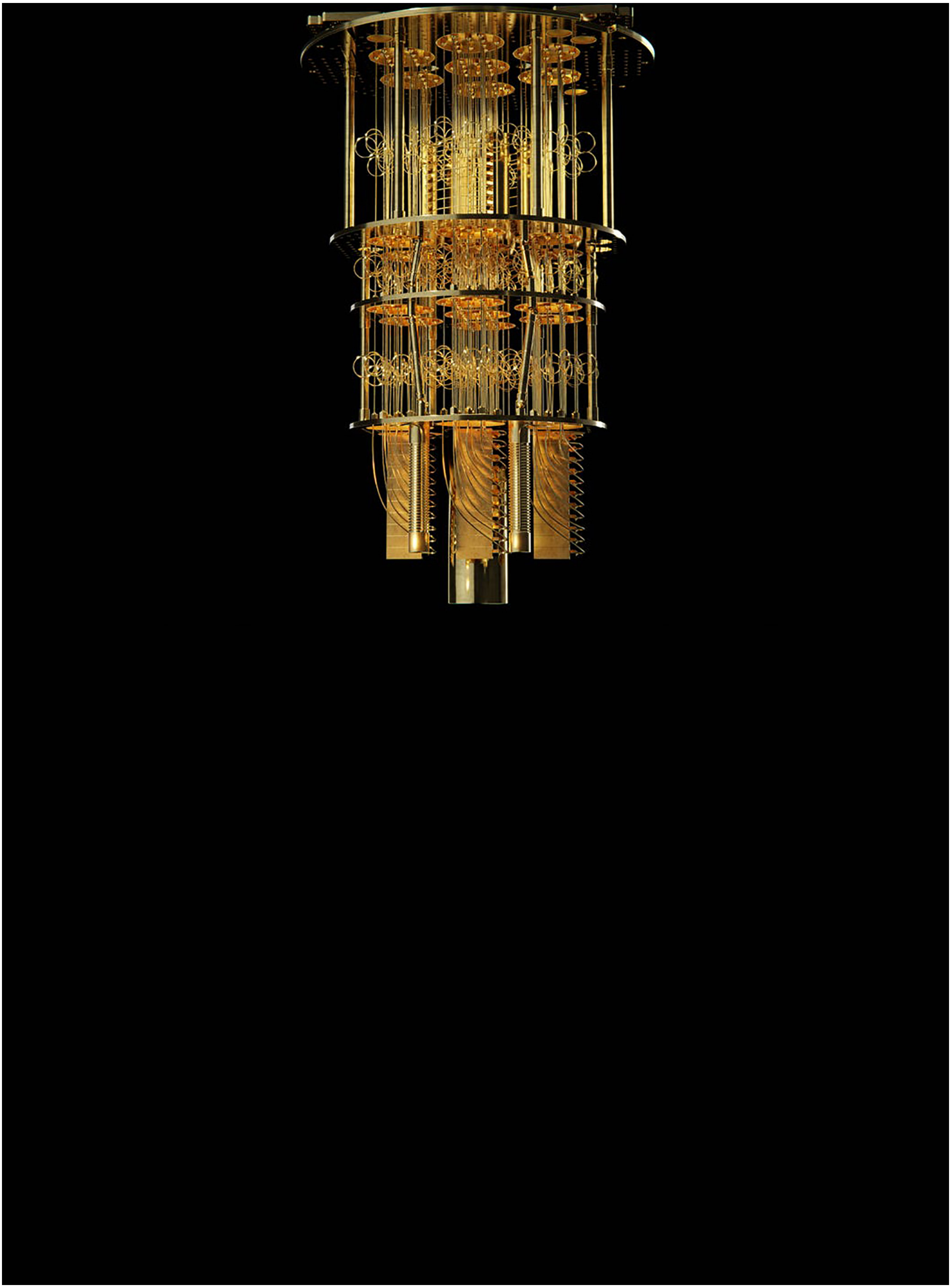
Acknowledgments

We would like to express our gratitude to all individuals who contributed to the development of this report : Luc Gaffet and Delphine Roma from Air Liquide, Jean Galand from Enedis, Christopher Arnoll and Pascal Cervoni from Bouygues Telecom, Cesar Roda Neve from Soitec, Didier Caudron from Sanofi, Philippe Dejean from Safran, Valentina Pozzoli from SNCF, Laurent Francez, Sebastien Deschamps, and Felix Mouhat from Saint Gobain, Ali El-Hamidi from CACIB, Olivier Hess and Anne-Lise Guilmain from Eviden, Etienne Decossin from EDF, Guillaume Leterrier from Valeo, Guillaume Brenaut, Nassima Bammar, and Thomas Chapuis from Renault, Daniel Vert from Systématics, Florent Staley, Tanguy Sassolas, Jacques-Charles Lafoucrière, Christian Gamrat, Patrick Cappe De Baillon, Richard Fournel, Benedicte Almozini, Philippe Caillol, Christophe Vautey, Valentin Savin, and Julie Lepaulle from CEA, as well as all the experts who were consulted. Thanks to Jayshankar NATH for the translation.

Note to readers

This report stems from a prospective effort led by CEA Y.SPOT and Futuribles. CEA Y.SPOT is the open innovation and societal connection hub of the CEA's Technological Research Directorate. In collaboration with Futuribles, a center for prospective analysis aiming to understand major ongoing transformations, the ambition of this report is not to be a technological manual but rather a platform for reflection on the potential futures of quantum computing, particularly its industrial and societal applications. Prospective analysis does not predict the future; it does not extend current trends into a « roadmap » format. Instead, it draws upon trends, weak signals, and disruptions to describe potential futures and assist in strategic decision-making in an uncertain world, aiding in long-term planning. The work presented in this document is a collective effort and may not necessarily reflect all opinions of the contributors, nor does it bind the organizations they represent or the CEA.

SUMMARY



Preface

For over thirty years, the CEA has been a major player in fundamental and applied research in the field of quantum computing. Its research focuses on two main tracks of qubits : superconducting and silicon. One of CEA's strengths is its ability to be present throughout **the entire value chain of quantum computing.**

In parallel with technological developments, it seems essential to consider the long-term impacts of quantum computing on uses and society. Increasingly, it is crucial to **align science and technology with usage and society, for the benefit of citizens.** We can no longer develop technologies without considering the questions of consequences and impacts on society. This is why we want to be able to project ourselves in the long term and already study the potential consequences of quantum computing on various sectors, both in terms of markets and stakeholders.

There is nothing richer than combining the visions of companies, and it is with this perspective that we have chosen to explore the long-term **value chain of quantum computing with 13 major companies.** Faced with the multitude of uncertainties still surrounding the advent of such computers, it is necessary today to consider the various possible futures.

Philippe Watteau
Director of Innovation DRT – CEA

EXECUTIVE SUMMARY

Given the abundance of articles published by the press, consulting firms, or scientific journals, it is currently very difficult for companies and industries to form an idea about the real upcoming impacts of quantum computing. It is with this in mind that CEA Y.SPOT has decided to conduct a prospective approach with the assistance of the Futuribles firm to assess the current state of knowledge and the various scenarios and possible applications by 2042. The originality of this study lies in its reliance on the **participation of 13 companies**[1] covering various sectors of industry and services, as well as numerous **academic experts** or startup representatives, allowing for diverse perspectives and the sharing of experiences. **This report is a public version of the study, which remains confidential to the partners involved in the process.**

This study has highlighted **24 key messages** that identify the main scientific and technical hurdles and milestones. Although there seem to be no insurmountable scientific barriers, we are only at the beginning of the quantum computer adventure, and the technological hurdles to overcome remain numerous and complex, including :

- **The number of entangled physical qubits :** several hundred will be necessary to see the first significant advantages on real applications in NISQ mode, thousands will be necessary for error correction implementation and the advent of FTQC[2].
- **The number of logical qubits :** reaching the threshold of 50 should provide a theoretical quantum advantage.
- **Error rates of quantum processors :** reducing error rates below the threshold of 10^{-3} is necessary for error correction implementation, they must be further reduced to take advantage of NISQ.
- Interconnecting quantum cores while maintaining processor fidelity levels.
- Formalization of the concept of quantum memory and its development.
- **Progress in the discovery or optimization of algorithms** applicable to noisy NISQ processors (especially optimization) or future FTQC architectures.

[1] Air Liquide, Bouygues Telecom, Crédit Agricole Corporate and Investment Bank, EDF, Enedis, Eviden, Safran, Saint-Gobain, Sanofi, SNCF, Soitec, Valeo, Renault

[2] For the definition of acronyms, please refer to the Glossary in Annex 1

Given the trajectories described in the selected scenarios, it appears that **the industrial deployment markets of quantum computing in the next ten years** will be in :

- Finance (portfolio optimization, risk management, etc.).
- Small molecule chemistry and materials (new materials, etc.).
- Logistics (agent tours, optimal loading, etc.) if significant progress is made in computers and algorithms.
- Healthcare, if there are very significant advances in computers and algorithms.

Assuming the existence of a universal, large-scale, error-tolerant quantum computer, **the greatest market impacts will be in the biomedical and pharmaceutical sectors** (new molecules, vaccines, etc.) **as well as in chemistry** (batteries, chemical reactions, fertilizers, etc.).

All of these technical milestones and hurdles have led to the formulation of **hypotheses validated by experts.** The working group supplemented these hypotheses to develop four scenarios, summarized below (see global diagram p. 34) :

These scenarios assume the achievement of different levels of technological maturity and are analyzed regarding the date at which they are likely to occur and their impact on computer usage and potential consequences for quantum actors or society.

THE NARROW GATE
Small NISQ & Analog

This minimal scenario assumes progress in the development of limited quantum computers. The scaling up of qubits and error correction face impasses : computers can only implement algorithms with low circuit depth or that cleverly tolerate a certain level of noise. Despite initial demonstrations of quantum advantages in speed and energy consumption for very small problems, algorithmic progress is insufficient to broadly open the field of applications. The experts consulted consider at 61.5 % that this first technological level will be reached as early as 2025 and at 84.5 % by 2032. If this scenario were not surpassed by this date, it would result in a considerable reduction in the domain's momentum in the private sector, although state funding would still be maintained in research.

EXTENSION OF THE QUANTUM DOMAIN

Large NISQ & Analog

In this second scenario, analog and NISQ processors make significant progress, reaching ~ 10,000 physical qubits, unlike the first scenario where this number stagnated at around a thousand qubits. The number of qubits scales up without significantly degrading error rates ($10^{-3}/10^{-5}$). Advances are also made in error mitigation and coupling with high-performance computing (HPC), optimizing the performance of analog machines or implementing algorithms with greater circuit depth in NISQ machines. Major algorithmic advances also take place to reduce their depth and improve noise tolerance. Industrial applications become more structured, especially in finance, telecommunications, and healthcare, with speed and energy advantages. However, the lack of error correction remains a major obstacle, as in the first scenario, limiting calculation fidelity and hindering processor scaling. Experts consulted believe this technological level will be reached by 2025 for 19 % of them, by 2032 for 77 %, and by 2042 for 92 %. If it is only achieved towards the end of the period, a reduction in investments would be likely and could affect FTQC projects due to the impasse on error correction, leading to vertical consolidation of actors.

THE DOORS TO FTQC ARE OPEN

Quantum Supremacy Arrives

In this scenario, fault-tolerant quantum computing (FTQC) emerges thanks to a significant breakthrough in error correction, allowing for the scaling up of qubits and the implementation of deep algorithms without degradation of calculation fidelity. Quantum processors manage to exploit up to 100 logical qubits, and the first interconnections between quantum cores appear, signs of progressive technological maturity. Gate-based machines coexist with analog machines. The latter specialize in optimization issues where they could maintain a cost or energy consumption advantage. The miniaturization of the control chain promotes these advances, although large-scale industrialization is hindered by high costs. Experts consulted estimate that 50 % of them believe this scenario will be achieved by 2032, and 81 % by 2042. In this scenario, potential consolidation of market players is anticipated, especially horizontal consolidation around a few « winner takes all » players or major nations.

THE QUANTUM LEAP

Towards Very Large Scale Quantum Computing

In this scenario, fault-tolerant quantum computing (FTQC) makes a significant leap, crossing the threshold of 100 logical qubits and paving the way for the exploitation of systems with thousands of logical qubits (VLSQ) towards the end of the period or beyond for widespread development. Industrialization of the control chain and drastic reduction in production costs enable control over hundreds of thousands of qubits. The advent of quantum memory (QRAM) and a modular architecture of quantum processors constitute notable advancements. The achieved performances allow for addressing major issues with industrial applications in various sectors. Experts consulted estimate that 15 % of them believe this scenario will be achieved by 2032 and 53.5 % by 2042. Emblematic quantum applications such as deciphering RSA-2048 cryptography systems remain inaccessible. The market segments with a diverse range of quantum machines, making the technology more accessible to businesses. However, industrialization and scaling up may require significant vertical consolidation. The social and political impact of quantum becomes tangible, with very concrete contributions and benefits for citizens (precision medicine, optimization of transportation routes, improvement of electric car autonomy, etc.), but also potential risks, such as the development of malicious uses (cybercrime, destabilization of financial markets, etc.).

Similar to AI, quantum computing appears as **a catalyst for upcoming digital transformations.** It is an evolution on which companies will need to position themselves and anticipate, even though these technologies will only gradually mature over the next 20 years. However, the induced changes in organizations will be such that it already seems necessary to acquire knowledge on the subject **to prepare and position oneself.** For this, French large groups must quickly assess the strategic interest of quantum computing for their activity.

INTRODUCTION TO QUANTUM COMPUTING

Introduction to Quantum Physics

To fully grasp the sequence of scenarios outlined in this study, it is necessary to understand some basic concepts of quantum computing.

Quantum physics encompasses the laws governing the realm of the infinitely small : atoms, particles, photons, electrons. This field saw the emergence of the first « quantum revolution »[1] in the mid-20th century, which led to the development of semiconductor materials, superconductivity, and modern electronics. Today, applications abound, ranging from electronics (transistors, photovoltaic cells) to optics (lasers, LEDs) to medicine (Magnetic Resonance Imaging, Positron Emission Tomography), and more.

The ongoing second quantum revolution pertains to the development of systems directly utilizing the properties of quantum superposition and entanglement. It paves the way for quantum metrology, quantum communications, and quantum computing.

In contrast to observable physical phenomena in the macroscopic world, the laws of quantum physics are paradoxical and counterintuitive. Some examples include :

- **Entanglement :** the phenomenon where two entangled objects, whether close or far apart, must be considered as a single entity.
- **Wave-particle duality :** a quantum object can be interpreted as both a wave and a particle.
- **Heisenberg's Uncertainty Principle :** it is impossible to precisely measure the position and velocity of a quantum object simultaneously.
- **No-cloning theorem :** it is impossible to create an identical copy of the state of a quantum object when that state is unknown.
- **Tunneling effect :** the wave nature of quantum objects allows them to pass through energy barriers.

In the following chapters, we will briefly introduce the basic concepts of quantum computing. Additionally, a glossary is provided at the end of the report (annex 1) for quickly finding the definitions of certain terms.

Qubits

In classical computing, the fundamental unit of information is the bit, which can only take two values : 0 or 1. By analogy, the fundamental unit of information in quantum computing is called **the qubit.**

The qubit has three fundamental properties :

- **Superposition :** the ability of a particle to be in multiple quantum states simultaneously. The state of the particle is a superposition of all these quantum states.
- **Entanglement :** quantum entanglement occurs when two or more particles are linked in such a way that they cannot be described independently, even if they are separated by distance.
- **Measurement :** superposition and entanglement exist as long as the quantum particles are neither observed nor measured. Observing or measuring a quantum state provides information but collapses the quantum system, leading to the disappearance of entanglement and superposition.

Various physical objects and technologies can be used **to realize a qubit : atoms, ions, electrons, spins, photons, etc.** Each technology corresponds to a different quantum machine, each with its own advantages and disadvantages : coherence time, speed, density, error rates, etc.

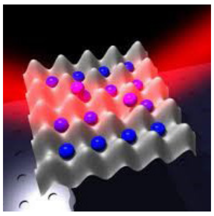
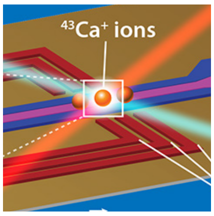
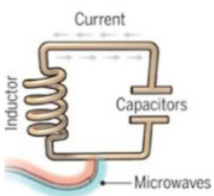
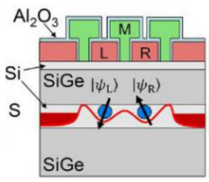
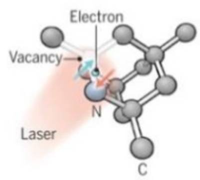
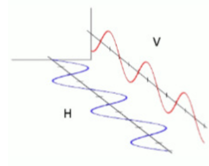
TYPES OF QUANTUM MACHINES

Quantum machines can be divided into two categories :

The first category is that of **analog calculators[2],** which utilize the physical principle of quantum annealing. A system of qubits is initialized in an energetic configuration that analogously represents the problem to be solved. By allowing the system to evolve towards its state of minimum energy, theoretically, the solution to the problem is obtained. Analog calculators can only address certain types of problems.

The second category is that of **gate-based quantum computers[3].** Input data is encoded, and logical operations are applied to the qubits according to a predefined algorithm until measurement yields the sought-after solution. When using « standard » qubits, which are noisy, it's referred to as a NISQ (Noisy Intermediate-Scale Quantum) computer. When employing « logical » or « perfect » qubits, it's termed as an FTQC (Fault-Tolerant Quantum Computer). This architecture of computers is versatile as it potentially allows the resolution of a vast array of problems.

Figure 1 : Main technologies used for creating qubits.

Cold atoms	Trapped ions	Superconductors	Electron spins	NV center	Photons
 Src : chicagoquantum.org	 Src : APS-Alan Stonebraker	 Src : factbasedinsight.com	 Src : O. Ezratty	 Src : factbasedinsight.com	 Src : EDF
Atomic energy levels		Current loop	Electron spin		Photon polarization

[1] See https://www.pourlascience.fr/sd/physique/il-etait-deux-fois-la-revolution-quantique-9293.php

[2 & 3] Please refer to the glossary in annex 1

Physical Qubits and Logical Qubits

Qubits are inherently unstable physical objects, highly sensitive to environmental disturbances. These disturbances cause changes in the state of the qubits, resulting in errors that accumulate throughout the computation.

To counter this, it is possible to **associate multiple physical qubits and apply error correction codes** to the system. In this case, this set of qubits behaves as a single « logical » qubit, which exhibits a much lower error rate. The goal is to create « perfect » logical qubits, generating an error rate lower than 10^{-12}, a limit commonly accepted by experts in the field.

Quantum Computation

Principles

Quantum computation is based on the development and use of **specific algorithms** that take advantage of the superposition and entanglement of quantum states. Unlike classical algorithms that process data sequentially, quantum algorithms use the intrinsic parallelism of quantum mechanics to simultaneously explore an entire domain of values and thus **« parallelize » certain computation steps.**

The development of quantum algorithms must take into account specific limitations. Thus, the **no-cloning theorem** makes it impossible to copy quantum states. Moreover, since it is impossible to measure a qubit without destroying it, its value cannot be used to implement tests or conditional loops in the quantum algorithm. Finally, the probabilistic nature of the results implies the need for repeated calculations.

These algorithms theoretically allow the quantum computer to solve real use cases for which classical algorithms are not satisfactory in terms of speed, energy consumption, or precision.

Current Limitations

Quantum computation theoretically offers significant advantages for **accelerating intensive computation by parallelizing certain steps. For some classes of problems, polynomial or even exponential acceleration is expected depending on the size of the problem.** However, the quantum computer currently faces numerous limitations.

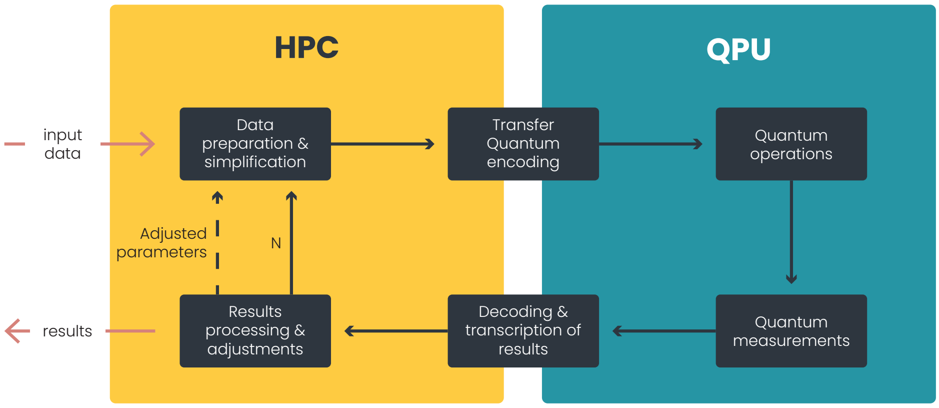


Figure 3 : Decomposition of a quantum algorithm.

In the absence of quantum memory, an algorithm incorporating quantum computation can be broken down into multiple phases, as represented in the figure below.

To assess the quantum advantage, **it is necessary to evaluate the entire chain, from data input to obtaining results.** This is not always done, and may be completely overlooked in theoretical claims of a quantum algorithm's advantage. Quantum acceleration can thus be completely invalidated by the time required to perform one of the processing cycle steps.

There are other practical limitations to the use of quantum algorithms. For instance, **if the number of available qubits is very limited, a drastic simplification of the problem must be made,** thereby reducing the interest in its resolution. Consequently, quantum machines cannot currently process large input datasets.

Additionally, the application of quantum algorithms will be closely linked to the characteristics of the machines used. Each algorithm requires a minimum number of operations to reach a result, in relation to the size of the problem. In NISQ mode, the quality of the qubits will impose limitations. **If the qubit coherence time is too short or if the qubit fidelity is too low, then it will be impossible to perform all necessary operations.**

Use Cases of Quantum Computing

Given the current knowledge in mathematics and algorithmics, we can identify major problem classes that can benefit from massively parallel computations and for which a quantum machine could theoretically be advantageous :

- **Combinatorial optimization :** involving simulating a system with a set of qubits and converging it to an optimum (routing, scheduling, cost, graphs, etc.).
- **Physical simulation at the atomic level :** applying the previous case to calculate the ground state (lowest energy state) of a molecule or a set of atoms (quantum chemistry).
- **Factorization of large numbers into prime factors :** the difficulty asymmetry between multiplication and factorization of large numbers is currently the basis of information security and encryption, especially on the Internet (RSA protocol). Significantly accelerating factorization calculation would therefore pose a major security breach in computer systems.
- **Database searching,** structured or unstructured.
- **Classification (clustering),** used to accelerate machine learning algorithms.
- **Solving partial differential equations :** attempting to use quantum computation parallelism to improve and/or accelerate simulations of multi-physics phenomena (material resistance, thermal, fluid mechanics, etc.).

[1] This algorithm was described in 1977 by Ronald Rivest, Adi Shamir, and Leonard Adleman.

INTRODUCTION

Quantum technologies are perceived as strategic and subject to significant public impetus within technologically advanced countries. This particular domain, where research and technology advance together, is highly active, undergoing numerous developments, and experiencing near-daily publications. The quantum ecosystem is also marked by rapid evolution. One characteristic of emerging technologies like quantum computing is t**he considerable weight of representations and promises,** along with the announcement effects associated with a global politico-strategic game of actors. In this context of real dynamics, the production of performative visions (without evidence), contradictory discourses, or destabilizing statements is facilitated.

To gain clarity in this landscape, we have decided to adopt a prospective scenario-based approach with the assistance of the consulting firm Futuribles. Our goal is not to offer an exhaustive approach to the subject but to **shed light on possible and coherent evolutionary trajectories over the next twenty years.** The objective is to provide insights and identify **key milestones to monitor in the future** to detect scenario tipping points. The uniqueness of our study lies in its reliance on feedback from use cases provided by 13 major companies, each reflecting on the potential consequences of quantum computing in their respective fields.

We have conducted a projection of the quantum machine sales market up to 2042, incorporating several detailed assumptions. Quantitatively evaluating the benefits this may generate for user companies and associated economic models remains challenging. We have chosen not to publish these evaluations in this study.

Furthermore, with the assistance of designers, we have attempted to assess the societal impact of this technology on citizens and everyday life through a design fiction approach. Using a few examples of everyday objects that could exist in 2042, we have sought to outline the positive or negative consequences that quantum technology could have.

KEY MESSAGES

At the conclusion of this study, we have selected 22 key messages that we wanted to highlight. We have chosen to classify them by broad themes rather than in order of priority. Some may seem obvious, while others are more subject to controversy, but this brief selection serves to underscore the key concepts in quantum computing today.

General Messages

01

Quantum computing is not intended to replace classical computing entirely.

The expected advantage of **quantum computing is limited to certain mathematical and physical problems** where the properties of entanglement and superposition can be utilized. With the absence of freely available machines for real-world testing, few quantum algorithms have been developed and tested. Currently, the most promising avenues include solving optimization problems for chemistry, finance (stochastic analysis), and exploring applications in high-performance computing (HPC), such as physical simulations and solid/fluid mechanics, although results in these areas are still limited.

02

In the coming years, progress toward quantum computing will rely on both increasing the number of qubits and improving their fidelity.

These two advancements are essential for error correction implementation or scaling up NISQ (Noisy Intermediate-Scale Quantum) problems. **It is impossible to predict which of the qubit technologies currently in development will achieve this first.**

03

The logic of quantum computing, characterized by massive tensorial calculations, is already contributing to the development of new approaches to classical computation and will continue to drive progress in the coming years (including quantum-inspired approaches with tensor networks, in particular).

04

In the next 5 to 10 years, most large public and private organizations with computational needs must be prepared for the development of quantum computing use cases.

However, implementation will depend on the availability of suitable hardware. There is a noticeable structuring of a quantum ecosystem that allows organizations to experiment and prepare for potential quantum computing applications, notably through emulators and use case repositories. **Emulators currently enable work with the equivalent of 30 to 40 « perfect » qubits[1],** completely entangled, with infinite coherence, providing a unique ability to access the « quantum » state of the machine. In the medium term, all use cases that can be implemented on more or less noisy quantum machines will be « ready ». In the longer term, software development environments will evaluate the potential use cases for Fault Tolerant Quantum Computing (FTQC).

[1] The capability to emulate 40 perfect qubits far surpasses the best hardware available today.

05

Workforce needs will be necessary to accompany the quantum revolution in the next 10 years.

In a context of gradual learning and global competition for skills in the field, anticipated investments will be necessary. Among the skills to be developed, the first level will be upstream skills related to the development of quantum technologies : hardware (scientists and engineers in quantum logies), and software (computer scientists for algorithm implementation and the transition from physical problems to mathematical problems). Moreover, **additional skills will need to be integrated within companies to reformulate use cases** into problems compatible with quantum computing.

06

The availability of hardware and software stacks is necessary to accelerate the development of algorithms, and then their qualification. Partner organizations emphasize the need for a more mature development environment (both software and hardware) to better explore use cases and associated quantum advantages.

07

Progress in quantum algorithms, including the combination of algorithms (including classical-quantum), is necessary to optimize the potential applications of a quantum computer.

Currently, only a few algorithms are operational, including combinatorial optimization algorithms. They are **limited in use to simplified cases** for the time being. For other complex applications such as solving Partial Differential Equations (PDEs) or physico-chemical simulations, algorithmic breakthroughs are necessary.

08

The first demonstrations of quantum computing advantages are on the verge of being achieved.

Quantum processors hold potential advantages in speed, energy consumption, or precision. It will be fundamental for the development of practical quantum computing to demonstrate these advantages in the coming years for problem sizes approaching industrial applications. **To date, there are very few cases of quantum computing showing practical advantages,** significant in cost, speed, or energy consumption compared to classical tools[1]. It is worth noting that other paths besides quantum computing are developing in parallel and could be competitive (Fujitsu’s Digital Annealer[2], Microsoft’s AIM photon processors[3], or Mythic AI’s analog computing[4]).

[1] Publication : « Financial Risk Management on a Neutral Atom Quantum Processor » authored by Lucas Leclerc et al., arXiv:2212.03223v1 – December 6, 2022, showcasing an investment portfolio optimization process three times faster, consuming only 3 kWh.

[2] https://www.lemondeinformatique.fr/actualites/lire-fujitsu-propose-une-machine-presque-quantique-avec-le-digital-annealer-2-75355.html

[3] https://www.microsoft.com/en-us/research/project/aim/

[4] https://mythic.ai/technology/analog-computing/

Machines & technologies

09

Error-tolerant and universally programmable Fault-Tolerant Quantum Computers (FTQC) with a significant number of logical qubits (> 100) are essential to begin addressing particularly interesting problems for industries (especially in chemistry-materials simulation).

10

Although there seem to be no insurmountable scientific barriers, we are only at the very beginning of the quantum computer journey, and there are numerous technological hurdles to overcome. The effort to overcome all of them will be comparable to that of developing classical computers. The most prominent ones include :

- Increasing the number of qubits and reducing their e**rror rates to less than 10^{-3} or even 10^{-4}.**
- **Error correction is the true litmus test** to overcome the limitations of noisy NISQ computers and transition to FTQC machines. While mathematical solutions exist, their hardware implementation remains one of the major technological challenges.
- **Developing and industrialising the control chain** presents major challenges in terms of addressing and noise. Ultimately, these command chains should allow the initialization, control, and measurement of a large number of physical qubits (from 100,000 to 10 million).
- Rapid and efficient connection between classical and quantum computers to l**imit the bottleneck of data exchange.**
- **Progress in enabling technologies** is also necessary in the fields of cryogenics, electronic components, and photonics.

11

In the absence of Quantum Random Access Memory (QRAM), quantum algorithms will focus on problems with high computational intensity requiring a small volume of input data. The feasibility of QRAM, both technically and scientifically, remains uncertain.

12

Some qubit technologies (superconducting, cold atoms, trapped ions, etc.) will be limited in scalability due to qubit connectivity and their maximum density on a single core. One solution could involve interconnecting quantum cores.

13

Different types of gate and analog computers will coexist in the next ten years (superconducting, trapped ions, silicon, etc.), unless there is a scientific breakthrough (winner-takes-all) or major crises (financial « winter »).

We are currently in an experimentation phase, which is expected to continue in the coming years before selection logics based on technological performance are established. Before the implementation of FTQC, it is likely that **certain qubit technologies will be better suited to solve certain types of problems.** This specialization could also result from economic models and actor dynamics, both among manufacturers and users.

14

Initially, there does not seem to be a major issue related to the energy consumption of Quantum Computing.

On the contrary, **the energy consumption of quantum computing could be an advantage compared to classical computing** in the era of NISQ and analog (especially since the number of computers will remain limited to a few thousand even in the most optimistic trajectories). This does not mean that quantum computing will not raise social acceptability issues regarding its environmental impacts. Initially at least, the development of quantum computing will lead to an increase in energy needs as these computers will be connected to independently sized supercomputers.

Transition to Industrial Stage

15

Beyond the availability of industrial hardware and software, the transition to an industrial level of quantum computing usage, i.e., reproducible on a large scale, and with a strengthened economic model, relies on several key elements :

- Development of quantum algorithms tailored to their use cases.
- Learning and training engineers in quantum algorithmics.
- Availability of quantum emulators to develop and test algorithms under optimal conditions.
- Creation of quantum capabilities in computing centers sponsored by states (HQI for France) beyond the « online » tools offered by global operators (IBM, Google, Microsoft, etc.).

16

The credibility of quantum actors' roadmaps will be tested in the next five years.

Quantum actors (IBM, Microsoft, IQM, etc.) present very ambitious roadmaps for the 2027-2029 horizons in their march towards FTQC, with considerable leaps to be made. It is essential to be particularly vigilant about the steps to be taken in these roadmaps and the announcement of their completion. The lack of a common glossary among quantum actors, widely accepted reference benchmarks by the industry, leads to relativizing some announcements. Nevertheless, metrics intended to compare performances are being developed : BACQ, QV (Quantum Volume), QSCORE (Quantum Score), etc. Furthermore, the adherence to these ambitious roadmaps is uncertain and could ultimately deter investors in a context of tightening access conditions to financing.

Use Cases, Applications, and Their Impacts

17

The industrial deployment markets in the next ten years are :

- **Finance** (portfolio optimization, risk management, etc.).
- **Small molecule chemistry and materials** (new materials, etc.).
- **Logistics** (agent routes, optimal loading, etc.) if significant progress is made.
- **Healthcare,** if very significant progress is made.

18

Over the next 15 years, the potential economic impacts of quantum computing on industrial sectors and organizations (including services) are anticipated to primarily involve performance and process improvements rather than disruption.

According to the potential use cases identified with partners (around a hundred), most of them have **limited impacts on business models,** either due to their nature (optimization, etc.) or due to the highly probable shared access to these tools for organizations in the same sector (regulatory aspects to avoid competition biases, especially in regulated sectors).

19

Assuming the existence of a large-scale, error-tolerant universal quantum computer, the largest market impacts will be in the biomedical and pharmaceutical sectors (new molecules, vaccines, etc.) as well as in chemistry (batteries, chemical reactions, fertilizers, etc.).

The structural evolutions of industries in the next 15-20 years will also be major, within the framework of ongoing transitions and disruptions in technologies and business models. The coupling between supercomputers, **quantum processors, and advances in AI will be leverages to accompany these disruptions** (autonomous vehicles, decentralized energy production management, etc.).

Ethical and Geopolitical Aspects

20

Applications of quantum computing in terms of research, optimization, simulation do not present particular ethical issues that are not included in existing uses of AI or HPC.

21

A race for quantum computing is observed among the major global powers. Quantum is perceived as a major sovereignty issue given its potentially critical strategic implications (economic, military, etc.).

This raises the question of the international diffusion prospects of quantum innovation and technologies, with a risk of confinement within rival geopolitical blocs, or even states. Beyond these geopolitical aspects, the question of **unequal access to key quantum computing technologies in certain regulated domains** is likely to create distorted competition. Legislators in this context may aim for homogeneous access to computers.

22

The « quantum » image : the low understanding of the subject and its issues is a barrier, even in the world of scientists, engineers, and business.

Pedagogical work appears necessary to promote the social acceptability of quantum and address potential discourses rejecting these technologies based on more or less fantasized arguments (environmental impact, increased inequalities and social control, etc.). **It is important in the future to communicate how quantum computing can address societal challenges for everyone :** better energy management, understanding climate, health, new materials, etc.

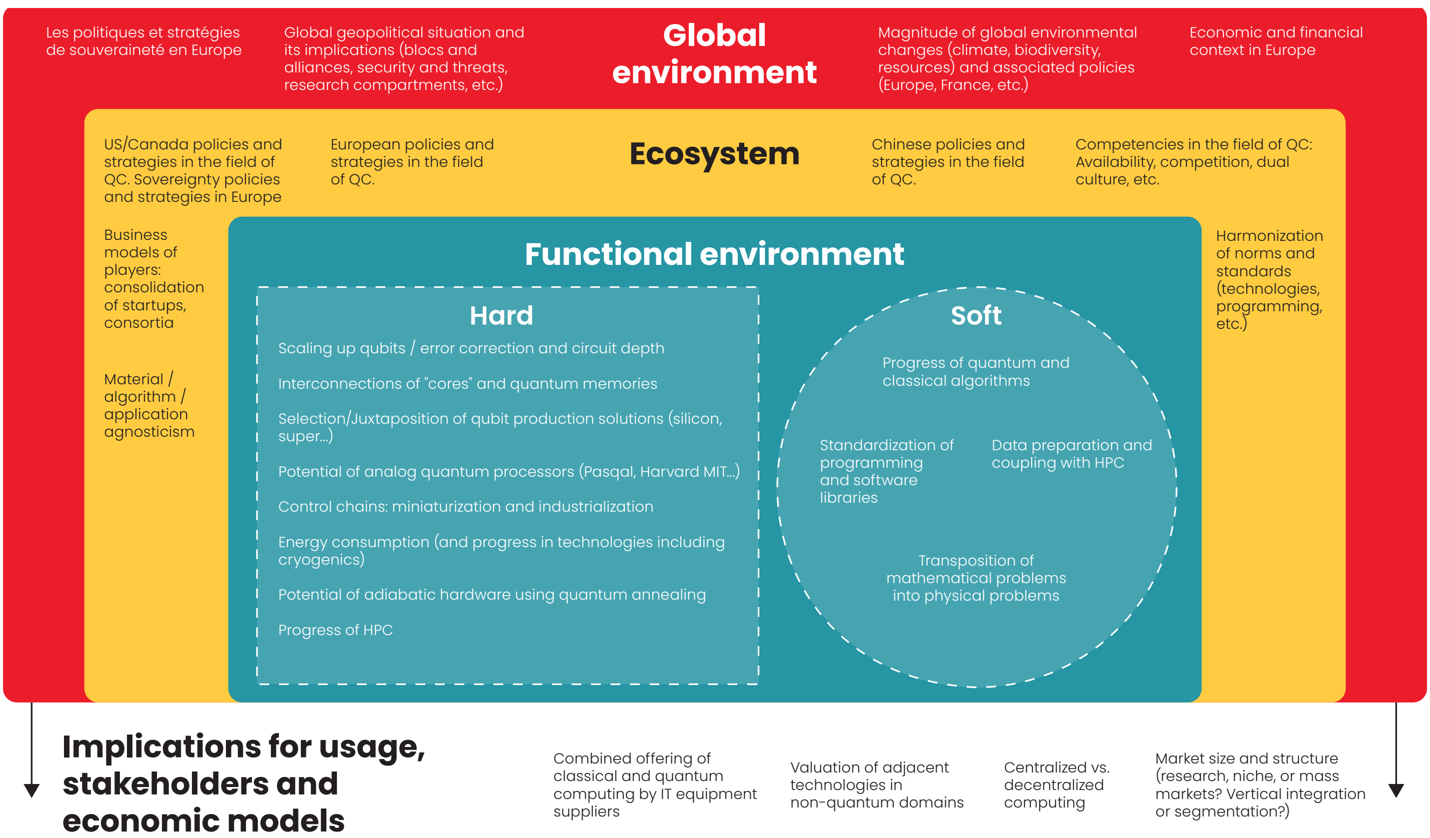
PROSPECTIVE METHODOLOGY

In an emerging field filled with uncertainties, the prospective methodology is particularly suitable for such studies. We relied on the consulting firm Futuribles with an approach based on **morphological scenario analysis**[1]**,** which allows for the evaluation of various possible or plausible futures. It's a collaborative effort involving 13 large companies from different sectors, as well as experts from academia, consultants, manufacturers, and startups. This work began in December 2022 for a duration of 12 months, including a cycle of 8 plenary meetings and 4 site visits (labs, computing centers, and startups). Our approach focuses on a **French scope** but adopts a global perspective, integrating ongoing or forthcoming developments in international quantum computing « hotspots » into the analysis. One advantage of this prospective study is that it can be updated by modifying the milestones and barriers identified in the scenarios.

Prospective System

The first step was to establish a broad initial vision of the prospective system, taking into account developments in the global environment, ecosystem, and actors, as well as technological and scientific aspects, uses, and impacts. **The complete version of the system includes 140 variables.**

[1] https://www.futuribles.com/lanalyse-morphologique/



After prioritization, we simplified the system using **15 variables distributed across four main domains** (see Annex 2 for the list of variables).

Each variable was detailed in a fact sheet describing the major barriers to quantum computing on which we made assumptions and milestones (confidential report). It is from these assumptions that we built our different scenarios.

Scenario Construction

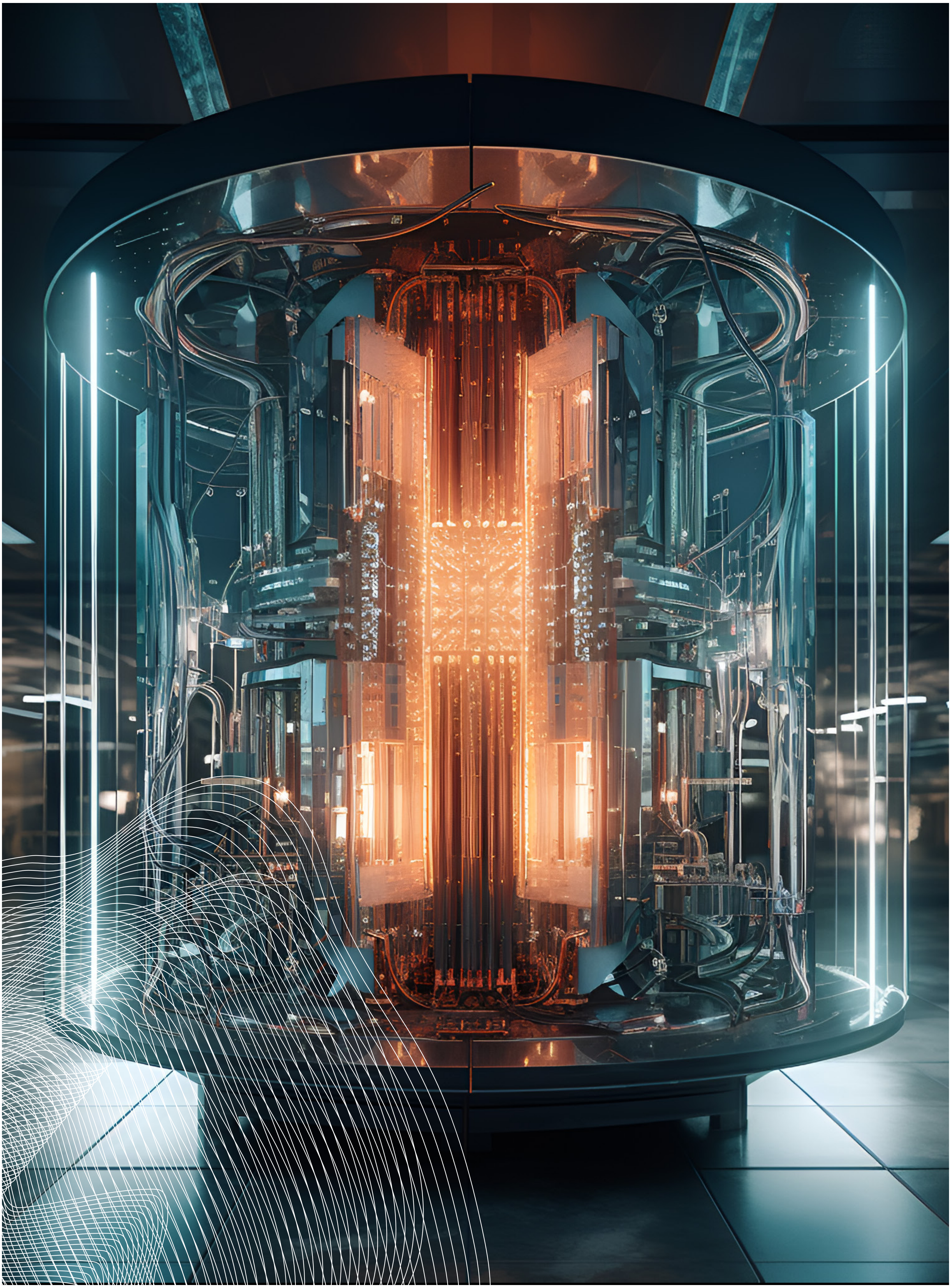
We constructed **4 scenarios based on the major trends and assumptions identified** for each variable in the prospective system. The construction of these scenarios is based on pivot assumptions primarily from the techno-scientific domains. These hardware and software parameters constitute the tipping elements from one scenario to another (mainly reflected in the evolution of the number of qubits and error rates). Assumptions from other variables helped outline the economic actors' scenarios and global contexts for each scenario.

Use Cases

In workshops, we asked **partners to position their use cases** in the different scenarios based on their sector (transport/logistics, finance, chemistry/materials, telecom, energy, health, etc.). This valuable information allowed us to assess the impact of quantum computing from the perspective of industrial users/companies, particularly based on the required performance of the computers to solve the associated mathematical problem (size, algorithm type, calculation depth, error rates, etc.).

Economic and Market Approaches

Based on interviews with quantum computing hardware manufacturers (machines, enabling technologies, etc.), we made a number of **market assumptions about the evolution of the number of quantum systems.** Applied to different scenarios, we evaluated a framework for the quantum computing market limited to the sale of quantum systems and their associated services (e.g., cloud, etc.), but we did not evaluate the impact of positive externalities (process improvements and increased revenues for users), which are difficult to assess.



SCENARIOS

The four scenarios represent different **performance milestones of the computers (number of qubits, error rates, etc.)** resulting from the availability, quality, and **scaling of several enabling technologies** (command chain, interconnection, quantum memory, etc.). It is necessary to add to these hardware-related parameters those related to progress in quantum algorithms and the software environment at large.

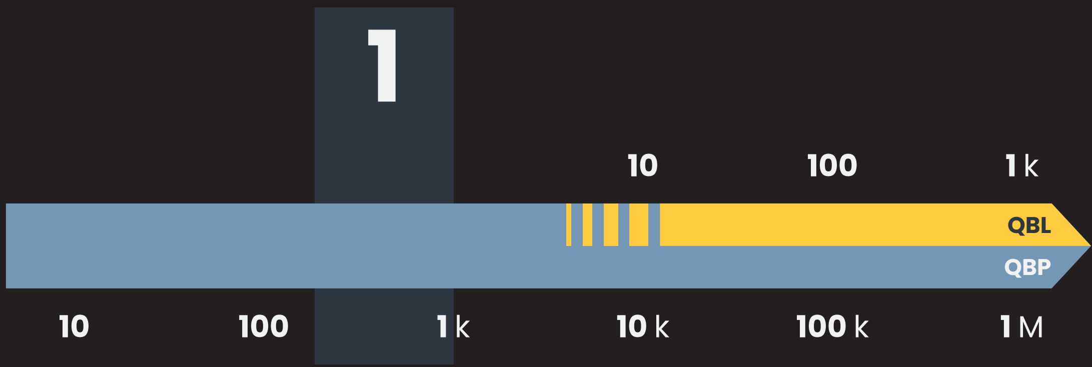
Indeed, the performance of the computers conditions the algorithms that can be implemented with exploitable results, especially in a context where gate-based computers would remain significantly noisy (NISQ). Conversely, quantum algorithms have more or less strong requirements in terms of circuit depth (number of logic gates, computation cycles, etc.) and data preparation, which determine the types of machines on which they can be implemented. Schematically, for a problem exploiting a given number of qubits, the greater the circuit depth of an algorithm, the more necessary it is to have qubits with limited error rates.

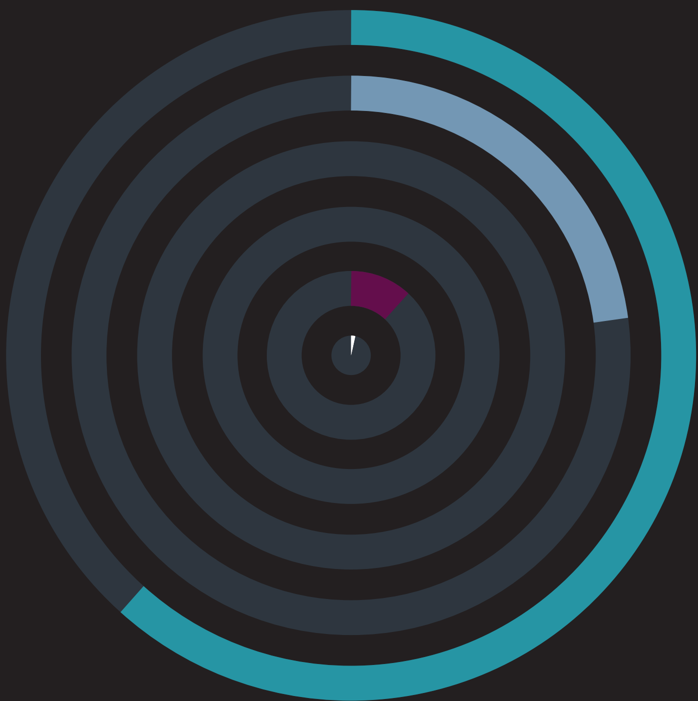
Quantum algorithmic research being an active research field, our scenarios include **assumptions of progress in the discovery of algorithms with limited circuit depth,** or which manage to obtain exploitable results despite the noise (noise tolerance). We have not formulated assumptions about breakthrough algorithms that would challenge the types of problems addressable by quantum computing.

For each scenario, we have identified precisely the technical-scientific milestones necessary for their realization, as well as the main applications and use cases. We have also included these scenarios in global contexts integrating economic and societal impacts. A percentage of likelihood regarding the achievement or surpassing of the scenario by 2042 is indicated, based on a survey conducted among the working group formed by the partners.

SCENARIO 1 • THE NARROW GATE

Small NISQ & Analog





% of GT members thinking that the scenario will be achieved :

61.5 BY2025

23 BY 2032

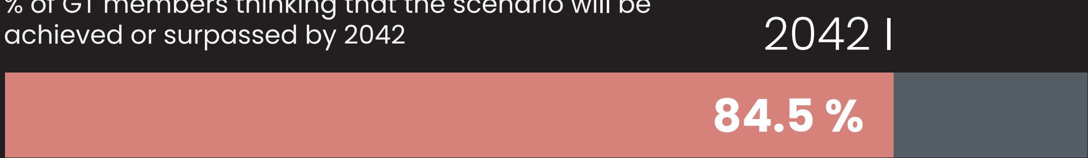
00 BY 2042

00 IN 2050 OR LATER

11.5 NEVER

04 NO COMMENT

% of GT members thinking that the scenario will be achieved or surpassed by 2042



General Description

In this scenario, quantum computing takes the form of « Mini-NISQ » and analog processors. Fault-tolerant quantum computers (FTQC) remain inaccessible. This is because increasing the number of physical qubits comes at the expense of their fidelity. The implementation of **error correction methods is not effective.** Consequently, **the industry fails to surpass the threshold of 1,000 entangled qubits** with a sufficiently low noise level (error rate exceeding 10^{-3}). In terms of applications, quantum processors in this scenario are primarily used for optimization on **problems with very low data volume but high computational intensity.** Despite these limitations, there are advantages in terms of speed (linear acceleration) and energy consumption for simple applications. In this context, **analog hardware appears highly relevant.** The limitations of the performance of the computers are exacerbated by insufficient progress in algorithmic research. **The number of shallow-depth circuit algorithms remains limited,** restricting implementation possibilities on the Mini-NISQ. This dual hardware and software impasse fuels a vicious cycle where algorithmic research stagnates due to the inability to test envisaged calculations under real conditions. **Therefore, there is a narrow gate for quantum computing applications,** but opening it further requires breaking new barriers.

Technical-Scientific Milestones

- < 1000 physical qubits noisy and entangled.
- Error rate between 2 physical qubits > 10^{-3}.
- Ineffective error correction.
- Few logical qubits unusable due to high noise.
- Classical/quantum data transfer limited by weak coupling with HPC.
- Limited algorithmic developments.

Computational Potential & Advantages

NISQ is utilized for **small-scale** problems, leveraging a few **noise-tolerant algorithms with shallow depth.**

Analog computing allows for tackling **certain problems more complex than NISQ** within a commercial relevance space.

Quantum advantages in speed (linear acceleration / polynomial start) and energy consumption for simple applications with simplified or small datasets :

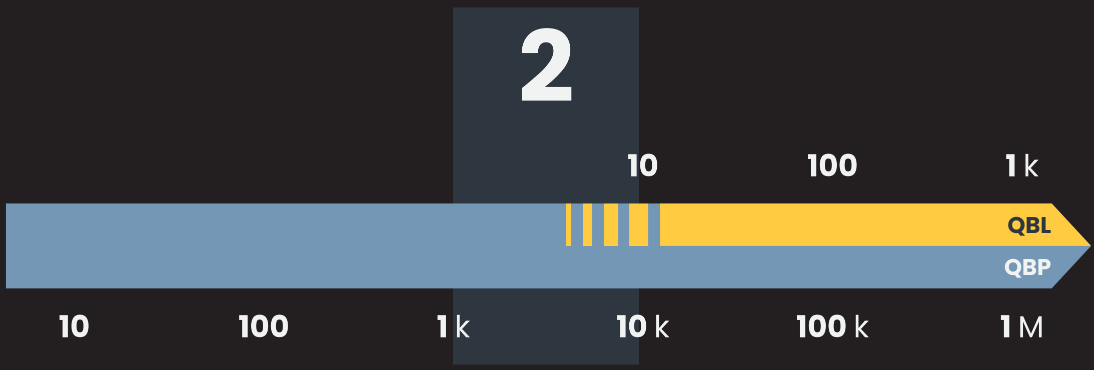
- Optimization with few degrees of freedom : logistics (routing), transportation (passenger seat organization), finance (customer risk assessment, etc.), pharma (clinical study preparation and batch scheduling).
- Data preparation for ML and clustering at a very small scale.

Economic and Societal Impacts

The absence of major breakthroughs, if this scenario persists, would l**ead to a reduction in funding** and quickly to **horizontal consolidation of the players.** Some entities abandon (start-ups, etc.) or get acquired by others who expand their technological portfolio. Some Tech Giants companies cease quantum investments or divest their activities. In this scenario, there is coexistence of NISQ and analog machines. NISQ and analog machines will be coupled with large HPC centers and are priced similarly to current machines. Government funding remains stable (research, security/military).

SCENARIO 2 • QUANTUM DOMAIN EXPANSION

Large NISQ & Analog



% of GT members thinking that the scenario will be achieved :

19 BY 2025

58 BY 2032

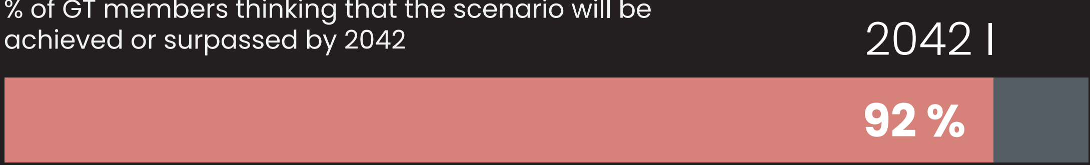
15 BY 2042

00 IN 2050 OR LATER

04 NEVER

04 NO COMMENT

% of GT members thinking that the scenario will be achieved or surpassed by 2042



General Description

In the second scenario, the landscape of quantum computing is characterized by deep analog systems and **NISQ gate processors capable of handling up to 10,000 physical qubits.** This period witnesses an **improvement in qubit fidelity** and progress in error reduction (although error rate reduction is limited to 10^{-5}). This scenario benefits from a continuous and joint progress dynamic of NISQ, HPC, and algorithmics. Breakthroughs occur in **the discovery of noise-tolerant algorithms and limited-depth circuit algorithms.** Concurrently, significant advances are observed in **error mitigation and coupling with HPC,** enabling the optimization of **the implementation of deeper algorithms.** Due to the larger number of available physical qubits, **analog quantum processors can address increasingly complex** use cases compared to scenario 1. **NISQ and analog systems coexist** in this scenario and thus compete for certain uses. Quantum processors in this scenario demonstrate **advantages in terms of speed (up to polynomial acceleration), precision of heuristic algorithms, and energy consumption.** However, their applications remain highly specific (optimization, small-scale simulation, machine learning and clustering assistance, etc.).

There are **bottlenecks for scaling error mitigation to more than a few 100 qubits** with current knowledge. If this scenario represents the state of the art in 2042, it will likely be challenging to further optimize gate fidelity and continue NISQ scalability. Extending the quantum domain beyond this scenario is a struggle against technological and scientific obstacles.

Technical-Scientific Milestones

- Analog and « deep » NISQ (< 10,000 physical qubits).
- Error rate between 2 physical qubits ranging from 10^{-3} to 10^{-5}.
- Progress in error mitigation but ineffective error correction.
- Several tens of logical qubits unusable due to imperfections or insufficient numbers.
- Advancements in the control chain to handle thousands of physical qubits.
- Better coupling with HPC optimizes data preparation.

Computational Potential & Advantages

NISQ for small-scale problems, mainly heuristic.

Analog leveraging NISQ progress on connectivity, qubit control, and possibly error mitigation, allowing for optimization and small to medium-scale simulation problems.

Industrial applications are structured with speed advantages (up to polynomial) and energy consumption advantages, but they remain highly specific :

Optimization with more degrees of freedom : finance (dynamic asset portfolio optimization and market forecasting), telecommunications (antenna placement in networks), transportation (scheduled transport plan adaptation).

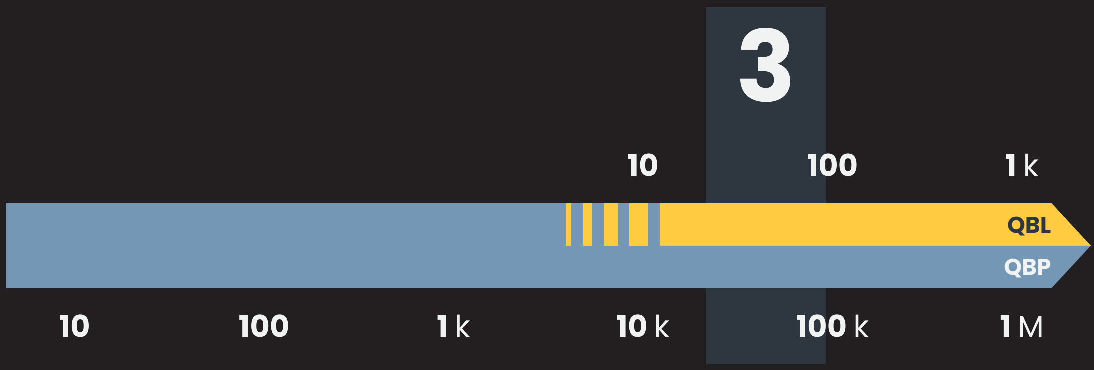
- Small-scale molecular simulation : healthcare (molecular interaction & solvent affinities), chemistry (material properties modeling < 100 atoms).
- Data preparation for ML and small-scale clustering.
- Fundamental research.

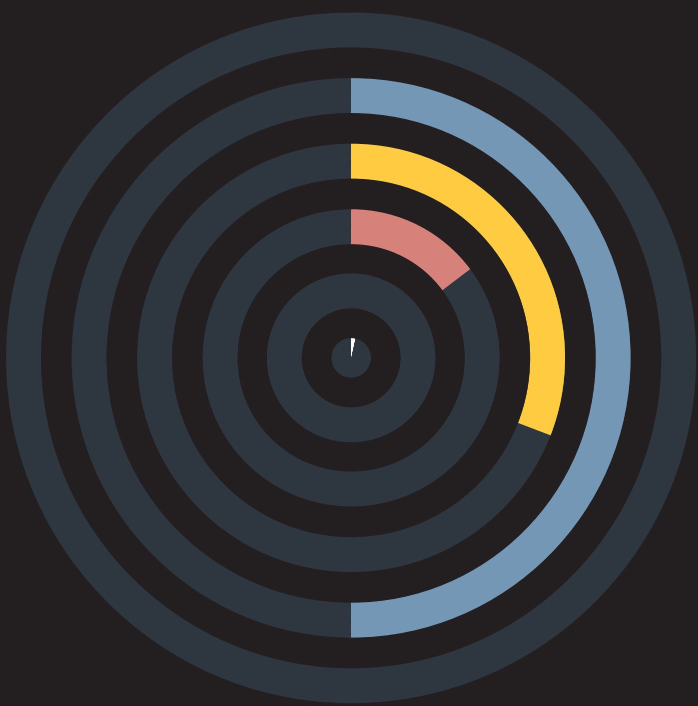
Economic and Societal Impacts

Impacts on industrial processes but no revolution in professions except in **finance and healthcare where impacts can be significant.** Drying up of public funding could hinder quantum computing development. There would be an increasing trend towards **vertical consolidation of actors** to offer comprehensive solutions to clients. As in the previous scenario, there is **coexistence of NISQ and analog machines.** NISQ and analog machines would be coupled with large HPC centers and priced similarly to current machines.

SCENARIO 3 • THE DOORS TO FTQC ARE OPEN

Quantum supremacy arrives





% of GT members thinking that the scenario will be achieved :

00 BY 2025

50 BY 2032

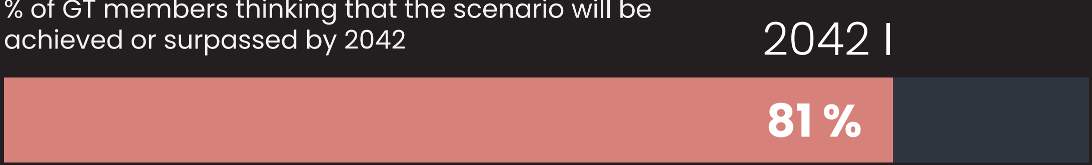
31 BY 2042

15 IN 2050 OR LATER

00 NEVER

04 NO COMMENT

% of GT members thinking that the scenario will be achieved or surpassed by 2042



General Description

This scenario marks **the beginning of fault-tolerant quantum processors (FTQC).** Progress in qubit control, miniaturization of the control chain, and the **first interconnections of quantum cores** allow for addressing tens of thousands of qubits. **The techno-scientific barriers are lifted on error correction,** and the threshold theorem is applied, enabling scalability of the number of qubits without degrading calculation fidelity.

However, the potential of FTQC applications is not fully realized due to **the number of logical qubits, which has not yet exceeded a hundred** in this scenario. Several factors may cause this limitation : limited industrialization of the control chain due to high costs and development inertia, limitation in the number of interconnections of quantum cores. **The absence of large-scale QRAM** remains a major hurdle in the development of high-volume data applications. The nature of the problems addressed remains similar to that of scenario 2, but t**he quantum computing speed advantage becomes more pronounced,** reaching super-polynomial levels for some applications. **The deterministic nature of FTQC algorithms allows for finding exact solutions to previously inaccessible problems. Analog systems continue to benefit from progress in scalability and fidelity improvement,** but their relevance begins to decrease in view of FTQC advancements. With the main obstacles in error correction and the control chain being lifted, the gates of FTQC are indeed open !

Technical-Scientific Milestones

- Error rate of physical qubits < 10^{-5}.
- Breakthrough in error correction facilitated by the scaling up of qubits less sensitive to certain types of errors or new error correction methods.
- Less than 100 logical qubits with an error rate below 10^{-12}.
- Scaling up of qubits enabled by miniaturization of control chain components and scaling up of production.
- Interconnections between a few quantum cores.
- Better coupling with HPC.

Computational Potential & Advantages

The potential of FTQC algorithms is unevenly exploited due to a still limited number of logical qubits.

The nature of the problems addressed would vary little compared to scenario 2; however, the quantum speed advantage increases **(up to super-polynomial),** and **quantum supremacy would be achieved in practical use cases.**

Analog computing benefits from qubit scalability/ fidelity progress, but **its relevance diminishes** in view of gate-based computing progress. It may maintain an advantage in energy consumption and cost compared to FTQC.

Examples of Use Cases :

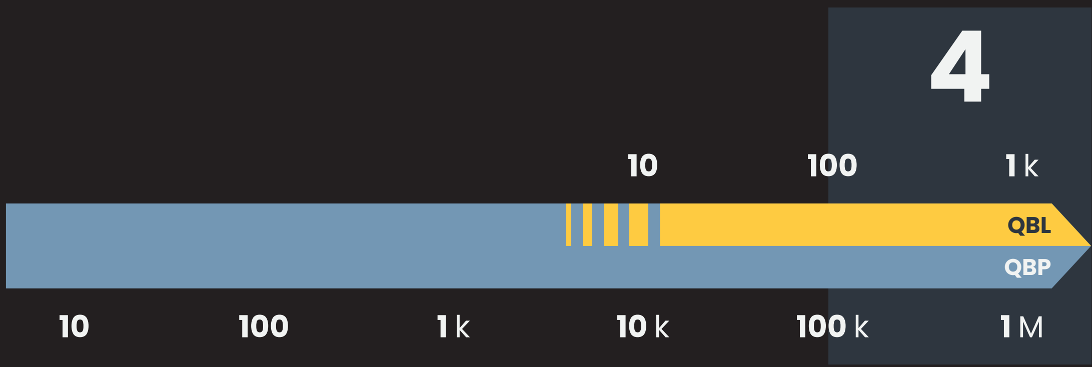
- Optimization : Health (fluid-based chemical processes - Lattice Boltzmann), Transport (adaptation of hazards in transportation), Finance (derivative pricing), etc.
- Simple aerodynamic simulation.
- Large-scale Machine Learning data preparation and clustering.
- Fundamental research.

Economic and Societal Impacts

Major companies are ready for the advent of FTQC (identified use cases, acquisitions of hardware and software solutions, HR, etc.), but processor industrialization is not yet realized due to high costs and development inertia, especially in the control chain. Market players are consolidating, indicating sector maturation. In a **world of blocks context,** the weight of public actors, **military research**, solutions, and quantum computing hardware being **concentrated around a few « winner takes all » actors/poles per major nations.** Gate-based machines coexist with analog machines possessing a significant number of physical qubits, which makes them increasingly relevant for optimization problems. We estimate that in this scenario, **the arrival of quantum machines will generate additional growth in the HPC market.** However, the price of quantum machines will remain in the same order of magnitude as before.

SCENARIO 4 • THE QUANTUM LEAP

On the road to Very Large Scale Computing



% of GT members thinking that the scenario will be achieved :

00 BY 2025

15 BY 2032

38.5 BY 2042

38.5 IN 2050 OR LATER

00 NEVER

08 NO COMMENT

% of GT members thinking that the scenario will be achieved or surpassed by 2042

53.5 % I 2042

General Description

In this final scenario, **FTQC takes a leap forward,** embarking on a trajectory towards very large-scale quantum computing (VLSQ). Quantum processors are now capable of **addressing hundreds of logical qubits** due to the industrialization of the control chain and the implementation of **a modular architecture allowing unlimited interconnection of cores.** The path appears clear for the development of processors with thousands of logical qubits. However, the time required to overcome key barriers for this scenario and scale up industrial production makes the development of VLSQ by 2042 unlikely. FTQC progress opens access to new types of problems and larger data sizes. **The advent of quantum memory** (QRAM) offers new perspectives for applications requiring large data volumes (research and addressing). The speed advantage of FTQC becomes even more significant, with exponential acceleration made possible by advances in algorithmics and qubit scaling. **Analog systems face the challenge of specialization and cost reduction to survive in the face of FTQC advancement. They persist in niche applications,** offering energy and/or cost advantages over FTQC. The quantum leap is achieved, opening up new perspectives for computing.

Technical-Scientific Milestones

- Over 100 logical qubits with an error rate below 10^{-12}.
- Industrialization and price drop for the control chain (by a factor of 100).
- Possible interactions between numerous quantum cores.
- Breakthrough on QRAM opens up new application perspectives.
- Modular architecture of quantum systems with unlimited interconnections and increasing coupling with HPC for data processing.
- Techno-scientific path now obstacle-free towards thousands of logical qubits (VLSQ), but development inertia by 2042.

Computational Potential & Advantages

New types of problems accessible and for larger data sizes.

Speed advantage up to exponential facilitated by progress on FTQC algorithms and qubit scaling.

Possible persistence of analog in some niche uses, with energy and/or cost advantage over FTQC.

Quick problem-solving at a high frequency addresses **use cases where timeliness is a critical issue.**

Examples of Use Cases :

• Optimization : Health (genome reconstruction), Communication (antenna placement in networks), Transport (adaptation of hazards in transportation), Finance (derivative pricing, random market), etc.

• Research in an unindexed database : health (search for a nucleotide sequence in a genome).

• Simulation : health (molecular interaction and affinities with solvents).

• Machine learning data preparation and clustering for AI sees significant development.

• Fundamental research.

The resolution of **large number factorization problems and partial differential equations** would no longer face major techno-scientific obstacles but **may not necessarily be achieved by 2042** due to scaling inertia of the computers.

Economic and Societal Impacts

AI is omnipresent in society and uses quantum computing to reduce its energy consumption. The social and political impact of quantum computing becomes tangible, with contributions to energy transition and health. The dissemination of the technology becomes increasingly controlled in contexts of malicious exploitation or sovereignty. There could be **potential risks of misunderstanding by the population feeling overwhelmed by quantum technology.** In this scenario, attention must be paid to **the segmentation of FTQC markets : a premium segment aimed at the most powerful HPC centers** but not exceeding the price of the best supercomputers and a mid-range segment with a more accessible price allowing for increased sales volumes. The market for **analog machines is heavily cannibalized by the arrival of gate-based machines and can only survive through drastic cost reduction.** In this scenario, quantum generates very significant additional growth in the HPC market.

Summary : Typology of Addressable Calculations Across Scenarios

Types of addressable problems * : problem size	**SC1 THE NARROW GATE**	**SC2 QUANTUM DOMAIN EXTENSION**	**SC3 THE DOORS TO FTQC**	**SC4 THE QUANTUM LEAP**
Optimization (Annealing & QUBO)	**	***	***	****
Simulation (VQE)		*	**	**
QML (QNN)	*	**	***	****
Research & addressing (Grover)				*
Factorization (Shor)				⌛
Differential equations (HHL)				⌛
Speed advantage VS classical	*Linear*	*Up to polynomial*	*Up to super polynomial*	*Quantum Supremacy*

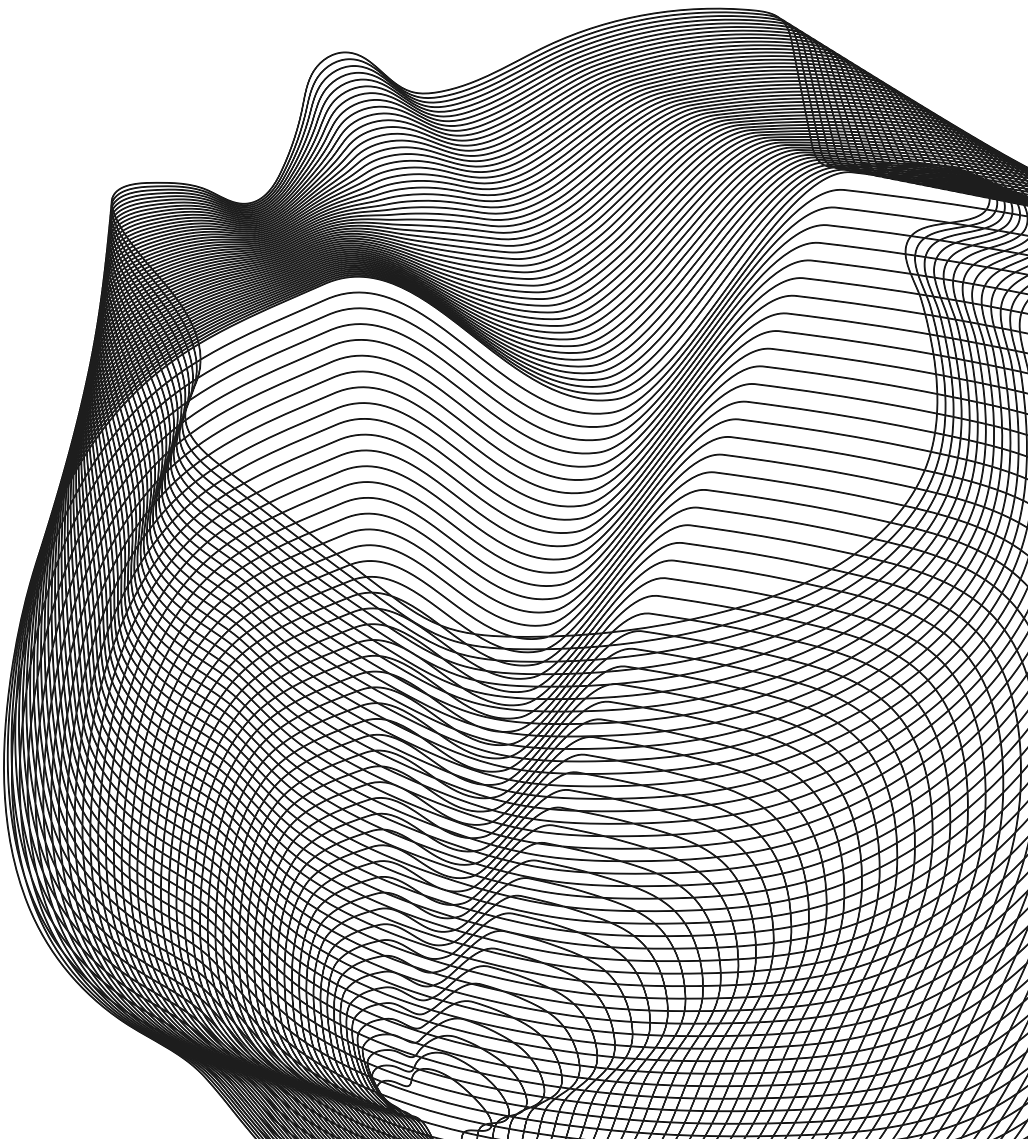
We have synthesized the types of problems addressable based on the scenarios, without distinguishing between problems addressable by types of machines (analog or gate-based).

Optimization problems and Quantum Machine Learning (QML) can be addressed as early as scenario 1 for small datasets, then for increasingly complex problems with the increase in the number of available qubits.

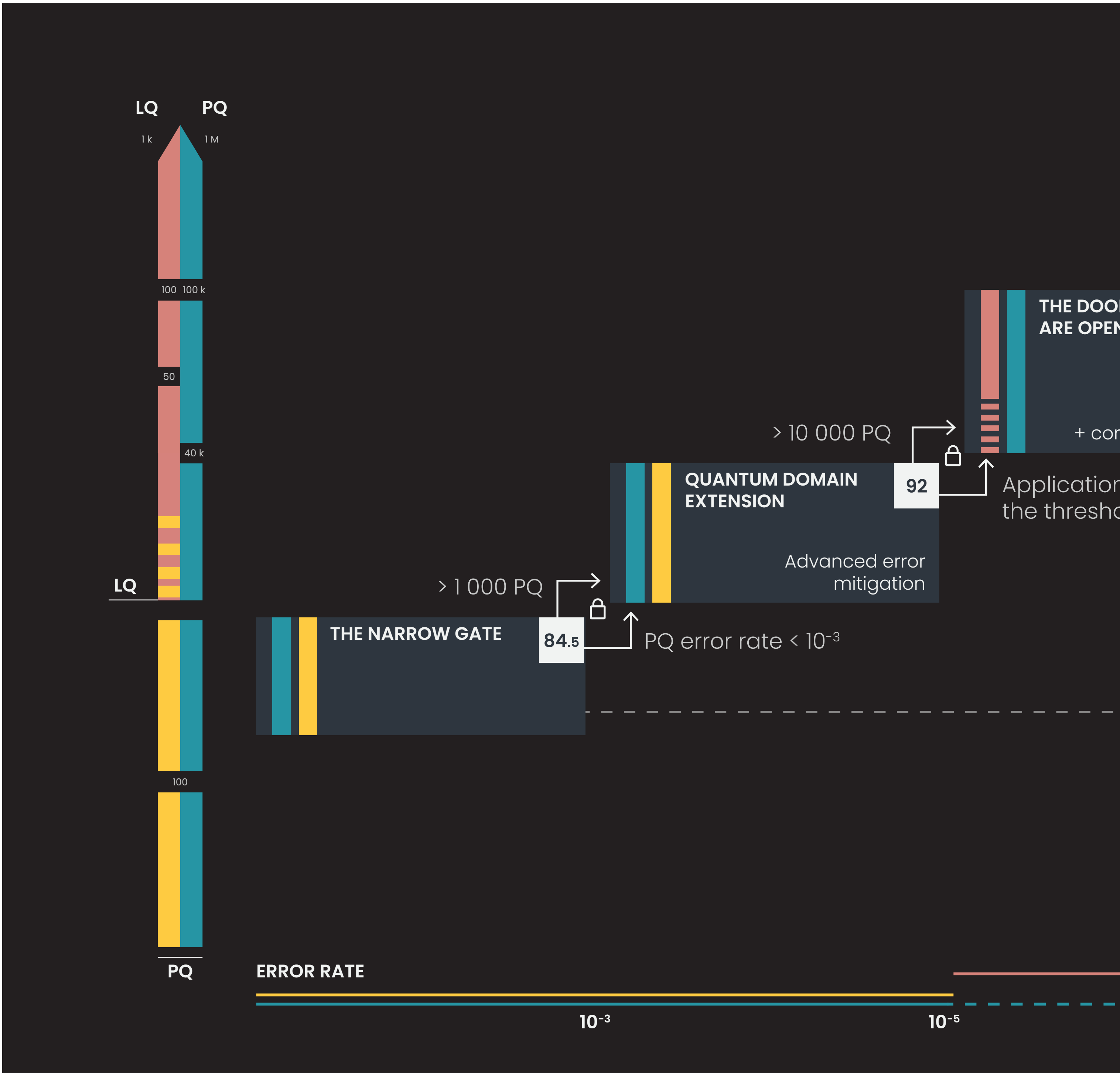
The number of addressable qubits from scenario 2 onwards allows for applications in physicochemical simulation and material development.

With scenario 4 and the advent of QRAM, quantum advantages should enable the processing of search and addressing algorithms.

Factoring large numbers requires a considerable number of logical qubits to be resolved, a number that is unlikely to be achieved before the VLSQ scenario (Very Large Scale Computing). Similarly, solving partial differential equations requires very high precision and computational intensity with a very large data flow. These characteristics are unlikely to be achievable before the advent of QRAM and VLSQ.



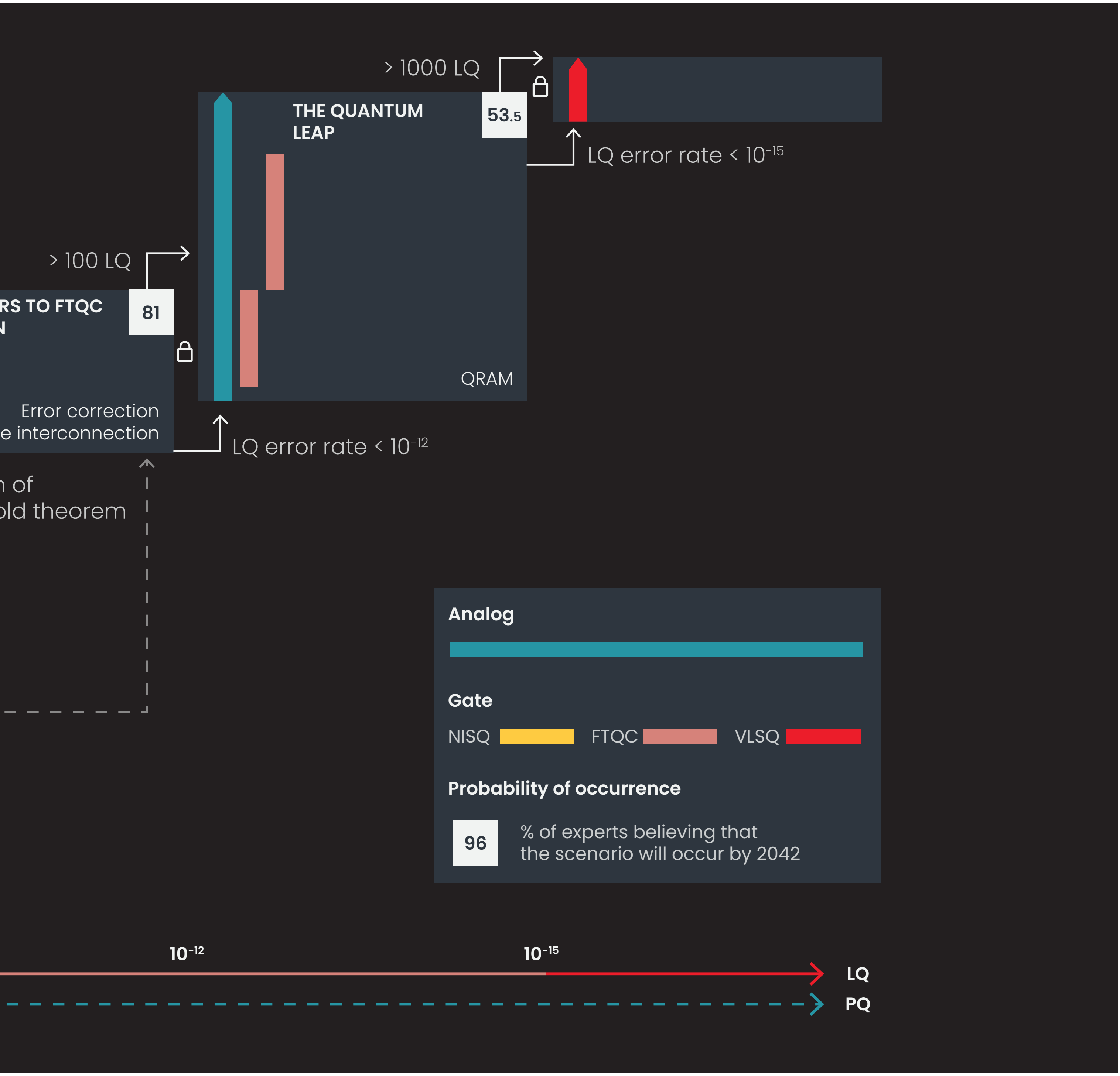
Scenario diagram



Legend of the Diagram

These scenarios follow a logic of progression of computer performance and achievable calculations along **2 important axes : the number of usable qubits and the error rate of these qubits.** We have symbolized with different colors the analog (blue), NISQ (yellow), FTQC (pink), and VLSQ (red) technologies.

On the x-axis, the scale represents the error rates of the physical qubits of NISQ and analog machines for scenarios 1 and 2, then the error rates of FTQC logical qubits for scenarios 3 and 4. From scenario 3 onwards, the correlation between error rates of physical and logical qubits can vary significantly depending on the technologies. The error rate of physical qubits is no longer a discriminating factor and is not indicated in the diagram (it remains a relevant factor for distinguishing analog machines). On the y-axis, the scale represents on a single logarithmic axis the number of physical and logical qubits. The correspondence between



physical qubits (QPB) and logical qubits (QBL) can vary greatly depending on the technologies. For clarity of representation, we have taken an overhead of 1,000 (1,000 QPB for 1 QBL), commonly accepted as relevant when writing this report. The scale of QBL is therefore not filled below 1000 QPB. Furthermore, a minimum of 40 logical qubits is required to have an advantage over emulation. The scale of QBL is dashed below 40,000 QPB.

For each scenario, an index of likelihood of achieving the scenario by 2042 has been displayed, based on a survey conducted among 24 quantum computing experts (see page 48).

Each scenario requires **a breakthrough to transition from one to another.** The different tipping dynamics between scenarios are symbolized by milestones and necessary technological breakthroughs. In scenario 1, The Narrow Gate, where analog and NISQ are represented, the barriers are the ability to surpass quantum cores with 1,000 physical qubits and to have a qubit error rate lower than 10^{-3}. **Scenario 1, The Narrow Gate, and scenario 2, Expansion of the Quantum Domain, have an equal probability of being realized by 2042.** However, it is important to note that a certain number of experts consider scenario 1 as already accomplished today or on the verge of being so. According to 11.5 % of experts, this scenario will be largely surpassed by 2042.

Scenario 2 thus allows notable advances in computing and quantum advantages in certain areas due to the increase in the number of qubits, progress in algorithmics, and error mitigation. Analog still coexists with NISQ and proves to be increasingly relevant for certain niche applications. However, two major barriers, namely successful error correction and interconnection of quantum cores, are not lifted. In this scenario, **logical qubits are achieved but are still imperfect, making them unusable for the majority of problems.**

The advent of scenario 3 relies on passing these two milestones : **error correction and interconnection between quantum cores.** Error correction becomes effective thanks to progress in error correction codes combined with an improvement in error rates ($< 10^{-5}$) and the ability to use a larger number of qubits (< 10,000), allowing for **the application of the threshold theorem** (see glossary definition in Annex 1). Another very important milestone, also mentioned in most quantum industry roadmaps, is the interconnection between « cores » that would allow both gate-based and analog technologies to exceed 10,000 physical qubits. **This scenario is less likely (81 %)** according to experts than scenario 2 but still quite credible by 2042. It should be noted **that breakthroughs in error correction could allow a leap from scenario 1 to scenario 3,** without going through the intermediate step of an « optimized » NISQ. Indeed, some industry roadmaps project 100 logical qubits by 2026[1].

As for the quantum leap, **scenario 4 is considered less likely in 2042 by study participants and experts (53.5 %).** It indeed requires crossing **the symbolic threshold of 100 perfect logical qubits** (i.e., with error rates below 10^{-12}) beyond which many problems can be addressed. Another **major barrier is obtaining a QRAM** that would make the efficient deployment of algorithms such as searching in unindexed databases possible, with numerous applications.

Achieving a VLSQ scenario is not envisaged in 2042 in this study, where we consider the use of **several thousand perfect logical qubits.** For reference, Shor's algorithm, which would break RSA 2048-bit encryption, requires several thousand logical qubits.

[1] Quera plans to rapidly increase the number of qubits, aiming for more than 3,000 physical qubits in 2025 and more than 10,000 in 2026.

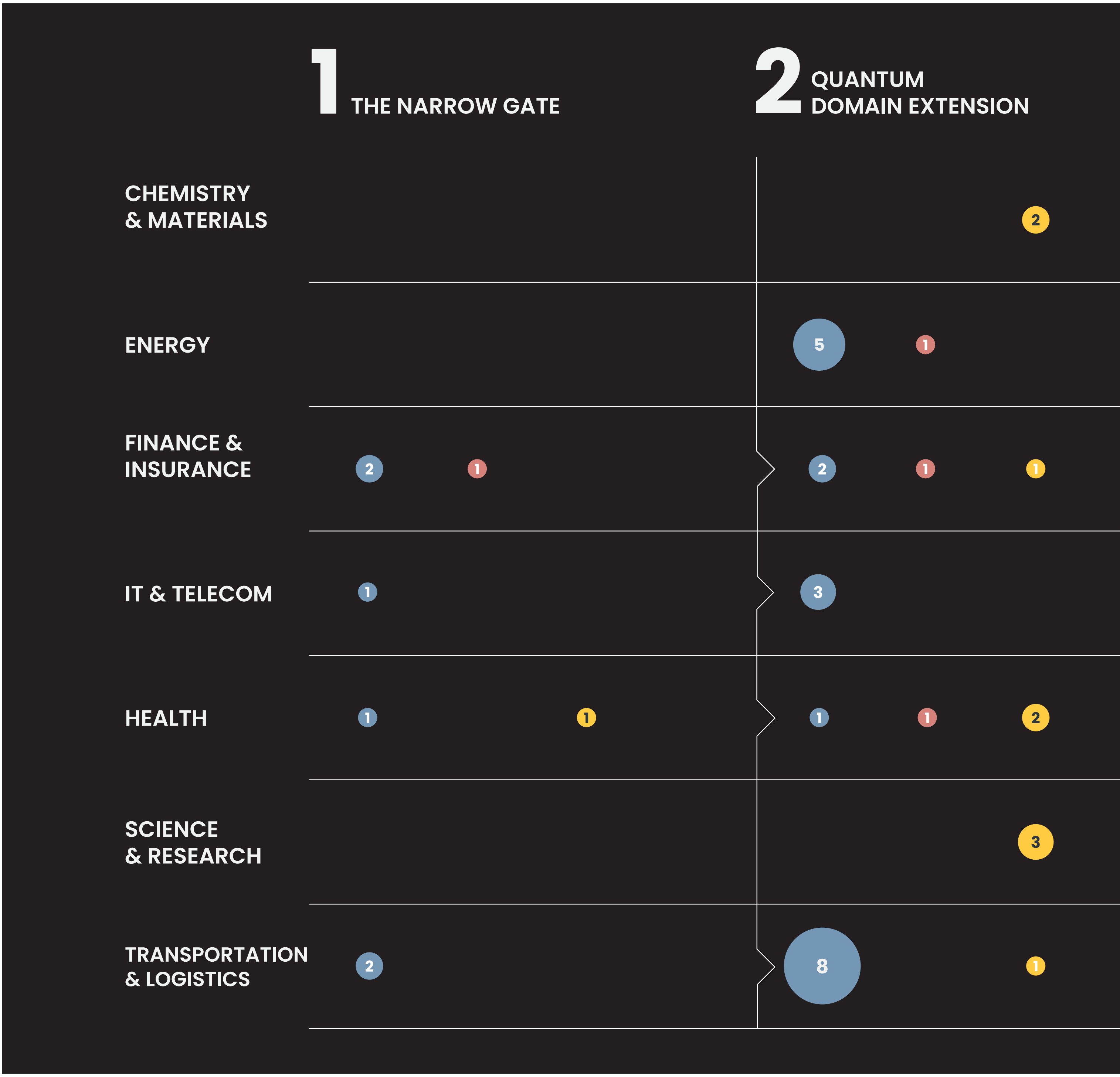
USE CASES

In the course of our work, we exclusively explored the **use cases provided by the partner members.** We assessed the computational resources needed to address the associated mathematical problem (data size, algorithm type, computational depth, error rates, etc.). Subsequently, we positioned them in relation to the four scenarios describing the levels of computer performance and computational potentials.

About a hundred use cases have been identified by the project partners, grouped into major sectors of activity. **The analyses presented here focus only on the use cases identified by the partners as potentially problematic within the scope of quantum computing.** We did not address all the use cases found in the literature as some did not seem to correspond to the potential of quantum computing (real-time data processing, excessively large problem size, etc.).

Next, the partners **assessed the impact on their sectors of activity of processing the use cases** through quantum computing and the **associated stakes** according to the scale below :

- 0 : None or very low impact
- 1 : Low impact (improvements/changes in processes)
- 2 : Medium impact (level of projects, new products, services, and customer territories)
- 3 : High impact (level of major areas of activity and missions, creation, disappearance, transformation)
- 4 : Crucial (survival/metamorphosis level)



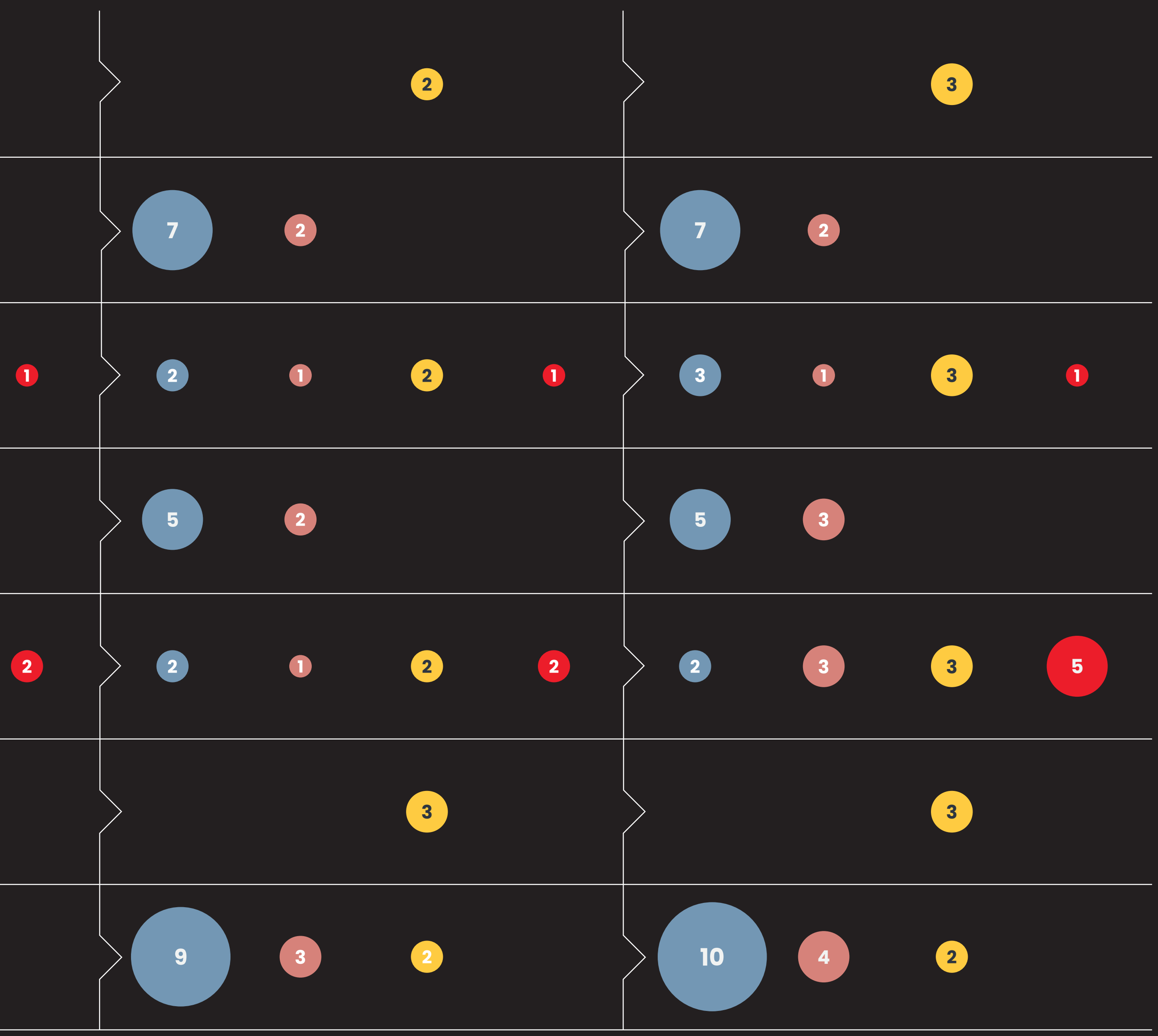
Legend

The size of the circles corresponds to the number of use cases that accumulate as we progress through the scenarios. For example, if we already detect 2 scenarios for transportation and logistics in scenario 1, 6 possible use cases are added in scenario 2, bringing the total to 8 use cases.

- Process Improvement / Change
- Project level - New products, services, customer territories (or disappearance)
- Level of major business areas and missions
- Survival level / Metamorphosis

3 THE DOORS TO FTQC ARE OPEN

4 QUANTUM LEAP



Chemistry, physics & fundamental research

Quantum computing could simulate complex quantum systems, aiding in the study of fundamental phenomena such as **superconductivity, particle physics, condensed matter, etc.** This could lead to advancements in understanding the laws of physics that should be shared. For instance, global collaboration in research on room-temperature superconductivity could be significantly accelerated by utilizing quantum computers. By accurately simulating complex materials at the atomic scale, researchers could discover **new materials** with properties potentially leading to revolutions in **energy storage, or clean energy production, etc.**

The capabilities of quantum computing may not only better simulate (i.e., find an approximate solution to) problems currently inaccessible to classical computing but could potentially solve them (i.e., find the best solution with certainty) in the long run. An example provided is N-Body problems, which are of major importance in fundamental research, particularly for studying nuclei in nuclear physics, solid-state physics, or chemistry.

Energy

Among the consequences of quantum computing applications in the energy sector, significant and diversified contributions are noted in **production, management, and energy efficiency according to the group's work.** These contributions include :

- **Enhanced safety of installations,** particularly in complex simulations. For example, modeling nuclear reactions (designing safer, more efficient reactors) or probabilistic safety studies.
- **Technical management of the electrical system, optimization of energy distribution,** including planning smart grid networks (reducing network losses, network reliability, etc.), optimization of hydraulic production methods.
- **Management of decentralized production and storage systems,** optimization of storage systems (including electric vehicle fleet charging – vehicle-to-grid).
- **Design of more efficient catalysts** (hydrogen generation, CO_2 capture and conversion, electricity production), simulation of materials for photovoltaic cells (improving solar energy conversion to electricity).
- **Optimization of renewable energy parks.** Quantum computing could find optimal configurations to maximize energy capture in wind or solar parks, considering meteorological and geographical variables.
- Progress in **research on nuclear fusion :** the ability to simulate extreme conditions could accelerate research on nuclear fusion.

For businesses, there is an increased need for experts or engineers for simulation and modeling (transition from the physical world to mathematics, data that can be processed by systems integrating quantum processors). The innovation opportunities in designing new catalysts are significant.

In terms of potential impacts for society, these elements contribute, among others, to supporting policies for transition towards greater energy efficiency, less carbon-intensive energy, and reduced losses.

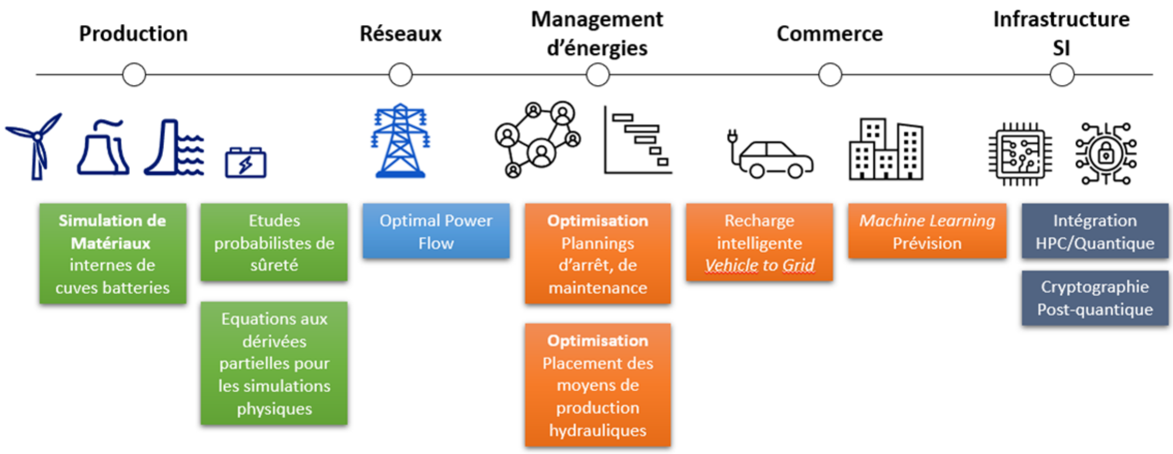


Figure 4 : EDF source, courtesy of EDF.

Health, pharmaceuticals & associates

In the healthcare sector, potential impacts include :

- **Acceleration in the development of new treatments** (molecules, vaccines, etc.) by simulating complex molecular interactions at an unprecedented level of detail. This involves accurately predicting how compounds interact with biological targets. This reduces the need for laboratory tests, accelerates market entry, reduces costs, etc.
- **Optimization of treatments,** their customization for complex diseases like cancer; quantum computing could help design drugs that specifically target the patient's biology, **particularly based on genetic data** (individual and tumor), thus offering greater efficacy and fewer side effects, as well as improving protocols (e.g., radiotherapy planning).
- **Early detection of pathologies** (identification of disease markers at an early stage), **rapid and deep analysis of medical images** (in connection with AI).
- **Advanced genomic analysis** (sequencing, rapid nucleotide chain identification).
- With very powerful quantum computers (considerable processing capabilities and very low error rates), **modeling protein structure,** which would be a major breakthrough in designing innovative treatments.

The impacts for society could be significant, with early disease detection improving survival rates and reducing long-term healthcare costs, personalized treatments reducing side effects. It is also worth noting the potential contributions to pandemic control. In the event of the **emergence of new viruses, the speed of designing new vaccines or antivirals would be crucial.** Quantum computing could reduce this time from several years to a few months or weeks.

For companies, these potential advantages are sources of disruption. In general, there should be an intensification of research and development in molecular simulation. In terms of preparation, this involves investments in equipment and specific training in quantum computing, close collaborations between pharmaceutical industries, and quantum technology companies.

Transport & logistics (road/rail)

Note : Although grouped here, the impacts differ depending on the areas : logistics, rail transport, road transport, and the automotive sector.

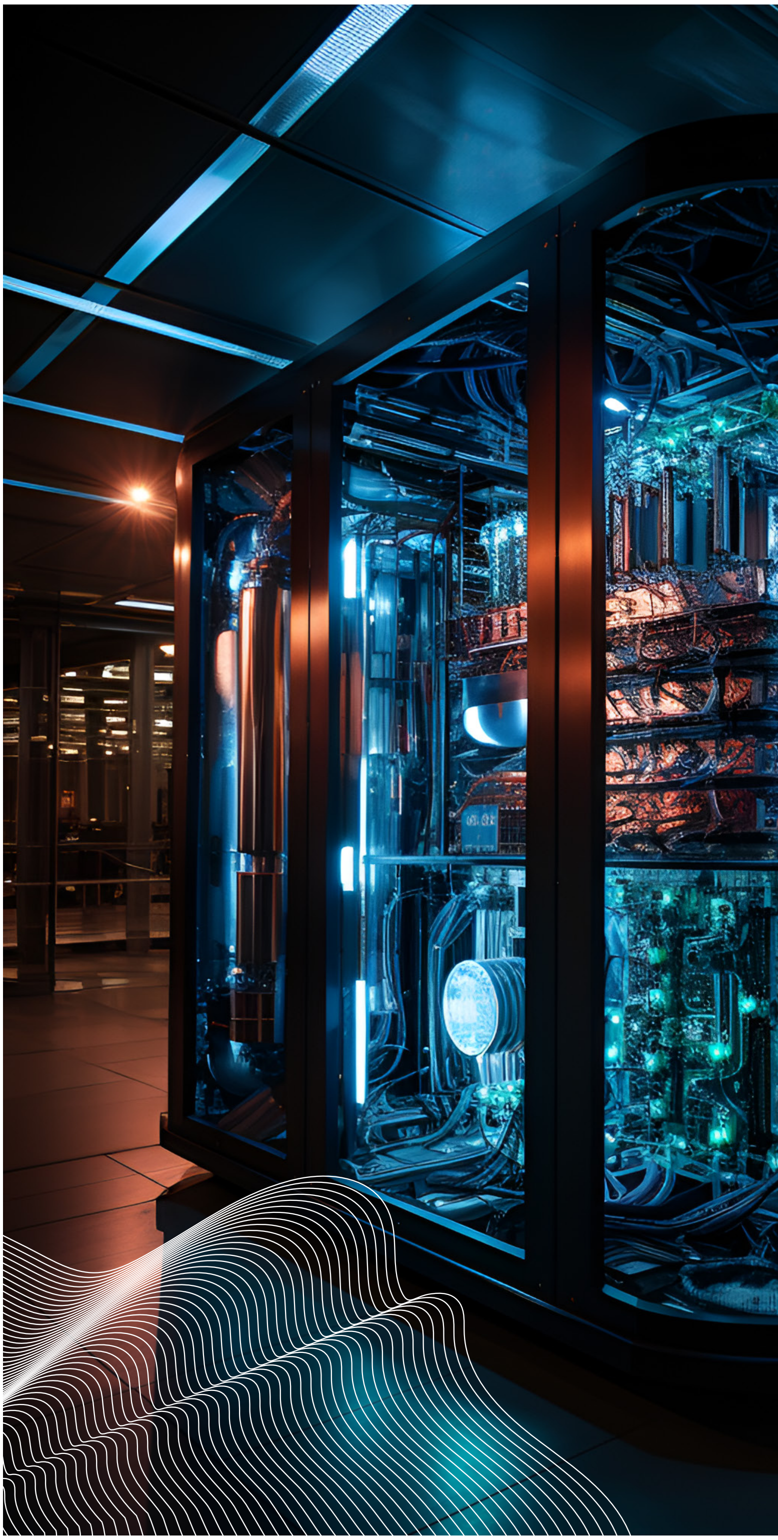
For the rail transport sector, the contributions would focus on deep improvement in the railway activities chain (production, operation, optimization of traffic control systems, crisis management and train reallocation, maintenance, etc.). Trains and resources could be **quickly reallocated based on changes in demand, delays, or emergencies,** thanks to quantum computing's ability to handle complex multifactorial scenarios and improved dedicated AI training. **Progress in predictive maintenance** is also noted : by analyzing real-time sensor data, AIs coupled with quantum machines could predict failures before they occur, thus **reducing downtime and costs.** AIs regularly trained by quantum calculations could be integrated into daily operations for planning and monitoring.

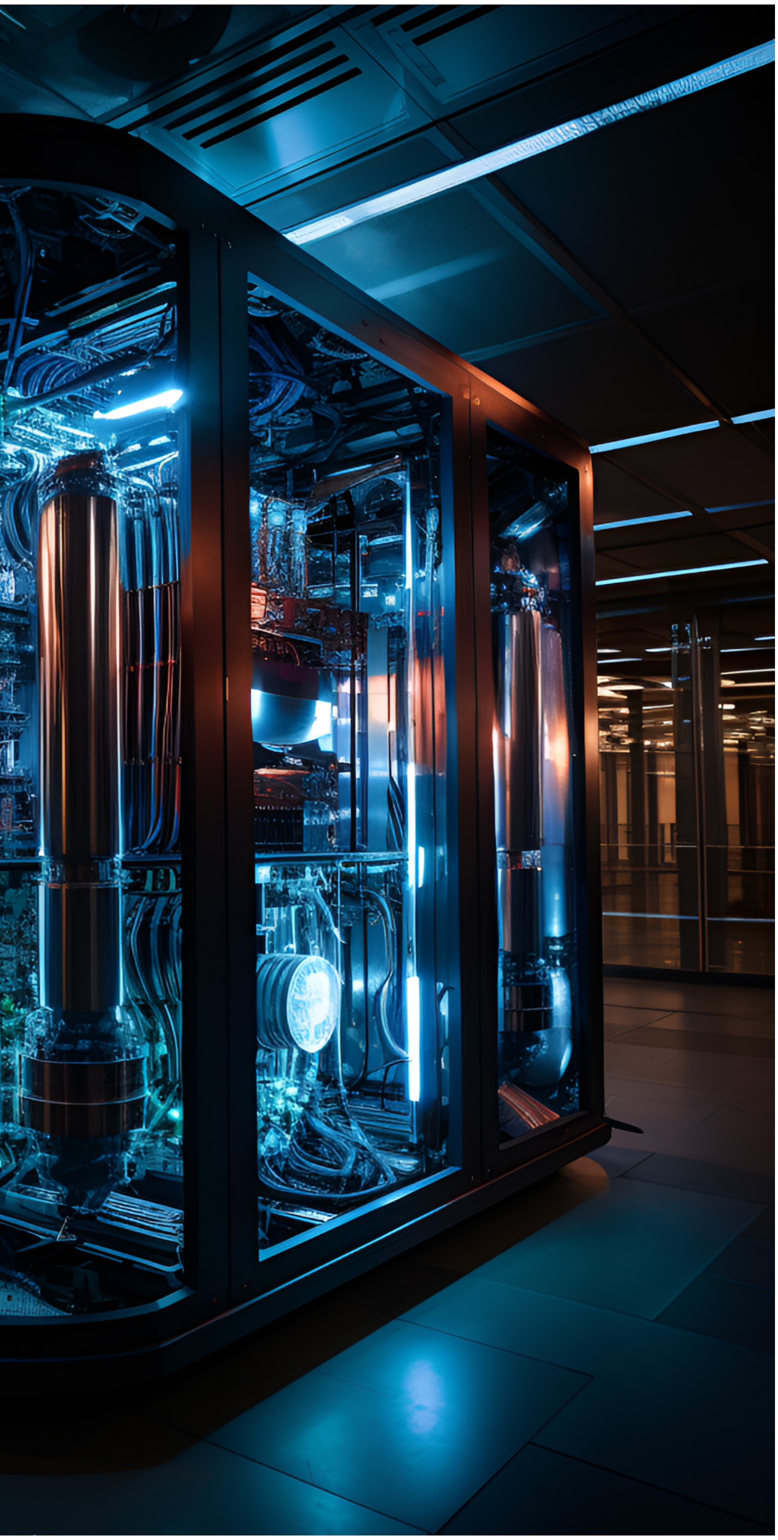
The effects could be potentially significant for society, with improvements in efficiency and punctuality of rail services, and **reduction of incidents and delays through better crisis management.**

In the field of **road transport,** potential contributions would involve the design of more energy-efficient vehicles (battery optimization, new materials), thus more accessible and durable, as well as predictive maintenance and fluid dynamics. In the long term, in the case of high quantum computing performance, it could be used to develop n**ew lightweight but strong materials,** improving the energy efficiency of vehicles. The same applies to the development of intelligent transport systems. By integrating traffic data, weather conditions, and signals from connected vehicles, quantum computing in collaboration with AI could **optimize traffic flow, reducing congestion and emissions.** These elements could also lead to the development of new personalized mobility offerings for travelers, integrated across multiple modes of transport and with specific services.

For logistics activities, the contributions would essentially focus on improvement (route optimization, parcel management, etc.). By calculating more optimized, or even optimal, routes, storage times and necessary resources are reduced. Quantum computing could minimize the costs and environmental impacts of freight transport.

Here, as in other sectors, an increased (theoretical) dependence on quantum computing could exacerbate inequalities between major players and small businesses, potentially leading to a monopoly or reduced competition.





Telecommunications

In the field of **telecommunications,** quantum calculations would enable better management of antenna positioning, fraud detection, and a more **relevant and effective pricing strategy.**

Moreover, quantum algorithms could be used to **detect intrusion attempts or anomalies in data traffic, offering a higher level of security.** An AI trained by quantum calculations could offer real-time management of network resources, adjusting bandwidth to needs.

There is also a r**isk of market consolidation,** where the most proficient actors in mastering quantum computing applications could **dominate and reduce competition,** potentially influencing prices and accessibility.

Finance (banking/insurance)

Among the significant impacts, we note **the optimization of asset portfolios,** market analyses using faster and more accurate AI, an **improvement in risk models,** which could integrate a multitude of economic, political, and environmental variables, providing a much more precise view of the risk profile of an investment.

In the event of validated quantum computing performance on these use cases, **sector actors will need to quickly adopt, or even generalize, quantum technologies to remain competitive.**

The impacts on activities and performances could be very significant and disruptive (even a slight optimization could have considerable repercussions). Furthermore, in a heavily regulated sector, it is likely that access to techniques that could offer a decisive competitive advantage will be widespread. Otherwise, a distortion of competition would be noted.

The socio-economic impacts will be indirect (reduction of fraud through anticipation, management and optimization of portfolios in a volatile context, credit risk analysis, etc.). We could envisage safer and more affordable financial services thanks to better risk management.

Use cases summary

Out of the hundred use cases reported by partner companies, most of them have **limited impacts on business models,** either due to their nature (optimization with limited gains, etc.), or due to the highly probable shared access to these tools for organizations in the same sector (regulatory aspects to avoid competitive biases, especially in regulated sectors). In the next 15 years, the potential economic impacts of quantum computing on industrial sectors and organizations will therefore **mainly be in terms of performance and process improvement,** not disruption. This is evident in the transportation or energy sector where the number of use cases grows as technological scenarios advance, but without the possibility of foreseeing a disruptive application today. However, from scenario 2 onward, use cases appear which, while not corresponding to disruptions of economic models, are **crucial turning points** that must be well negotiated for stakeholders **in the healthcare, finance, and insurance domains.** These impacts only strengthen as progress is made in subsequent scenarios. To a lesser extent but with **strong impacts in chemistry, materials, and science and research.**

[1] https://hyperionresearch.com/wp-content/uploads/2022/11/Hyperion-Research-SC22-HPC-Market_Combined-1.pdf

[2] https://www.intersect360.com/wp-content/uploads/Webinar-Intersect360-WW-HPC-AI-Unified-2022-market-size-and-2023-27-forecast.pdf

[3] https://www.tomshardware.fr/diapo-24-ans-devolution-des-supercalculateurs-puissance-multipliee-par-15-million/

[4] https://www.lemondeinformatique.fr/actualites/lire-15-millions-de-dollars-pour-l-ordinateur-quantique-d-wave-2000q-67179.html

[5] https://thequantuminsider.com/2023/04/10/price-of-a-quantum-computer/

MARKET FOR QUANTUM COMPUTERS

« I think there is a market for maybe five computers in the world. »

- Thomas Watson, IBM president in 1943

As we have seen previously, **quantum computers are unlikely to develop independently of HPC (High Performance Computing) systems,** necessary for pre- and post-processing of data. It seems judicious to estimate the future markets for quantum processors by having a vision of the HPC market by 2042.

HPC Market

The information on the HPC market is derived from studies by Hyperion Research[1] and Intersect360 Research[2]. According to these studies, **the total HPC market in 2021 was around $35 billion** (including sales of servers, storage, services, applications, etc.). The hardware portion of the HPC market represented between $11 and $15 billion in 2021, according to sources. The primary uses of HPC are in research, state security, defense, finance, and biology.

The high-performance computing market is highly concentrated : in 2021, HPE led with over 34 % of the market share. The top European company was ATOS, ranked 5th globally, with approximately 4 % of the market share. According to sources, the growth of the HPC server market is estimated to be between 5.6 % and 6.9 % per year for the years 2021-2026.

In the very high-end market segment, it is estimated that there will be between 31 and 45 Exascale supercomputers worldwide by 2027, with a value between $10 and $14 billion. Over a 20-year period, the collected data shows that **the price of supercomputers averages around €100 million,** with recent increases for Exascale reaching €400 million.

In comparison to HPC machines, **the price of quantum machines is in the range of tens of millions of dollars :**

- $15 million for D-WAVE[3]
- Several tens of millions for the IBM suite, including the quantum computer and associated services[4]

Assumptions

Following discussions with our partners, we can propose some plausible assumptions for the structuring of the quantum computing market :

- **The HPC + Quantum System market can only offer significant growth potential in the coming years if the cost/benefit ratio is significantly favorable.** This will only be true if the cost of HPC & quantum systems drops sharply or if the application offered by HPC & quantum systems leads to a significant increase in benefits for the end user.
- **Major global computing centers (Tier 0 / Tier 1), already owners of high-performance HPC systems, will be early adopters of the quantum market.** Backed by states and large companies, they will have the human and financial capabilities to integrate quantum computers internally. It is worth noting that this market is limited and can be considered limited to the top 500 HPC systems worldwide.
- **As new applications develop, it will likely be necessary for industrial users to have an in-house HPC + Quantum Systems computing center.** This will mainly be the case for certain strategic niches, especially in the case of sensitive data that cannot be shared (military, finance, health, etc.), or for applications that require regular and/or time-constrained access (health, logistics, transportation, etc.). In such cases, owning a machine would likely be cheaper and less risky for the end user.
- **For less constrained users, quantum computing will be accessed via cloud service operators such as IBM, AWS, OVH, etc.**
- **There is currently no second-hand market for HPC. Therefore, there will likely not be one for quantum systems either.** The cost of owning these machines is very high, around 10 % of the initial price per year. There is therefore no advantage to using obsolete machinery. Systems are replaced gradually with more efficient ones.
- Due to rapid technological obsolescence, **the market will be mainly driven by regular machine replacements.** As a result, the additional cost due to rapid system depreciation will need to be absorbed by usage benefits.
- **Vertical integration of actors is highly probable to consolidate value throughout the process and generate economies of scale.** The major investors in the quantum domain are well-known across all computing domains : chip manufacturers (Intel, NVIDIA, etc.), service providers (IBM, AWS, OVH), HPC manufacturers (ATOS, etc.). Concentration of actors through mergers & acquisitions is expected as developments unfold and winning technologies emerge.

Scenarios and Quantum Computing Market

The projected size of the quantum computing market will depend very significantly on the scenario analyzed. We have considered that **the markets for quantum systems will be roughly of the same order of magnitude for Scenario 1, The Narrow Gate, and Scenario 2, Extension of the Quantum Domain.** Therefore, we have based our analysis on only 3 scenarios.

A. Market Development in the Narrow Gate and Extension of the Quantum Domain Scenarios

In this scenario, there are only NISQ and analog machines, but no FTQC. There is no interconnection between different quantum cores, limiting the number of physical qubits to around 10,000 per quantum machine.

We estimate that in this case, **the arrival of quantum machines will not generate additional growth in the HPC market.** In other words, there will be no additional sales of HPC to address new use cases accessible by NISQ or analog machines. Therefore, quantum systems will likely only develop in conjunction with the most powerful HPC systems during replacements. We estimate **the annual volume to be a few hundred quantum machines in total.**

In this scenario, the market is divided into 2 types : **NISQ machines and analog machines.** NISQ and analog machines will be technologically comparable and **will likely be in similar price ranges**, in the order of current prices.

B. Market Development in the Scenario The Gates of FTQC are Open

In this scenario, we have access to FTQC gate-based quantum machines. Up to ten quantum cores (QPUs) are interconnected, allowing for quantum systems with powers of **less than 100 logical qubits but more than 40 logical qubits** (the current emulation limit). Even though the applications covered by FTQC are much more extensive than in the previous scenario, the limited number of logical qubits and the absence of QRAM limit the range of accessible applications.

These gate-based machines coexist with analog machines possessing a significant number of physical qubits, ranging from 40,000 to 100,000. **Analog machines are dedicated to optimization problems** where the large number of qubits significantly increases the complexity of the addressed problems.

We estimate that in this scenario, the arrival of quantum machines will generate additional growth in the HPC market. This growth directly translates to the renewal volumes of quantum computers and will exceed the volumes of Scenarios 1 and 2. However, the price will remain in the same order of magnitude as before. FTQC and analog machines will be technologically comparable and will be sold at similar price ranges.

C. Market Development in the Quantum Leap Scenario

In this scenario, the barriers of interconnection and QRAM are lifted. It is then possible to offer **modular FTQC quantum systems** based on interconnected quantum cores (QPUs) while significantly reducing the cost of QPUs. We could have FTQC quantum machines with **powers reaching several hundred logical qubits**. The modular approach and significant reduction in the unit cost of QPUs would segment the FTQC system market into 2 submarkets :

- **A high-end market,** aimed at the most powerful HPC centers, with FTQC systems offering **between 100 and 1,000 logical qubits** by 2042. The power of these computers allows them to handle applications inaccessible to other technologies. Therefore, they are **offered at a high price** as a premium option included in the value proposition of new HPCs. The volumes of these exceptional machines will be limited and will only concern **the renewal of very high-end HPCs.**
- **A mid-range market** opens up for powers **between 40 and 100 logical qubits.** These systems are used for less demanding applications. The more affordable price of these machines allows for higher sales volumes beyond several hundred.

Despite the increase in the number of available logical qubits, **the market for analog machines is heavily cannibalized by the arrival of gate-based machines,** which are more versatile and flexible. To adapt, **this market focuses on very specific and specialized applications** (such as rapid and recurrent optimizations), offering significant volumes. **This can only be achieved through a drastic cost reduction.**

Due to the lifting of major barriers, it would be possible to deploy quantum systems massively for many applications. We could hope that this scenario **generates a very significant additional growth in the HPC market.**

[1] https://www.yolegroup.com/product/report/quantum-technologies-2023/

SURVEY & EXPERT FEEDBACK

We conducted a survey among experts from various fields of quantum computing : algorithmics, command chain, cryogenics, hardware, error correction, HPC (list below). Some came from academic laboratories, others from the private sector (manufacturers, service companies, and consultants).

We wanted to gather opinions on the likelihood of realizing our scenarios by 2042 on one hand, and their views on a number of propositions or statements that were controversial on the other hand.

Experts who responded to the survey :

ALICE ET BOB VIGNON Blaise, ESSIG Antoine

C12 DESJARDINS Pierre

CEA SAVIN Valentin, SASSOLAS Tanguy, DARTOIS Stéphane, BLANCO Nicolas, SNIZHKO Kyrylo, SANGOUARD Nicolas

CNRS DIAMANTI Eleni

COLIBRITD GUIRAUD Laurent

CONSULTANT EZRATTY Olivier

EDF MIKAEL Joseph

EUROQUIC BOTTER Thierry

INRIA LEVERRIER Anthony

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS SCHOPFER Félicien

MULTIVERSE COMPUTING KUREK Michel

PASQAL HENRIET Loic

QUANDELA RICOU Arno

QUOBLY VINET Maud, PERNUCHOT François

SYSTEMATIC VERT Daniel

THALES BARBARESCO Frederic

UNIVERSITÉ MONTPELLIER BOURREAU Eric

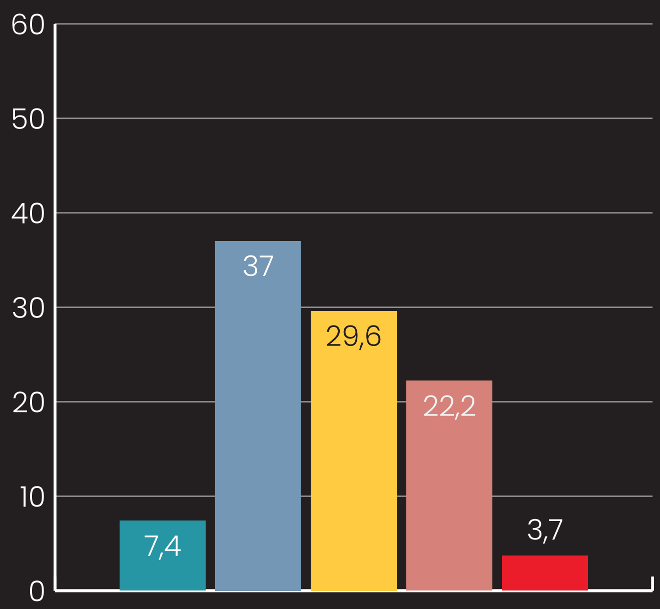
WELINQ DARRAS Tom

Legend

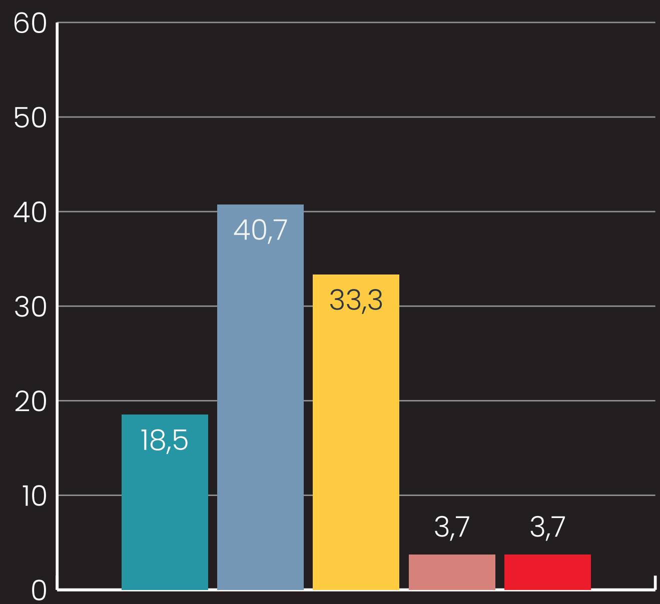
- Completely agree
- Rather agree
- Rather disagree
- Strongly disagree
- Cannot say

The survey results are expressed as percentages.

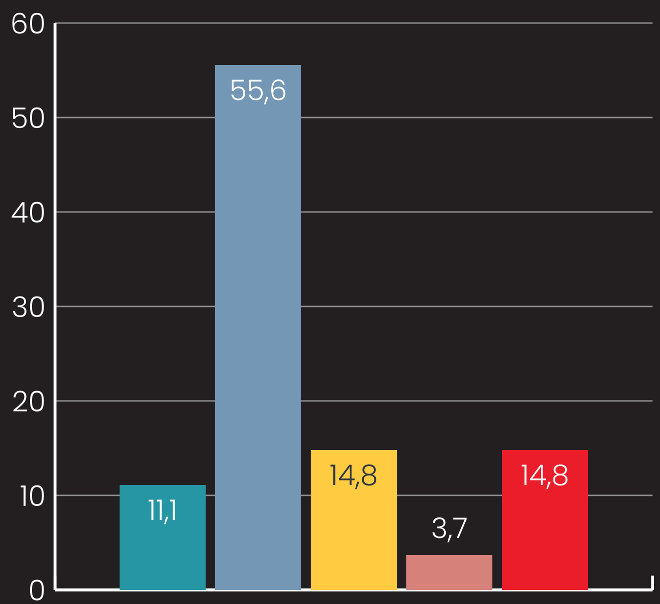
There will never be useful applications (of industrial scope) for NISQ on real datasets.



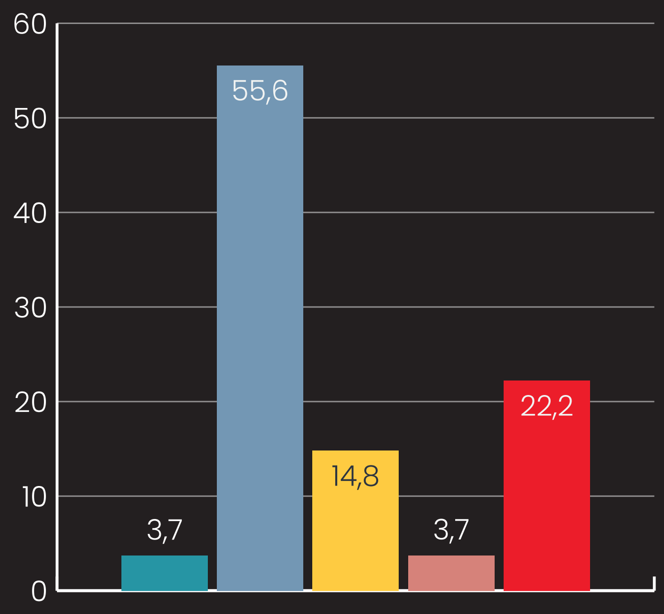
NISQ is an intermediate techno-scientific stage in the advent of FTQC.



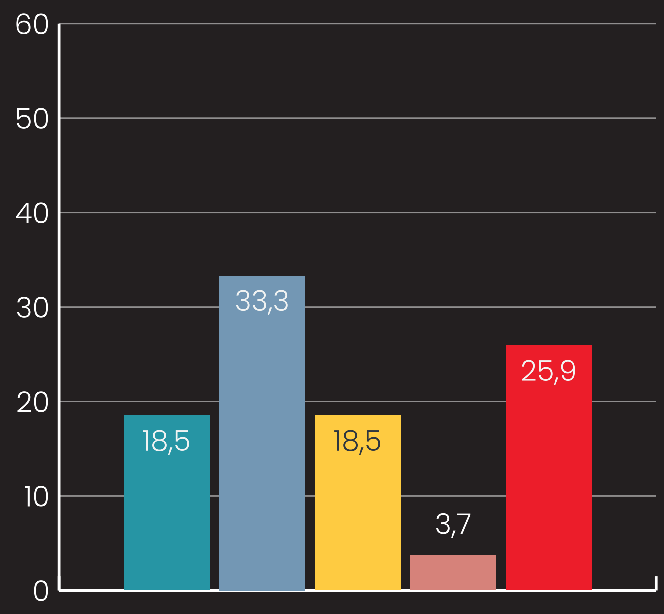
Industrial applications will emerge for analog systems before NISQ.



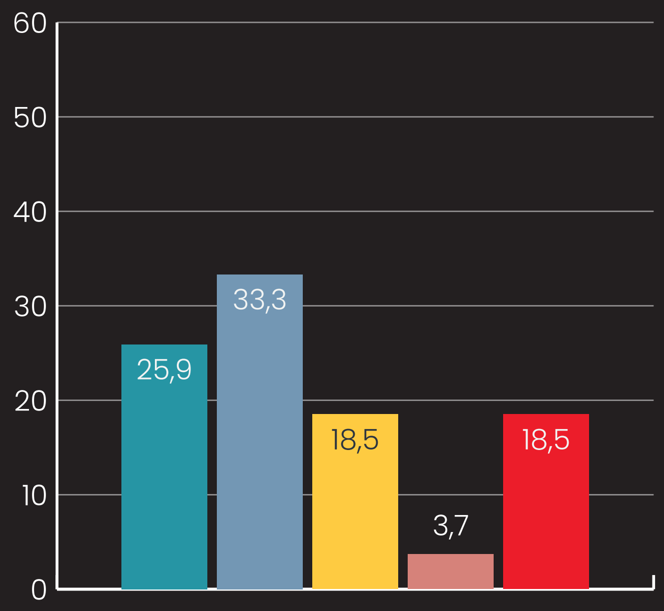
The first forms of quantum advantage will not be related to acceleration but to energy consumption and/or result precision.



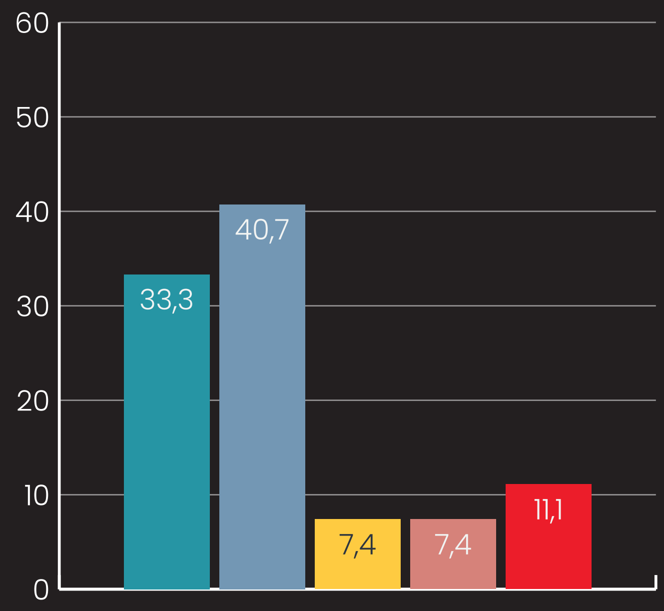
Interconnection between 2 quantum cores will begin to be possible within 10 years.



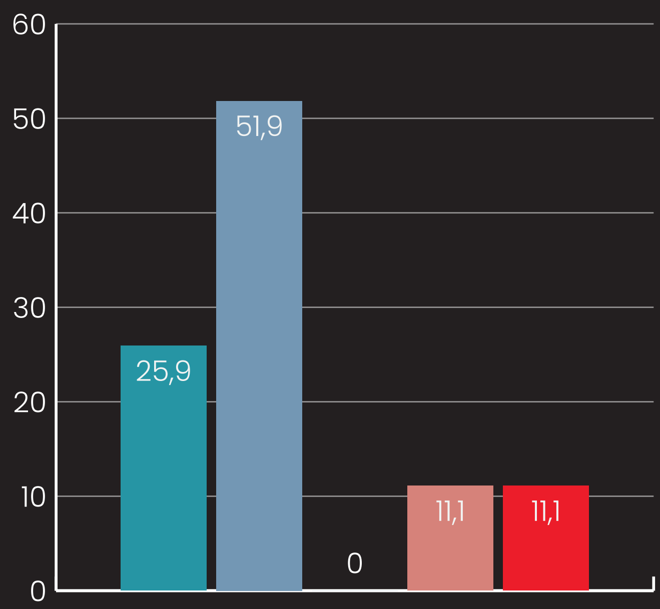
The threshold of 10,000 controllable and entangled physical qubits will be reached within 10 years.



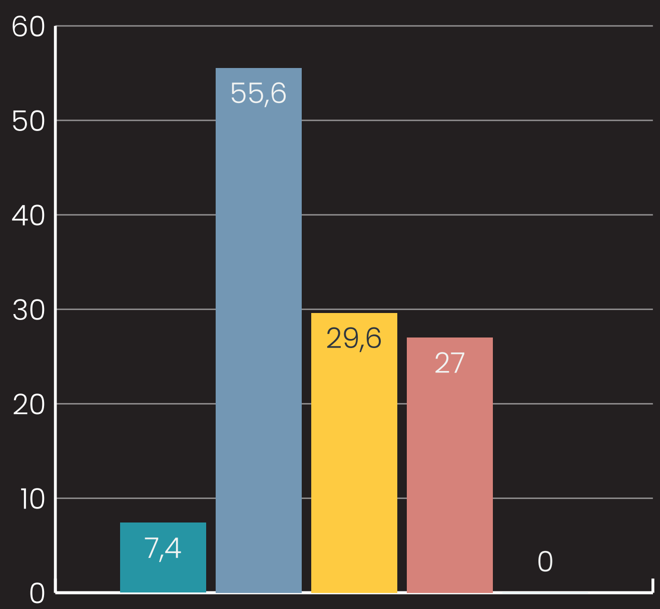
A concentration of actors will take place within the global quantum ecosystem in the next 10 years.



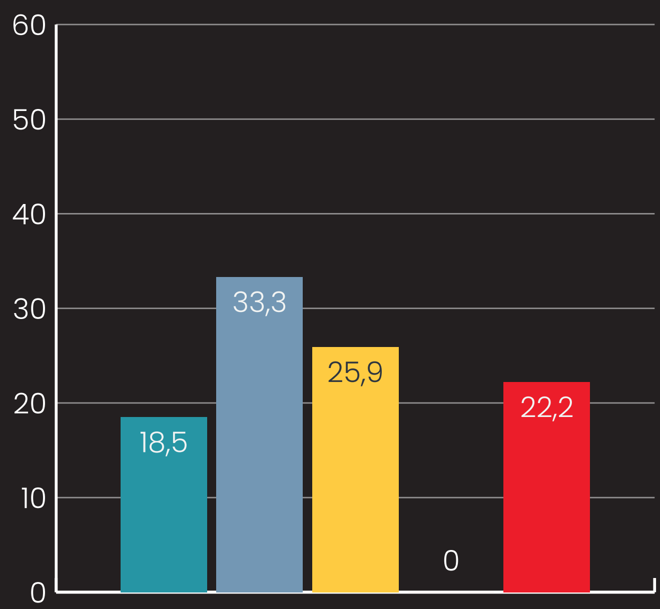
In the coming years, architectures based on certain quantum technologies will specialize in certain types of problems.



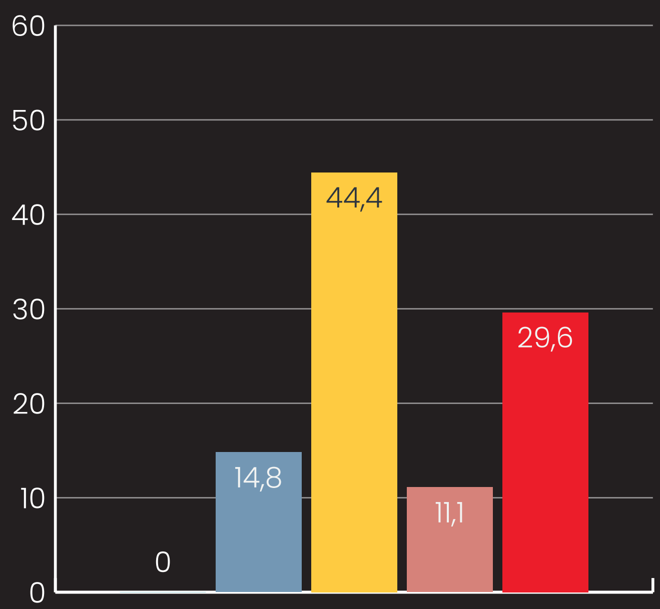
FTQC will coexist with analog technologies (different applications and nature of advantages, diversity of access models, etc.).



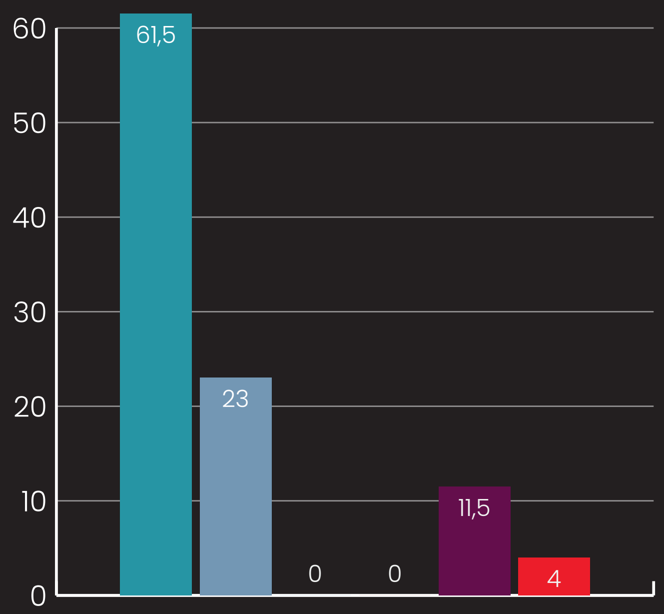
A standards war will occur between major regions of the world and between major players in the next 10 years



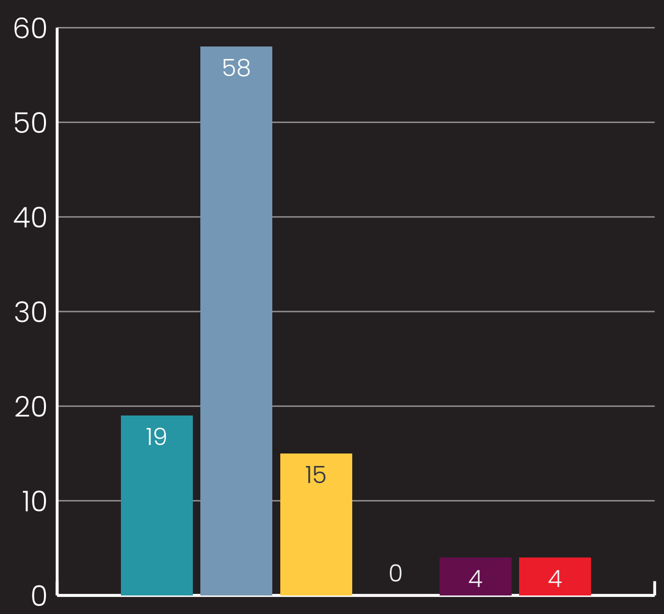
The first mass market for quantum applications will be coupled with AI technologies.



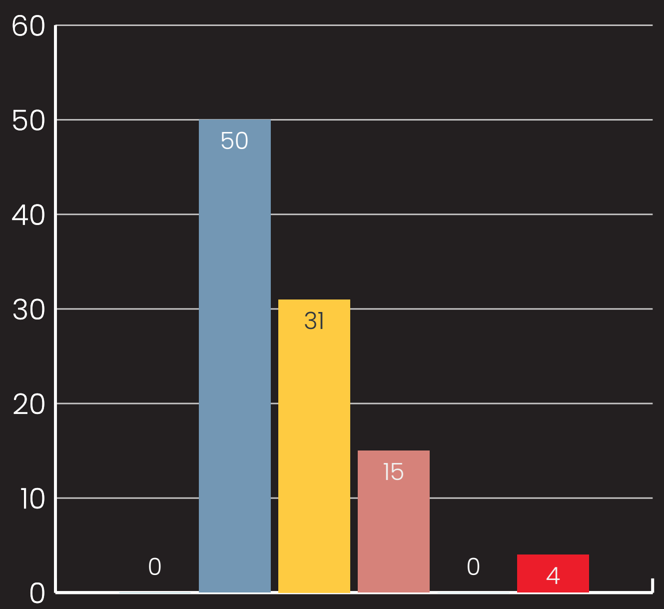
In your opinion, scenario 1, The Narrow Door, will be achieved :



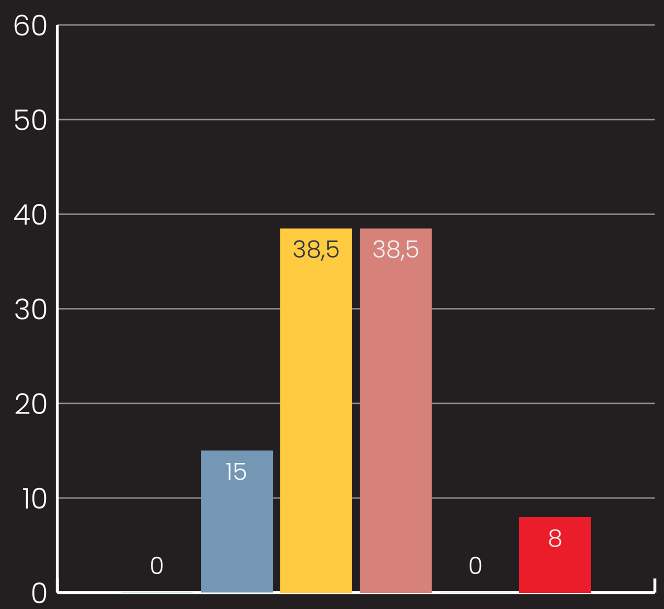
In your opinion, scenario 2, Quantum Domain Extension, will be achieved :



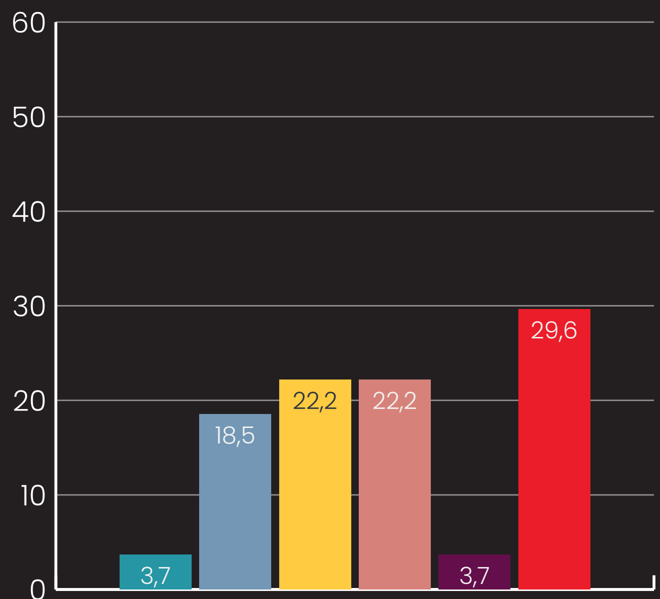
In your opinion, scenario 3, The FTQC Gates Are Open, will be achieved :



In your opinion, scenario 4, The Quantum Leap, will be achieved :



When will QRAM be operational ?



Legend

- Very soon, by 2025
- By 2032
- By 2042
- In 2050 or later
- Never
- Cannot say

The survey results are expressed as percentages.

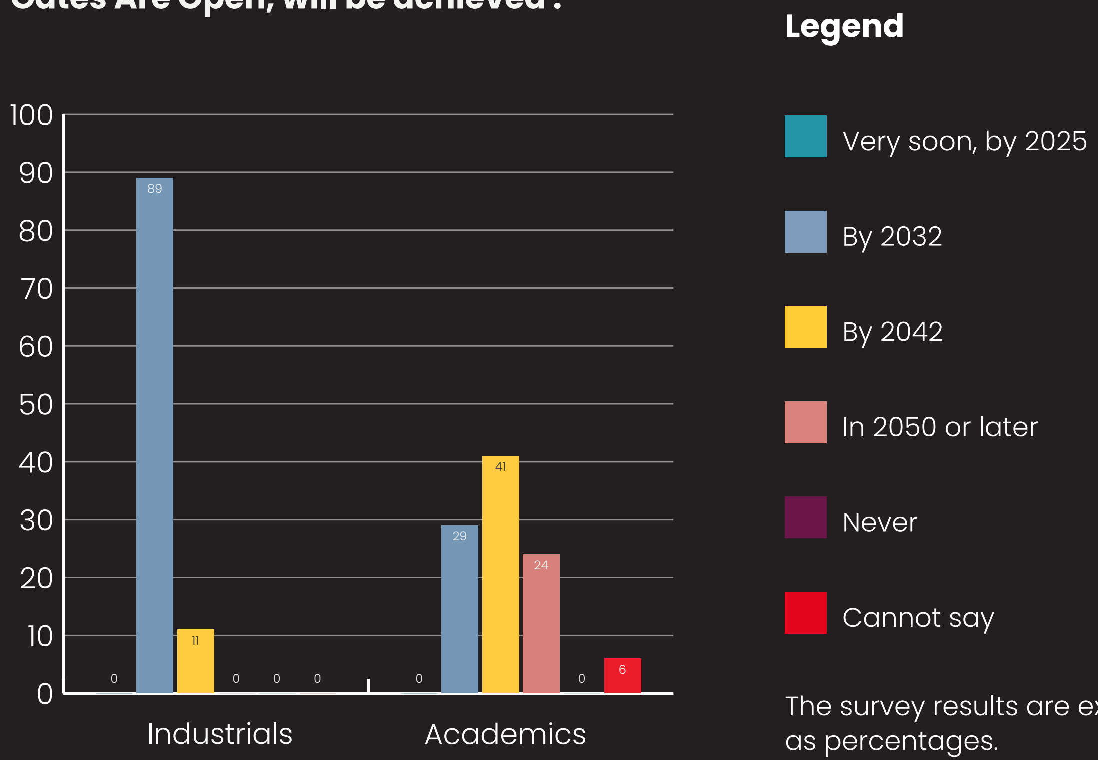
Biases

We notice that some propositions reach a consensus (quantum advantage related to energy consumption, concentration of actors within 10 years, etc.) while others clearly show a significant divergence in responses (NISQ being an intermediate step in the advent of FTQC, the advent of QRAM or interconnection of quantum cores within 10 years).

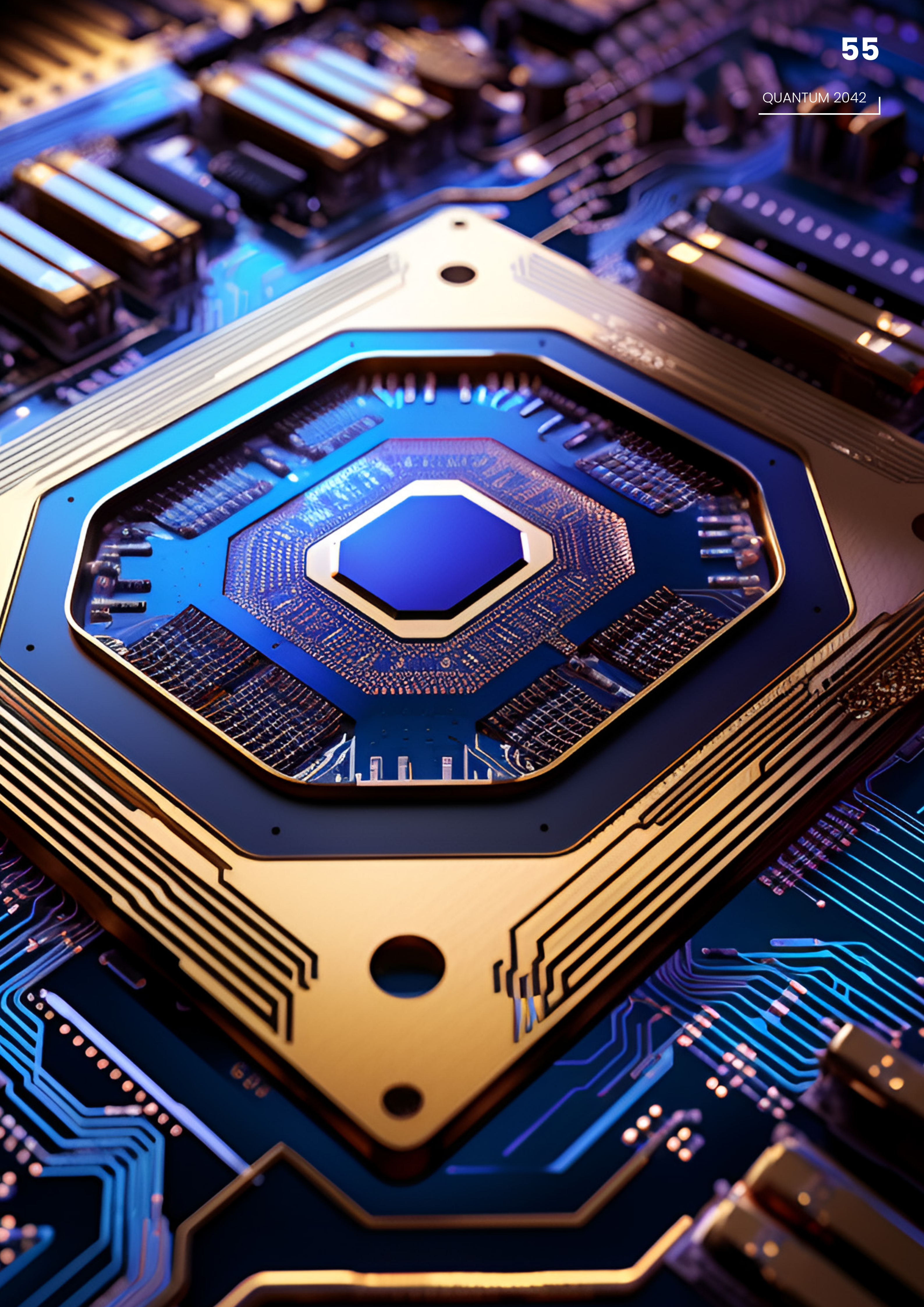
This is naturally linked to the wide variety of technological profiles of the experts but also to their background (academic or private sector).

Unsurprisingly, we observe that market players in the quantum computing industry are much more confident in the possibility of technological progress than academics.

In your opinion, scenario 3, The FTQC Gates Are Open, will be achieved :



The survey results are expressed as percentages.



DESIGN FICTION

As part of the Quantum 2042 project, we have complemented the prospective study with an approach that allows for more immediate exploration of the possible consequences of the advent of quantum computing.

Indeed, the ins and outs of quantum computing can sometimes seem very abstract, and it can be challenging to concretely relate them to « real life ».

To address this, we have adopted an approach of speculation through design, called Design Fiction, which uses design tools and skills not in a logic of seeking desirable solutions, but with the intention of sparking debate. This helps to ask the right questions around a complex subject. Design Fiction is not intended to create marketable concepts, but rather traces of possible futures that can inform the choices of future societies. It also does not consist of an exhaustive study of possible uses, but rather the production of anecdotes, of singular productions that allow us to break free from « ready-made thinking ».

Bringing together Design Fiction and quantum computing seemed relevant to us for 4 reasons :

- The hypothesis of using quantum computing is a leap into the unknown, and Design Fiction fits into this logic of shedding light on the future.
- Quantum computing, due to its physics and applications (which are very specific mathematical problems), poses representation challenges that design, as a producer of forms, can naturally tackle to simplify its reception.
- The very idea of high-capacity quantum processors is highly speculative, yet quantum computing using them already exists through quantum algorithms, creating a sensation of strange banality that is quite characteristic of Design Fiction.
- The current state of quantum computing is already almost a form of fiction, in the announcement of certain achievements, for example. The current rise of « fake news » enhances this sense of uncertainty, creating fertile ground for credible Design Fictions.

Thus, just as archaeologists unearth traces of the past to understand the lifestyles, techniques, and social rules of past civilizations, we have imagined human productions, called artifacts, that could exist in the hypothesis of a « quantum leap » (cf Scenario 4). In the following pages, you will find the analysis of the 4 artifacts that we believe are most relevant to share in this report.

Bruno TRUONG & Germain MAGAT

During the public presentation of this report, participants were invited to share their feedback through a short questionnaire. Feel free to do the same :

participate

Out of 10 identified artifacts, we presented 7 during the public presentation on December 1, 2023. To create the illusion of objects truly from the future, we commented on and analyzed them as if we had not ourselves conceived them. Furthermore, we presented ourselves as members of a fictitious association, the « French Association of Predictive Archaeology » (a.f.a.p) in order to create a sense of disbelief in the audience, and therefore spontaneous reactions.

a.f.a.p
association
française
d'archéologie
prédictive

Photo credits : J.LEPAULLE / CEA

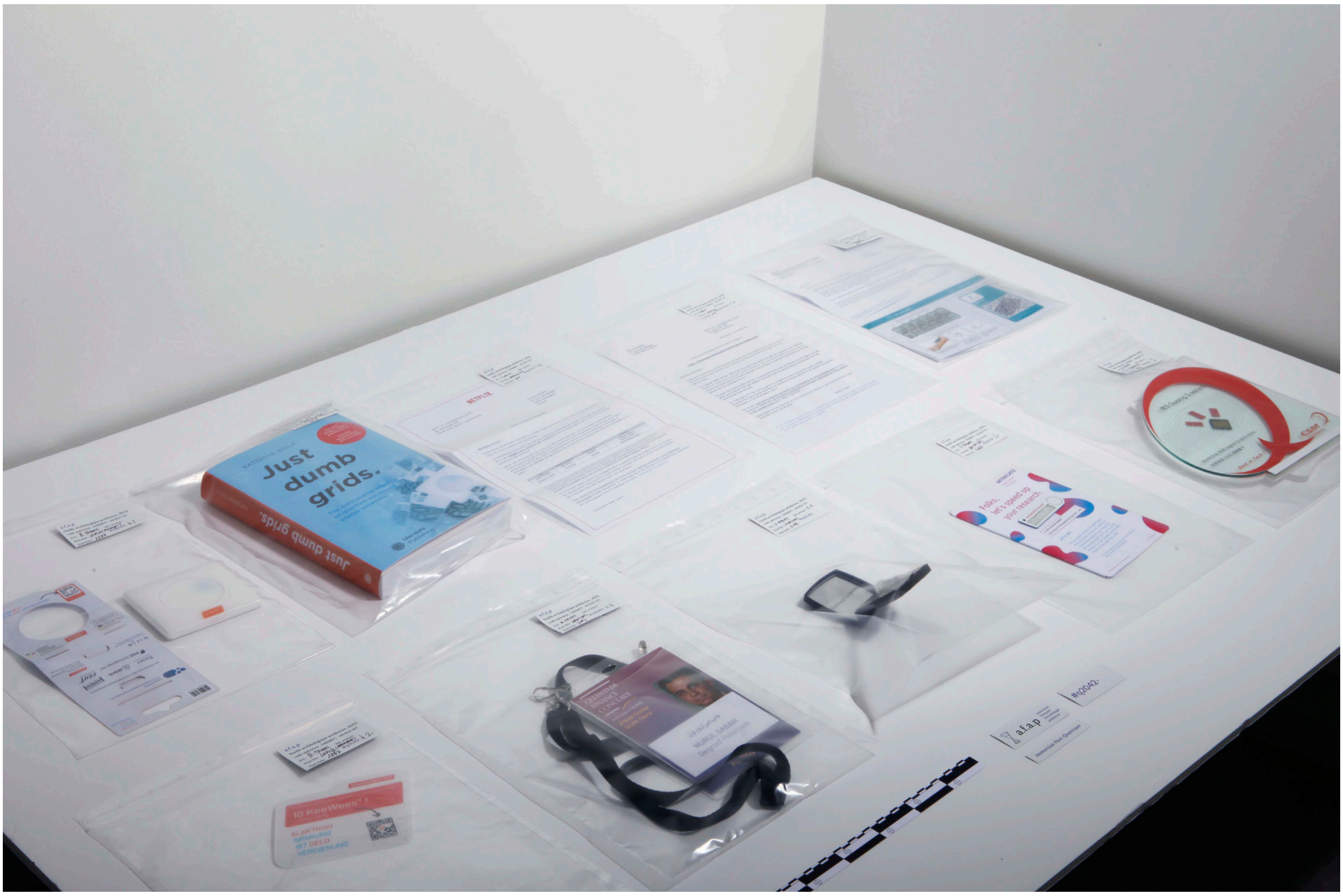


Photo credits : B.TRUONG / CEA

Intricate Qaas

The company INTRICATE operates certain areas (« grids ») of a quantum supercomputer (Q-HPC) called System Qne, based in San Jose (USA).

This artifact **raises the question of the public-private balance in access to quantum computing** and large instruments in general. INTRICATE earns revenue through consulting and co-publication.

A footnote mentions the possible requisition of the « grids » solely for the benefit of American RTOs. This highlights the unstable balance between liberalism and sovereignty created by a tool that could be of strategic importance geopolitically.

Quantum computing access card, intended for research teams.

Photo credits : B.TRUONG / CEA

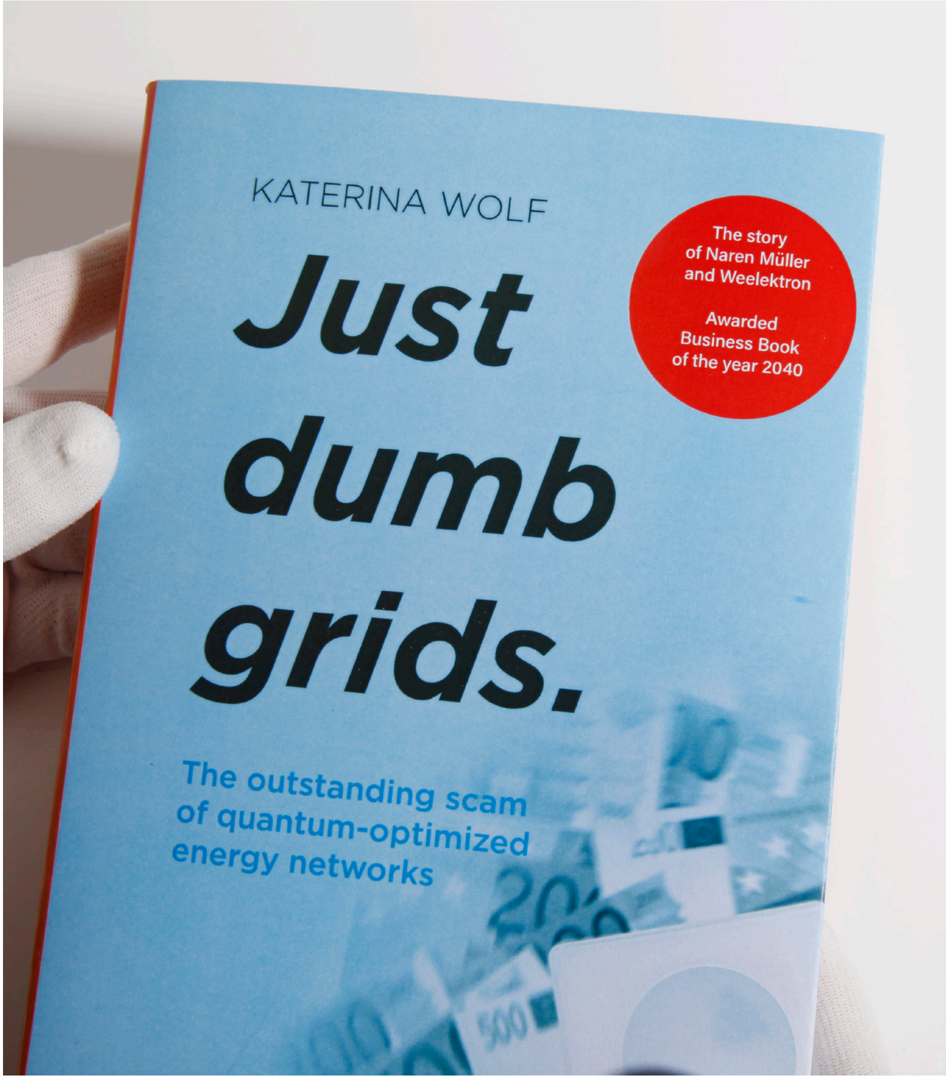
Product and packaging Weelektron

Weelektron

Apparently a connected device resembling a switch, associated with a mobile application, targeted at the general public (likely sold in retail stores). The promise seems to be the ability to save or earn money by consuming less energy.

It is assumed that these devices are distributed throughout buildings, forming an intelligent network for energy management with very fine granularity.

They would allow for the payment of individual electricity consumption exclusively, and perhaps even transform it into a form of currency. **This artifact highlights the diversity of companies that in the future could be involved in the value chain of quantum computing : manufacturers of electrical products, real estate companies, etc.**



Just Dumb Grids

This book denounces the incredible scam of energy networks optimized by quantum technology, as evidenced by the subtitle.

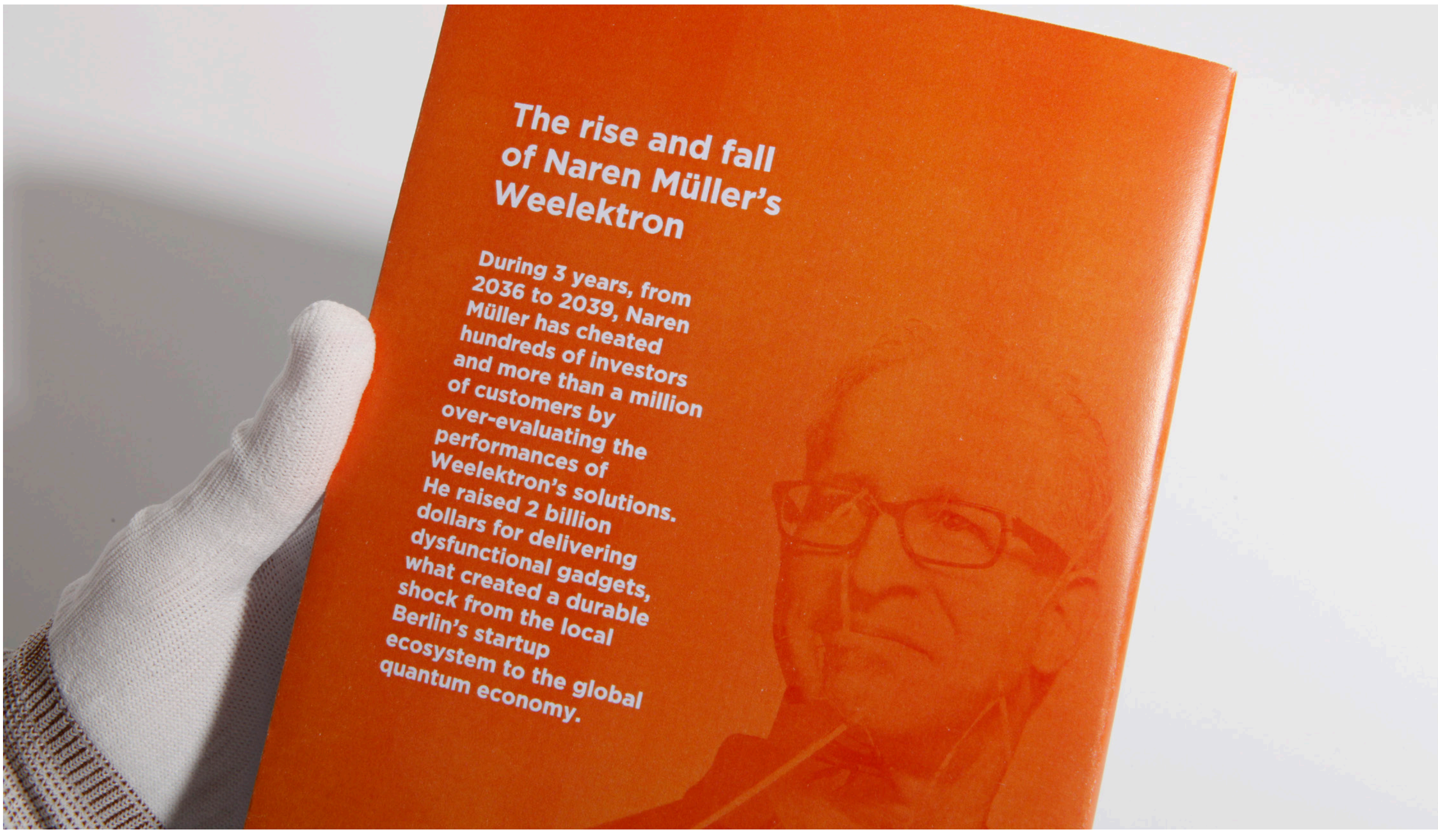
It specifically focuses on exposing the $2 billion fundraising of Weelektron, a company that capitalized on the quantum speculation bubble.

The promises made by Weelektron products apparently have never been fulfilled.

This artifact highlights **the risks of a technological sector that can oversell and fail to deliver on its promises.** Worse, it can be conducive to scams as seen in biotech (Theranos) or cryptocurrencies (FTX).

Award-winning book by Katerina Wolf « Just Dumb Grids »

Photo credits : B.TRUONG / CEA

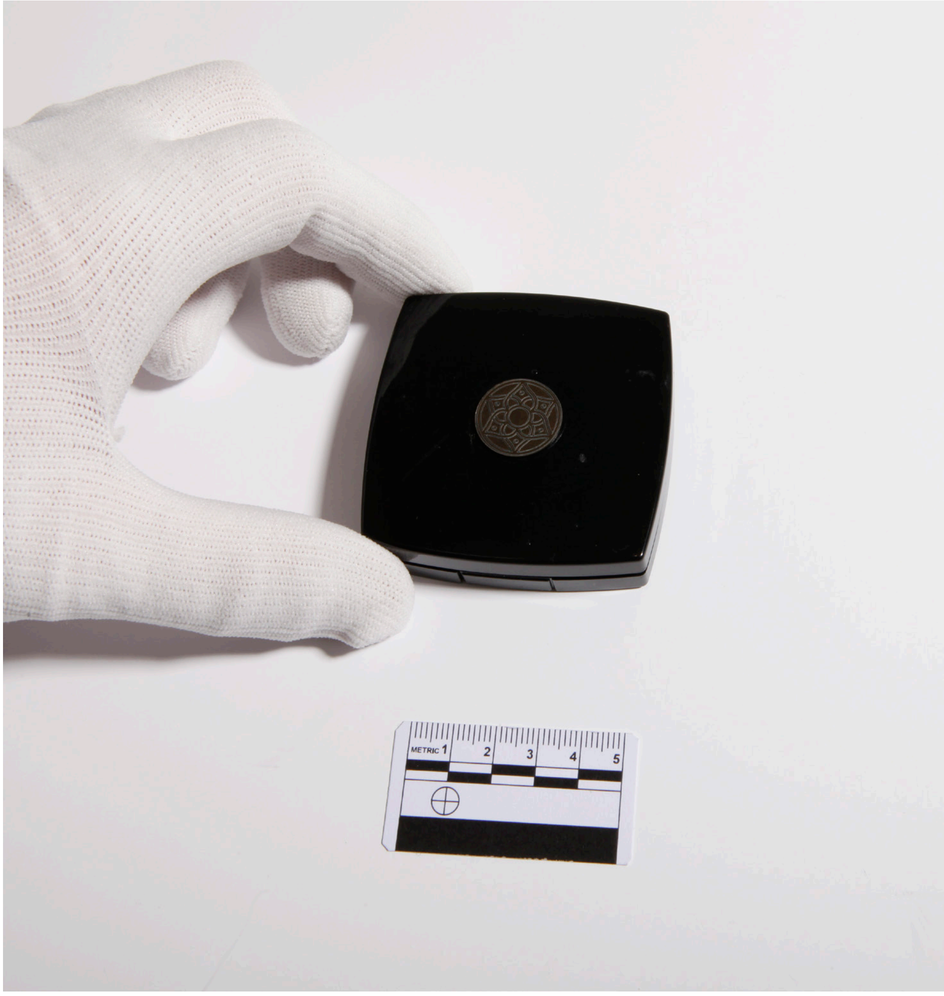


Embrace Longevity

In the late 2040s, precision therapies seem to have extended beyond the scope of treating rare diseases or cancers. This type of personalized medicine tailored to patients and their conditions appears to have become more accessible, albeit remaining expensive. **A very affluent population will have the means to avail themselves of it to prolong life.**

It seems that the use of quantum computing has opened up new avenues in the field of hyper-personalized medicine in this form.

This artifact highlights **the risks of a two-tiered healthcare system, amplified by quantum computing.** Similar to the financial sector, should these technologies be regulated or simply subjected to market forces ?



Black-branded case containing a microtube, inscriptions « Precision Therapy », « Al-Bakri Clinic Dubai » and « Embrace Longevity »

Photo credits : B.TRUONG / CEA

CONCLUSION

Today, few stakeholders have a comprehensive view of quantum computing, whether it be in terms of investments, hardware and software developments, or applications. Given that the subject is constantly evolving, it remains the subject of debates and controversies among experts and industry players, making it even more complex to understand **the temporal horizons** for the materialization of quantum computing potentials. In this report, we aimed to highlight the fact that it is possible to identify **milestones and obstacles to overcome and to monitor the progress of certain associated indicators** (hardware scalability, number of qubits, error rates and correction, etc.). Technological and scientific breakthroughs are necessary for the development of quantum computing. Their potential occurrence leads to **nonlinear evolutionary trajectories.**

Some technoscientific obstacles have been overcome in the past, allowing the transition from the proof-of-concept stage to current experiments. For example, in its latest roadmap[1], **IBM recently announced its development efforts on new error correction codes** that could significantly reduce the number of physical qubits required to obtain logical qubits. Some players like Quera are aiming for 100 logical qubits by 2026[2]. Another major effort by IBM lies in **the interconnection between quantum cores with the Heron processor.** These two major hurdles are gateways to accessing scenario 3, The gates of FTQC are open. These developments are of course to be closely monitored to update the positioning of quantum technology in relation to the scenarios proposed in this report.

Like AI, quantum computing is a catalyst for upcoming digital transformations. The development trajectories of quantum computing will not evolve independently of the evolutions of structures and performances of **HPC supercomputers, artificial intelligence, and data management. The three domains appear increasingly interconnected.** On one hand, quantum computing will result from a hybridization between HPC and quantum computing, necessary for computation exploitation. On the other hand, AI could optimize the management of this control chain[3], data preparation, and even facilitate quantum programming (generative AI), while benefiting from the power of quantum computing to optimize its learning methods. Thus, exploring the consequences of potential advances in quantum computing is also exploring the contributions of developments and couplings between these three components for processing complex problems. Faced with the energy consumption problem of digital and servers, initiatives are emerging (e.g., QEI, etc.) studying **the use of quantum machines to spend less energy** for equivalent computation. Faced with the increasing server consumption related to generative AI in recent years, reflections are emerging to u**se quantum computing for learning,** notably through QNLP (Quantum Natural Language Processing).

Also, it is important not to lose sight of the fact that other advances in classical computing will emerge by 2042. They may either challenge or accelerate quantum computing. What is certain is that the momentum initiated in quantum computing is already leading to small revolutions in classical computing (quantum-inspired, etc.).

[1] IBM Debuts Next-Generation Quantum Processor & IBM Quantum System Two, Extends Roadmap to Advance Era of Quantum Utility - Dec 4, 2023

[2] https://www.quera.com/press-releases/quera-computing-releases-a-groundbreaking-roadmap-for-advanced-error-corrected-quantum-computers-pioneering-the-next-frontier-in-quantum-innovation

[3] C'est notamment l'approche de Q-CTRL. https://www.hpcwire.com/off-the-wire/q-ctrl-announces-new-ai-capabilities-for-boulder-opal-quantum-software/

RECOMMENDATIONS

Like AI, quantum computing is a catalyst for future **digital transformations.** This is a turning point that companies must grasp and even **anticipate.** While the widespread use of quantum computing may not be present within the next 10 to 20 years, some sectors can already start using it. However, the changes induced in organizations will be such that it **already seems necessary** to acquire knowledge on the subject to **prepare and position oneself.** For this, large French groups must quickly assess the strategic interest of quantum computing for their business.

We propose the following recommendations and actions for companies wishing to prepare for the era of quantum computing :

1. Internally appoint **« quantum » focal points responsible** for identifying and evaluating potential use cases for quantum computing within their organization and market. Listing the use cases of quantum computing within an organization can be challenging and requires involvement from all stakeholders (R&D, logistics and procurement, production, etc.). It is essential to first list the mathematical problems and resolution methods already used internally and assess whether they could benefit from the use of existing quantum algorithms on enhanced computers. It is also necessary to research the development of new classical or quantum algorithms that could have significant impacts on resolution.
2. **Train and test use cases** on various available environments (emulators, quantum machines) as developments progress. After identifying the most relevant use cases, one must understand the barriers to their implementation and assess them in available testing environments. Most quantum actors offer these services on different and mostly proprietary environments. Eviden, for example, offers to emulate different quantum machines through its Quantum Learning Machine (QLM).
3. If possible, **pool needs and exchange experiences** with other actors who share similar expectations in other sectors. Exchanging viewpoints and difficulties is important to get a more precise idea of emerging changes in a field. However, working in structures grouping actors from the same sector does not necessarily promote exchanges, as competitive issues limit the willingness to share and be open. For complex subjects like quantum computing, participating in networks that bring together actors from different sectors allows for better information gathering and the initiation of collaborations without hindrance.
4. **Implement a monitoring action on the evolution of quantum technologies** and its impact on the organization, both in France and abroad. To better evaluate the evolution of changes in this field, it is important to maintain continuous research action to search for information on the latest publications or articles to know how to position one's company. It is not necessarily during the « hype » phase that the most significant signals appear.
5. **Participate in influence and working groups in standardization bodies.** Large American and Chinese groups are very present in standardization bodies. It is important that French companies in quantum computing are present to counter orientations that could disadvantage them.
6. **Bring quantum computing out of the expert** domain to ensure that the population can appropriate and clearly see the benefits.

A1 • QUANTUM COMPUTING GLOSSARY

The lack of consensus on these definitions among experts and industrial actors makes this exercise an evolving work, which has been submitted to debate among the partner members of the working group.

A

Analog Quantum Computer

Category of quantum computers solving problems by analogy with the behavior of a quantum system that can be considered as a set of qubits. In fact, these computers do not implement quantum gates. In mathematical terms, analogies involve the evolution of a Hamiltonian. Hamiltonians are operators describing the energy of a system. The two main categories of analog computers are analog quantum processors with a reconfigurable qubit network (Pasqal type) and simulated quantum annealing computers using a fixed-structure qubit network (D-Wave annealing type).

C

Circuit Depth

The circuit depth of a quantum algorithm refers to the number of quantum gates (elementary operations applied to qubits) that must be executed sequentially to accomplish a given task. It is an important measure of the efficiency of quantum algorithms. A lower circuit depth means the algorithm can be executed faster. In the context of noisy gate-based quantum computers, reducing circuit depth also limits error propagation throughout the calculations and thus preserves the meaning of the results. In this sense, it is one of the major research fields of quantum algorithmics. Alongside other methods like error mitigation, it contributes to obtaining algorithms that are relatively tolerant to noise.

Connectivity

The number of physical qubits that can interact with another qubit while maintining quantum coherence. This is often the number of nearest neighbors of the physical qubit array, but some technologies allow interaction beyond the nearest neighbors.

E

Entanglement

In quantum mechanics, qubits can be in a particular state called entangled. When qubits are entangled, the combined state of the two qubits cannot be described independently by considering each qubit separately. Instead, the state of the two qubits is interdependent and described as a whole : any measurement or change of one of the qubits instantaneously affects the other, regardless of the distance between them. If you measure the state of one qubit and find a certain property, you instantly know what property you will find when measuring the other qubit, even if they are far apart.

Error Correction

A method aiming to reduce the error rates of a quantum system to present a very low apparent error rate (at least less than 10^{-12}) and an infinite coherence time to be able to apply the most demanding and complex algorithms (FTQC). It involves using hardware and software tools tailored to the architecture of qubits, especially their connectivity, to distribute quantum information over several tens/hundreds/thousands of physical qubits, identify and correct errors through clever measurements. There are different types of error correction codes, each with its advantages and disadvantages : stabilizer codes, topological codes, etc.

Error Mitigation

Error mitigation in quantum computing involves techniques aimed at reducing or correcting errors that occur during quantum algorithm execution. These errors can result from factors like quantum noise, hardware imperfections, or algorithm limitations. These algorithms aim to mitigate errors by analyzing the output of quantum computations and applying corrections to reduce their impact. This can involve techniques such as error extrapolation, error cancellation, and error suppression.

F

Fidelity / Error Rate

The fidelity of a quantum computer refers to its robustness against different types of errors that can affect the coherence of qubits and the quality of quantum operations. Manufacturers generally communicate error rates for 1 or 2 qubit gates, or as a percentage. In our scenarios, we refer to the error rate of a quantum system as the maximum error rate among the useful and accessible operations of that quantum system (upper bound). The fidelity of a quantum computer corresponds to the difference between a theoretical system with perfect fidelity and the overall error rate of the computer for a given calculation. For example, a computer with a 1 % error rate is said to have a fidelity of 99 %. It is important to note that, in practice, this quantum fidelity depends on the « computing volume » i.e., the number of physical qubits in the system multiplied by the circuit depth of the algorithm used to perform the calculation. Unitary errors propagate more as we increase the application of logic gates and increase the size of the quantum register.

FTQC
(Fault-Tolerant Quantum Computer)

A universal quantum computer resistant to errors due to error correction implementation. This type of machine is necessary to apply algorithms with significant circuit depth. It also allows encoding any type of quantum algorithm.

I

Industrial Application

An invention is considered to have an industrial application if its subject matter can be manufactured or used in any kind of industry. The term « industry » should be understood as the exercise of any standardized and mass-produced technical activity, including services, agriculture, mining activities, etc.

L

Logical Qubit (LQ)

Abstraction used to represent the basic unit of quantum information in a quantum algorithm or circuit. Unlike the physical qubit, which is sensitive to different types of errors and quantum decoherence, the logical qubit is characterized by ideal stability and fidelity, allowing for the application of algorithms with a large circuit depth[1]. More concretely, a logical qubit (QBL) is obtained by assembling physical qubits that enable error correction. The lack of homogeneity in the definition of a logical qubit leads to communication among stakeholders that can be confusing.

Some manufacturers like Google claim to have reached the first stage of their roadmap towards error correction and will likely develop the first examples of logical qubits in the coming years. However, error rates obtained on logical qubits currently appear to be higher than those of noisy physical qubits on which they are based[2]. Thus, obtaining a QBL does not necessarily mean that it will be useful in terms of computation: its fidelity must be sufficient to apply algorithmic operations without increasing error rates. Furthermore, obtaining a few dozen logical qubits with very low noise will not be enough to demonstrate quantum supremacy.

Schematically, the existence of «non-useful» logical qubits is represented in the milestones of our scenarios by hatching in the ordinate of the QBLs. Thus, in our initial scenarios, we could obtain demonstrators of several logical qubits without necessarily achieving FTQC[3].

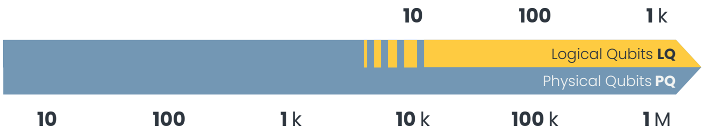


Figure 10 : Scale of physical and logical qubits used in techno-scientific scenarios

N

NISQ (Noisy Intermediate-Scale Quantum Computer)

A gate-based quantum computer, noisy and uncorrected, using noise-tolerant or low-depth circuit algorithms (generally hybrid classical-quantum algorithms solving variational problems). The use of NISQ is considered while awaiting the implementation of effective and large-scale error correction methods.

O

Overhead

An English term referring to the ratio of the number of physical qubits required per logical qubit for error correction application. Manufacturer overhead announcements vary from around thirty physical qubits to ten thousand physical qubits per logical qubit. These announcements assume that overhead does not degrade with the scaling up of error correction, which has not yet been proven. For correspondence between the milestones of logical and physical qubits in our scenarios, we set a cautious value for overhead at 1,000. This value is expected to decrease significantly over time, with some manufacturers already publishing reductions of around 14 times with LDPC[4] error correction codes or 60 times using cat qubits[5].

P

Physical Qubit (PQ)

An information unit whose physical support is a quantum system with two superposable and entangled states with other qubits. Our scenarios assume that physical qubits are all entangled with each other. This is not currently the case in manufacturers' announcements : the number of physically entangled qubits compared to the number of physical qubits can vary by a factor of 10 to 100.

Q

Quantum Advantage

The demonstrated superiority of a quantum computer over a classical computer for a specific problem, based on one or more defined criteria (speed, quality of results, energy consumption).

Quantum Decoherence

The inevitable degradation of the quantum properties of entanglement and superposition of a quantum system due to interactions with its environment, leading to a situation where the system obeys the laws of classical physics.

Quantum Supremacy

Quantum Supremacy is the ability of a quantum computer to solve a problem that is impossible to solve within a reasonable time frame using classical computing and algorithms, considering the specific application.

T

Threshold Theorem

It states that it is possible to achieve reliable quantum computations, even in the presence of errors, provided that the overall error rate remains below a certain critical threshold (commonly accepted to be 1 %). In other words, the threshold theorem suggests that if quantum errors, such as measurement errors or errors due to interactions with the environment, remain below a certain critical level, it is possible to effectively correct these errors. Some researchers are working on techniques to further lower this threshold, which would enable the development of more robust and efficient quantum computers.

V

VLSQ (Very Large Scale Quantum Computer)

Subcategory of FTQC, designating computers with gates composed of thousands of logical qubits. The VLSQ paves the way for the application of the most emblematic current algorithms (Shor, HHL, etc.).

[1] See definition on the previous page

[2] https://www.theregister.com/2023/02/22/google_milestone_quantum/

[3] See « Scénarios techno-scientifiques » section

[4] https://arxiv.org/pdf/2308.07915.pdf

[5] https://arxiv.org/pdf/2302.06639.pdf

A2 • THE VARIABLES OF THE PROSPECTIVE SYSTEM

Techno-scientific hardware variables

H1. Scaling up of gate-based computation and error correction

H2. Control chains : miniaturization and industrialization

H3. Interconnections of « cores » and quantum memories

H4. Energy consumption (and progress in cryogenic technologies)

H5. Potential of adiabatic hardware using quantum annealing

H6. Potential of reconfigurable analog quantum processors

H7. Progress in HPC

H8. Photonic quantum computing and MBQC

H9. Qubit production technologies

Techno-scientific software variables

S1. Progress in quantum and classical algorithms

S2. Data preparation and coupling with HPC

Ecosystem variables

E1. Norms and standards

The following elements related to the ecosystem have not been the subject of specific prospective insights :

E2. Economic models of stakeholders : consolidation of start-ups, formation of consortia, horizontal and vertical integration, etc.

E3. Skills in the field of QC : Availability of resources, competition for access, development of a dual classical-quantum computing culture, etc.

E4. Policies and strategies : European, US, Canada, China in the field of QC.

THANK YOU TO OUR PARTNERS

CEA
Research and Technology Directorate
Foresight & Innovation Service

Y.SPOT
17, avenue des Martyrs
38000 Grenoble
www.yspot.fr

Study Contacts :
Timothée SILVESTRE – Prospective Studies Officer
timothee.silvestre@cea.fr

Christophe VAUTEY - CEA Quantum HUB Manager
christophe.vautey @cea.fr