EuroQCS

European Quantum Computing & Simulation Infrastructure

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Executive Summary

Future prosperity of countries and regions all over the world will crucially depend on mastering new technologies whose disruptive potential will impact the society and the economy as a whole. Indeed, in our digital society, data is increasingly becoming a strategic asset of the economy; and only countries that control the relevant technologies will be able to widely collect, analyze, exploit and deploy those data in industrial activities while, at the same time, protecting them from unwarranted access.

Within this context, it is now widely recognized that Quantum Technologies (QT) will play a special role, making possible what is difficult or even impossible today, e.g., the development of entirely new drugs, the optimization of traffic flows or financial strategies and portfolios, the discovery of new materials, the use of unbreakable communication protocols, and many more.

To keep Europe at the forefront of conceiving, developing and commercializing QT, the European Commission has established in 2018 a large-scale research and innovation initiative known as the Quantum Flagship, with the declared long-term vision of creating a quantum internet, a network interconnecting quantum computers, simulators and sensors and distributing information to secure our digital infrastructure.

In 2018, Europe also established the European High Performance Computing Joint Undertaking (EuroHPC JU), a joint initiative between the EU, European countries, and private partners to develop a world class supercomputing ecosystem in Europe. The EuroHPC JU enables European countries to coordinate their supercomputing strategies and investments together with the EU with the objective to further develop, deploy, extend, and maintain a world-class supercomputing and data infrastructure in the EU, ranging from petascale to exascale and based on competitive European technology.

This HPC supercomputing infrastructure shall integrate quantum computers and simulators (QCS) into a European Quantum Computing & Simulation[1] infrastructure (EuroQCS) in addition to cloud access to stand-alone QCS. This strategy will make it possible to substantially enhance the computing capacity of the EuroHPC JU's supercomputers.

Indeed, as decades of experience in conventional supercomputing demonstrate, the successful integration of new or even disruptive technologies into HPC systems, such as the quantum technologies developed under the Quantum Flagship, especially QCS, requires a focus on all three fundamental components of the HPC ecosystem: users and their applications, software, and hardware.

QCS are in fact complex devices capable of harnessing quantum mechanical effects and phenomena to carry out difficult computational tasks. As such, they are very different from conventional "accelerator"-type of devices that speed up existing classical algorithms and software. This fundamental difference implies that to tap into their full potential a broad user base will need to invest time and effort in developing new kinds of algorithms and software that take full advantage of quantum mechanical effects and that can be used to address and solve important real-world

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[1] In this instance, quantum simulators refer to special purpose devices designed to study specific quantum systems and not to software programs that run on conventional computers to simulate or emulate quantum systems. Although the most recent quantum simulators are already programmable, they may be contrasted with even more generally programmable digital quantum computers, which can solve a larger variety of problems. Other specialized quantum computers are quantum annealers, which are analog devices. In this White Paper no distinction between quantum simulators and quantum annealers is made.

problems. On top of this user/software interaction, there is also the software/hardware interaction. As software is hardware-dependent and quantum hardware is currently implemented on a variety of physical platforms (including, but not limited to, cold atoms/ions, super-/semiconductors, photons) this software/hardware interaction will require the development of a QCS full software stack. Using an interface layer in this latter stack, the user connects a wide range of software to any one of several QCS architectures within a single HPC environment.

Additionally, co-designing application codes with "hybrid" computing architectures in mind, while using large scale (up to exascale) HPC architectures, will make it possible to address research challenges that cannot be met with current HPC architectures: initially in the fields of quantum chemistry, condensed matter physics, high-energy physics, plasma physics, and material science, to be extended at a later stage to specific industrial problems. Availability of real-world use cases are then expected to trigger private investment in hybrid HPC/QCS solutions, thus supporting the Quantum Flagship objective of bootstrapping a vibrant European QT market. Moreover, in case of yet limited scalability of pure quantum computing devices, hybrid HPC/QCS solutions are expected to improve still significantly solving difficult computational problems.

The purpose of this White Paper is twofold. First, it expresses the views of European members of the QT and HPC communities on how to federate QCS and HPC resources, thus heralding a new generation of hybrid quantum-classical machines in which the quantum device plays the role of an accelerator with the goal to enhance conventional supercomputers. Second, it indicates how this federation can be realized within the framework of the EuroHPC JU and its two main activities pillars, (1) the procurement and operation of HPC and data infrastructures and (2) the HPC research and innovation program.

In this respect, the following recommendations should be considered

1. **Applications by lead users and developers** will be crucial and should be given the highest priority. It is sometimes assumed that when the infrastructure and system software will be available, then the applications will flourish in a natural way for the benefit of science and industry. This has proven to be wrong even in the case of classical accelerators and cannot be expected to happen in the case of quantum information processing where entirely new concepts and algorithms must be envisaged. To ensure that the high expectations on QT are met, and that as many domains as possible are impacted, intense research must be supported on workflows and applications taking advantage of HPC/QCS components. This includes libraries, both hardware dependent and independent, as well as benchmarking related to applications. Significant funding should be devoted to projects identifying potential applications and developing the corresponding algorithms in close cooperation between HPC/QCS hardware/software researchers, HPC centers and Centers of Excellence (CoE), and domain experts from industry and academia.
2. The development of appropriate **quantum software, compilers, runtime systems and quantum programming languages** will be critical for any impact in the HPC context and should be included in the EuroHPC JU programs. A European quantum programming platform and the standardization of the already developed and future European software solutions are of particular interest.
3. A key objective concerning **access to quantum hardware**, is a deeper QCS-HPC integration. The demonstrated European technology of modular frameworks should be encouraged. Co-location in a few selected HPC sites, not limited to exascale centres, seems appropriate especially in cases where the technological features are sufficiently mature. At the same time, distributed approaches should be implemented to enable higher modularity and to increase inclusiveness of different European QCS solutions. In addition, as QC is most

of the time ‘in the cloud’ today, what is needed is the hardware and software infrastructure (APIs, connections, etc) to be able to use it seamlessly from an HPC center. In the longer term, this is the key for a deep integration and federation of the quantum and digital HPC ecosystems as a whole.

4. Preparation for the QCS-HPC convergence must also invest on **training** of active researchers and users, as well as contributions to **education** within university curricula in computer science/engineering and in computational sciences, to support early quantum literacy at least at the level of MSc and PhD. This should include not only efforts in programming quantum applications, but also in building the host and control side, as well as operating and deploying such systems as part of HPC solutions. This effort can only be successful if conducted in close synergy with the leading organizations involved in quantum and HPC training, including HPC centers and CoE, and in the European higher education system.

The envisaged initial funding (2021-2022) of € 60 million, as indicated by EuroHPC JU, expected to be matched by the national members of EuroHPC JU, will be used to fund up to three European projects to build EuroQCS. This includes investment in QCS to be connected to HPC machines, their operation and related research.

Timeline of the EuroQCS Infrastructure

- **2021** Procurement and deployment of five European peta-scale supercomputers (capable of O(10^{16}) calculations per second) – potential EuroQCS sites.
- **2021** Start of the project High Performance Computer and Quantum Simulator hybrid (⟨HPC|QS⟩) of the Horizon 2020 call "Advanced Pilots towards the European Exascale Supercomputers" – Call ID: H2020-JTI-EuroHPC-2020-01) under the topic "Pilot on quantum simulator" – Call ID: EuroHPC-2020-01-b.
- **2021-22** Procurement and deployment of three European pre-exascale systems (capable of O(10^{17}) calculations per second) – foreseen as EuroQCS sites
- **2022-23** Quantum Flagship ramp-up phase with intermediate scale (50 to 200 physical qubits) QCS prototypes ready
    - Intensive exploration of use cases, leveraging of QLM environments, remote or on premise access of various prototypes and pilot systems, preparation of applications for wider deployment
    - Support the break-even point development of applications towards quantum computing – if applicable – for algorithms practical exploitation of Noisy Intermediate-Scale Quantum (NISQ) devices and use cases for hybrid calculations
- **2023-25** Procurement and deployment of two European exascale systems (capable of O(10^{18}) calculations per second) – foreseen as EuroQCS sites
- **2025** Testing phase with intermediate scale prototypes
    - Enhance the NISQ processing regime with error mitigation methods, enabling deeper algorithms
    - Develop cross-hardware benchmarking of NISQ based systems, quantum application and algorithm theory, software architecture, compilers and libraries, as well as Electronic Design Automation (EDA) and simulation tools
    - Identify promising applications to consolidate toward creating a first generation of applications based on NISQ devices
    - Launch of the European Quantum Computing & Simulation Infrastructure (EuroQCS)
    - Demonstrate automated system control and tune-up
- **2027** Deployment and access to intermediate scale platforms
    - First generation of production large scale applications based on NISQ devices running on the EuroQCS)
    - Demonstration of quantum algorithms outperforming their best classical counterpart
    - Demonstration of use cases/applications that can establish complex workflows and can employ exascale HPC systems and emerging novel quantum accelerators
- **2030** Integration of large scale (> 200 physical qubits) platforms from Quantum Flagship full phase
    - Demonstration of quantum processors fitted with quantum full error correction and robust qubits with a universal set of gates to outperform classical computers
    - Expanded suite of quantum algorithms for software and cross-platform benchmarking, including digital error corrected systems, and optimizing compilers and libraries

- ○ Availability of prototypes and applications that effectively employ hybrid calculations for carefully selected use cases. Demonstration of how to use the EuroQCS with scalable complex workflows.

1. Current landscape in high performance and quantum computing & simulation

With the end of Dennard Scaling around 2005-2007 and the end of Moore's Law around the corner, two fundamental drivers for the performance growth in HPC are breaking away. Consequently, there is an imperative need for devising new computing paradigms and computer architectures coupled with new algorithmic and software development paradigms to sustain a continued drive for the much-needed growth in computing capabilities across the plethora of application areas in physical/engineering sciences as well as machine artificial intelligence (AI) and high-performance data analytics (HPDA).

a. Rise of Quantum Information Processing

QCS may represent the most promising of these new computing paradigms, being now widely recognized to have the potential of leading to a giant leap in future computational resources. Quantum computing is a computational technology that considerably might enhance classical computing and create new directions in computing and data processing. In the short term, there is no other computational technology with the potential to complement HPC.

Quantum devices started to appear at the beginning of this century, when it was shown that the construction of the type of hardware theorized by quantum physicists in the late 90's was indeed possible by exploiting the enormous advancements in the ability to detect and manipulate single quantum objects (photons, electrons and atoms). Early prototypes of these new quantum devices appeared in university labs in the early 2000s and were developed from there into real (quantum) processing units - thanks to huge investments from private industry leaders (like IBM, Google, Intel, Microsoft, Honeywell, ...) and new startups (like D-Wave Systems, Rigetti Computing, PsiQuantum, Xanadu) created specifically to take advantage of the new (market) opportunities. It soon became clear that a real quantum revolution was underway, the second since the one that led to quantum theory at the beginning of the 20th century (and which led to the development of computers, telecommunications, satellite navigation, smartphones, modern medical diagnostics, etc.).

As shown in Tables 1 and 2[2], today most of the developed countries have important government-driven or government-supported initiatives in QT, and especially QCS, with most approaches embracing all value chain, or a significant fraction, from technologies and supply to applications and use, from research to the market, mobilizing universities, research and technology organizations, governmental entities and companies.

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[2] Sources:
https://www.qureca.com/overview-on-quantum-initiatives-worldwide/
https://cifar.ca/wp-content/uploads/2021/05/quantum-report-EN-11-accessible.pdf

Table 1. List of EU countries with sizable investments in QT and especially QCS.

Country	**Programs/initiatives**	**Companies (incomplete)**	**Organizations' involved**
Austria	"Quantum Austria" (€ 100 million in 2021 on top of about € 20 million annually for QT research)	Alpine Quantum Technologies (AQT), Infineon, ParityQC	Ministry for Economy and Research, FWF, FFG, AWS, Universities in Innsbruck, Vienna, Graz, Linz, …
France	Plan quantique national launched in 2021 (€ 1.8 billion)	Atos, Pasqal, Alice&Bob, Quandela, C12, ...	Ministries for Research Defence and Economy, ANR, SGPI, GENCI, CEA, CNRS, INRIA, ONERA, CNES, University Paris Saclay, University Grenoble Alps, Sorbonne University, PSL, Paris University...
Germany	Framework Programme in 2018, further consolidated in 2020. Complemented by different regional actions. (€ 2.2 billion)	IQM, SwabianCQC, Infineon, Fujitsu, Google, IBM, Kiutra, Menlo, Toptica, …	BMBF + other ministries, DFG, DLR, Max Planck Society, Fraunhofer Society, Helmholtz Association, Leibniz Association…
Ireland	Various government or government-approved initiatives (~ € 20 million in 2020-21 for national and European co-funding, with potentially more under consideration through the National QT Strategy under discussion in 2021)	Accenture Labs, Equal1 Labs, IBM, Rockley Photonics	ICHEC, National University of Ireland Galway, Tyndall National Institute, Trinity College Dublin, University College Dublin, Maynooth University
Italy	Various government or government-approved initiatives Piano Nazionale Ricerca (PNR) Piano Nazionale Ripresa e Resilienza (PNRR) (€ N/A)		Ministry of research, CNR, CINECA, INRIM, INAF, INFN, Sapienza Università di Roma, Università Federico II, Università di Padova, ...
Finland	Various industrial, government or government-approved initiatives (€ N/A)	IQM, BlueFors, Aivon, Algorithmiq, Okmetic, Picosun, Quantastica, Rockley Photonics, ...	VTT, Aalto University, CSC, JYU, TUNI, ...
Spain	Government-approved initiatives (€ 60 million)	Qilimanjaro Quantum Tech, Multiverse Computing	BSC, IFAE, ICFO, RES
Sweden	Various industrial, government or government-approved initiatives (€ N/A)	Low Noise Factory, Phase Space Computing,...	WACQT, Chalmers University, ...

Netherlands	Quantum Delta NL (€ 615 million)	Orange Quantum Systems, Qblox, QphoX, Qu & Co, QuiX, Single Quantum, ...	QuSoft, QuTech, ...

Table 2. List of non-EU countries with sizable investments in QT and especially QCS.

Country	Programmes/initiatives	Companies (incomplete)	Organizations involved
Australia	Several, in particular related to quantum dots (about AUD 100 million for the company SQC only)	SQC	CQC2T
Canada	Very active in quantum technologies for a decade, with federal support. A more formal national quantum strategy is expected soon. ($ 766 million)	1Qbit, Anyon systems, D-Wave Systems, Xanadu, Zapata Computing	Regional governments, different federal entities in research, economic development, technology, defence…
Israel	Israeli National Quantum Initiative ($370 million)	Acktar Ltd., Mellanox Technologies - MLNX, Accubeat Ltd., Rafael Advanced Weapons Systems, Israel Aerospace industries - ELTA, Quantum Machines, Raicol, Qedma quantum computing Ltd, Random Quantum, ClassiQ, QuantLR, IBM, QDM, Elbit - KiloLambda, Elbit Elisra, Opsys, Israeli center of diamond technologies, LightSolver, Tabor	ISF, ISERD, INQI, HUJI, Weizmann, Technion, Tel-Aviv University, Bar-Ilan University, Ben-Gurion University
Japan	Coordinated national strategy including a 10-20 year vision ($ 470 million)	Fujitsu, Hitachi, Mitsubishi, NEC, NTT, Toshiba	MEXT, METI, JST, RIKEN, AIST, QST, NTIC…
UK	Five-year national plans 2015, 2019 ($ 1.3 billion)	Cambridge Quantum Computing, Rigetti+Oxford Instruments, ORQA, Duality	UKRI, EPSCR, NPL, DSTL, QCHQ…
US	National Quantum Initiative Act in 2018, but strong federal initiatives since the late 90s. ($ 1.2 billion)	Amazon, Google, IBM, Intel, IonQ, Microsoft, PsiQuantum, Rigetti Computing, Honeywell,...	DOE, DOD, DARPA, IARPA, NSF, NIST, NASA, NSTC…

China	Quantum technology R&D identified as a strategic industry and area for innovation in China's Five-Year Plans (China's social and economic development plans) since the 11th plan (2006-10), and in "Made in China 2025" (China's 2015 strategic plan for its manufacturing sector). (Estimated $ 10 billion)	Alibaba, Baidu, Huawei, Origin Quantum, QuantumCTek, Tencent...	Ministry of Science and Technology (MOST) Ministry of Industry and Information Technology (MIIT) National Development and Reform Commission (NDRC) National Natural Science Foundation of China (NSFC) Chinese Academy of Sciences (CAS)...
Singapore	National Quantum Strategy, and National Quantum Computing Hub ($ 250 million)	Horizon, Entropica Labs	MOE, NRF
India	National Mission on Quantum Technologies and Applications (NM-QTA), 2021-2025 (€ 931 million)	Atos, IBM, Microsoft, national MNCs, SMEs and startups	Ministry of Science and Technology, Department of Science and Technology, Centre for Development of Advanced Computing (C-DAC), Indian Institute of Science Education and Research, Indian Institute of Science (IISc)

b. QCS: state of the art[3], TRL and QTRL, SWOT analysis

Currently available QCS NISQ architectures can be roughly grouped into three categories (roughly following according to the five required conditions for quantum computing defined by DiVincenzo[4]):

a. **Proof-of-concept architectures.** These architectures represent entirely new approaches to encode and manipulate quantum information. They are generally not yet mature and some are still requiring significant additional efforts to go beyond a conceptual stage. Nevertheless, these developments are necessary and may lead the field in the years to come.

b. **Proof-of-performance architectures.** These architectures have demonstrated the necessary capabilities (initialization of the quantum register; manipulation through a gate-set compatible with universal quantum computation; register's read out at the end of the computation) to implement quantum algorithms. Architectures in this group have qualitatively met DiVincenzo's requirements but need improvements in quantitative performance.

c. **Application-ready architectures.** These architectures have realized error rates below 1 in 100 quantum gate operations and individual control of qubits in quantum registers consisting

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[3] More details can be found in the European Quantum Flagship, Strategic Research Agenda, March 2020, https://qt.eu//app/uploads/2020/04/Strategic_Research-_Agenda_d_FINAL.pdf

[4] The DiVincenzo criteria requires that a quantum computing architecture meets the following conditions (DiVincenzo, Fortschritte der Physik. 48 (9–11): 771–783):

1. A scalable physical system with well characterized qubits;
2. The ability to initialize the state of the qubits to a simple fiducial state;
3. Long relevant decoherence times;
4. A "universal" set of quantum gates;
5. A qubit-specific measurement capability.

of 20 and more qubits. They are employed to implement the first applications of quantum computers and prove quantum advantage.

Currently pursued architectures in group a) are molecular spin qubits, topologically encoded qubits and valley qubits; for group b) one has

b.1 Neutral-atom qubits. Neutral atoms have been used successfully in optical lattices or tweezer arrays (with Rydberg atoms) for some of the largest scale quantum simulations to date, with promising applications also for quantum computing. Next to long coherence times and single atom addressability, they offer direct scalability towards 196 particle size systems[5] and 10^3-10^4 in the near future. Today, they have already enabled some of the most complex and advanced quantum simulations with applications from material science, high-energy physics to statistical physics. In many cases, these simulations address computationally intractable regimes[6] and have been used to benchmark classical computing methods and validate new numerical techniques.

b.2 Semiconductor based qubits. Semiconductor-based qubits make use of today's electronics technology. Employing nanofabrication techniques, quantum dots have been defined in which individual electrons can be confined. Also, isolated donors have been positioned in semiconductor substrates and used to trap individual electrons. In both cases, the spin of one or more electrons is considered the most promising qubit representation, since spin coherence is longer than the coherence of charge states or other degrees of freedom. These devices can be measured and controlled fully electrically, again much like transistors in today's digital electronics.

b.3 Photonic qubits. Integrated quantum photonics has enabled the generation, processing, and detection of quantum states of light in high component density, programmable devices, supporting multi-qubit operations. With low decoherence properties, photonics provides routes toward NISQ era machines that outperform classical computers[7]. Manufacturing a fault tolerant universal quantum computer in photonics is now being pursued commercially, as single photon sources and photon-photon interactions, mediated through light-matter interaction, provide significant reductions in overheads.

Finally for group c) one has:

c.1 Trapped ions. Trapped ion set-ups have been the first successful platform for the demonstration of quantum information processing (including Shor's algorithm for factoring numbers and quantum chemistry), as well as quantum error correction, with long qubit coherence times and high fidelities demonstrated for state preparation, single-, two-and multi-qubit gates, and state detection. All building blocks for initialization, manipulation and readout have been demonstrated at the fault-tolerant threshold.

c.2 Superconducting qubits. Superconducting qubits are applied world-wide by many research groups and demonstrated at very different levels, from two-qubit gates to integrated systems with 50 and more qubits and full software support[8]. The technology, which is fully programmable, is ready for small systems integration of quantum computing in quantum sensing or quantum communications applications. In the context of quantum computing in a NISQ regime, combined

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[5] Pascal Scholl, Michael Schuler, Hannah J. Williams, Alexander A. Eberharter, Daniel Barredo, Kai-Niklas Schymik, Vincent Lienhard, Louis-Paul Henry, Thomas C. Lang, Thierry Lahaye, Andreas M. Läuchli, Antoine Browaeys
Programmable quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms
arXiv:2012.12268

[6] Outperforming of a classical computer with a neutral atom quantum simulator has been demonstrated in S. Trotzky et al., Nature Physics **8**, 325–330 (2012).

[7] Quantum advantage in a photonics quantum computing architecture has been shown in Zhong, H.-S. et al. Science 370, 1460-1463 (2020)

[8] Quantum advantage in a semiconductor quantum computing architecture has been shown in Arute, F. et al. Nature 574, 505–510 (2019).

with an error mitigation scheme, chemical simulation has been demonstrated with results at very high precision.

Additional characterization of QCS platforms can be achieved by adopting both the view of an industrial product as quantified by the usual TRL scale[9], as well as a more technology-oriented view as described by the Quantum TRL (QTRL) scale[10]. For example, a unique QTRL 9 computer sitting in an experimental lab, accessed remotely by users would be qualified as TRL 5, far from being a commercially successful product. On the other hand, a system fully packaged and production ready can have a TRL of 8 or 9 despite having only a small number of qubits and therefore being of QTRL 5. Therefore, in Table 3, the TRL level focuses on the number of qubits available to the users rather than on the packaging of the solution.

Table 3. List of QTRL and TRL of the most advanced QCS platforms.

Technology	QTRL	TRL	EU assets/players
Trapped ions	QTRL 5	TRL 6-7	AQT (10 qubits)
Neutral (Rydberg) Atoms	QTRL 5	TRL 6-7	Pasqal (100 [196] qubits)
Superconducting qubits	QTRL 5	TRL 5	IQM (5 - 20 qubits)
	QTRL 2	TRL 1	Alice&Bob
	QTRL 1-3	N/A	Oxford Quantum Circuits (4 qubits)
	QTRL 3-5	TRL 3-5	Qilimanjaro Quantum Tech (5 qubits)
Photonic qubits	QTRL 4	TRL 4	Quandela, Duality quantum Photonics, Quix (5-12 qubits)
CMOS silicon spin	QTRL 1-3	N/A	CEA LETI / CNRS

Finally, in Table 4 we present a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis of EuroQCS as a whole.

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[9] Definition of TRL are according to Horizon 2020 Framework Programme of R&D&I by the European Commission https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

[10] Definition of QTRL are given in https://www.fz-juelich.de/ias/jsc/EN/Research/ModellingSimulation/QIP/QTRL/_node.html

Table 4. Comparative SWOT analysis of the EuroQCS infrastructure.

Internal	
Strengths	**Weaknesses**
Strong HPC centers in EuroHPC JU and nationally	HPC centers not prepared for quantum
EuroHPC JU funding for HPC-QC infrastructure	Public funding lower than in competing regions
Several top level R&D teams in QC across Europe	Pace of EU QC technology development too slow
IP-protected HPC integration technology in EU	Missing presence in standardization bodies
European QC programming platform available	European QC programming platform not taken up
External	
Opportunities	**Threats**
Large interest for creation of more EU QC companies	Risk of monopoly by non-European companies
Talents available to create software dev teams	Software standards imposed from outside EU
EuroQCS will motivate code developers	QC programming platforms from US dominate
Numerous industrial end users interested	European end users prefer non-EU vendors
Strong EU tech companies	Dependency on non-EU tech / resources (He_3, …)

c. Creating a Pan-European HPC-QC Infrastructure

It is a crucial element of the European digital strategy[11] to create an integrated and federated world-class exascale supercomputing and quantum computing infrastructure. This can be realized through:

- the deep integration of QCS and HPC systems;
- the federation of European HPC and QCS resources to make them accessible to a wide range of public and private users across Europe (including European public data spaces, as presented in the European Data Strategy 2020).

These ambitious objectives can only be achieved through a synergistic action of the QT and HPC communities and their existing initiatives and infrastructures briefly described in the following.

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[11] See the European Commission Communication “2030 Digital Compass: The European way for the Digital Decade”: https://eur-lex.europa.eu/resource.html?uri=cellar:12e835e2-81af-11eb-9ac9-01aa75ed71a1.0001.02/DOC_1&format=PDF

i. The European Quantum Flagship and Fleet

In order to keep Europe at the forefront of conceiving, developing and commercializing quantum computing and other quantum technologies, the European Commission has established in 2018 the Quantum Flagship large-scale initiative, which, in its initial ramp-up phase, has funded 24 projects for roughly € 150 million in the Flagship's five different pillars: Communication, Computing, Simulation, Metrology/Sensing and Basic Science. The second phase of the initiative is being funded within the Horizon Europe (HE) Framework Programme, with a planned budget of roughly € 240 million in 2021 and 2022.

In addition, QUANTERA is a European Research Area Network (ERA-NET) in the field of QT involving 32 funding organizations from 27 countries, which has funded or is funding 38 projects for a total budget of € 45 million.

Finally, two more strategic infrastructures are planned within the Digital Europe Programme:

- The "European Quantum Communication Infrastructure" (EuroQCI) for the transmission and storage of information and data in an ultra-safe way through the integration of QT and systems in conventional communication infrastructures both terrestrial (national and cross-border level) and spatial (EU and other continents level);

- The "European Quantum Computing & Simulation Infrastructure" (EuroQCS) for remote user access to quantum computing and simulation hardware devices via a coordination node that manages web access to several hardware and/or software nodes located in different Member States, some of which may also provide access (for a limited period of time) to the quantum hardware (see below).

ii. The European Pilot ⟨HPC|QS⟩

In 2021, work will begin on the EuroHPC JU "Pilot on quantum simulator" project ⟨HPC|QS⟩. The aim of ⟨HPC|QS⟩ is to prepare European research, industry and society for the use and federal operation of QCS. These are future computing technologies that are promising to overcome the most difficult computational challenges. ⟨HPC|QS⟩ is developing the programming platform for the quantum simulator, which is based on the European Atos Quantum Learning Machine (QLM), and the deep, low-latency integration into modular HPC systems based on ParTec's European modular supercomputing concept. A twin pilot system, developed as a prototype by the European company Pasqal, will be implemented and integrated at CEA/TGCC (France) and FZJ/JSC (Germany), both hosts of European Tier-0 HPC systems. The pre-exascale sites BSC (Spain) and CINECA (Italy) as well as the national Quantum Learning Platform at ICHEC (Ireland) will be connected to the TGCC and JSC via the European data infrastructure FENIX. It is planned to offer quantum HPC hybrid resources to the public via the access channels of PRACE.

To achieve these goals, ⟨HPC|QS⟩ brings together leading quantum and supercomputer experts from science and industry, thus creating an incubator for practical quantum HPC hybrid computing that is unique in the world. The ⟨HPC|QS⟩ technology will be developed in a co-design process together with selected exemplary use cases from chemistry, physics, optimization and machine learning suitable for quantum HPC hybrid calculations. ⟨HPC|QS⟩ fits squarely to the challenges and scope of the Horizon 2020 call "Advanced Pilots towards the European Exascale Supercomputers" under the topic "Pilot on quantum simulator" by acquiring a quantum device with two times 100+ neutral atoms. ⟨HPC|QS⟩ develops the connection between the classical supercomputer and the quantum simulator by deep integration into a modular supercomputing architecture and will in addition provide cloud access and middleware for programming and execution of applications on the quantum simulator through the QLM. A Jupyter-Hub platform will guarantee safe access through the European UNICORE system to its ecosystem of quantum programming facilities and application libraries.

iii. EuroQCS – Goal and Roadmap

The aim of EuroQCS, which is at the boundary of EuroHPC JU and the European Quantum Flagship, is to become a federated European infrastructure for hybrid classical-quantum computing with remote access to QCS devices.

EuroQCS will unify access to a variety of HPC and QCS resources that are co-located and deeply integrated in supercomputing centers, or to stand-alone systems accessible via the cloud or connected to the supercomputing centers through classical network links in a first stage, and infrastructure developed by EuroQCI in the long term. EuroQCS will collaborate with existing or ongoing efforts and facilities such as those offered by PRACE, FENIX, EOSC, EuroHPC JU and the Quantum Flagship. In addition, EuroQCS will feature access to hardware-/software-nodes, some of which would also provide limited access to key hardware.

EuroQCS will ensure a coherent and forward-looking view of quantum resources from the various portals up to the local systems. This approach will promote and pool excellence distributed across Europe, reduce costs, remove barriers to entry, and achieve modularity that allows access to new equipment and capabilities as they become available. EuroQCS will promote a peer-review-guided selection mechanism of user proposals as is fully accepted and existing for classical HPC workloads/projects on national and European (PRACE) level.

Access will be evolutionarily developed through (i) classical quantum emulation software and hardware running on and integrated with HPC systems so that quantum software developers can run their algorithms on emulated quantum hardware while access to real QCS is developed; (ii) quantum computation and simulation hardware based on different qubit platforms including, among others, trapped-ion qubits, superconducting qubits, molecular-spin qubits, photonic qubits, and neutral-atom qubits; (iii) quantum testbed facilities for hardware developers, e.g., for testing components required for developing scalable qubit ecosystems for operational and high-performance environments; (iv) a quantum application database with verification and validation routines, quantum advantage demonstration algorithms, and prototype use cases.

Experienced users, including both interested industry and academic partners will be able to test their algorithms and protocols on different quantum architectures via cloud access. For advanced QCS systems, the deep integration into classical supercomputers will be crucial for demonstrating hybrid quantum-classical co-processing systems as well as providing a test-bed benchmark for verification and simulation of quantum hardware. This dual approach will allow the development of both quantum applications (software, compilers) and quantum programming languages, operating and runtime systems, in synergy with a broader user community from science and industry, and its application in the HPC context.

On a hardware level, facilities at centralized sites would allow users to access well maintained infrastructure (control systems, stable lasers, microwave generation) for testing innovative developments in focused areas of technology, opening up a rapid- turnaround, low-threshold entry into the field for hardware developers in academia and industry. Interaction with existing HPC is crucial in three important aspects. First, simulations of even moderate size of quantum systems are exponentially difficult on classical computers, and classical HPC is the best tool we currently have for quantification, optimization, and benchmarking of experimental systems and quantum algorithms and processes, until novel and scalable methods for classical validation of quantum computation and simulation results, not necessarily through brute-force simulation, will be developed. Second, current quantum simulators already allow one to benchmark and validate new classical algorithms[12], thus reinforcing HPC capabilities. Third, direct access to HPC resources will enable the development of tightly coupled hybrid workflows and the experimentation with the needed APIs, language extensions, data staging strategies and resource management techniques.

iv. European HPC Infrastructure Landscape (EuroHPC JU)

Currently, the EuroHPC JU is supporting the development of a world-class supercomputer infrastructure by procuring and deploying in 2021 in the EU five petascale supercomputers (capable of at least 10^{15} calculations per second) and by 2021/22 three pre-exascale supercomputers (capable of at least 10^{17} calculations per second). In addition to these plans, the EuroHPC JU aims to acquire by 2023/25 exascale supercomputers (capable of at least 10^{18} operations per second), with at least one being based on European HPC technology.

The five petascale supercomputers are located in the following supercomputing centers:

- Sofiatech Park, Bulgaria: supercomputer PetaSC, supplied by Atos and based on a BullSequana XH2000 supercomputer
- IT4Innovations National Supercomputing Center, Czech Republic: supercomputer EURO_IT4I, supplied by Hewlett Packard Enterprise (HPE) and based on an HPE Apollo 2000Gen10 Plus and HPE Apollo 6500 supercomputers
- Luxprovide, Luxembourg: supercomputer MeluXina, supplied by Atos and based on the BullSequana XH2000 supercomputer platform
- IZUM, Slovenia: supercomputer VEGA, supplied by Atos and based on a BullSequana XH2000 supercomputer
- Minho Advanced Computing Centre, Portugal: supercomputer Deucalion, supplied by Fujitsu and based on the Fujitsu PRIMEHPC (ARM partition) and Atos Bull Sequana supercomputer platforms

The three pre-exascale supercomputers are or will be located in the following supercomputing centers:

- CSC – IT Center for Science, Finland: supercomputer LUMI, supplied by Hewlett Packard Enterprise (HPE) and based on a Cray EX supercomputer
- CINECA, Italy: supercomputer LEONARDO, supplied by ATOS and based on a BullSequana XH2000 supercomputer
- Barcelona Supercomputing Centre, Spain

The hosting candidates for the two exascale supercomputers are planned to be selected in the second half of 2021.

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[12] K. Van Houcke et al., Nature Physics **8**, 366–370 (2012)].

2. Towards Practical Quantum Computing & Simulation

Practical quantum computing relies on hybrid computing using both classical supercomputers (HPC systems) and QCS. These needs will require deep integration of quantum devices into HPC infrastructures in the form of quantum-classical hybrid computing systems.

a. Needed synergy between HPC systems and QCS

As QCS mature and become more and more useful for real-world applications, it is becoming also clear that they are insufficient in addressing practical problems when operated as stand-alone systems. Realizing the full QCS potential requires their integration with classical systems to manage input/output, orchestrate large(r) workflows and implement (part of) the algorithms not suitable for quantum hardware. A hybrid HPC/QCS approach appears, therefore, to be a very promising route to follow, with HPC architectures managing the core workflows and still performing the needed non-quantum computing tasks, and QCS systems acting as powerful accelerator hardware. Additionally, hybrid HPC/QCS systems will still be a step forward in solving difficult problems if stand-alone quantum systems cannot be scaled up sufficiently or for application subcomponents not suited for quantum processing. The potential applications of such hybrid machines are vast and include finance, energy, oil and gas, aerospace, transportation, chemistry, pharmacology, materials design, health care and areas like optimization, simulation or machine learning.

As with non-quantum, von Neumann dominated computing, user uptake will depend on ensuring a seamless interaction between the users, the software, and the hardware (see Fig. 1). The first layer of interaction is between the users and the application software. The impact of quantum computing will heavily depend on a broad user base that will invest time and effort in understanding the real power of quantum computers and how they can be used to solve important real-world problems. At the moment, concrete, fully worked out quantum hybrid quantum-classical applications for solving industrial problems are few. Identifying such potential applications and developing the corresponding algorithms requires close cooperation between quantum and HPC researchers and domain experts from industry and academia.

The second layer of interaction is between the software and the various hardware platforms.

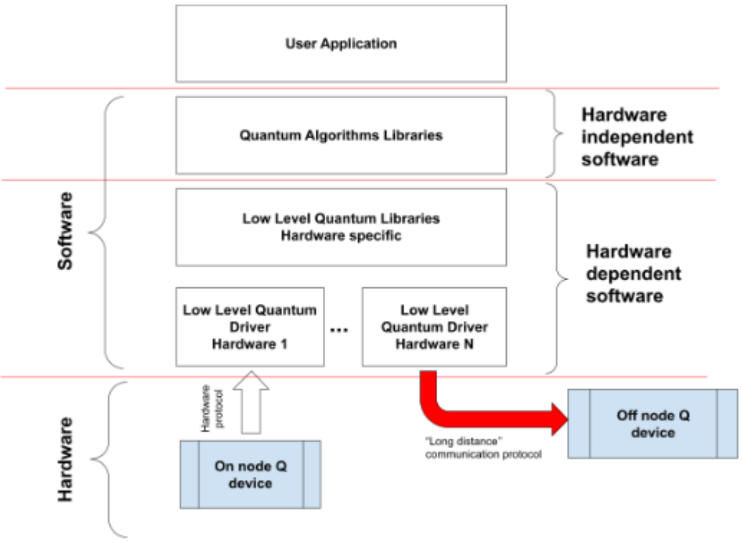

Figure 1. Interaction between the users, the software and the hardware.

Enabling this interaction is a significant technological challenge: contrary to conventional software, quantum software is largely hardware dependent, and thus requires an interface that can connect a wide range of software to any one of a number of quantum computer architectures within a single HPC environment. However, not only is this interaction crucial for eventually putting quantum computers to widespread use, it is vital to the development of future quantum-enhanced HPC systems.

b. Hybrid HPC/QCS computations

Hardware and software of HPC systems is very different from that of QCS systems. HPC systems typically consist of a large number of nodes partitioned into subsets of nodes that are assigned (in most cases exclusively) to users for the duration of their submitted job. Accelerators are typically associated with and accessible from individual nodes; increasingly, multiple accelerators are available on a single node. Consequently, these systems are programmed with parallel programming models that can coordinate computations across nodes and use such local accelerators to speed up specific portions of the computation.

QCS systems, on the other hand, are typically self-contained, with quantum information and coherence preserved locally. Expected running times in near term quantum devices are reduced by coherence times, typically of a few microseconds. Due to the fragility of quantum information over long distances, connections to other computers/systems are usually based on classical technology.

A limited form of quantum connectivity between quantum systems has, however, already led to secure quantum communication technology using quantum cryptography, and research is on-going to extend and strengthen quantum links between nodes (“quantum internet”). This will allow authentication and privacy to be enhanced in a quantum-secure way, but larger quantum entanglement between QCs is still in a primordial stage.

In order to integrate HPC and QCS these fundamental differences between the two computational paradigms need to be bridged. This can only be done successfully if all levels of the system stack – from hardware to the application – are considered. Particular challenges to be addressed are listed in Appendix A.

c. HPC/QCS integration from a systems approach

One has to distinguish between applications that request lowest possible latency between HPC and QCS systems and those where latency does not play a critical role. Deep integration of QCS into the HPC infrastructure is crucial for enabling application scenarios going beyond pure digital or pure analog quantum processing. This is particularly the case for coupled simulation codes using a feedback loop, connecting parts running on traditional (von Neumann-based architectures) and those being simulated on a quantum computing system. The use of more service-based approaches is appropriate when close and very frequent feedback between the HPC system and QCS is not required.

What is more, the choice of a particular type of QC technology has inherent consequences in terms of hardware integration in existing or future HPC facilities. At this stage, a number of points can be identified to be further considered. These are the volume of the device, the weight of the device, the resistance to external disturbances (vibrations, EM fields, ...), the distance to the main computer, the presence of a front-end computer, the form factor and the type of connectivity for compact solutions, the specific fluid, the cooling requirements, the safety requirements - technical, physical, regulatory (e.g., presence of lasers, cryogenic systems). Only for systems where these technological features are already mature enough, a location at the HPC center can be envisaged for production use of HPC/QC devices. In the other cases, the experimental systems will be operated in the lab, and remote access will be provided using classical networks as a first step, and the EuroQCI infrastructure in the longer term. Additionally, hybrid approaches of shared HPC/QC lab environments housing experimental systems from both worlds will be critical to study novel integration techniques and to understand synergies as well as challenges.

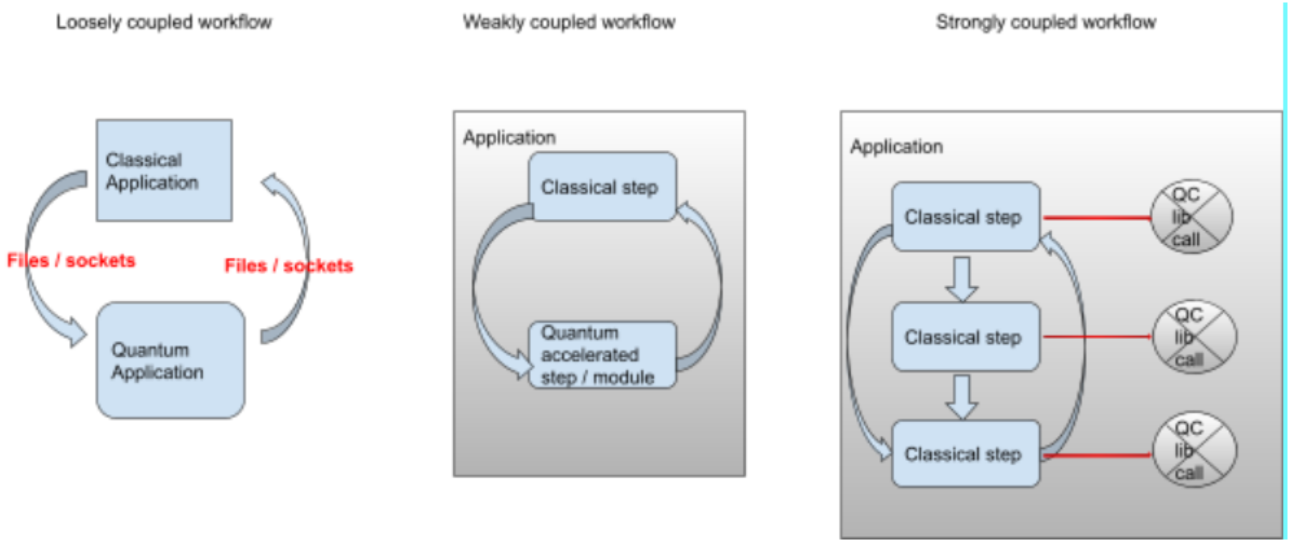

Figure 2. Users' workflows can require different types of coupling of the HPC system to the QCS one. In the loosely coupled workflow programs exchange information from time to time. In the weakly coupled case, inside an application, macro steps are done on the QCS system. Finally the strong coupling depicts situations where micro steps[13] require the usage of quantum accelerated algorithms.

d. Architecture of the Integrated HPC/QCS Infrastructure

The usage model of HPC systems is increasingly based on workflows. The integration of those computing workflows, that exploit both QCS and HPC capabilities, must be designed in accordance with the usability policy of the system. We envision several ways to leverage quantum resources as depicted in Fig. 2:

- The quantum code is a program in a workflow consisting of a sequence of programs that communicate data between different steps, one or more of which use the quantum device. If the data rates involved are small and the different codes run long enough, a co-location of the QCS with the HPC system is not required;

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[13] A micro step usually takes less than a second.

- The quantum code is a function within a code, for example in an optimization algorithm. Here, the quantum device may be addressed via a library. To be able to provide lowest latency co-location is required;

- The sharing of the quantum device is of concern: depending on its nature, it could be shared between users or must be reserved for exclusive use. The workflow and resource management mechanism must be sensitized to this problem.

The integration of a quantum device in an HPC system requires investigating several aspects such as:

- The low-level way to communicate between the main computer and the quantum device, possibly involving large data-flow rates (depending on the algorithms run) or lowest latency;

- The integration of quantum control hardware and front-end systems into the HPC systems;

- The integration of QC resources in the scheduling and resource management system to allow the users to describe different kinds of workflows, especially if needed access to a remote[14] quantum device (e.g., a non-quantum job run at TGCC needs access to a JSC quantum device);

- The integration of the compilation suite into the production environment;

- The extension of classical HPC programming models and tools to seamlessly integrate and orchestrate dynamic hybrid HPC/QCS application workflows and dataflow;

- The way to integrate quantum libraries to codes.

The Modular Supercomputer Architecture (MSA) concept, developed in the series of European-funded DEEP projects, provides solutions for dynamically allocating resources from one autonomous supercomputer system to a second, including joint code compilation and co-scheduling.

For applications, <u>where latency plays an important role</u>, the MSA technology meets the requirements for a deep, lowest latency embedding of a QC into a traditional HPC system. The MSA approach coherently orchestrates heterogeneity by integrating hardware components that can expose common properties at system level. These hardware components act as individual modules of an integrated system connected via a federated high-speed network. Consistent with the MSA, QC will be an additional module of the modular supercomputer that is most tightly coupled with existing modules such as a quantum simulator, the general-purpose CPU, and (multiple) accelerator modules (e.g., GPU).

Unlike stand-alone machines where operations are based on an isolated resource with independent resource management and scheduling, MSA introduces novel usage models. On the one hand, MSA allows tightly coupled simulation codes to benefit from efficient data exchange over a shared high-speed network, and on the other hand, it allows workflows in which one or more stages run on the QC while pre- and post-processing tasks can be performed on other modules of the MSA system.

The QCS modules can also be geographically distant. For applications where <u>latency is not so critical</u>, physical distance has a lesser impact on the performance. Latency-critical applications will require that sufficiently powerful standalone servers are directly connected to the QCS, in case the HPC resource is not co-located, in order to maintain the required close data-loop between classical

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[14] by remote we mean not on premise, operated by another computing center.

and quantum parts of a specific algorithm or application. Such long-distance integration further requires that cybersecurity, resource allocation, and scheduling policies be properly set up, taking into account both sites' legal obligations and providing at least loosely coupled logical integration. The directly coupled server at the QCS enables a tight, low-latency feedback loop between non-quantum and quantum components, and connects QCS and the large-scale HPC services over a high-speed long-distance network connection. On the longer term, integration with the EuroQCI infrastructure is expected.

Especially for QCS machines still in an experimental stage, the geographically decentralized approach enables the set-up of classical and quantum resources in locations that are well suited for the respective module. For example, proximity to sustainable power sources for the power-hungry classical HPC infrastructures, and workshop facilities and shielded environments for the low-power, but sensitive quantum computers.

To conclude, by basing the EuoQCS infrastructure on the modular approach, on the one hand deeply connected for more mature systems, on the other hand more distant for experimental systems, the EuroQCS ecosystem becomes maximally inclusive and pan-European, connecting multiple HPC resources and QCS across Europe.

3. Shaping the Ecosystem

In order to unleash the potential of hybrid quantum-classical computing, it is essential to bring together and synergize two primary stakeholder groups, leveraging quantum computing activities that have already started in European HPC centers as described in Table 5.

Table 5. Quantum computing activities of European HPC centers.

HPC Computing Centre	Country	QC activities
BSC	Spain	Development of an HPC simulator for the study of large-scale quantum circuits based on tensor networks. Proposal of algorithmic optimizations of hybrid classical-quantum circuits using machine learning tools. Application of small quantum circuit optimization to study physical properties of condensed matter systems. Installation of quantum hardware to develop real hybrid systems for quantum computation
CEA TGCC	France	TGCC is CEA’s large facility for supercomputing for research and industry; it is a two-fold computing complex: - CCRT – Computing Centre for Research and Technology, started as early as 2003 – is the industrial component of TGCC, with a supercomputer co-funded by CEA and its industrial partners. CCRT is fostering early user bootstrapping to quantum programming with an Atos QLM since 2018[1] - The research component of TGCC hosts and operates GENCI’s HPC machines for French and European research use; TGCC is getting ready to host a quantum simulation system in the context of HPCQS EuroHPC project. TGCC is designated as the reference computing centre for the French National Quantum Programme. TGCC, together with GENCI and other French partners, in line with EuroHPC and EuroQCS, will further setup and

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[1] https://atos.net/en/solutions/quantum-learning-machine

		expand a generic quantum computing platform designed to host a diversity of quantum computing technologies when they become mature and production ready. This effort is meant to be part of the wider federated European one.
CINECA	Italy	CINECA's QC activities are divided into different types: from the point of view of dissemination, CINECA organizes every year a workshop called High Performance Computing and Quantum Computing (HPCQC), where the scientific community (Italian and non-Italian) gathers to share their achievements in the field of quantum computing. This year we are organizing the fourth edition (first edition: December 2018). In addition, we also organize schools (this year the first edition of Introduction to Quantum Computing and Practical Quantum Computing School) and individual events (such as the various workshops organized by our partners AWS, Pasqal, D-Wave Systems and IBM). The dissemination also takes place through our website www.quantumcomputinglab.cineca.it, where the videos and slides of the previous editions of the HPCQC workshop and schools can be seen. From the quantum as a service point of view, CINECA has entered into agreements with Pasqal and D-Wave Systems for the free supply of calculation hours for Italian universities and research centers (distributed through the ISCRA project). Furthermore, on Marconi100, our Tier-0 supercomputer, several opensource emulators are installed that can be freely used by our audience of users. Among the various emulators are Qutip, Qiskit, QuEST, Cirq, Pulser. From the point of view of software development, we are engaged in a collaboration with the University of Padua for the development of a Tensor Network HPC-ready emulator (multi node and multi GPU) to be installed on our machines. From the point of view of participation in European projects: we are currently part of the HPCQS consortium (which won the Pilot on Quantum Simulator project) and other consortiums. From the point of view of industrial activities: we have a strong collaboration with various industries in our area. With them we have carried out PoCs related to various problems of interest to them, trying quantum-type approaches. We have won an industrial project in the context of EuroCC which will start in October and will have drug discovery as its research area.
CSC	Finland	Within EuroCC, the CSC has so far developed and delivered three two-day hands-on courses on quantum computing and algorithms using the CSC HPC platform. In addition, two webinars on the fundamentals of quantum programming have been produced for a non-expert audience. CSC is part of the Finnish Quantum-Computing Infrastructure (FiQCI) consortium, established in 2020, which aims at providing a stable, mature platform for research and development, where quantum computing forms an integral part of the supercomputing ecosystem as a whole. CSC is leading the integration effort of the LUMI pre-exascale ecosystem within the Nordic-Estonian Quantum Computing e-Infrastructure Quest (NordIQuEst), which develops cross-border, low-latency HPC/QCS solutions combining several classical and quantum computing resources. Initially, CSC will integrate LUMI with the quantum computers of the Wallenberg Centre for Quantum Technology (WACQT) in Sweden and VTT in Finland.

ICHEC	Ireland	Quantum Programming Ireland (QPI) Initiative led by ICHEC, with focus on national and European hybrid HPC/QCS systems, R&D and skill development in quantum computing software and applications. This includes provision of platform services through the national Quantum Learning Platform and skills development programme through industry- and academia-driven Quantum Programming Certification Course.
JSC	Germany	Jülich UNified Infrastructure for Quantum computing - JUNIQ - provides science and industry in Europe with access to QCS technologies of different types and levels of technological maturity. JUNIQ provides access via a uniform cloud platform and will integrate QCS in the form of quantum-classical hybrid computing systems into JSC's modular HPC environment. JUNIQ develops software tools, algorithms, and prototype applications, and provides world-class support and training. The research group Quantum Information Processing - QIP - co-developed the Jülich Universal Quantum Computer Simulator (JUQCS), which was used to set the world record for simulating quantum computers with 48 qubits and to benchmark the Google quantum processor Sycamore in the Quantum Supremacy Experiment. Members of the group QIP are working in the Quantum flagship project OpenSuperQ. Use cases of QIP: companion planting (optimization), tail assignment problem (optimization), protein-DNA binding (machine learning), and remote sensing image classification (machine learning).
LRZ	Germany	The QIC (Quantum Integration Center) at LRZ has been established in 2021 to further on-site integration research for hybrid HPC/QC systems. Lab space is currently being established as a joint HPC/QC lab environment to study physical, logical and programming integration. QIC houses the BMBF funded DAQC project, which targets the development of three generations of Digital-Analog Quantum Computers to be located at LRZ and to be directly connected with HPC systems. Further, LRZ is part of the Munich Quantum Valley (MQV), a major Bavarian Initiative (as collaboration of MPG, FHG, TUM, LMU and BaDW/LRZ) for the development of QC systems using three promising technologies. LRZ is scheduled to house several of the MQV QC systems and leads the Q-DESSI project to develop an integrated quantum system software and programming environment (as joint work with TUM and LMU). Additionally, LRZ houses an ATOS QLM and is closely working with Intel to enhance the scaling of their Quantum Simulator, IQS. LRZ also offers a robust training program and is in the process of establishing a portal for its users for easy access to different commercial QC offerings.

1. **Developer community**
   This is composed of a wide range of scientific and technical experts who are involved in the development, deployment and service provisioning of hybrid HPC/QCS systems for national and/or European users.
   Key players in this community include the QT experts (involved in the engineering and development of QCS hardware systems), Computer Architects and Electrical Engineers (driving

the host and control side of QCS systems), HPC/QCS software developers (involved in system software, runtime and programming tools), HPC/QCS application developers (also involved in the user community), and HPC centers (involved in the integration and service provision of HPC/QCS systems). These players are also often involved in delivering training and skills development activities.

2. **User community**
   This is composed of prospective users of the hybrid HPC/QCS systems who investigate and develop applications across a number of sectors to exploit QC and HPC.
   Such users often span scientific, industry and public sector organizations that are either actively working in applying QC to pilot use-cases relevant to their domain, or seek to monitor the evolution of QCS systems and technologies in order to define their strategy for adopting QC into their scientific or industrial applications.
   Following are some potential application areas that cover a wide range of domains with varying levels of understanding about the potential impact of QC in each:
   - Mathematics and its applications (cryptography, factorization, quantum search, solving linear equations, spectral/quantum Fourier transforms)
   - Simulation of physics systems (condensed matters, high-energy and plasma physics, field theories, strongly correlated systems)
   - Chemical and pharmaceutical industry (molecular analysis, design of material, catalyst and drug)
   - Engineering and manufacturing (job-shop scheduling, layout optimization in product packaging)
   - Automotive industry (materials design for batteries, fabrication process optimization)
   - Transport and logistics (traffic flow predictions, scheduling, route optimization)
   - Financial services (asset management, portfolio optimization, risk estimation)
   - And, more emerging.

Enabling increased collaboration across the HPC/QCS developer community in Europe will maximize knowledge transfer across the community to identify common challenges in developing and operating hybrid HPC/QCS systems, implementing software applications, and collaboratively define solutions potentially leading to Europe-driven standards and best practices.

Additionally, it is important to actively engage with the user community in order to prepare them with the skills required for exploiting the emerging hybrid HPC/QCS systems, as well as to continually apprise them of the evolving QC technologies, their maturity and capabilities. This demystification and collaborative development of applications will facilitate a co-design approach and avoid premature expectations about the capabilities of emerging HPC/QCS systems. This is essential to ensure a steady and collaborative progression in developing and adopting the technology.

a. Synergizing the EuroQCS developer community

A number of European Member States have developed (or are in the process of developing) national quantum initiatives to drive the funding and streamlining of their national efforts and participation in co-funded European programmes. These national initiatives and the Member State organizations implementing the work programmes are at different levels of maturity, while sharing the technical and strategic objectives – to operationalize national hybrid HPC/QCS platforms, connect them to their European counterparts, develop the system software and programming toolchains to develop strongly coupled hybrid HPC/QCS platforms and application workflows, and support the user community in the exploitation of these platforms.

Presently, individual collaborations amongst organizations have allowed the HPC/QCS developer community to share experiences and discuss potential for knowledge transfer across different Member States. For instance, a few interested EuroHPC National Competence Centers (under the EuroCC project) have formed a focus group on Quantum Computing. Such independent efforts are a positive development and highlight the interest in the developer and user communities. However, in order to amplify and accelerate the progress and expertise for European leadership in the development and adoption of EuroQCS, a structured pan-European framework will be essential. Such a framework would provide a mechanism for all Member State organizations to accelerate their collaboration, knowledge sharing and exchange of resources across the entire hybrid HPC/QCS value chain: development, deployment, operation and (potentially shared) usage of the infrastructure, systems, software, applications and training.

On the other hand, a number of EU programs that are focused on HPC have expanded to include QCS. Through the Horizon and Digital Europe Programmes, the Quantum Flagship, EuroHPC JU (particularly EuroCC, CASTIEL, ⟨HPC|QS⟩), PRACE, European Digital Innovation Hubs (EDIH) allow focus on different stages of the development, deployment, operationalization and service provision of QCS as well as hybrid HPC/QCS systems at the European level. For instance, the upcoming EDIHs will be implemented in each member state by consortia composed of research performing organizations, HPC centers and enterprises, and will serve as one-stop shops to help industry and public sector to dynamically respond to and adopt existing and emerging HPC (including QCS), AI and Cybersecurity technologies. Particularly, the Test Before Invest and Skills Development services in the EDIHs are ideal channels to provide access, support and expertise for adoption of the emerging hybrid HPC/QCS systems and technologies.

The above-mentioned EU programs focus on specific objectives and impact for developing and providing HPC/QCS systems and services. However, there is still a significant opportunity that remains to increase their synergy and provide increased fine-granular clarity on the roles and collaboration amongst them. For instance: access to platforms, support and training on HPC/QCS systems between PRACE, EuroHPC JU and EDIH; development of software components, tools and environments between Quantum Flagship and EuroHPC JU. A framework that explicitly elucidates and implements direct collaborations among the Horizon and Digital Europe Programmes would significantly maximize the impact and outcomes from their activities, while also increasing R&D collaboration and connected services between these programs.

b. Supporting the user community

If Europe is to remain at the forefront of the QCS arena, it must make a coordinated effort to build both a highly skilled workforce of application developers and highly skilled QCS end users. As the likely evolution indicates that QCS will be accessible via hybrid HPC/QCS machines, users will need to master competencies in the use of both quantum and high-performance computing technologies. This will be a challenge for practitioners from all areas of computer science. Moreover, this challenge can only be met if the leading organizations in quantum and high-performance computing come together and formulate a plan for joint knowledge sharing and competence transfer across Europe. In QT, the first steps in this direction are being driven by the QTEdu Coordination and Support Action, which is developing quality-controlled QT education programs in sectors corresponding to the three pillars addressed by the QT Flagship Strategic Research Agenda: Secondary Education, Higher Education, and Industry Education.

The major European HPC centers all have extensive training and skills transfer programs addressing all different areas of HPC. Lately, HPC centers' training offer also covers introductory aspects of quantum computing. With the advent of quantum simulators, the development of quantum algorithms is attracting increasing interest from advanced HPC users in addition to the "pure" quantum computing community.

The transfer of HPC capabilities has been very successful in a number of European initiatives such as PRACE, the FET QT, and the flagship initiatives of the Human Brain Project, as well as in numerous other EU projects over the past two decades. This has led to a tremendous amount of experience being built up among training providers and a deep trust within the many QT and HPC user communities across Europe. Thus, the HPC centers already provide a solid foundation for a future European skills transfer program in quantum computing and hybrid technologies. However, it is crucial to establish a closer network between the HPC and QT communities also in the field of education and training in order to fully exploit the experience in using new, emerging technologies. We need to take this to the next level and enable early adoption of quantum computing so that Europe remains a major player in QT.

Almost a decade ago, PRACE Training Centers were established across Europe. The initiative provided a coordinated training and skills transfer program in HPC techniques and technologies. It has evolved, and today a constantly updated program of training events is offered, along with a training portal with training materials, tutorials (videos), a code repository, and a series of MOOCS for individual immersion. An obvious development would be to complement the current program with training in quantum computing and the specific skills needed to use the emerging HPC/QCS systems.

With the establishment of the EuroHPC JU, the path to shared European exascale computing resources is laid out, with pre-exascale systems to be deployed in 2021-2022. This deployment will be accompanied by specific competence development programs for both industry and academia (e.g., in the EuroCC and CASTIEL projects). The EuroHPC JU's skills development program needs to be complemented by a similar effort on quantum computing and hybrid technologies.

Most of the basic training of future generations of European researchers will be provided by universities and research organizations. This being said, and in order to ensure Europe's sustained leadership in quantum computing, it is critical that various aspects of quantum technologies be incorporated into university curricula. Quantum computing technologies and quantum algorithms must become part of undergraduate level education in both computer science and computer engineering. In the applied sciences, it must be convincingly made clear that knowledge of quantum computing is an advantage for future professionals.

Established HPC centers must play an important role in bringing the necessary knowledge and expertise about QC to end users. This was already the case when HPC centers played an important role in introducing other new technologies, such as the use of compute nodes with Graphical Processing Units (GPUs). In addition, HPC centers have a unique overview of the HPC research community and can therefore better help identify the needs of the user base with a "bird's eye" viewpoint that higher education institutions often lack. In many cases, HPC centers are organizationally close to or even part of universities, especially universities with research in QT. Therefore, joint creation of training and skills transfer curricula for QC and hybrid technologies by these two types of actors can be envisioned as a natural, synergistic way forward.

c. Outreach

The second quantum revolution has been underway for nearly a decade and it has already been five years since the quantum flagship was founded. Private giants like IBM and Google and startups like

D-Wave Systems and Rigetti Computing have solidified their success in the field of quantum computing development. The world of quantum computing as a science, which existed many years before the realization of the first quantum computer prototype, is finally beginning to become technology.

But still the overwhelming majority of public opinion, including, unfortunately, a significant part of people involved in the scientific world, is unaware or insufficiently aware of the existence and concreteness of this new field of applications.

Unfortunately, even today, facts that are well known to experts, such as the close correlation between the world of HPC and the world of quantum computing, are still unknown or little known outside the sphere of people who are involved or actively interested in the developments of this new scientific field. Lack of communication in this type of activity, which often sees funding methods based on the participation of state governments, can create uncomfortable situations, especially from the point of view of underestimating the real effort required to realize the ambitious projects envisaged by the joint action.

Therefore, it is very important for EuroQCS to communicate in understandable terms and effectively all the steps intended to achieve the main objectives for the project of realization of a network of European supercomputers associated with quantum accelerators and to be able to achieve, at least in this new field, a technological European independence.

All HPC centers involved here have activated in-depth paths of quantum technologies focused on computational use. Many of them have simultaneously and naturally undertaken the beginning of a popularization campaign aimed at promoting quantum computing as a topic closely related to the HPC world.

In addition to the dissemination channels from supercomputing centers and from the bodies involved in the joint action, it is possible to leverage also on two other industry-oriented dissemination channels:

ETP4HPC Association. The European Technology Platform for High Performance Computing (ETP4HPC) is a private, industry-led and non-profit association with more than 100 members, from research organizations to small and large companies. Its main mission is to promote European HPC research and innovation in order to maximize the economic and societal benefit of HPC for European science, industry and citizens. A private member of the EuroHPC JU, ETP4HPC think-tank proposes research priorities and programme contents in the area of HPC technology and usage, by issuing a Strategic Research Agenda (SRA). ETP4HPC is adding quantum computing and its articulation with conventional HPC to its new SRA being elaborated in 2021.

TERATEC Association. Teratec is an association bringing together more than eighty companies and research laboratories constituting a European cluster of competence in high performance computing. Teratec members encompass many industrial and academic HPC stakeholders, from suppliers to users. Teratec promotes all HPC-related technologies and methods in order to tackle societal challenges and increase scientific and industrial competitiveness, thanks to high performance numerical simulation, data analytics, machine learning and AI. Teratec Quantum Computing Initiative (TQCI) is a specific action launched by Teratec to prepare the emergence of this new computing paradigm, leveraging its strong membership from research organizations and technology providers to advanced industrial users.

4. Recommendations

To ensure the success of the EuroHPC JU quantum plans, we have the following recommendations prioritized into three classes: Fundamental, important, and desirable. By "fundamental" we mean that if it is not met, the project will fail, and by "important" we mean that if it is not met, the quality of the project will be severely compromised. By "desirable" we mean that the recommendation is needed, but can be fulfilled later.

Fundamental Recommendations

1. Establish EuroQCS as a European federated quantum computing & simulation centre of excellence (CoE)
2. Establish a well-defined framework to support increased collaboration and knowledge transfer in the European HPC/QCS ecosystem between related Digital Europe and Horizon Europe Programmes, particularly to synergize the developer and user communities across member states
3. Support the development of software components, tools, runtimes and environments to ease the use of hybrid classical-quantum computing, targeting industrial quality and usability
4. Support the development of HPC-QCS integration technology (connectivity, middleware, and libraries to enable the deep integration of QCS in HPC infrastructures)

Important Recommendations

1. Promote EU quantum computing & simulation research and foster its outcomes and applications in the EuroHPC JU and EU computing centers
2. Foster the uptake of key enabling technologies for quantum computing & simulation. Support the development of scientific software applications for the use of HPC/QCS in relevant scientific and technological fields
3. Disseminate EU technology achievements, contribute actively to the definition and emergence of global standards that are relevant, practical and useful for HPC/QCS systems and their use

Desired Recommendations

1. Support the establishment of start-ups and their sustainable growth
2. Support open-source developments to create an operating system for quantum devices.
3. Promote and monitor the development and deployment of quantum computing & simulation technologies in Europe across federated, pooled efforts

Appendix A: Challenges in the HPC and QCS integration

In order to integrate HPC systems and QCS fundamental differences between the two computational paradigms need to be bridged. A first set of specific challenges to be addressed is listed here. As EuroQCS progresses, more may follow.

Integration at the hardware level

- Interconnection networks and connectivity between HPC and QCS nodes (hardware and protocol);
- Interconnection with emulators, such as the Atos QLM, for a smooth transition from experiments to production;
- Interface between different QCS devices (e.g., photonic and superconducting quantum devices);
- Scalability of QCS control, as the number of qubits scales;
- Error correction systems;
- Unified memories;
- Hardware monitoring (e.g. loss of coolant for mK implementations).

Integration at the system software level

- Scheduling, hybrid job submission;
- Resource management (system level);
- Offload / Data transfer and staging;
- Integration of error correction on QCS with HPC mechanisms (system level);
- QCS resources allocation.
- Virtualization and multi-user support

Integration at the programming environment level

- Integration into a base language
  - Single source programming for hybrid HPC/QCS paradigms;
  - Offload model like in OpenMP;
- Set of libraries providing (initially basic) algorithms, such as FFT for example;
- Integrated debugging and performance analysis working in user space.

Integration at the application/workflow level

- Resource management (user/application level);
- Granularity of offload;
- Integration of error correction on QCS with HPC mechanisms (user/application level);
- Data transfer between HPC systems and QCS counterparts.

Appendix B: QCS Hardware and Software Development in Europe

The following table lists the current European QCS hardware and software developers. The hardware developers include component manufacturers, quantum computing hardware developers and full-stack suppliers. The software developers include both tools providers (compilers, simulators, qubit control software) as well as application software providers.

Company name	**Location**	**Type**
AegiQ	UK	Hardware
Aivon	Finland	Hardware
Algorithmiq	Finland	Software
Alice&Bob	France	Hardware
AQT	Austria	Hardware
aQuantum	Spain	Software
Atos	France, Germany	Software
Bluefors	Finland	Hardware
C12 Quantum Electronics	France	Hardware
Cambridge Quantum Computing	UK	Software
ClassiQ	Israel	Software
Delft Circuits	Netherlands	Hardware
Duality Quantum Photonics	UK	Hardware
eleQtron	Germany	Hardware
equal1.labs	Ireland	Hardware
Fujitsu	Germany/Spain	Hardware
Google Germany	Germany	Hardware/Software
GTN LTD	UK	Software

Company name	Location	Type
HQS Quantum Simulations GmbH	Germany	Software
IBM Deutschland Research and Development	Germany	Hardware
IBM Zurich Research Laboratory	Switzerland	Hardware
Infineon Technologies	Germany	Hardware
Intel Ireland	Ireland	Hardware
IQM	Finland, Germany	Hardware
JoS QUANTUM	Germany	Software
Ketita Labs	Estonia	Software
kiutra	Germany	Hardware
Leonardo	Italy	Software
Menlo Systems	Germany	Hardware
Miraex	Switzerland	Hardware
Molecular Quantum Solutions	Denmark	Software
Multiverse Computing	Spain	Software
MuQuans	France	Hardware
NextGenQ	France	Hardware
Nordic Quantum Computing Group	Norway	Software
Okmetic	Finland	Hardware
Orange Quantum Systems	Netherlands	Hardware/Consulting
Oxford Ionics	UK	Hardware
Oxford Quantum Circuits	UK	Hardware

Company name	Location	Type
Oxford Instruments	UK	Hardware
ParityQ	Austria	Software
Pasqal	France	Hardware
PhaseCraft	UK	Software
PicoQuant	Germany	Hardware
Picosun	Finland	Hardware
PiDust	Greece	Software
Q-Lion	Spain	Software
Qblox	Netherlands	Hardware
QC Ware France	France	Software
QEDma Quantum Computing	Israel	Software
Qilimanjaro Quantum Tech	Spain	Hardware/Software
Qnami	Switzerland	Hardware
Qu&Co	Netherlands	Software
Quandela	France	Hardware
Quantastica	Finland, Estonia, Serbia	Software
QuantFI	France	Software
Quantopticon	UK	Software
Quantum Factory	Germany	Hardware
Quantum Flytrap	Poland	Software
Quantum Hardware Systems	Poland	Hardware
Quantum Machines	Israel	Hardware/Software

Company name	Location	Type
Quantum Mads	Spain	Software
Quantum Motion Technologies	UK	Hardware
Quantumz.io	Poland	Software
QuantWare	Netherlands	Hardware
Qubit Pharmaceuticals	France	Software
QuiX	Netherlands	Hardware
Quside	Spain	Hardware and software
Rahko	UK	Software
Riverlane	UK	Software
Rockley Photonics	US, Finland, UK	Hardware
SHYN	Bulgaria	Software
Single Quantum	Netherlands	Hardware
Sparrow Quantum	Denmark	Hardware
SpinUp AI	UK	Software
Squtech	Germany	Hardware
Strangeworks Deutschland	Germany	Software
Terra Quantum AG	Switzerland	Hardware/Software
Toptica	Germany	Hardware
TundraSystems Global LTD	UK	Hardware
Universal Quantum	UK	Hardware
Y Quantum – Why Quantum Technologies, Ltd.	Portugal	Software
Zurich Instruments	Switzerland	Hardware