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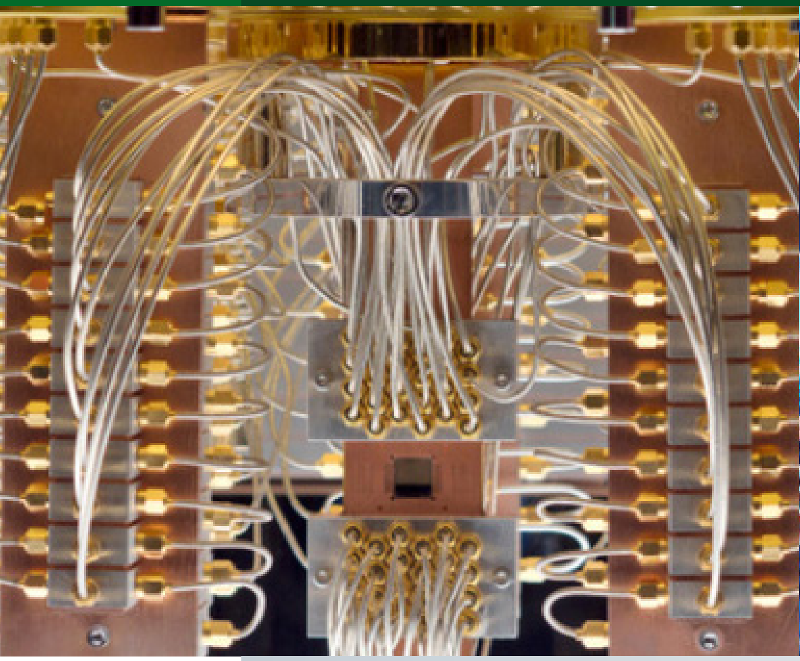

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Strategic Calculation

High-Performance Computing and Quantum Computing in Europe's Quest for Technological Power

Alice PANNIER

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Executive Summary

Computing power plays a key role in enabling data analytics and machine learning, in cybersecurity, for scientific research, and in military domains like nuclear warhead design and detonation simulation. Computing has industrial ramifications, not least due to a relatively small number of players that hold key spots in the value chain. This study focuses on two complementary segments of computing: high-performance computing (HPC, also known as "supercomputing"), and quantum computing.

HPC has for several decades been used in scientific research, meteorology, and the military – and states continue to drive the needs for massive computers. But the field is also witnessing a diversification of uses, with new needs stemming from big data applications for industry. Meanwhile, quantum computing is still at an experimental stage but has highly disruptive potential, as it promises to multiply computing power exponentially. Quantum information technologies have experienced swift progress in recent years, even if large-scale quantum computers might still be a decade away.

The race for computing power, including quantum computing, has become a key element of the US-China technological competition, but it is also a strategic priority for Europe. Aside from national strategies, collective efforts in Europe to pool resources are ongoing, as the EU strives to develop federated computing services and data infrastructure, and a local industry.

Europe faces multiple challenges, from the supply of chips to energy consumption, and risks, from export restrictions to company takeovers. In addition, public procurement choices highlight internal debates and contradictions when it comes to developing Europe's technological power, as the line between scientific research and strategic advantage gets blurred. Europe is also facing a well-known problem of lack of private investment in disruptive technologies. Yet, today, quantum technologies do offer an opportunity to learn lessons from past developments in the field of classical computing, and to take the right actions early on.

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Introduction

Computing power plays a key role in enabling data analytics and machine learning, in cybersecurity, for scientific research, and in military domains like nuclear warhead design and detonation simulation. Computing also has industrial ramifications, not least due to a relatively small number of players that hold key spots in the value chain. This leads some to argue that the contours of computational power define who has control over and access to the benefits of computer-based technologies like artificial intelligence.[1]

This study focuses on two complementary segments of computing: high-performance computing (HPC, also known as "supercomputing"), and quantum computing. Both are very distinct in terms of maturity. HPC has been widely used in scientific research, meteorology, the military, finance, and industry since the 1990s. Arguably, a nation's ability to deploy supercomputers constitutes a form of soft power, as well as being a scientific and national security imperative. Today, a few countries around the globe are engaged in a race to deploy the next level of supercomputers, known as exascale machines. But the field is also currently witnessing a diversification of uses, with new needs stemming from big data applications for industry.

Meanwhile, quantum computing is still at an experimental stage but has highly disruptive potential, in both civilian and military domains. It seeks to exploit the properties of quantum mechanics and as such, constitutes a whole new paradigm in computing. Indeed, quantum computing indeed will multiply computing power exponentially, with considerable cybersecurity implications and industrial and scientific applications. The field has experienced swift progress in recent years, even if large-scale quantum computers might still be a decade away.

The race for computing power, including quantum computing, has become a key element of the US-China technological competition. Yet, the competition is far from being solely a US-China matter. For logical reasons considering its applications and implications, computing power is a strategic priority for European governments as well as for

1. T. Hwang, "Computational Power and the Social Impact of Artificial Intelligence", working paper, 2018, p.7, available at: https://papers.ssrn.com; M. C. Horowitz, "AI and the Diffusion of Global Power", Centre for International Governance Innovation, November 16, 2020, available at: www.cigionline.org.

the European Union. This is especially the case when it comes to quantum computing. Countries around the world have recognized that quantum science has moved from an academic field of research to a fast-growing technological sector.[2] Consequently, they are developing strategies in the field, so that current dynamics are akin to a space race.

This study examines the state of play of technological developments and international competition in HPC and quantum computing, with a particular emphasis on where France and Europe stand in the global race for computing power. The first section presents current dynamics in the HPC sector: on the one hand, the enduring role of states in shaping supercomputers as a strategic sector, and on the other hand, the ongoing "democratization" of the field, with growing uses in industry. The section then addresses the geopolitical considerations that supercomputing raises for Europe, as well as ongoing strategies aimed at enhancing Europe's technological power in the field.

The second section addresses quantum computing. After introducing the main principles of quantum computing, the section reviews recent progress and remaining technological hurdles, as well as the strategic and economic applications and implications of quantum computing. It then looks at the quantum strategies deployed by the US, China, and European countries, with a particular emphasis on the French 2021 Quantum Plan.

This report shows that HPC and quantum computing present both opportunities and challenges for European countries as they seek to leverage the potentials of computing power for the data economy and national security, as well as for addressing critical societal challenges in areas of health and climate change.[3] Aside from national strategies and investments in HPC and quantum technologies, collective efforts in Europe to pool resources are ongoing. The EU is indeed striving to develop federated computing services and data infrastructure, and to secure resilient supply chains in components, technologies, and knowledge, not least to limit risks of disruption.

Computing technologies raise challenges for Europe -from the supply of chips to energy consumption - and risks, from export restrictions to company takeovers. Yet in both HPC and quantum computing, procurement choices challenge Europe in its internal debates and contradictions when it comes to developing its

2. G. Brennen *et al.*, "An Australian Strategy for the Quantum Revolution", *op. cit.*, p.10.
3. M. Heitor, Portuguese Minister for Science and Technology and Higher Education, cited in Council of the EU, "Council Agreement Secures EU financing of High Performance Computing", Press release, May 28, 2021, available at: www.consilium.europa.eu.

technological power, as the line between scientific research and strategic advantage gets blurred. Europe is also facing a well-known problem of lack of private investment in disruptive technologies. Quantum technologies do offer an opportunity to learn lessons from past developments in the field of classical computing, and to take the right actions early on. If Europe fails, it will have not only economic but also serious security implications.

High-Performance Computing

High-performance computing (HPC) refers to computer systems often called "supercomputers" with extremely high computational power, able to solve very complex problems at high speed.[4] The development of supercomputers has been and remains largely state-driven, as their acquisition and running costs are high and as they have uses in national security (e.g., nuclear simulation), scientific and medical research, and climate modelling. Nonetheless, the rise of the big data economy and the computing power required to train Artificial Intelligence (AI) algorithms and to run simulations, together with the growth of cloud computing, have "democratized" the recourse to high-performance computing in industry. Today, US computer and processor companies dominate the market in Europe, while China has developed indigenous technology. Europe is seeking to catch up by supporting its industrial base and developing its processor technology but is facing internal hurdles that are industrial, technological, and political.

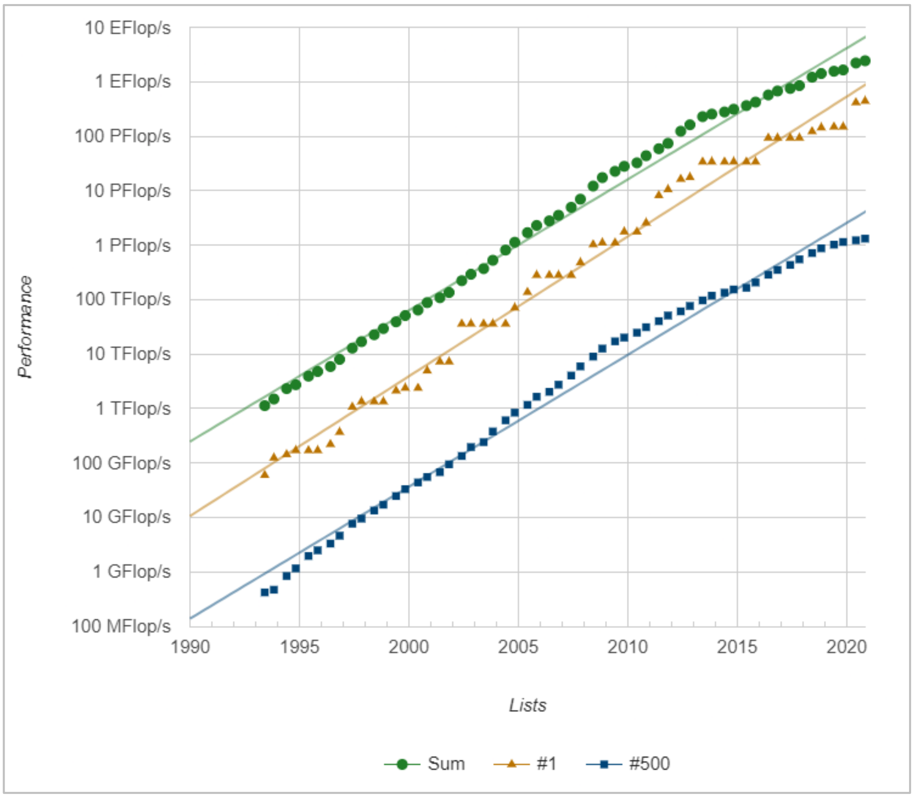
Trends in High-Performance Computing

The current concept behind high-performance computers appeared in the late 1980s-early 1990s with the advent of massively parallel processing, whereby supercomputers started to be built with hundreds of thousands of processing cores. The chart below shows the pace at which computing power has grown from the 1990s onward as a result. Computing power in the HPC jargon is measured in floating point operations per second (flop/s). While it was previously measured in gigaflop/s (i.e., one billion (10^9) operations per second), computer power is now measured in petaflop/s (10^{15} operations per second) and, very soon – possibly by the end of 2021 – in exaflop/s: 10^{18} or one quintillion (one billion billion) operations per second. To provide an

4. Council of the EU, "Council Agreement Secures EU financing of High-Performance Computing", *op. cit.*

indication of scale, a petaflopic supercomputer is about one million times more powerful than a high-end laptop.[5]

Performance Development in Supercomputers



Source: Top500.

Governments have historically played an important role in the development and growth of computer technology, especially HPC technology[6] – even if, in recent decades, computer chip development has been mainly driven by the private sector, not least by the smartphone industry. The public sector is still the main consumer of concentrated computing power today. In 2018, in Europe, over 90% of HPC operating time was by universities or academic research centers, whereas the remaining 10% served commercial purposes and end users.[7] Chief among state-driven uses of computing power are national security uses: supercomputers can be used to design, develop, manufacture, and test weapons (including nuclear weapons) and weapons platforms; collect, process, analyze, and disseminate intelligence; for cryptography; for combat simulation; for missile defense, etc. Supercomputers are also used for weather forecasting and

5. R. Verger, "Meet the New Fastest Supercomputer in the World", Popular Science, June 13, 2018, available at: www.popsci.com.
6. See, G. J. McLoughlin and I. F. Fergusson, "High-Performance Computers and Export Control Policy: Issues for Congress", Congressional Research Service, Report, May 5, 2005.
7. B.-S. Gigler *et al.*, "Financing the Future of Supercomputing", European Investment Bank, Report, 2018, p. 35

scientific research, including medical research. The Covid-19 pandemic is said to have engendered new needs, for biomedical applications, new drugs development, and digital twins of humans (see below).[8]

Since supercomputers have dual applications, they have been subject to export restrictions since the 1990s.[9] Today, the US-Chinese competition clearly plays out in the realm of HPC, due to concerns about both intellectual property and the potential uses that can be made of US chip technology. In April 2021, the Biden administration added several entities involved in HPC to the Entity List, including China's National Supercomputing Center (which is involved in the simulation of hypersonic vehicles). This prevents export of US technology to such entities.[10]

The Global Distribution of Computing Power

Across the globe, a small number of countries possess significant supercomputing capabilities. China and the US lead the race, followed by second tier HPC powers: Japan, Germany, France, Netherlands, Ireland, the UK, and Canada (see Table 1).

In terms of companies, in the HPC sector, the top three vendors are Lenovo (China, #1 vendor worldwide, with 36.8% market share), Inspur (China, 11.6%), Hewlett Packard Enterprise (HPE, US, 9%), Sugon (China, 7.8%) and Atos (France, 7.2%). If we include Cray, which HPE acquired in 2019, and which holds 6.4% of the market, HPE has moved up to the second place, with 17.4%. The picture changes if one looks at computer performance rather than market share.[11] Then, the first player is Fujitsu (Japan, 19.8%). The *Fugaku*, unveiled in June 2021, is the most powerful machine in the world. It has three times the power of the second most powerful. Its computing power is equivalent to 20 million smartphones combined,[12] and it is halfway towards the exascale (see below).

8. S. Van Dorpe, "Supercomputer Scrap Shows EU's Digital Dilemma", *Politico*, June 10, 2021.
9. See McLoughlin and Fergusson, "High Performance Computers and Export Control Policy", *op. cit.*, for an overview of the development of US export controls for HPC in the 1990s to early 2000s. For an account of the Cold-War period, see F. Cain, "Computers and the Cold War: United States Restrictions on the Export of Computers to the Soviet Union and Communist China", *Journal of Contemporary History*, Vol. 40, No. 1, 2005, pp. 131-147.
10 E. Nakashima and G. Smith, "China Builds Advanced Weapons Systems Using American Chip Technology", *Washington Post*, April 10, 2021.
11. The Top500 ranking is a benchmark rather than a precise indication of computers' performance, as the evaluation is not done based on how they perform real-life applications.
12. S. Matsuoka, Director of the RIKEN Center for Computational Science, at the Forum Teratec 2021, on June 22, 2021, video available at: https://teratec.eu.

Table 1: Distribution of Supercomputers in the TOP500 List by Country

	Country	Number	System share (%)
1	China	188	37.6
2	United States	122	24.4
3	Japan	34	6.8
4	Germany	23	4.6
5	France	16	3.2
6	Netherlands	16	3.2
7	Ireland	14	2.8
8	UK	11	2.2
9	Canada	11	2.2
10	Italy	6	1.2
11	Brazil	6	1.2
12	Saudi Arabia	6	1.2
13	South Korea	5	1
14	Poland	4	0.8
15	Singapore	4	0.8

Source: Top500, June 2021.

As we can see from the Table 2, public sector institutions – whether government departments or university research laboratories – possess the most powerful machines. Nvidia and Eni (the Italian oil and gas company) appear as two notable exceptions in the top-ten list. Aside of the top ten, we find large digital companies, and in particular cloud service providers, like Microsoft Azure's and Amazon Web Services, which have acquired significant computing resources of their own.[13] Weather forecast agencies also rank high as HPC users across the globe.

The performance of a supercomputer for a given task depends not only on the number of the machine's cores and on the speed of the interconnecting network, but also on the type and architecture of its chips.[14] One difficulty with HPC is that higher performance tends to come at the cost of flexibility: hardware built for specific purposes outpaces general purpose computers. Thus, many countries (the USA, Canada, Japan, the UK, Germany, or France) have recently acquired large calculation instruments specifically dedicated to AI for their

13. There is a slight difference between a supercomputer and networks of servers. Amazon's Elastic Computer Cloud (EC2) is an internet-enabled network of servers that provides on-demand computing power, rather than a stand-alone cluster with its own local interconnection.
14. Hwang, "Computational Power and the Social Impact of Artificial Intelligence", *op. cit.*, p.8.

research communities. This includes the RIKEN Center in Japan, which developed the *Fugaku*; the Joint Academic Data Science Endeavour (JADE), in the UK in 2018; or the GENCI (*Grand équipement national de calcul intensif*) in France, which inaugurated a new machine for AI research (the *Jean Zay*), in 2020.

Table 2: Most Powerful Supercomputers in the World

	Country of location	Manufacturer	Processor	Name	Site	Performance[15]
1	Japan	Fujitsu	Fujitsu/ARM	*Fugaku*	Riken Center for Computing Sciences	442,010
2	USA	IBM	IBM/Nvidia	*Summit*	Department of Energy (DOE) /Oak Ridge National Laboratory	148,600
3	USA	IBM/Nvidia/ Mellanox	Nvidia	*Sierra*	DOE/Lawrence Livermore National Laboratory	94,640
4	China	NRCPC[16]	Sunway	*Sunway TaihuLight*	National Supercomputing center in Wuxi	93,014
5	USA	HPE Cray	AMD/Nvidia	*Perlmutter*	DOE/ National Energy Research Scientific Computing Center	64,590
6	USA	Nvidia	AMD/Nvidia	*Selene*	Nvidia Corporation	63,460
7	China	National University of Defense Technology	Intel	*Tianhe-2A*	National supercomputer center in Guanzhou	61,444
8	Germany	Atos	AMD/Nvidia	*Juwels Booster Module*	Jülich Research Center	44,120
9	Italy	Dell	Nvidia	*HPC5*	Eni S.p.A.	35,450
10	USA	Dell	Intel	*Frontera*	University of Texas	23,516

Source: Top500, June 2021.

15. Linpack Performance in teraflop/s.
16. NRCPR: National Research Center of Parallel Computer Engineering & Technology.

It is thus essential to consider the processors that enable HPC machines and the central role that chip manufacturers (AMD, Intel or Nvidia)[17] play in shaping and structuring the realm of computing power. The international landscape of processors has greatly evolved over the past few years, with the breakthrough of Nvidia, a Californian company created in 1997.[18] Computers rely on central processing units (CPUs), as well as increasingly on graphics processing units (GPUs), which allow visual computing (such as 3D, video, computer vision and image recognition).[19] Nvidia designs GPUs, originally aimed at the gaming industry, and which now equip supercomputers around the world (see Table 2). Indeed, GPUs turned out to accelerate significantly computing power for certain applications like machine learning. As such, they constituted a real revolution in HPC. In 2017, Nvidia launched a GPU based on a new architecture ("Volta"), designed for AI and especially for self-driving cars, which now equips America's two most powerful supercomputers, *Sierra* and *Summit*. The company also started manufacturing its own supercomputers. Nvidia is now hoping to acquire ARM, a British, world-leading chip designer acquired by Japanese holding SoftBank in 2016 for £24.3 billion (€29 billion). As of September 2021, it seems the move is likely to be blocked by the UK government, due to anti-competitiveness and national security concerns, in a context of heightened geopolitical competition surrounding computer chips.[20]

The Next Level: Toward an Exascale Machine

Currently, the world of high-performance computing is characterized by a race for the development of exascale computers. Exascale computers will be capable of carrying out one billion billion (one quintillion) operations per second.[21] In other words, exascale machines will be twice as powerful as the world's most powerful machine to date,

17. They are the major producers of processors used in HPCs. But it is worth noting that AMD and Nvidia are "fabless" companies that design the chips but let manufacturing companies such as TSMC "bake" them; while Intel does both the design and the manufacturing.
18. Interview with Olivier Ezratty, independent consultant, April 6, 2021.
19. GPUs distribute computational tasks across a large number of cores to be processed in parallel, in contrast to CPUs, which feature a smaller number of more powerful cores that handle just a few tasks simultaneously. See Hwang, "Computational Power and the Social Impact of Artificial Intelligence", op. cit., p.10.
20. K. Donaldson and G. Turner, "U.K. Considers Blocking Nvidia Takeover of Arm Over Security", Bloomberg, August 3, 2021, available at: www.bloomberg.com. ARM's architecture for processors is today the world's most widely used set of standards.
21. E. Jeannot, quoted in "High-Performance Computing : INRIA involved in eight European projects", INRIA News, May 27, 2021, available at: www.inria.fr.

and twenty times more powerful than the best European machine.[22] Exascale machines will make a difference in specific areas of simulation and 3D visualization used in nuclear power research (e.g. next-generation nuclear warheads), climate sciences (e.g., forecasts of the consequences of temperature changes), high-resolution meteorology and oceanography, as well as biological and medical research (e.g. cardiac physiology). But a country's place in the world's computing power rankings are also an expression of national sovereignty and a soft power tool, as suggested by Emmanuel Jeannot of INRIA.[23]

There are no exascale machines deployed today,[24] but government programs are underway in the United States, Europe, China, and Japan. Developing exascale machines is a matter of cost as well as access to technology. The latter is a particular problem for China due to export restrictions of US technology. As for the cost, it is illustrative that the R&D funding for the *Fugaku* has been around €1 billion over 10 years.[25]

China and the United States are planning to have their own exascale machine operational in late 2021 and 2022, respectively. In July 2015, former US president Barack Obama launched a National Strategic Computing Initiative calling for the accelerated development of an exascale computing system that integrates hardware and software across a range of applications representing government needs.[26] HPE Cray is planning to deliver its first exascale computer, *Frontier*, to the Oak Ridge National Laboratory (ORNL, attached to the Department of Energy) in late 2021, with full user operations in place in 2022. ORNL already hosts *Summit*, which ranked as the world's most powerful machine in 2018-2020. While China did not have a single supercomputer in 2001, China superseded the US in terms of performance and number of supercomputers worldwide in 2016.[27] Today, China now owns the highest number of the Top500 supercomputers worldwide, even if its machines are less performant than American ones, overall. China hopes to have its first exascale machine, based on indigenous technology, operational in late 2021, and as such could be the first nation to operationalize an exascale

22. *Ibid*.
23. Interview with Emmanuel Jeannot, Scientific Delegate of INRIA Bordeaux, July 28, 2021.
24. Japan's *Fugaku* has attained exaflopic performance according to an alternative new benchmark (Top500, "November 2020", no date, available at: www.top500.org). Besides, the folding@home project, which connects thousands of home computers that can lend out idle processing power, linked through the Internet, reached one exaflop/s calculation power already.
25. Interview with Jacques-Charles Lafoucrière, Program manager, CEA, July 26, 2021.
26. White House, "Executive Order – Creating a National Strategic Computing Initiative", July 29, 2015, available at: https://web.archive.org.
27. B.-S. Gigler *et al.*, "Financing the Future of Supercomputing", *op. cit.*, p. 18 and p. 41.

computer.[28] In addition, Beijing has included a target of having 10 national exascale supercomputing centers in its 14th Five-year-development-plan spanning 2021-2025. Other countries around the globe are seeking to build exascale machines, but they are less advanced than China, the US or Japan. This list includes South Korea, which is aiming for a national exascale computer, relying on Korean processors, by 2030.[29] Europe, for its part, is seeking to deploy exascale machines by 2022-2023, as we shall see in the next section.

The "Democratization" of High-performance Computing

Given its costs and possible uses, HPC was not a critical business need for many companies until the emergence of the big data economy. Today, the functions of computing power are changing, and HPC is "democratizing",[30] as it plays an important role in facilitating the development of the big data economy.[31] Indeed, with the proliferation of data, there is growing demand for extracting insights from such big data, and for near-real time analysis.[32] HPC is especially attractive for AI technologies such as deep learning. They require a lot of computing power, so much so that the amount needed worldwide to train AI programs doubles every 3.4 month.[33]

HPC-enabled big data analytics and simulation have plenty of uses in industry, in all design and manufacturing processes: digital twinning,[34] design customization, operations management, maintenance, optimization, or assessment. Instead of developing costly physical prototypes – and the customized tools and machines that may be required for building such prototypes, as well as lengthy testing – processes are transferred to a digital environment, which reduces development costs and time to market.[35] HPC-based

28. T. P. Morgan, "A First Peek at China's Sunway Exascale Supercomputer", The Next Platform, February 10, 2021, available at: www.nextplatform.com.
29. B. Garé, "La Corée du Sud en route vers le HPC exascale", L'Informaticien, May 28, 2021, available at: https://linformaticien.com.
30. Nvidia, "Accelerated Computing and the Democratization of Supercomputing", Technical Overview, 2018, available at: www.nvidia.com.
31. Council of the EU, "Council Agreement Secures EU financing of High-Performance Computing", *op. cit.*
32. S. Gibson, "High-Performance Computing Use Cases and Benefits in Business", Tech Target, April 5, 2019, available at: www.searchcio.techtarget.com.
33. C. Deluzarche, "La puissance de calcul nécessaire pour entraîner l'IA double tous les 3,4 mois", Futura Tech, November 14, 2019, available at: www.futura-sciences.com. Thanks to improved hardware, training times for a given algorithm might be shrunk from weeks or days to hours or minutes. See M. Horowitz, "Strategic Competition in an Era of Artificial Intelligence", CNAS, Report, July 25, 2018.
34. A digital twin is a virtual model aimed to accurately reflect a physical object, that is updated with real-world data, for purposes of simulation and monitoring.
35. B.-S. Gigler *et al.*, "Financing the Future of Supercomputing", *op. cit.*, p. 37.

simulation is also relevant for 3D simulation of fluid dynamics, in driving simulation for autonomous vehicles, for tank simulation in the oil and gas business, in finance for the optimization of portfolio risk management, in crisis management scenarios (e.g. forest fires), etc.

Besides industry, growth in uses of HPC and digital twinning continues to be driven by research, including medical research and climate sciences. In fact, the need for computing power in science is ever growing.[36] By way of illustration, since 2020, Japan has been using its *Fugaku*, to simulate the spread of Covid-19.[37] In the future, digital twinning of the human body, based on individuals' DNA, will in theory allow medical treatments to be tailored to a person's physiology and needs.[38] When it comes to climate, the European Union (EU) launched its "Destination Earth" (DestinE) project in 2021, as part of its Green Deal plan.[39] The plan is to create digital twins of the Earth to simulate the effects of climate change, through a high precision digital model of the Earth to monitor and simulate natural and human activity. The project will span 2021-2030. By 2025, the project will include a cloud-based platform, with four to five operational digital twins.

Due to the generalization of its uses, the market for HPC has become quite dynamic: its growth rate for businesses has been estimated at +9.8% from 2017 to 2022[40]. Market turnover reached $41 billion (€35 billion)[41] in 2020 worldwide, and is expected to reach $66.5 billion (€56.7 billion) in 2028.[42] We are thus seeing an evolution of HPC from the realm of government and research and large corporations to having a more central place in the general economy.

Aside from greater demand, the growth of the HPC sector is fueled by sinking costs and the greater affordability of hardware, as well as the move of HPC from "on premises" to (partly) on the cloud, whereby HPC users can access high-speed data processing from commercial services such as Amazon Web Services.[43] A report suggests that the on premises

36. Interview with Jacques-Charles Lafoucrière, Program manager, CEA, July 26, 2021.
37. "Japanese Supercomputer, Crowned World's Fastest, Is Fighting Coronavirus", BBC, June 23, 2020, available at: www.bbc.com.
38. European Commission, "Advanced Computing", last updated July 9, 2021, available at: www.digital-strategy.ec.europa.eu.
39. European Commission, "Destination Earth", last updated July 8, 2021, available at: www.digital-strategy.ec.europa.eu.
40. S. Gibson, "High-Performance Computing Use Cases", *op. cit.*
41. Throughout the paper, Euro amounts are at August 2021 conversion rates.
42. Emergen Research, "High-Performance Computing Market Size to Reach USD 66.46 Billion in 2028", April 19, 2021, available at: www.globenewswire.com.
43. S. Gibson, "High-Performance Computing Use Cases", *op. cit.*; S. Shah, "How Long until Cloud Becomes the Preferred Environment to Run HPC Workloads?", Computer Weekly, January 27, 2021, available at: www.computerweekly.com; Alliance des Sciences et Technologies du Numérique, "Infrastructure de recherche pour l'Intelligence artificielle", Report, January 2018.

HPC market, worth $24 billion (€20.5 billion) in 2020 and will grow at 7% a year by 2024, while the HPC cloud market was worth only $4.3 billion (€3.7 billion) in 2020 but will grow at 17% a year until 2024.[44] As an indication of these trends, the world-leading, Taiwan-based chip manufacturer TSMC expects that, due to "unprecedented demand for compute power in cloud datacenters and communication infrastructures",[45] "the main driver of its growth in the next several years [will] be high-performance computing, overtaking its current smartphone business."[46]

Is Europe's Computing Power Catching up?

In 2018, the President of the European Investment Bank (EIB) regretted that "while a third of the global demand for HPC capabilities comes from European industry, SMEs and researchers […] only 5% of the HPC capabilities [were] being provided by European HPC centers".[47] Europe hosts one main player in supercomputing – Atos – but it is seeking to host more machines on the continent through collaborative ventures, and to develop capacities in areas of the HPC value chain where Europe is largely absent, notably processors.

The Limits of Europe's Computing Power

The French company Atos-Bull is the sole European supercomputer hardware company. It is the result of successive French governments' objective to be sufficiently industrially autonomous to develop and maintain nuclear weapon systems. This goal drove France's post-World War II techno-industrial planning in telecommunications, atomic energy, space capabilities, and computer science. Another motivation to have a French supercomputer company was the US embargo on the export to France of state-of-the-art computer equipment, for fear that the equipment could possibly fall into Soviet hands.[48] When Bull was taken over by General Electric in 1964 and left

44. *Ibid*.
45. TSMC, "High-Performance Computing Platform", no date, available at: www.tsmc.com.
46. A. Patterson, "TSMC Bets on HPC for Future Growth", EE Times Asia, October 22, 2020, available at: www.eetasia.com. The CEO of TSMC, C. C. Wei said in April 2021: "We are witnessing a structural increase in underlying semiconductor demand as a multi-year megatrend of 5G and HPC-related applications are expected to fuel strong demand for our advanced technologies in the next several years… we expect demand for our N5 family to continue to grow in the next several years, driven by the robust demand for smartphone and HPC applications". See C. C. Wei, "Q1 2021 Taiwan Semiconductor Manufacturing Co Ltd Earnings Call", Transcript, April 15, 2021, available at: https://investor.tsmc.com.
47. B.-S. Gigler *et al.*, "Financing the Future of Supercomputing", *op. cit.*, p. 1.
48. J. W. Cortada, "Public Policies and the Development of National Computer Industries in Britain, France, and the Soviet Union, 1940–80", *Journal of Contemporary History*, Vol. 44, No. 3, p. 504.

Europe with no challenger to US companies in a strategic sector, France launched the "*Plan Calcul*" ("computing plan") to support the emergence of a French national champion in computing. The Plan failed to create a new industrial actor from scratch, but Bull was eventually nationalized in 1982 and re-privatized in 1994. Finally, Atos took over Bull in 2014.

For the past two decades, Bull and then Atos-Bull has, been an important player in the supercomputer business. Since 2001, five years after it launched its nuclear simulation program ("*Simulation*"), the French Alternative Energies and Atomic Energy Commission (CEA, which oversees the French nuclear deterrent), has endeavored to have a "sovereign", national industry of supercomputers.[49] The CEA got into a partnership with Bull, which delivered its first machine to the CEA (the *TERA-10*) in 2005. By 2012, Bull had three machines in the world's top 20. Today, Atos-Bull continues to provide the CEA with *Simulation*, and the French Ministry of Armed Forces more broadly for other uses. Nowadays, the need for 3D computing for future generations of nuclear weapons is what is driving the search for ever more powerful computers and the pursuit of exascale machines.

But Atos and other European companies are not present all along the production cycle for supercomputers. Atos has its own interconnection system (BXI) but relies on non-European manufacturers for processors: the US-based companies AMD, Intel and Nvidia. As suggested by a representative of Atos, the company is indeed "agnostic" when it comes to Processing Unit providers.[50] French and EU authorities have, however, identified the absence of a European provider as a problem and sought to develop alternatives. In 2019, the head of the CEA's military arm estimated that, while the CEA has been working with Intel, in the future, there should be "a sovereign European processor," because France would "not want to be subject to an inability to have these processors."[51]

Another problem is public procurement choices. Government procurement programs are a key determinant of HPC hardware providers' outlooks. This is especially true when companies have little chance to sell into foreign markets. Today, the United States and China are keeping their market closed to foreign vendors. In the US, the domestic industry is currently strongly supported with a "Buy-American" requirement for the purchase of supercomputers.[52]

49. "Audition de M. François Geleznikoff, Directeur des applications militaires du CEA", Commission des Affaires étrangères, de la Défense et des Forces armées du Sénat, November 27, 2019, available at: www.senat.fr.
50. Interview with Philippe Duluc, CTO Big Data and Security, Atos, July 12, 2021.
51. "Audition de M. François Geleznikoff", *op. cit*.
52. B.-S. Gigler *et al.*, "Financing the Future of Supercomputing", *op. cit.*, p. 46.

A European company like Atos thus cannot hope to export its machines to the US or China, and its market is largely located in Europe (UK included), Brazil, and India.[53] What is more, unlike in the US or China, public procurement in the EU is open to non-EU entities, a practice that does not always favor local providers. It is indeed striking that the *Jean Zay*, the CNRS largest and most recent supercomputer, is HPE-built, and not Atos-built. New initiatives aim at boosting the European HPC sector (see below), but debates have arisen about whether to give precedence to EU-based options in public procurement choices. This may change with the International Procurement Instrument, a new piece of legislation currently being negotiated in Brussels, and which would introduce a principle of reciprocity in the openness of public procurement markets, in response to legislation such as the "Buy American" Act.[54]

A further limitation is the absence of European companies in cloud-based HPC services. Cloud-service suppliers in Europe remain largely American companies. For example, the French firm Atos has partnered with Google Cloud to provide a hybrid cloud solution for data analysis and machine learning.[55] This is not without problems for data security.[56] Consequently, the EIB has pushed for the development of European cloud offers, including HPC applications.[57]

Europe, finally, has a funding problem, the European Investment Bank in 2018 called for significant investments to be made in infrastructure, access to big data, and tailor-made complex software solutions.[58] Mariya Gabriel, then Commissioner for Digital Economy and Society, identified a funding gap in European HPC of €500 million to €750 million per year, compared to the USA, China, or Japan.[59] One conclusion of the report was that no single country in Europe by itself has the capacity to sustainably set up and maintain an exascale HPC ecosystem within a competitive timeframe.

53. Top 500, "Statistics: Sublist Generator", no date, available at: www.top500.org.
54. J. Titievskaia, "EU International Procurement Instrument", European Parliamentary Research Service, Briefing, March 2020; J. Hanke Vela, "EU Readies Response to Biden's 'Buy American' Pitch", *Politico*, May 4, 2021.
55. Atos, "Atos Acquires Google Cloud Premier Partner Maven Wave", Press Release, December 18, 2019, available at: https://atos.net.
56. See A. Pannier, "The Changing Landscape of European Cloud Computing: Gaia-X, the French National Strategy, and EU Plans", Ifri, *Briefings de l'Ifri*, July 2021.
57. B.-S. Gigler *et al.*, "Financing the Future of Supercomputing", *op. cit.*, p. 50.
58. *Ibid.*, p. 1.
59. *Ibid.*, p. 2.

Plans for More Computing Power: The EuroHPC Joint Undertaking

As its use has become more common, HPC has become a priority issue for most EU Member States in recent years, and with it an attempt to address the limits of Europe's computing power. The need became more pressing from 2015 onward, after both US and China developed their plans for HPC. There was thus pressure in Europe to aim for exascale computers too, and to make Europe not only a consumer but also a producer of computing power.[60] Within Europe, too, Thierry Breton, the current EU Commissioner for Industry, then CEO of Atos, strongly supported the initiative.[61] The result has been new HPC initiatives and funding at a European scale, as part of a broader agenda for European digital infrastructures.

Two initiatives in Europe are ongoing: a plan to build European supercomputers, including exascale HPC, known as the EuroHPC Joint Undertaking (JU), and a plan to develop a European microprocessor for extreme-scale computing, known as European Processor Initiative or EPI. In 2017, seven member states — Germany, Portugal, France, Spain, Italy, Luxembourg, and the Netherlands — signed a declaration establishing the EuroHPC Joint Undertaking. The legal and funding entity was established in 2018. The EU Commission's DG Connect did a lot of the initial work, before EuroHPC became autonomous in September 2020.[62] In the meantime, two private actors (the Big Data Value association, and ETP4HPC) joined the public-private partnership, as well as several countries, including Norway and Turkey (but not the UK) – reaching 33 members.

The principle is one of co-funding between the EU, the member states and private actors federated in an association. Participating countries and entities coordinate their efforts and pool their resources. During the initial phase of 2019-2021, the JU had a €1 billion budget. On July 13, 2021, the European Council adopted a regulation on establishing the EuroHPC, thus allowing existing activities to continue.[63] The new regulation will grow the initiative's budget, staffing and missions. EuroHPC funding for 2021-2027 (to be matched by participating states) will come from Digital Europe (€2 billion), Horizon Europe (€900 million) and the Connecting Europe facility (€200 million).

60. Interview with Marie-Hélène Pautrat, Head of European partnerships, INRIA, April 9, 2021.
61. *Ibid*.
62. Anders Jensen, Executive Director of the European High Performance Computing Joint Undertaking (EuroHPC JU), at the Supercomputing Frontiers Conference 2021, July 19, 2021, video recording available at: https://supercomputingfrontiers.eu.
63. Council of the EU, "European High Performance Computing Joint Undertaking: Council adopts Regulation", Press release, July 13, 2021, available at www.consilium.europa.eu.

The funding will be used toward a dual goal: to deploy top-of-the-range supercomputing infrastructure across Europe to match users' needs, and to develop a research and innovation ecosystem for HPC technologies in Europe. The JU aims to deploy two exascale machines by 2023, which France and Germany are hoping to host.[64] In France, the partnership between the CEA and Atos-Bull, via the GENCI, is driving the progress toward exascale, and the post-*TERA 1000* machine. In November 2020, they chose to integrate Fujitsu's A64FX processor technology, the same that equips the *Fugaku*, to develop the first French exascale computer.

Before exascale machines are built, eight hosting entities, around Europe, have been selected to host five petascale and three pre-exascale machines. Each of the five petascale machines will be worth between €12 million and €30 million each.[65] The first computer, the Atos-built *Vega*, was inaugurated in March 2021 in Slovenia.

The plan also includes three pre-exascale machines (at 10^{17} flop/s). Two are currently under construction: one, LUMI in Finland (Cray-HPE, with AMD CPUs and GPUs); and the second, Leonardo, in Italy (Atos-built with Nvidia GPUs), respectively worth €144 million and €120 million.[66] The third one, MareNostrum 5, will be located at the Barcelona Supercomputing Center, but its procurement is currently in limbo. In this case, the shared desire to procure petascale or exascale machines to respond to users' needs conflicts with another goal, which is to support and develop European industrial capabilities in HPC. Two bids competed for winning the procurement contract: a US-Chinese consortium with IBM and Lenovo, and Atos. The initial technical evaluation showed that IBM and Lenovo offered a more powerful machine at a better price. Atos' advantage, by contrast, was to have a supply chain that is more embedded in Europe — so one question was whether the latter should be a defining criterion in favor of choosing Atos.[67] The EuroHPC criterion of "EU added value" does include an evaluation of how much a bid "reinforce[s] the digital technology supply chain in the Union".[68] In light of this requirement, the EuroHPC advisory board recommended opting for the Atos offer: a choice which France supported, but Spain opposed. The issue became so political as to be the object of a discussion between the Spanish Prime Minister Pedro Sanchez and the French President Emmanuel Macron in March

64. European Commission, "Supercomputing in the DIGITAL Europe Programme", last updated August 4, 2021, available at: https://digital-strategy.ec.europa.eu. Interview with Marie-Hélène Pautrat, Head of European partnerships, INRIA, April 9, 2021.
65. Van Dorpe, "Supercomputer Scrap".
66. *Ibid*.
67. *Ibid*.
68. European Commission, "European High Performance Computing Joint Undertaking: General Invitation to Tender", SMART 2019/1084, Descriptive document, available at: https://etendering.ted.europa.eu.

2021. In May 2021, EuroHPC cancelled the tender, under the justification that the Covid-19 pandemic had changed the specifications required for the machine.[69]

The Future of European Supercomputers: Energy Efficiency and Technological Sovereignty?

Access time to EuroHPC machines will be allocated to European scientific, industrial, and public sector users in such way that it maximizes the positive impact of these systems on R&I. Indeed, the second goal of EuroHPC, parallel to infrastructure deployment, is to develop an R&I ecosystem for HPC in Europe that includes hardware and software capabilities, applications, training, and skills.[70] That ecosystem, in turn, should contribute to Europe's double agenda: the Green Deal, and technological sovereignty.

Energy consumption is becoming a major issue for the expansion of computing power and of the data economy. The huge increase in computing power and energy is in large part attributable to the training of machine learning programs. Aside from environmental considerations, this also has an economic cost. The electricity bill for a supercomputer amounts to tens of millions of euros per year.[71] The *Fugaku* consumes 30 to 40 megawatt, with a corresponding yearly cost of up to €40 million per year.[72] For a country like France, the limitation to the deployment of an exascale machine is not so much technical as financial. In France, the current budget allocated to HPC only permits to consume half of that energy.[73]

As part of Europe's Green Deal, any plan to develop HPC in Europe has to address the question of energy efficiency. Europe is already well positioned in the Green500 ranking, another ranking by Top500 that looks at power efficiency (in GFlops/Watt) in supercomputers: there are four Atos-Bull machines in the top 10, which is better than in the regular ranking where only one Atos-Bull machine makes in to the top 10 (see Table 2).[74] The EU intends to continue down this path. As part of EuroHPC, the laboratories that apply for hosting machines must be exemplary in terms of energy-

69. Van Dorpe, "Supercomputer Scrap".
70. The new JU regulation which came into force in August 2021 also includes new additional areas of work, including federating, securing and hyper-connecting the super-computers, and looking into quantum computing infrastructures similar to EuroHPC in future (cf. infra).
71. INRIA, "Optimiser le calcul haute performance, un défi scientifique et écologique", April 14, 2021, available at: www.inria.fr.
72. Interview with Jacques-Charles Lafoucrière, Program manager, CEA, July 26, 2021.
73. *Ibid.*
74. Top500, "Green500", June 2021, available at: www.top500.org.

efficiency. For instance, the LUMI, which is being installed in Finland, will be powered by hydropower from a nearby river.

Europe's two agendas of the Green Deal and technological sovereignty are coming together when it comes to processors: not only do processors play a big role in defining the power efficiency of a machine, but the past couple of years have also showed that foreign dependences on such technology causes risks of disruption.[75]

The project for European low-power microprocessors known as European Processor Initiative (EPI) was launched in 2015 and started in practical terms in 2018. It gathers 28 public and private partners, including the CEA, STMicroelectronics, BMW, and various universities and research labs, and is coordinated by Atos. The EPI will create advanced processors for HPC applications. The main guidelines for a first generation of processors were announced in June 2019, and this vision was further materialized with the operational launch of SiPearl, a start-up company responsible for the design of the chips. A first prototype of processor, Rhea (which is largely based on a design by the British company ARM) was presented in January 2020. SiPearl hopes to launch Rhea in 2022 and to deliver it on time for the European exascale supercomputers in 2023. Aside from supercomputers, SiPearl aims to develop other microprocessors for other, bigger markets like autonomous vehicles, edge computing, and datacenters.[76]

The EPI's processors aim to be extremely energy-efficient: SiPearl promises it will halve the energy consumption of supercomputers.[77] In principle, they also aim to fill a political and strategic goal, as they are "proudly designed in Europe to set out Europe's technological sovereignty".[78] Yet, at this point, the enterprise is faced with a lack of investment: presently the HPC sector is largely financed by national or European budgets and grants, but private investments are missing to make it viable.[79] Finally, it is worth noting that the processors will indeed be *designed* in Europe, but the chips will most likely be manufactured by TSMC.

75. Council of the European Union, "Regulation on Establishing the European High Performance Computing Joint Undertaking (HPC) — General Approach", May 2021, p. 28, para. 16.
76. T. Trader, "ISC21 Preview: EPI Chair Jean-Marc Denis Shares Vision for Future Supercomputers", HPCwire, June 24, 2021, available at: www.hpcwire.com.
77. European Processor Initiative, "Project: EPI", no date, available at: www.european-processor-initiative.eu.
78. SiPearl, Press Kit, January 2020, available at: https://sipearl.com.
79. Interview with Jacques-Charles Lafoucrière, Program manager, CEA, July 26, 2021; B.-S. Gigler, *et al.*, "Financing the Future of Supercomputing", *op. cit.*, p. 36

Quantum Computing

According to Moore's law, computing power doubles every two years, as the number of transistors on integrated circuits doubles. This trend is facilitated by the gradual reduction in the size of semiconductors, together with other advancements in digital electronics. However, we now frequently read that we are reaching the end of that law, as we are close to reaching the physical limits of nanoscale computer chips. According to a 2018 report by the European Investment Bank, "by 2025, hardware configurations could come to the end of exponential capacity increase" of classical computers.[80] In contrast to these physical limitations faced in classical computers, quantum computing exploits the characteristics of quantum physics and promises to multiply computing power exponentially. Consequently, quantum computing has become a strategic field in which governments, research laboratories, technology companies are increasingly investing, with a view to reaping the benefits of the quantum advantage.

A Revolution in Computing

Quantum information sciences emerge from the consideration that quantum physics (i.e., at the atomic or sub-atomic level) has implications for how systems like computers process information. In turn, quantum effects can be leveraged for computing information. Quantum computing is one segment of the field of quantum information sciences, which is vast and also includes communication and cryptography, metrology and sensing, and simulation, with wide-ranging application domains.[81] Quantum information technologies currently stand at various levels of readiness. Compared to sensing and cybersecurity applications, quantum computing is the furthest away from market readiness, but it also has the highest disruption potential.[82]

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80. B.-S. Gigler *et al.*, "Financing the Future of Supercomputing", *op. cit.*, p. 46.
81. This study only deals with quantum computing. There are many potential strategic applications for other quantum technologies, e.g., satellite-based quantum sensing and enhanced image processing could enable the identification of underground nuclear installations, while quantum gravimeters could significantly improve the accuracy of drilling by sensing density fluctuations that indicate oil and mineral deposits. Quantum radars could potentially overcome stealth technologies and be resistant to advanced forms of jamming.
See G. Brennen *et al.*, "An Australian Strategy for the Quantum Revolution", pp. 14-15; K. M. Sayler, "Defense Primer: Quantum Technology", Congressional Research Service, In Focus, June 7, 2021.
82. Quantonation, "Portfolio", no date, available at: www.quantonation.com.

Toward Quantum Computers: Technological Progress and Challenges

Principles of Quantum Computing

Quantum computing emerged recently, and its development has accelerated in recent years. In 1995, scientists understood that quantum algorithms will make it possible to perform calculations in record time, and that this posed security challenges for information systems.[83] The following year, IBM proposed the first principles of the quantum computer and introduced the first 2-quantum bits (qubit) computer. Five years later, in 2001, IBM researchers managed to factor the number 15 using quantum bits.

Quantum computers, as they exploit the special properties of matter in quantum mechanics, constitute a whole new paradigm in computing – whether in terms of hardware or software. In classical computing, the bit is the basic unit for storing information. Its value is either 1 or 0. In quantum computing, rather counter-intuitively, the basic unit, the qubit, can be "more or less 0" and "more or less 1", in varying proportions.[84] This superposition of states allows the multiplying effects of quantum computers compared to classical ones: where a classical computer can provide a result of a calculation at the end of a chain of successive instructions, qubits allow 2^N simultaneous combinations and provide an instantaneous solution at the time of measurement (however without indication of the process). Consequently, quantum machines allow certain computations to be performed exponentially more quickly than by classical computers.

A Diversity of Technological Avenues

To exploit the properties of quantum physics, a quantum computer manipulates the states of particles using lasers or electric and magnetic fields. Different quantum processor technologies are currently undergoing experimentation in quantum research laboratories. Most industrial teams, including IBM and Google, as well as the UK in collaboration with California-based Rigetti, have focused on qubits as superconducting circuits that are cooled to extreme temperatures close

83. CIGREF, "Informatique quantique: Comprendre le quantum computing pour se préparer à l' inattendu", Report, February 2020.
84. In classical physics, one can determine the state of an object, its position, speed, weight, etc. In quantum physics, a particle can be X% in one state (e.g., excited or ground), Y% in another state, and Z% in yet another. These variations are probabilistic, and when one measures a qubit, its exit value will be either 0 or 1 (the wealth of quantum states thus only occurs before the measurement). See A. Middleton *et al.*, "Quantum Information Processing Landscape 2020: Prospects for UK Defence and Security", Defence Science and Technology Laboratory, Report No. DSTL/TR121783, June 2020, Appendix A.

to absolute zero, where certain materials conduct electricity with no resistance.[85] They are the qubit technologies that appear to be the most advanced.[86] "Trapped-ions" is another technology that is also very promising. These are electrically charged atoms (ions) that are cooled and "trapped" with lasers. This technology is pursued by Honeywell, IonQ (sponsored by the United Arab Emirates with the University of Maryland) and the EU Quantum Flagship project "AQTION". Photon-based technologies are also being developed, not least by China's University of Science and Technology. Finally, the emergence of quantum computing goes hand in hand with technological advances in many scientific and technological fields: nanotechnologies, cryogenics, materials sciences, lasers, etc.

It is unclear today which qubit technology or technologies will eventually prevail.[87] Currently, governments, technology companies and investors need to adopt a "Darwinian" mindset: even if still at an experimental stage, it would be risky to bet on the failure of quantum computers or to choose one technology over another.[88] Eventually, there are probably going to be different types of quantum computing systems that will coexist.

Remaining Challenges

The American physicist John Preskill developed the concept of "quantum supremacy", which will be attained when a quantum machine solves a mathematical problem that no classical computer can solve, due to physical limitations. For instance, a calculation that would require millions of years to solve, or that would require more particles than there are in the universe.[89] Some US and Chinese laboratories have successfully set out on a race for "quantum supremacy" (see below). However, most governments, research labs and start-ups around the globe are seeking to harness "quantum advantage", and to develop practical uses of quantum computing. Quantum advantage will come down to combining a quantum machine with a classical machine to reach a level of acceleration of computing that is sufficiently significant to provide advantage compared to classical machines. To this day, however, how, and when the industry will reach the point

85. E. B. Kania and J. K. Costello, "Quantum Hegemony? China's Ambitions and the Challenge to U.S. Innovation Leadership", Report, CNAS, 2018; J. Kung and M. Fancy, "A Quantum Revolution: Report on Global Policies for Quantum Technology", CIFAR, April 2021.

86. CIGREF, "Informatique quantique", *op. cit.*, p. 36.

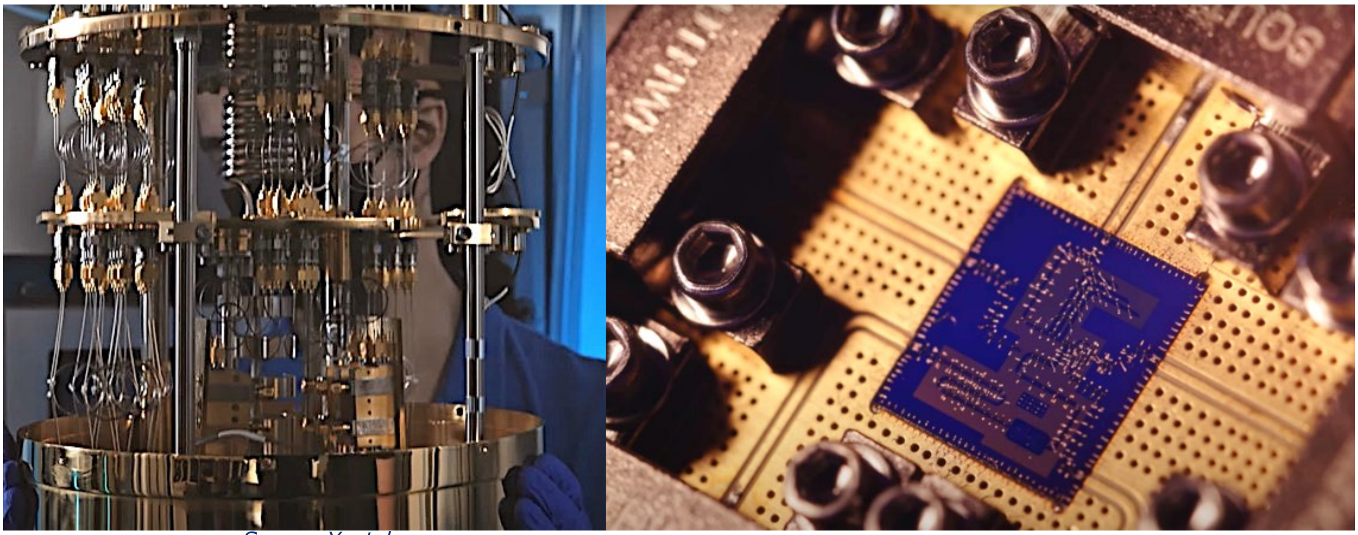
87. J. Kung and M. Fancy, "A Quantum Revolution", *op. cit.*

88. Interview with Emmanuel Jeannot, Scientific Delegate of INRIA Bordeaux, July 28, 2021.

89. Interview with Neil Abroug, Head of National Quantum Strategy, Secrétariat Général pour l'Investissement, June 30, 2021.

where a quantum computer can solve a relevant problem faster than a classical computer for concrete commercial applications, remains an unknown.[90]

Chandelier (cryostat) and Processor by French Start-Up Alice&Bob



Source: Youtube.

According to the US Department of Energy, we are currently at the same point in the development of quantum computing as scientists in the 1950s were when conventional computers ran on vacuum tubes.[91] The technologies behind classical computers are today sufficiently performant to create, transfer, store information with a reliability rate close to 100%, and few resources (memory, CPU) are needed to correct errors that inevitably result from electronic components. We are far from there with quantum computers: they remain extremely sensitive to interactions with their environment (so-called "noise"), which affects the properties of quantum bits and the quality of the output. The mere day-to-day vibrations of buildings in which a quantum machine is located can lead qubits to "decohere" and lose their programmed quantum information.[92] Quantum hardware requires intricate wiring to control and measure qubits and this also introduces noise, in a way that increases as the number of qubits grows.[93] Thus, a key challenge is to solve the noise and errors caused by the fragility of quantum

90. M. Swayne, "IBM Unveils Japan's First Commercial Quantum Computer", The Quantum Daily, July 27, 2021, available at: https://thequantumdaily.com.
91. Office of Science, "Calculating the Benefits of Exascale and Quantum Computers", July 28, 2020, available at: www.energy.gov.
92. IBM, "Five years ago today, we put the first quantum computer on the cloud. Here's how we did it", May 4, 2021, available at: https://research.ibm.com.
93. M. Swayne, "OQC Delivers the UK's First Quantum Computing as-a-Service", *The Quantum Daily*, July 7, 2021, available at: https://thequantumdaily.com.

systems.[94] Noise-correction, though adaptations in code, algorithms or hardware is thus a central workstream of quantum research.

Today, Noisy Intermediate-Scale Quantum computers (NISQ) are a first generation of quantum computers that are not so precise, but which can demonstrate technologies and that algorithms are valid. They provide experimentation grounds to identify use cases and develop quantum algorithms. Practical uses will come later. NISQs contain between around 50 to a few hundred qubits. Below 40 qubits, a classical computer can be faster than a quantum one, however, above 60 qubits, a quantum computer is always faster.[95]

It is estimated that a quantum computer with 1,000 to 5,000 qubits will start having real world applications, and implications for cybersecurity.[96] But the "Grail" of quantum computing science,[97] that would constitute a real "game-changer",[98] would be the advent of large-scale, general-purpose quantum computers (known as LSQs). But their arrival is uncertain.[99] If some, like Google, have already succeeded in performing quantum calculations which demonstrated quantum supremacy,[100] the error rate is so high that we are still very far from achieving the promises of quantum computing. Today, the best qubits make a mistake every 1,000 operations — that is 10 billion billion more errors than a classical computer.[101] Thus, most experts argue that to have an efficient error correction rate, these computers would need to have millions of qubits.[102] This presents another problem which is space: today, an experimental quantum computer of a few dozen qubits occupies a full room, not least due to refrigeration and shielding requirements. Another option is to develop a qubit technology that can limit or correct errors. In either case, it is necessary to develop qubit technology that can be manufactured at scale.

Two other necessary lines of effort are classical-quantum computers integration, and software design. Quantum computers will not operate independently but, instead, for the foreseeable future, will work in conjunction with classical computers. A classical computer will

94. J. Kung and M. Fancy, "A Quantum Revolution", *op. cit.*
95. Interview with Philippe Duluc, CTO Big Data and Security, Atos, July 12, 2021.
96. CIGREF, "Informatique quantique", *op. cit.*, p. 35.
97. *Ibid.*, p. 36
98. E. Gibney, "Quantum Gold Rush: The Private Funding Pouring into Quantum Start-Ups", News Feature, *Nature*, October 2, 2019, available at: www.nature.com.
99. *Ibid.*
100. It is worth noting that the problems solved in recent Google experiments to prove quantum supremacy have no practical application.
101. S. Rolland, "Course à l'ordinateur quantique: 'Alice & Bob aura besoin de nouveaux financements face à la concurrence d'Amazon'", *La Tribune*, May 8, 2021.
102. CIGREF, "Informatique quantique", op. cit., p.36. Although this depends on the type of quantum bit technology, as error rates vary.

be able to do bulk information management and data processing, while the quantum part of the machine could solve a specific problem.[103] The realization of hybrid machines that integrate quantum and classical computers still pose many engineering challenges from both a software and a hardware point of view.[104]

When it comes to software, companies are today designing software that runs on classical supercomputers that mimic perfect quantum computers, as well as quantum computer emulators. However, practical considerations severely limit the circuit sizes which can be emulated.[105] Due to the laws of quantum physics, a classical computer can only simulate a quantum computer of up to around 40 qubits.[106] Nonetheless, simulators and emulators are useful to help researchers experiment with quantum systems and to develop algorithms that can make use of the peculiarities of quantum computers as well as their future applications.[107]

Applications and Implications of Quantum Computing

Conscious of the step-change that will come when quantum machines are ready, both industries and governments are examining the practical use cases of the intermediate devices that will likely be available within a decade.[108]

To begin with, quantum machines will speed up the development of AI as they will allow acceleration of deep learning and neural networks, with both civilian and military applications. In the military domain, for instance, quantum AI could facilitate the development of autonomous weapon systems, and accurate intelligence, especially when coupled with other quantum technologies.

Besides AI, quantum computers will be especially suited for tasks of factorization, optimization, and simulation. Factorization is especially relevant for cryptography and makes the cybersecurity implications of future large-scale quantum computers a major concern for states.[109] In 2015, the US National Security Agency (NSA) updated

103. Interview with Julian van Velzen, Lead Quantum Technologist, Capgemini, July 20, 2021.
104. *Ibid.*, and interview with Philippe Duluc, CTO Big Data and Security, Atos, July 12, 2021.
105. A. Middleton *et al.*, "Quantum Information Processing Landscape 2020", *op. cit.*, pp. 10-11.
106. Interview with Philippe Duluc, CTO Big Data and Security, Atos, July 12, 2021.
107. E. Gibney, "Quantum gold rush", *op. cit.*
108. See HPCwire, "12 European Companies and Research Labs Join Forces to Boost Industrial Quantum Computing Applications", October 5, 2020, available at: www.hpcwire.com.
109. Interview with Olivier Ezratty, independent consultant, April 6, 2021.

its encryption system to make it "quantum resistant".[110] While significant advances in quantum computing are still required to break current encryption methods, a fully functioning quantum computer could allow a country or a non-state actor to break any public encryption key that is secured with current technology.[111] That includes the RSA, the cryptosystem currently used to secure online payments. According to some estimates, it would take a classical computer 300 trillion years to crack an RSA encryption key (of 2,048 bits), while a quantum computer with 4,000 stable qubits could in theory do the same in just ten seconds.[112] Conversely, quantum technology can also be used to secure communications.[113]

Complex simulation will arguably form a key part of the uses of quantum computers. The simulation of molecules requires a lot of computing power, as the bonds and interactions among atoms behave probabilistically, with exhausts classical computing logic.[114] According to a quantum scientist, quantum computing is thus about "simulating nature, using the laws of nature".[115] Simulation at the molecular scale could have applications in medicine (e.g., for creating targeted medicines), in energy (e.g., more efficient batteries), in sustainable agriculture (e.g., fertilizers), or even for developing processes to capture CO_2 present in the atmosphere.

Finally, quantum computers would be very useful for optimization tasks required for autonomous vehicles. With a fully autonomous fleet, it should theoretically be possible to optimize the individual journey of each vehicle according to its place of departure and destination. Conventional algorithms could work with a limited quantity of vehicles, but beyond a few hundred vehicles and journeys, traditional

110. E. B. Kania and J. K. Costello, "Quantum Hegemony?", *op. cit.*
111. J. Kung and M. Fancy, "A Quantum Revolution", op. cit., p. 10.
112. A. Herman, "Q-Day Is Coming Sooner Than We Think", *Forbes*, June 7, 2021.
113. Defense services and some corporations are now developing post-quantum cryptography, based on new sets of classical algorithms. However, whether such encryption is effectively quantum-resistant cannot be proven at this point, in the absence of cryptographically relevant quantum computers. Another way to secure communications in the quantum era is to use quantum technologies to secure information. For instance, Quantum key distribution (QKD) uses quantum entanglement to secure communications transiting via fiber-optic cables and satellites: eavesdropping on a quantum communication would, theoretically, be immediately detected. QKD however is very expensive and not ready for commercial use, as it requires entirely new types of infrastructure, and signals remain easily distorted. See M. Lee, "Quantum Computing and Cybersecurity", Belfer Center of International Affairs, Report, July 2021, pp. 8-9.
114. E. Lucero, "Unveiling Our New Quantum AI Campus", Google, May 8, 2021, available at: https://blog.google.
115. The Quantum Daily, "Quantum Technology: Our Sustainable Future", Documentary movie, July 2021, available at: www.youtube.com.

calculation capacities would be largely saturated.[116] Optimization is also key for actors in the energy sector in the development of electrical networks and the management of electricity consumption in the context of a multiplication of electric vehicles.

Considering the enormous scientific and technological uncertainties that remain, the full business implications of quantum technologies will unfold and sediment over time.[117] According to a report by Boston Consulting Group, we should expect quantum computing to develop toward maturity over three generations spanning the next 25 years.[118] It is likely that ad hoc civilian uses of quantum machines will develop over the next 10 to 15 years, and that a quantum computer capable of breaking current encryption methods will see the light by 2040.[119]

In any case, quantum computers will not replace conventional computers. They will likely be complex and fragile machines with much narrower functions than universal classical computers, and they will thus be rare: at least at first, only a few machines will exist and be accessible on the cloud.[120] Given the complexity of the field of quantum technologies, delegating them to providers on a cloud would avoid companies being forced to develop extremely advanced skills that are difficult to acquire.[121] Thus, quantum computers will not become a replacement but a complement to current HPC tools.

Despite these limitations, quantum computing will have significant business and financial implications. The Boston Consulting Group sees a potential addressable quantum computing market of £4 billion (€4.7 billion) by 2024.[122] In a slightly less optimistic scenario, the Quantum Economic Development Consortium and Hyperion Research foresee a 27% yearly growth from 2020 onward, with a global market worth $830 million (€701 million) by 2024.[123]

116. O. Ezratty, "Comprendre l'informatique quantique", September 2020, p. 16, available at: www.oezratty.net.
117. *Ibid.*, p. 10.
118. M. Russo *et al.*, "The Coming Quantum Leap in Computing", Boston Consulting Group, May 16, 2008, available at: www.bcg.com.
119. Interview with Olivier Ezratty, consultant, April 6, 2021; CIGREF, "Informatique quantique", *op. cit.*, p. 6; Sayler, "Defense Primer", *op. cit.*
120. Interview with Julian van Velzen, Lead Quantum Technologist, Capgemini, July 20, 2021.
121. CIGREF, "Informatique quantique", *op. cit.*, p. 6.
122. S. Venkataramakrishnan, "Rigetti to Build UK's First Commercial Quantum Computer", *Financial Times*, September 2, 2020.
123. Quantum Economic Development Consortium, "Global QC Market Projected to Grow to Over $800 Million by 2024", no date, available at: https://quantumconsortium.org.

Europe in the Quantum Race

The decade of the 2010s has seen a clear acceleration of global competition around quantum information processing technologies. Illustratively, while in 2014, the British Ministry of Defense judged the field of quantum information processing as "too immature" for near-term defense and security application, the UK Defense Science and Technology Laboratory (DSTL) reported in June 2020 that "the progress achieved both nationally and globally has exceeded early expectations", so that today "many regard the rush to develop quantum computing as a new 'space race'".[124]

Quantum computing has become a race not least because there are risks of lagging behind. A first risk is cybersecurity, as explained above, as quantum computers will be able to break current encryption protocols. Another risk is access to technologies.[125] Quantum cryptography and quantum computers indeed are making their way onto defense and strategic goods lists, and are thus becoming subject to export restrictions.[126] The enabling technologies that are needed to make quantum computers work can also be placed under control: certain qubits require extremely cold temperatures that are obtained thanks to cryostats, a technology whose export to China the US is considering blocking.[127]

US-China Competition and Quantum Technologies

Currently, the most advanced countries in the field for quantum computing, in terms of technological advancement and government strategy and funding, are the United States and China – who have both already claimed quantum supremacy – as well as Europe (notably the UK, Germany, France and the Netherlands).[128]

124. A. Middleton *et al.*, "Quantum Information Processing Landscape 2020", *op. cit.*, p. i.
125. Decode Quantum, "A la rencontre de Neil Abroug, coordinateur de la stratégie quantique nationale française", podcast episode, May 2021, available at: www.spreaker.com.
126. G. Brennen *et al.*, "An Australian Strategy for the Quantum Revolution", *op. cit.*, p. 14. Quantum cryptography is already on the US and the EU's lists of controlled items. In 2018, the Trump administration added quantum computing and sensing to the list of technologies that should be subject to control.
127. Gouvernement, *Faire de la France une économie de rupture technologique*, 2020, p. 51; A. Alper, "U.S. Finalizing Rules to Limit Sensitive Tech Exports to China, Others", Reuters, December 17, 2019, available at: www.reuters.com.
128. New national strategies and investment plans are quickly multiplying around the world. Canada also has an important quantum computing ecosystem. It is a leader in a technology called quantum annealing. See J. Kung and M. Fancy, "A Quantum Revolution: Report on Global Policies for Quantum Technology", CIFAR, April 2021.

The US

Washington's concerns of being overtaken by China have grown since Beijing demonstrated its capacity in satellite-based quantum communications in 2017.[129] In 2018, President Donald Trump launched the National Quantum Initiative, with $1.2 billion (€1 billion) in public funding for an initial period of 5 years, until 2023.[130] Trump set up a National Quantum Coordination office within the White House, and in August 2020, the US launched its national quantum research centers, and an additional $237 million (€200 million) was voted as part of the 2021 budget.[131] The United States Innovation and Competition Act (USICA), voted by the Senate in early June of 2021 and which will soon be examined by the House of Representatives, proposes to allocate $150 billion (€128 billion) between 2022 and 2026 for research, innovation and education in critical and emerging technologies, including quantum technologies.

Aside from the government, big technology firms are pouring huge amounts of money into their own research in quantum science — although their internal investment figures are not disclosed.[132] The financial power of private investors and the attractiveness of large digital companies like IBM, Google, and Intel have given those companies a head start in quantum research. It was IBM that proposed the first principles of a quantum computer and introduced the first two-qubit computer. By 2016, the company had managed to simulate a molecular structure and reached the theoretical threshold of quantum supremacy with 50 qubits.[133] The following year, Intel unveiled a 49-qubit calculator, and Google a 72-qubit processor. In September 2019, Google claimed to have achieved quantum supremacy with a 53-qubit quantum computer using superconductors. It succeeded in completing in just over three minutes a calculation that Google said would take 10,000 years to solve by a conventional supercomputer.[134] IBM downplayed this achievement as they affirmed the calculation would take only 2.5 days on the most powerful of supercomputer.

129. G. Brennen *et al.*, "An Australian Strategy for the Quantum Revolution", Australian Strategic Policy Institute, Report No. 43/2021, p. 14.
130. MIT Technology Review, "President Trump Has Signed a $1.2 Billion Law to Boost US Quantum Tech", December 22, 2018, available at: www.technologyreview.com.
131. C. Goujard, "Germany Unveils Powerful Quantum Computer to Keep Europe in Global Tech Race", *Politico*, June 15, 2021.
132. Including IBM, Google, Alibaba, Hewlett Packard, Tencent, Baidu and Huawei. See E. Gibney, "Quantum gold rush", *op. cit.*
133. CIGREF, "Informatique quantique", *op. cit.*, p. 10.
134. J. Kung and M. Fancy, "A Quantum Revolution", *op. cit.*, p. 8.

Since 2016, IBM has offered an online quantum programming interface, IBM Quantum Experience. This platform offers a quantum programming simulator that gives access to 22 IBM computers. To date more than 325,000 users have registered with it and more than 700 articles have been published based on work carried out on this machine.[135] Aside from IBM, other American companies like Microsoft, Amazon and Rigetti, as well as the Canadian Xanadu, offer online services of small-scale quantum computing chipsets with capacities of up to 65 qubits.[136] When it comes to on-premises machines, US companies, starting with IBM, have already built and exported quantum computer prototypes. IBM's strategy is to make its technology available online, so as to encourage early adoption of its product.[137] It has exported the first ever commercial quantum computer (albeit still experimental), the 20-qubit Quantum System One, to Germany and Japan, to drive quantum R&D there. And it is currently working towards making a stable quantum computer capable of handling more than 1,000 qubits by 2023.[138]

China

Meanwhile in China, efforts have been ongoing since 2015, after the 2013 Snowden revelations prompted anxiety over the extent of US intelligence capabilities and activities and intensified the government's focus on quantum communications and computing.[139] Beijing has thus sought to leverage quantum networks to secure China's most sensitive communications.[140] Simultaneously with Obama's plan entering the field, Beijing listed quantum as a part of the major science and technology priorities to be developed by 2030. There is limited information about total funding on quantum technologies in China. Officially, China spent over $302 million on quantum sciences between 2013 and 2015.[141] In 2017, Beijing announced a $10 billion investment into a new quantum computing research center. While estimates of China's actual spending on quantum research vary, the country is leading in terms of patent holding in quantum communication and cryptography hardware as well as software.[142]

135. IBM, "Five Years Ago Today, We Put the First Quantum Computer on the Cloud", *op. cit.*
136. G. Brennen *et al.*, "An Australian Strategy for the Quantum Revolution", p. 16.
137. Interview with Olivier Ezratty, consultant, April 6, 2021.
138. Deutsche Welle, "IBM Unveils First Quantum Computer in Germany", June 15, 2021, available at: www.dw.com.
139. E. B. Kania and J. K. Costello, "Quantum Hegemony?", *op. cit.*
140. *Ibid*. p. 13.
141. *Ibid*.
142. D. Garisto, "China Is Pulling Ahead in Global Quantum Race, New Studies Suggest", *Scientific American*, July 15, 2021, available at: www.scientificamerican.com.

Robust research has led to rapid progress and even leadership in other quantum technologies (cryptography and communications), as was illustrated when China launched the world's first quantum communication satellite in 2016.[143] When it comes to quantum computers, China's efforts have been more recent, but Beijing has been quick to catch up. In December 2020, a group of researchers from the University of Science and Technology of China (USTC) made a credible claim to have achieved quantum supremacy, using a photonic system to complete a calculation in 200 seconds that would have taken a supercomputer 2.5 billion years.[144] That is to say that the calculation was performed 100 trillion times faster than with a classical supercomputer. In June 2021, China again demonstrated quantum advantage, this time with a system based on superconducting circuits.

Europe's Growing Quantum Ecosystem

Around the world, several countries have either developed or are in the process of designing strategies and investment plans to shape their ecosystems. The UK, Germany and France have significant quantum research capacities and public, and flourishing start-up ecosystems. The Netherlands, Austria and Switzerland also have significant research and innovations capacities in quantum computing, although they are not analyzed specifically in this study.[145]

The UK

There are serious players in quantum technologies in Europe, among which the UK. The head of the Government Communications Headquarters (GCHQ) suggested in April 2021 that the UK must develop "sovereign capabilities" in quantum computing, not least to respond to cyber threat posed by China.[146] The country is not starting from scratch, far from it. It launched its National Quantum Technologies program as early as 2013. The government planned to invest £400 million (€467 million) in the first phase (2014-2019) and £350 (€400 million) in the second.[147] In the past year, the UK government has renewed its commitment to quantum and other information technologies in a series of policy documents and

143. E. B. Kania and J. K. Costello, "Quantum Hegemony?", *op. cit.*
144. J. Kung and M. Fancy, "A Quantum Revolution", *op. cit.*, p. 8.
145. In April 2021, the Dutch National Growth Fund awarded €615 million to Quantum Delta NL, the public-private foundation that executes the National Agenda for Quantum technologies. It hopes to train 2.000 researchers and engineers and scale 100 start-ups. The report by J. Kung and M. Fancy ("A Quantum Revolution", *op. cit.*), provides a good overview of national quantum strategies around the world.
146. "UK Spymaster Issues Warning Over China's Cyber Threat", *Financial Times*, April 22, 2021.
147. J. Kung and M. Fancy, "A Quantum Revolution", *op. cit.*, p. 17.

decisions.[148] The March 2021 *Integrated Review* – the main document guiding the UK's foreign, security and defense policy in the post-Brexit context – placed a strong emphasis on technological power and suggested UK should be a leader cyber technologies including quantum technologies and new forms of data transmission.[149]

Like in the US, new research centers and policy strategy positions are being set up. In June 2021, the Boris Johnson announced he would create a National Science and Technology Council, chaired by the Prime Minister, as well as a new Office for Science and Technology Strategy, based in the Cabinet Office, and a new role of National Technology Adviser.[150] A new National Quantum Computing Centre is being set up and will open in 2023. In September 2020, the UK government passed a £10 million (€11.7 million) agreement with US-based company Rigetti to build the UK's first commercially available quantum computer.[151] The UK also has homegrown companies. Meanwhile, in July 2021, Oxford Quantum Circuits (OQC), a UK-based start-up, announced that the company has launched the nation's first commercial "quantum computing-as-a-service" built entirely using its proprietary technology.[152] OQC did not disclose how many qubits its machine contains, but in 2017 the company was working on a 9-qubit system.[153]

Germany

The German government is also investing in quantum technologies. An investment of €2 billion over 5 years was announced in June 2020 as part of a major stimulus injection,[154] which builds on an initial government effort of €650 million for the period 2018-2022. One must add to this the contribution of Länders, including for example Bavaria's recent €300 million investment in a "Quantum Valley".

In June 2021, German Chancellor Angela Merkel reflected on the fact that quantum computing can play a key role in our endeavor to "acquire technological and digital sovereignty", as Germany and

148. B. Johnson, "We're Restoring Britain's Place as a Scientific Superpower", *Daily Telegraph*, June 21, 2021.

149. HMG, *Global Britain in a Competitive Age: the Integrated Review of Security, Defence, Development and Foreign Policy*, 2021.

150. Prime Minister's Office, "Prime Minister Sets Out Plans to Realise and Maximise the Opportunities of Scientific and Technological Breakthroughs", Press release, June 21, 2021, available at: www.gov.uk.

151. Department for Business, Energy & Industrial Strategy, "Government Backs UK's First Quantum Computer", Press release, September 2, 2020, available at: www.gov.uk.

152. M. Swayne, "OQC Delivers the UK's First Quantum Computing as-a-Service", *op. cit.*

153. R. Scammel, "'Only Working Quantum Computer in UK' Now Accessible in the Cloud", Verdict, July 7, 2021, available at: www.verdict.co.uk.

154. M. Swayne, "Qubit Alles: Germany Invest 2 Billion Euros in Quantum Technology, Build Two Quantum Computers'", *Quantum Daily*, June 15, 2020, available at: https://thequantumdaily.com.

Europe find themselves in the context of a "very intense competition".[155] Merkel hopes to promote the development and production of quantum technologies in Germany to form a new industrial pillar, both in terms of hardware and software. Before that is the case, however, the first step taken was to commission the construction of at two quantum computers in Germany. The first machine was unveiled at the Fraunhofer institute for applied research, near Stuttgart, in June 2021. It is an IBM, the Quantum System One computer, the first of its type in Europe which was installed near Stuttgart, in June 2021. This will allow German researchers to work more intensively on future quantum applications. The choice of an IBM machine (and the cloud that comes with it) was justified by the fact that there are, currently, few leading European quantum companies.[156] In the first step of its quantum computing strategy, Germany has been more focused on developing uses of quantum technologies than on supporting national quantum hardware companies.

France

In February 2021, Emmanuel Macron unveiled a National Plan for Quantum technologies that aims to make France the 3rd largest spender in the world on quantum technologies, behind the US and Germany. The French plan has been in preparation since 2018, after Thierry Breton, then CEO of Atos, called on the French government to elaborate a quantum strategy. At the time, he was one of the few French industrialists to be vocal on the issue.[157] The Ministry of the Economy took on the issue and requested a parliamentary report, which was followed by a government roadmap on quantum technologies elaborated in spring 2020. The French plan for quantum technologies should have been announced in 2020 but was postponed due to the Covid-19 pandemic, and the announcement was made in February 2021. The plan is for a total of €1.8 billion public-private investment (including €1 billion public funding) between 2021 and 2025, going toward education and training, research, support for start-ups, and support for industrial deployment and innovation.

With the strategy, France's goal is to master decisive quantum technologies, including quantum accelerators, simulators and computers, business software for quantum computing, sensors, and communication systems.[158] The bulk of the funding will go to quantum computing, with NISQ and LSQ totaling €784 million.

155. C. Goujard, "Germany Unveils Powerful Quantum Computer", *op. cit.*
156. *Ibid.*
157. Interview with Neil Abroug, Head of National Quantum Strategy, Secrétariat Général pour l'Investissement, June 30, 2021.
158. Gouvernement, *Stratégie nationale sur les technologies quantiques*, 2021, p. 10.

The choice of which qubit technology to favor is based on an analysis of the chances of success of a given technological avenue, the presence of a critical mass of researchers in France, and the presence of an industrial base able to build the technologies.[159] Trapped ion technologies (developed by Honeywell, IonQ and AQT (Austria), for example) are considered very promising but difficult to develop in France due to a lack of a critical mass of researchers.[160] In the context of limited funding, the objective is to gradually diminish risks, but for the time being, France is treating all technological avenues equally.[161]

The 2021 Quantum Plan draws lessons from the past failures at government planning, that is to say large, national investments in certain strategic sectors and infrastructure.[162] According to Mathieu Landon, in charge of industry in the French Prime Minister's office, one lesson learned is that such state strategies must be based on ecosystems, where there are already research and industry, rather than building an ecosystem from scratch.[163] The French quantum ecosystem is already rich. It builds on research institutions (the CNRS, especially Paris-Saclay University, the CEA, and INRIA) as well as large companies involved in quantum computers (Atos) and telecommunications (Orange and Thales), and quantum-relevant enabling technologies, such as cryogenics (Air Liquide).[164]

Atos has become involved in quantum simulation and testing algorithms for future quantum computers. In 2017, it started commercializing the Atos Quantum Learning Machine, a quantum computer simulator, capable of processing up to 30 qubits in memory. Atos delivered simulators to the Oak Ridge National Laboratory, which is part of the United States Department of Energy (DOE), to the Argonne National Laboratory in the United States, to the CEA, and to the Hartree Center, a British research laboratory.

Aside from large companies, over recent years, France has seen its quantum start-ups flourish. Of the world's 260 quantum technology start-ups and SMEs, almost 10% are thought to be in France.[165] Pasqal is a hardware quantum company, created in 2019 which is developing a quantum computer based on atoms manipulated by lasers, intended for high-performance computing centers. It is backed by the Optics Institute of the University of Paris-Saclay. The company has so far built

159. Interview with Neil Abroug, Head of National Quantum Strategy, Secrétariat général pour l'investissement, June 30, 2021.
160. *Ibid*.
161. Neil Abroug in the podcast Decode Quantum, "A la rencontre de Neil Abroug".
162. Interview with Matthieu Landon, Technical Adviser Industry, Research and Innovation, Cabinet du Premier Ministre, April 14, 2021.
163. *Ibid*.
164. Cryoconcept, a small company founded in 2000 as a spin-off from the CEA, specializes in extreme cryogenics. It was acquired by Air Liquide in the fall of 2020.
165. O. Ezratty, "Comprendre l'informatique quantique", *op. cit.*, p. 7.

a quantum machine that works on its premises, and it has also received an order for two other machines to be delivered early 2023 to the GENCI in France, and to the German research center in Jülich.[166] The start-up has already also entered partnerships with Atos and Crédit Agricole.[167] Pasqal has also decided to make their computer available on a cloud.[168]

Alice & Bob is another promising start-up. It was created in February 2020 as a spin-off of an ENS-INRIA team. It raised €3 million a few months later from French funds Elaia Partners and Breega.[169] The "cat qubit" is a ground-breaking discovery on self-correcting qubits that led to the creation of the start-up. The start-up is aiming to create an error-free, or "ideal" quantum computer, "which is one of the fundamental scientific problems that has limited development of more powerful quantum computing".[170] It plans to deploy the world's first ideal quantum processor in the cloud by 2026.[171] Amazon is seeking develop a quantum computer on the basis of this very technology, following scientific publications on self-correcting qubits.[172] While this is testament to the relevance and excellence of their discovery, it places them in competition with a tech giant that has incomparable financial room for maneuver and scientific teams that are ten to twenty times larger than the French start-up's.

Pending Issues for Europe

Collaborative Projects: When Science Becomes Strategic Technology

International collaboration is central to scientific research, and vital in Europe to reach the scale necessary to compete globally in quantum technologies. Since 2018, the EU too has made quantum technologies a priority and has committed €1bn to co-finance collaborative research programs over 10 years. The Quantum Flagship is one of the largest and most ambitious research initiatives of the EU. In fact, it is currently

166. "Notre armée mise sur la pépite de la quantique Pasqal, Parly salue des applications pour la défense 'hautement stratégiques'", *Capital*, June 8, 2021, available at: www.capital.fr.

167. I. Vergara, "Informatique quantique: les nouvelles ambitions du fonds Quantonation", *Le Figaro*, March 3, 2021

168. K. Poireault, "EDF, Total, Airbus… Les grands industriels se lancent dans la programmation quantique", *L'Usine Nouvelle*, June 17, 2021, available at: www.usinenouvelle.com.

169. S. Rolland, "Course à l'ordinateur quantique".

170. M. Swayne, "Quantum Startup 'Alice&Bob' Raises $3.3 Million for Plans to Build Error-free Quantum Computer", *The Quantum Daily*, May 27, 2020, available at: https://thequantumdaily.com.

171. "Alice & Bob – Building an Ideal Quantum Computer", video, July 12, 2021, available at: www.youtube.com.

172. P. Arrangoz-Arriola and E. Campbell, "Designing a Fault-Tolerant Quantum Computer Based on Schrödinger-Cat Qubits", AWS Quantum Computing Blog, April 12, 2021, available at: https://aws.amazon.com.

the largest international funding framework for quantum technology.[173] It brings together research institutions, academia, industry, enterprises, and policy makers, in a joint and collaborative initiative on an unprecedented scale. Among the funded programs are a quantum computer (accelerator) based on trapped ions ("AQTION", based at the University of Innsbruck) and a quantum simulation platform ("PASQuanS"), carried out at the Max Planck Institute in Munich. Atos leads both projects, on the industry side. The EU is also funding projects in other quantum technologies, especially quantum communications.[174] Bilateral collaborations within Europe are also developing – partly motivated by the goal of securing EU funding – as illustrated most recently by the signing of a Memorandum of Understanding between France and the Netherlands, for academic cooperation but also to build synergies between French and Dutch companies and create quantum unicorns.[175]

The transition of quantum sciences from the realm of academia to concrete applications with security and industrial applications has been creating new dilemmas for the EU's collaborative projects and cooperation with non-EU members. The UK, as explained above, but also Switzerland, and Israel have significant quantum research ecosystems and are willing to join the EU's Horizon Europe programs in quantum and space. The EU Commission, and in particular Thierry Breton, has opposed the participation of several non-EU countries, (including the UK, Switzerland and Israel) in EU research programs on quantum computing, saying the goal is to "make independent European capacities in developing and producing quantum computing technologies of strategic importance", with applications in security and dual-use technologies.[176] However, a group of EU countries led by Germany, pushed to maintain the openness to Associated Countries in quantum and space research programs, arguing that the bid for technological sovereignty should not get in the way of scientific collaboration.

The Global Race Is Also One for Capital

While it has yet to reach the volume and quantity of other industries like artificial intelligence, the ecosystem of quantum technology companies, especially start-ups, continues to grow around the world.

173. J. Kung and M. Fancy, "A Quantum Revolution", *op. cit.*, p. 13.
174. European Commission, "The European Quantum Communication Infrastructure (EuroQCI) Initiative", last updated July 23, 2021, available at: https://digital-strategy.ec.europa.eu.
175. Secrétariat d'État chargé de la Transition numérique et des Communications électroniques, "Quantum Strategy: Memorandum of Understanding between France and the Netherlands on Quantum Technologies", Press Release, August 31, 2021.
176. E. Kelly, "Viewpoint: EU Will Be 'Shooting Itself in Foot' If It Bars UK, Switzerland, Israel from Quantum and Space Projects", Science Business, March 18, 2021, available at: https://sciencebusiness.net. At the time of writing, the status of the UK is still undetermined.

Some estimate that there are over 260 quantum technology startups and SMEs globally.[177] Many start-ups are still at the stage of applied research and sometimes still fundamental research, and quantum computing remains an uncertain technological sector.[178]

Investment is at the heart of the matter. As suggested above, funding is key for allowing researchers to conduct their experiments, but also for scaling up and commercializing quantum systems. Besides, if, as mentioned above, future import restrictions on quantum technologies are feared, foreign takeovers of successful companies are too. Private sector investment is needed, if France and Europe are to retain their talents and prevent individual researchers and promising start-ups from going overseas. Globally, the private sector's involvement in the funding of quantum start-ups has boomed: quantum-computing companies landed $779.3 million (€662 million) in 77 deals in 2020, a surge from $288.3 million (€194 million) in 69 deals in 2019.[179] Several quantum technology start-ups are now valued at several hundred million euros and at least two are now publicly traded.[180]

The current investment boom in quantum start-ups is so far playing into the hands of US venture capital funds and large digital companies. The Canadian firm Xanadu, too, raised $100 million (€85 million) largely from US investors, including the CIA's investment branch, In-Q-Tel.[181] In the UK, the leading British start-up PsiQuantum was established in 2016, but has since settled in California. It is promising to build a one-million qubit large-scale, general purpose quantum computer by 2025. The move to the Silicon Valley was partly motivated by a need to raise capital.[182] PsiQuantum has, so far, successfully raised a total of $665 million (€565 million) including, in late July 2021, $450 million (€382 million) from mostly US investors such as BlackRock and Microsoft's venture fund, M12.[183] The story recalls that of DeepMind, the British AI company that Google acquired for £400 million (€628 million) in 2014.[184] The UK government has taken action on the issue, when in July 2021, it set up a new fund for R&D intensive firms, including quantum companies.

177. O. Ezratty, "Comprendre l'informatique quantique", *op. cit.*, p. 7.
178. *Ibid.*
179. S. Castellanos, "Xanadu Lands $100 Million as Investments Pour into Quantum Computing", *Wall Street Journal*, May 25, 2021.
180. G. Brennen *et al.*, "An Australian Strategy for the Quantum Revolution", *op. cit.* p. 10.
181. Interview with Philippe Duluc, CTO Big Data and Security, Atos, July 12, 2021.
182. *Financial Times*, "PsiQuantum Expects Commercial Quantum Computer by 2025", March 13, 2021.
183. Crunchbase, "PsiQuantum", no date, available at: www.crunchbase.com.
184. House of Commons, "Draft Enterprise Act 2002 (Share of Supply) (Amendment) Order 2020", Parliamentary debate, July 13, 2020, available at: https://hansard.parliament.uk.

To be eligible, businesses must have secured funding commitments from private investors venture capitalists.[185]

All countries which get into the quantum race but have limited private investment indeed face the same risks as UK companies. This is especially true for Europe, where venture capital is scarce.[186] Quantonation is a Paris-based investment fund — the first in the world that is specialized in quantum technologies.[187] It was set up in late 2018, and funded Pasqal in 2019. Quantonation supports quantum companies in their early stages, but for later stages, other investment funds must take over and invest hundreds of millions to help seeded companies grow. This is where there is a risk for European companies that seek to commercialize products, and there is a real challenge for ensuring not only that companies are not taken over by foreign capital, but also that they can grow in Europe.

185. M. Swayne, "Quantum Projects Could Get Boost from UK's £375 Million Plan to Drive Investment in Innovation", *The Quantum Daily*, July 21, 2021, available at: https://thequantumdaily.com.
186. On this point see also K. Sahin and T. Barker, "Europe's Capacity to Act in the Global Tech Race Charting a Path for Europe in Times of Major Technological Disruption", DGAP, Report, No. 6, April 2021.
187. Interview with Christophe Jurczak, Managing Partner, Quantonation, July 13, 2021.

Conclusion

The democratization of high-performance computing and new levels of conventional computing power, together with the emergence of disruptive quantum information technologies are changing the calculations of governments, researchers, and private companies alike. Private companies are finding new ways to use the potential of data analysis, governments are developing strategies to gain relative technological power and ensure the security of their digital systems, while scientists can hope to make new discoveries in medicine and in the fight against climate change. Technological progress is also promising to significantly reduce the energy consumption of computers, which has become a bigger concern as uses continue to grow.

The global distribution of computing power is changing. While the US has for long dominated the sector of conventional computing, not least with the defining role played by IBM, China's Lenovo has now become the first HPC company worldwide in terms of market share. Today, the US and China are also neck and neck in the race for quantum computing, with massive investments and impressive technological achievements. These raise the risk of developing hardware-dependent tools and technology dependencies.

But the ongoing quantum revolution is nurturing a wealth of actors, from research laboratories to start-ups and investment funds, which could further redistribute computing power across the globe. Technologies with a lower level of readiness offer Europe in particular a chance to position itself early in this emerging sector and develop capacities along the value chains of quantum computing in hardware and software. European governments, including France and Germany, as well as EU institutions, have made significant efforts in this direction. Together with private investors, they will need to remain committed throughout the life cycle of this emerging and highly disruptive technology.

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